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Research & Innovation for Climate Neutrality 2050

Challenges, Opportunities & the Path Forward

Research and Innovation

Research and Innovation for Climate Neutrality by 2050: Challenges, Opportunities and the Path Forward

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Research and Innovation for Climate Neutrality by 2050: Challenges, Opportunities and the Path Forward

A report submitted by ICF S.A.

in association with

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Glossary

A/F - Afforestation/reforestation

ACT - Accelerating CCUS Technologies

AI – Artificial Intelligence

AIM - Agricultural Innovation Mission for Climate

AUD - Australian Dollar

BE - Biomass

BECCS - Bioenergy with carbon capture and storage

BEECs - Building Energy Efficiency Codes

BEV - Battery Electric Vehicle

BIM - Building Information Modelling

C - Carbon

°C - Degree Celsius

CBAM - Carbon Border Adjustment Mechanism

CC(U)S - Carbon Capture, (utilisation) and Storage

CDR - Carbon dioxide removal

CEM - Clean Energy Ministerial

CEN-TC - CEN Technical Committee

CGIAR - Consultative Group on International Agricultural Research

CH$_4$ - Methane

CO$_2$ - Carbon Dioxide

COVID-19 - Coronavirus disease 2019 caused by the coronavirus SARS-CoV-2

CRCF - Carbon Removal Certification Framework

CRM - Critical Raw Material

DAC - Direct Air Capture

DACCS - Direct Air Capture with Carbon Storage

DG RTD - European Commission’s Directorate General for Research and Innovation

DOE - Department of Energy

DSO - Distribution System Operators

EC - European Commission

ECPA - Energy and Climate Partnership of the Americas

ECTP – European Construction Technology Platform

EEA - European Environment Agency

EERA - European Energy Research Alliance

EIC - European Innovation Council

EIIs – Energy Intensive Industries

EIT - European Institute of Innovation & Technology

EMS - Energy Management System

EOL - End-of-Life

ERA-Nets - European Research AREA-Net

ESPR - EU Ecodesign for Sustainable Products Regulation

ETIPs - European Technology and Innovation Platforms

ETS - Emissions Trading System

EU – European Union (synonymous with EU-27)

EU ETS - EU Emissions Trading System

EU-27 - European Union 27 Member States

EV - Electric Vehicle

FAO - Food and Agriculture Organization

FED - Final Energy Demand

GCCA - Global Cement and Concrete Association

GDP - Gross Domestic Product

GFAR - Global Forum on Agricultural Research and Innovation

GHG - Greenhouse Gas

GlobalABC - Global Alliance for Buildings and Construction

GPT - General-Purpose Technologies

Gt - Billion tons

GWh - Gigawatt hour

H_2 - Hydrogen

H2020 - Horizon 2020

HVAC - High Voltage Alternating Current

IAMs - Integrated Assessment Models

IBF - International Bioeconomy Forum

ICAO - International Civil Aviation Authority

ICs - Innovation Challenges

IDB - Inter-American Development Bank

IEA - International Energy Agency

IMP - Illustrative Mitigation Pathways

IMP-LD - Illustrative Mitigation Pathways Low Demand

IMP-Ren - Illustrative Mitigation Pathways Renewables

IoT - Internet of Things

IPBES - Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC - Intergovernmental Panel on Climate Change

IRA - Inflation Reduction Act

IRENA - International Renewable Energy Agency

IT - Information Technology

IURC - International Urban and Regional Cooperation

IWG - Implementation Working Group

JRC - Joint Research Centre

JTI - Joint Technology Initiatives

JUs - Joint Undertaking

KPI - Key Performance Indicator

kW - Kilowatt

kWh - Kilowatt hour

LCA - Life Cycle Analysis

m^3 - Cubic metre

MI - Mission Innovation

ML – Machine Learning

MoU - Memorandum of Understanding

MRV - Monitoring, Reporting, and Verification

Mt - Million tonnes

N_2O - Nitrous Oxide

NBS - Nature Based Solutions

NDC - National Determined Contributions

NGOs - Non-Governmental Organisations

NUWEPs - Neglected, Underutilised, and Wild Edible Plants

OAE - Ocean Alkalinity Enhancement

OECD - Organisation for Economic Co-operation and Development

OIN - Office of Innovation

OINR - Office of Innovation Research Extension Unit

OLADE - Latin American Energy Organisation

P2P - Peer-to-Peer

PPA - Power Purchase Agreement

PROSEU - Prosumers for the Energy Union

PV - Photovoltaics

R&D - Research and Development

R&I - Research and Innovation

RD&D - Research, Development and Demonstration

RD&I - Research, Development and Innovation

RES - Renewable Energy Sources

RES-H - Renewable Energy Sources - Geothermal heat

RSB - Roundtable on Sustainable Biomaterials

RTO - Research & Technology Organisations

RUL - Remaining Useful Life

SDGs - Sustainable Development Goals

SET Plan - Strategic Energy Technology Plan

SLs - Solution Landscapes

SMR - Small Modular Reactors

TCPs - Technology Collaboration Programmes

TRL - Technology Readiness Level

TSO - Transmission System Operator

TWh - Terawatt-hour

UAE - United Arab Emirates

UN - United Nations

UNDP - United Nations Development Programme

UNICEF - United Nations Children's Fund

US - United States of America

USD - United States Dollar

UTM - Urban Transition Mission

V2G - Vehicle to Grid

VC - Venture Capital

VPP - Virtual Power Plant

WEEE - Waste Electrical and Electronic Equipment

WFP - World Food Programme

WWF - World Wide Fund for Nature

Summary

OBJECTIVES OF THE STUDY

Transforming Europe into a climate neutral economy and society by 2050 requires extraordinary efforts and the mobilisation of all sectors and economic actors, coupled with all the creative and brain power one can think of. Each sector has to fundamentally rethink the way it operates to ensure it can transform towards this new net-zero paradigm, without jeopardising other environmental and societal objectives both within the EU and globally. In this context, the EU has seen the emergence of a vibrant ecosystem of cleantech innovators and investors over the last decade, supported - among other - by ambitious policy frameworks and research and innovation (R&I) agendas at national and EU level. This is only the beginning: indeed, as stressed by the IEA and the OECD, our ability to meet climate neutrality targets directly depends on our ability to innovate. Half of the greenhouse gas (GHG) emissions that must be achieved by 2050 are deemed to be dependent on solutions that are currently only at the demonstration or prototype stage.[1] The current level of innovation, however, is insufficient to meet the net-zero challenge.[2] To seize its "*man on the moon moment*", the EU must intensify its efforts and revisit its approach to R&I to ensure it is fit for purpose and well equipped to support the next wave of breakthrough innovations that will be required to achieve climate neutrality in the EU and globally by 2050.

The objective of this report is to contribute to this fresh thinking, with analytical rigour and broad-based stakeholder-involved reflections, to open up the consideration-space beyond narrow and siloed analysis of individual solutions, yet simultaneously also identifying specific high-risk and high-impact innovation areas for climate change mitigation. The study has set out to answer four research questions:

- Which climate mitigation solutions or group of solutions can be identified as both high-risk and high-impact and therefore require public support to reach market maturity in the next 10-15 years?
- Which are the opportunities and challenges of breakthrough & disruptive technologies in: (1) Net carbon dioxide removals (for GHG emissions which cannot be avoided from today's perspective) and (2) General-purpose technologies (GPTs) that can be developed and applied for climate change mitigation purposes?
- How can systemic interactions of climate change mitigation approaches be integrated in the development of R&I agendas?

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[1] IEA, 2021. Net Zero by 2050 A Roadmap for the Global Energy Sector. Available at: https://www.iea.org/reports/net-zero-by-2050

[2] OECD, 2023. DRIVING LOW-CARBON INNOVATIONS FOR CLIMATE NEUTRALITY. OECD SCIENCE, TECHNOLOGY AND INDUSTRY POLICY PAPERS No. 143. Available at: https://www.oecd-ilibrary.org/docserver/8e6ae16b-en.pdf?expires=1701870650&id=id&accname=guest&checksum=BD5A0FA19D9219F2546FC3DD90056DD8

- How can EU engagement in international fora be strengthened to facilitate the rapid development and diffusion of breakthrough solutions to fight climate change in the next 10-15 years?

OVERVIEW OF THE METHODOLOGY

To address these research questions, an exploratory research approach was adopted. Exploratory research is used to explore new topics or to propose new ideas on already well-developed topics. It does not follow a prescriptive methodology but allows the research team to adapt the approach as the research progresses. Based on this approach the above research questions were addressed from different angles while drawing on various complementary concepts and frameworks. This has allowed to test a set of hypotheses on breakthrough & disruptive technologies for climate mitigation and generate new insights. Key features of the research approach include:

- A comprehensive **literature review** to contextualise the study and identify relevant solution areas.
- An analysis of a variety of **climate neutrality scenarios** to identify key R&I areas and the nexuses that must transform to achieve climate neutrality by 2050.
- The design of **Solution Landscapes** to map climate mitigation solutions in a structured way. Building on recent literature around the design of low-carbon R&I programmes, the Solution Landscapes combine a “Solution Tree” with a “Challenge Tree” with the objective to: (1) Adopt a needs-based approach and ensure all the solutions identified serve a specific purpose and/or address a specific challenge or bottleneck on our way to climate neutrality; (2) Structure the study around a broad definition of the concept of ‘solution’ and avoid the pitfall of overfocusing R&I programmes on technological solutions only; and, (3) Consider solutions in their broader context by focusing on both ‘technical’ and ‘social’ challenges preventing our collective progress towards climate neutrality. In total 17 Solution Landscapes gathering more than 150 R&I areas were identified.
- A series of **Foresight Workshops & extensive stakeholder engagement**. Overall, more than 100 experts from academia, business, finance, policy and civil society were engaged in the study.
- The design and implementation of a detailed **evaluation framework** to systematically screen the R&I areas identified in the Solution Landscapes and identify the ones with both the highest mitigation potential and the highest need of policy support. Building on the results of the literature review, the framework is composed of 22 criteria clustered in five pillars. Each of the identified R&I areas were assessed based on qualitative expert judgements supported by the literature review.
- The adoption of a **systemic perspective & needs-based approach** in the assessment of R&I areas and associated nexuses. Starting from the essential needs that must be addressed in a sustainable manner to allow for more than 10 billion flourishing lives on earth while reaching climate neutrality, i.e.: Shelter, Energy supply, Mobility, Food, Water, Social interaction and participation, the Solution Landscapes were clustered in three *nexuses* gathering the set of solutions required to address the identified needs. These nexuses were then used to structure the analysis at different levels: (1) Analysis of the results of the

evaluation framework at nexus level; (2) In depth-analysis of the three nexuses to identify challenge, solutions, spillover effects, and potential risks and trade-offs that result from these interactions; (3) Identification of a series of case studies to root the analysis and recommendations in concrete examples of innovative solutions. To support this systemic analysis, the *"positive tipping point"* framework introduced in the Box below was also leveraged.

How can R&I programmes play a role in triggering positive tipping points?

Changes in complex systems are often non-linear and triggered by multiple intentional and non-intentional interventions, whose cause and effect may not be proportionate. A **tipping point** represents a critical point in a system beyond which an important and often disproportionate change occurs. Understanding the tipping point mechanisms that will bring about such conversions are important to policy makers, since they can help to achieve important scaling effects, generating greater system impacts from limited available public resources. The positive tipping point framework can be used as a guide to inform the design of R&I funding programmes, extending them beyond their typical techno-centric focus. The framework identifies different levers that need to be actioned in order to create the right conditions for the emergence of large scale, systemic tipping points.

Levers include: **Economic competitiveness & affordability**: to stimulate demand, proposed new and alternative solutions must be economically competitive to existing solutions; **Performance & attractiveness**: proposed alternatives must meet - or outperform - existing solutions on required levels of performance or quality; **Accessibility**: the solutions, or the change in behaviour proposed by the alternatives, can be conveniently accessed by stakeholders; **Cultural norms & desirability**: alternatives are also socially desirable/acceptable and normalised across stakeholders; **Capability & information**: stakeholders have the right information to use the solution, or act on the behaviour; and, **Complementarity**: proposed solutions are surrounded by complementary innovations, including across the whole value chain, allowing their rapid deployment leading to the displacement of the old solution suite.

The framework identifies different "reinforcing feedback loops" to achieve these conditions at scale (e.g., social contagion, increasing returns on adoption, information cascade, etc.) and intervention types that should be implemented to trigger these feedback loops, create the right enabling conditions and eventually tip the system. In designing R&I programmes, the framework puts the broader enabling environment on an equal footing with "innovation and technology" focused interventions.

KEY FINDINGS

1. Solution landscapes (SLs) for climate neutrality

The SLs were used to map the climate mitigation solutions and R&I areas in a structured way, based on the results of the climate neutrality scenario analysis. Particular attention was given to the role of GPTs in addressing the identified challenges and supporting the development of new solutions. In total, 17 Solution Landscapes were designed, resulting in a long list of more than 150 R&I areas with the potential to significantly contribute to climate mitigation efforts. The Box below shows how the SLs are clustered by type of scenarios depending on the type of overarching goal they aim to address and the solutions they cover.

Overview of the 17 Solution Landscapes, clustered by type of scenarios depending on the type of overarching goal they aim to address

Solution landscapes driven by techno-economic climate-neutrality scenarios

1. Solar PV
2. Wind energy
3. Power system flexibility
4. Energy storage
5. Hydrogen economy
6. Industrial decarbonisation
7. Green steel
8. Built environment
9. Decarbonising mobility

Solution landscapes linked to greenhouse gas removals

10. Direct air (CO2) capture (DAC) technologies
11. Point source capture technologies (including biomass)
12. Durable storage (including in long-lived products)
13. Terrestrial ecosystem-based removals
14. Ocean-based ecosystem removals

Solution landscapes driven by lifestyle/societal trends climate neutrality scenarios

15. Circular economy
16. New food
17. Digitalisation

2. R&I areas to enable climate neutrality

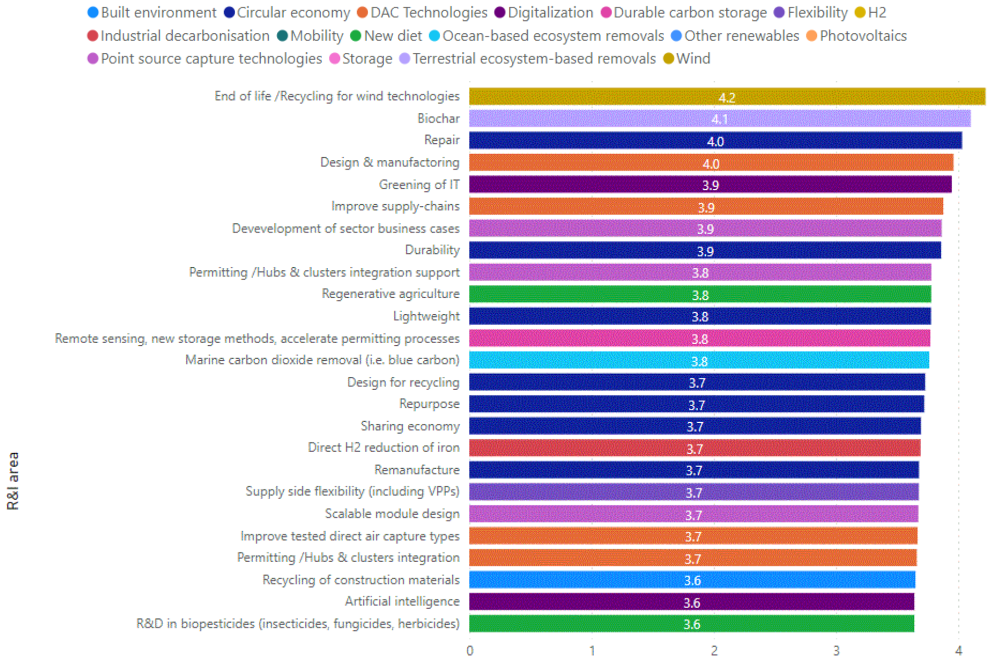
A **detailed evaluation framework** was designed to screen all R&I areas and identify those with both the highest mitigation potential and the highest need of policy support. The objective of the framework was to identify R&I areas that:

- Are not commercially available yet, but do not face insurmountable obstacles to achieve commercialisation in a 10–15-year timeframe (Pillar 1 – Techno-economic feasibility);
- Have an important climate mitigation potential (Pillar 2 – Mitigation potential);
- Does No Significant Harm to (i.e., negatively impacts) other environmental objectives (Pillar 3 – Environmental impact);
- Have the potential to generate socio-economic benefits and meet acceptance (Pillar 4 – Socio-economic impact); and,
- Are not already benefiting from extensive support from existing R&I programmes in the EU and beyond (Pillar 5 – Current level of support).

The results of the screening provide a composite index scoring R&I areas from 0 to 5, 5 being the highest and indicating the types of R&I areas that should be prioritised by R&I programmes. The R&I areas scoring the highest in the evaluation framework are listed below (shown by Solution Landscape colour coding in Figure 1).

It is important not to regard this approach as a ranking exercise. The selected R&I areas should be seen in a broader context that considers the challenges and interactions between different areas following a more systemic approach – as well as within specific nexuses. Although the evaluation framework highlights a precise list of R&I areas, this should be seen as a supporting mechanism for a broader exercise selecting areas to be considered when looking at the nexuses and needs.

Figure 1. 25 highest scoring R&I areas resulting from the evaluation framework, colour coded by Solution Landscape. Source: ICF & partners, 2023.

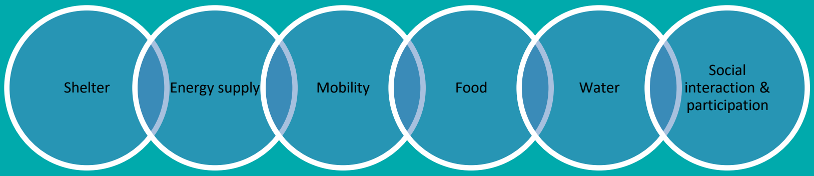


3. A systemic view on societal needs: Three nexuses for climate neutrality R&I actions

The results of the climate neutrality scenarios analysis and the SLs were then confronted with a needs-based approach aiming to link specific solutions and R&I areas to broader societal needs that must be met to succeed the transformation the economy towards a truly sustainable model. As stressed by the European Environmental Agency (EEA), the transition towards climate neutrality requires a fundamental transformation of the "*production-consumption systems that meet [our]* *demand for energy, food, mobility, and shelter*".[3] The Box below illustrate how this transformation was approached in this study.

The transformation of our society towards climate neutrality can be addressed through three nexuses

Overall, the needs that the climate neutral economy will have to meet sustainably to provide a flourishing live for the global population are:



Meeting these needs in a net-zero economy will require thoughtful measures centred on three *nexuses* where technological and societal innovation is possible and required:

- Mobility – Built environment – Energy nexus
- Circularity – Industry – Carbon removals and capture nexus
- Agrifood – Carbon removals nexus

Each of the nexuses also has large interconnections with UN Sustainable Development Goals (SDGs). In this study the focus is put on the energy and GHG emission relevant nexuses, while there are further interconnections to be considered with sustainable development targets such as water, biodiversity, etc. These objectives were considered in the study but the detailed analysis of the Climate – Biodiversity – Water nexus is for example beyond the scope of this study.

To identify high impact / high risks R&I areas across the three nexuses defined above, the results of the evaluation framework were further developed, focusing on the priority R&I areas emerging from the identified nexuses.

Mobility – Built environment – Energy nexus

Within this nexus (Figure 2), three of the five R&I areas that ranked first are related to **end-of-life treatment** and **recycling**, including those materials used for wind and PV technologies that will start to require recycling as the earliest such developments across Europe reach their end-of-life, and construction materials (e.g., cement, steel) from buildings either renovated or demolished. **Alternative building materials** such as green steel and cement, together with nature-based materials, stand out alongside further R&I efforts towards promoting prefabrication and modular construction methods.

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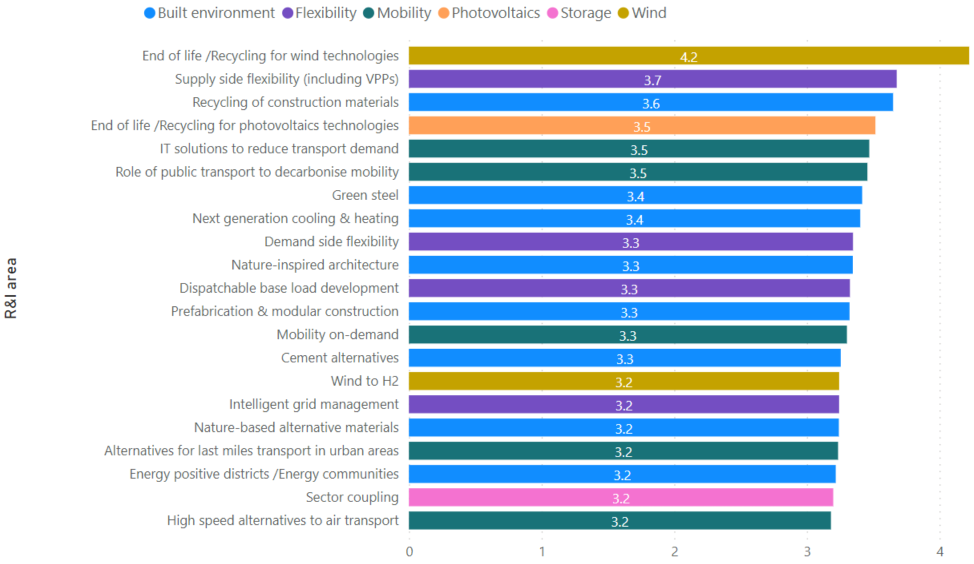
[3] European Environment Agency, 2023. Imagining sustainable futures for Europe. Available at: https://www.eea.europa.eu/publications/scenarios-for-a-sustainable-europe-2050.

R&I within the **mobility** sector is another theme of importance, with the solutions scoring highest linked to limiting overall transport demand (through IT solutions and mobility-on-demand) and the role of public transport to decarbonise mobility.

R&I efforts in **supply and demand side flexibility** (especially around virtual power plants (VPPs)) score high and can be seen as a key enabler for the transformation of the full nexus. Surprisingly, **energy storage solutions** do not score high, calling for a further investigation of these solutions as they represent a key enabler and an important challenge for the transformation of the nexus overall. The principal reasons for the relatively low scores of energy storage solutions in the evaluation framework comes from the exposure of these technologies to critical raw materials (primarily batteries), as well as a relatively low novelty factor for many storage technologies such as pumped hydro storage or gravity storage. The availability of significant existing R&I funding for storage technologies, particularly batteries, is also a key reason. Therefore, and as highlighted above, this outcome should be interpreted in the context and purpose of the evaluation framework applied. These technologies and solutions still remain critical in reaching the climate neutrality target.

Figure 2. Evaluation framework results for the mobility, built environment and energy nexus. Source: ICF & partners, 2023.



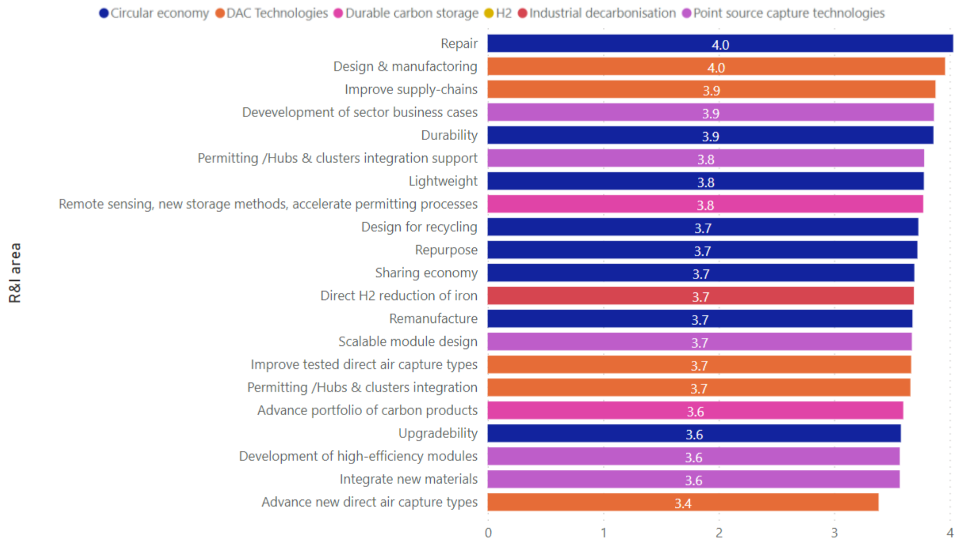
Circularity – Industry – Carbon removals and capture nexus

Several R&I aspects of the "**circular economy**" solution landscape score high given their transversal nature (Figure 3), specifically those in relation to industrial decarbonisation (notably steelmaking with direct hydrogen reduction of iron, and cement production), as well as the potential applications of carbon dioxide removal/capture in industry. Due to this transversal nature, these R&I areas are not defined very precisely, calling for more refined research to identify specific R&I needs.

This analysis, combined with that from the "Mobility – built environment – energy" nexus, represent, however, a strong call to mainstream the 5 Rs of circular economy, i.e., "**Reducing, Reusing, Refurbishing, Repairing and Recycling"** across all R&I efforts, underpinning a need for both technical and social innovations to be supported.

In addition, decarbonisation efforts of key industrial processes such as steelmaking and cement production might have significant synergies with carbon removal and carbon capture technologies, notwithstanding a fundamental necessity of decarbonisation of these processes even outside a carbon removal/capture framework. A deeper technical integration of **Carbon Dioxide Removal (CDR)/Capture technologies** in industry will also need to be accompanied by new conceptions of business models in this sector. The CDR R&I areas that scored highest are linked to Direct Air Capture (DAC) design/manufacturing/supply chains improvements and the need to further refine the business case for point source capture technologies across sectors. These findings dovetail well with the Commission's November 2022 proposed Carbon Removal Certification Framework (CRCF) Regulation, which aims to scale up the CDR industry whilst ensuring greenwashing is avoided[4].

Figure 3. Evaluation framework results of the circularity – industry – carbon removal and capture nexus. Source: ICF & partners, 2023.



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[4] European Commission, 2023. Carbon Removal Certification. Available at: https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/carbon-removal-certification_en

Agrifood – Carbon removals nexus

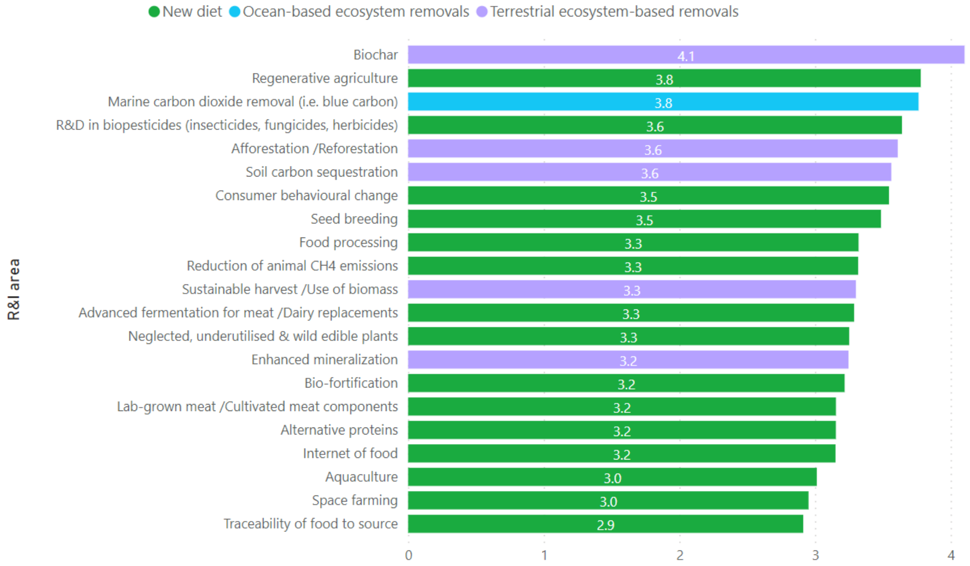
The agrifood-carbon removal nexus (Figure 4) covers technologies related to novel and/or improved agricultural techniques and behaviour, as well as terrestrial and marine ecosystem-based CDR methods. Some of the terrestrial removal technologies which can be integrated into existing agricultural systems have high mitigation potential according to the evaluation framework (e.g., biochar, afforestation/reforestation (A/F), soil carbon sequestration). **Biochar** production is mature, but applications for removals remain underdeveloped. R&I should target durability, MRV requirements, and adoption-related questions regarding business cases and barriers among farmers and communities.

The integration of such removal technologies has high synergies and common practices with approaches related to the science and business of transitioning towards a **regenerative agriculture**, which in turn has links to the development and application of **biopesticides** (replacing chemical pesticides), which could help stimulate new market opportunities in advancing biological pest control. Finally, **consumer behavioural change** also scores high and represents an important mechanism that will be vital in embracing new approaches and business models.

Note that these areas can also have other positive side effects like increased biodiversity, which is a key objective of regenerative agriculture and biopesticides but is also typically observed in **afforestation/reforestation (A/F)**. The important connections of these R&I priorities to water availability and use as well as the promotion of Nature Based Solutions (NBS) are also worth reiterating in the context of overall Green Deal policy objectives.

Similarly, **blue carbon** solutions (including capture and storage of CO_2 in mangroves, as well as seagrass and kelp farming) have positive GHG mitigation (and biodiversity) implications and can be integrated with many forms of sustainable aquaculture. R&I efforts are however still needed to support their scale up through appropriate implementation and monitoring technologies and practices that track both the carbon flows and ecosystem effects under realistic application scenarios – including remote sensing. Transdisciplinary R&D can also enable resolving regulatory and public acceptance barriers including governance problems of the high seas and domestic law. In addition, R&I funding for ocean-based carbon removals ought to further develop and assess the potentials and risks of currently immature methods (e.g., artificial up-/down welling, ocean alkalinity enhancement (OAE), and micro-nutrient fertilisation). While the theoretical potential of these solutions is very large, they require careful examination to enhance the understanding of how the complexity of marine systems (tipping points; biological and biogeochemical responses under hypoxic and/or anoxic conditions; and, abundances and diversity of phytoplankton) intersects with realistic application scenarios. R&I in MRV systems and regulatory and socio-economic aspects need to be researched in applied transdisciplinary settings.

Figure 4. Evaluation framework results of the agrifood-carbon removal nexus. Source: ICF & partners, 2023.



General considerations on the prioritisation of R&I areas across nexuses

As stated above, while this prioritisation exercise has enabled the identification of key R&I areas to focus on, given the objective of the research (and therefore the chosen criteria), it is important not to regard the approach as a ranking exercise. Instead, this approach should support an informed decision making based on different criteria, as well an objective and structured overview which could also be weighted if needed to answer a specific research question.

Further notes of clarification are important in this context:

- Each defined R&I area should contain an interwoven set of technologies and solutions, not only including winners but also enabling and supporting solutions. Important **enabling solutions** requiring attention in each defined group include both Materials and GPTs.
- Each defined nexus contains **key enabling conditions** identified in the "positive tipping points framework" and comprising: (1) Economic competitiveness & affordability; (2) Performance & attractiveness; (3) Accessibility; (4) Cultural norms & desirability; (5) Capability & information; and, (6) Complementarity.
- For the identified solutions **further steps** follow (and which have been carried out in detail for the selected case studies as detailed in section 6 of the report), which put those identified solutions in context by applying the various systemic approaches described above. This includes identifying:
  - the relevant nexuses;
  - relevant challenges (technical, societal and regulatory).
  - dependencies;
  - enabling properties of the solution; and,
  - important related tipping points.

- It is further important to focus on **limiting factors** in innovation landscapes and nexuses (just like innovation in an industrial plant can be held back by individual factors ranging from technological scalability, resource- and supply-chain constraints, permitting and regulation, acceptance, politics, economics, personnel capacities, abilities to link into future revenue sources such as carbon markets and an intricate mix of the above).
- Also, in order to align the defined group of technologies and solutions determined by the above approach with the mission / future need they should target, a core narrative needs to be established (again carried out for the selected cases) by combining all the assessments with both the tipping point and mission-based approaches (employing **back-casting from needs** and thinking about various possible endpoints).
- Though an important paradigm of R&I funding, there are significant **challenges in picking winners** when it comes to accelerating technology solutions toward a particular societal objective – as is the case for achieving a climate change mitigation goal. There is inherent uncertainty and dynamism in the innovation landscape, which precludes stringent anticipation over longer periods of time, for which several competing technology solutions may indeed reach the greatest potential. R&I in the realm of climate change is a rapidly evolving field, making it difficult to foresee which technologies will ultimately prove to be most effective in achieving climate goals – not least because societal factors play into these dynamics in often unexpected ways. With bounded rationality and an inherent limitation in the anticipatory capacity of R&I funding institutions, one cannot assume that R&I decisions and their outcomes could ever be optimally determined. This raises questions about the approach of heavily investing in a particular technology or solution, given the risk that it may be surpassed by another, more effective or efficient innovation.
- In addition, the systemic investigations during this study have shown that only picking winners will still fail because of limiting factors and missing enablers which may not show up as winners at first glance. Therefore, **a multi-dimensional approach should always be applied**. Nevertheless, it is still essential to identify what might be important high-risk and high-impact R&I areas to fund, and therefore require public support to reach market maturity in the next 10-15 years.

Despite the importance of systemic interactions and overcoming trade-offs that might arise, breakthroughs do not fall from the sky: they happen when **incremental progress** crosses a threshold, causing the impression of sudden appearance. It is therefore necessary to continue to work on increments to achieve leaps forward – and hence why it is necessary to fund focused innovation by picking specific innovative solutions and advancing GPTs. This is a necessary aspect of accelerating high-risk, high-impact R&I solutions towards scaling over the required timeframe to achieve climate neutrality in Europe.

4. Challenges and opportunities of breakthrough & disruptive technologies in net carbon removals

Challenges

Given that for climate neutrality residual emissions and removals must be in balance, removals – as a broad category of action – play a particularly relevant role in achieving European climate neutrality and even moving beyond towards a net-negative emission economy. The IPCC foresees three distinct roles for removals: (1) immediately accelerating the downward slope of net-emissions; (2) achieving climate neutrality in the mid-term; and (3) achieving net-negative system-wide emissions thereafter. While the first role can be seen in competition with policies accelerating the diffusion of mitigation technologies which are already more mature and most likely cheaper than CDR (e.g., accelerated building rehabilitation programmes), the second and third role are clearly important cornerstones on "the last miles" to net climate neutrality. This is why the study investigates in a dedicated chapter the R&I needs of the CDR.

Research and innovation related challenges in this space are strongly tied to the public-good nature of most removal methods. Without decisive and tailored R&I support, as well as a clear runway toward long-term policy support, this entire category of action could falter. Each removal method has its own profile of opportunities, challenges and limitations, including notably in relation to resource requirements, such as for: a) biomass; b) water; c) heat; d) power; and e) land. Such resource constraints, limited maturity and high costs of carbon removals and Carbon Dioxide Removal (CDR) have been cause for concerns over excessive reliance on CDR in IPCC scenarios. Removals, which rely on natural sinks in the oceans or on land, furthermore, face significant MRV challenges. Successful mobilisation of removals toward net-zero thus demands a tailored portfolio approach.

Carbon dioxide removal methods are sometimes categorized into ‘nature-based solutions’ and other (more technology-reliant) approaches. These are, however, not well-defined solution categories. Following the definition of the IUCN[5], whether or not a removal application is a *nature-based solution* depends on the form and context of its use in each specific case (rather than representing a technology-inherent characteristic). This points to the challenge of ensuring context-appropriate utilization of this broad cluster of mitigation technologies and practices.

Another key challenge lies in the early Technology Readiness Level (i.e., TRL 1-2) of many removal methods. This indicates that there is substantial potential for development and disruption to the market within a time-horizon of 10-15 years. To realise this potential, large scale private and public investments are required.

At the same time there are several removal methods, which are technologically fully mature, the mobilisation of which, however, requires innovation in incentivisation through regulation, policy and carbon markets. Capturing carbon emissions from point sources – including those combusting (some) biomass – is being piloted in several

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[5] The International Union for the Conservation of Nature (IUCN) defines nature-based solutions as: “Actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature." (See https://www.iucn.org/our-work/nature-based-solutions)

European countries (e.g., in Sweden, Iceland, and the Netherlands) and should be scaled through a combination of adequate incentives to unlock attractive business models and immediate development of necessary transport and storage infrastructures (hubs and clusters). R&I interventions are needed to identify opportunities and limiting factors for such business models and infrastructure developments.

Review articles in the interrelated fields of carbon removal and CCS, already offer a broad-based, interdisciplinary overview of the CDR landscape. Much of the CDR challenge is in the sphere of political adoption. Yet research and innovation does have an important role to play in bringing down cost, resolving resource challenges through more efficient processes and facilitating adoption of smart MRV approaches. There are, however, gaps in the academic literature when it comes to newer technological approaches; and R&I interventions should be carefully designed to not lock-out newer (and yet undiscovered) innovation spaces, including new sorbent materials or thermodynamic processes for capturing and releasing CO_2.

Opportunities

As described above, five SLs were developed to capture the set of R&I areas and the associated opportunities related to net carbon removal. These SLs are presented in detail in the separated Annex including all the SLs. Given the objective to adopt a systemic perspective across the study, these SLs were integrated in the different *nexuses* described above. It is however important to recognise that they are interconnected both amongst each other as well as with disruptive GPTs. New information and communication channels could for example impact all net carbon removals solution, especially in regard to socio-economic and political aspects of MRV, social acceptance, and regulation. Given the specific role that GPTs are expected to play for net carbon removal solutions, specific opportunities and challenges were identified.

Specific opportunities and challenges of GPT related to CDR

(i) Remote sensing/Earth Observation:

Opportunities: Remote sensing is much needed to be embedded into MRV systems, especially for ecosystem-based CDR, where (re-) emissions and carbon uptake happen over large areas (rather than point source emissions or DAC), and controlling re-emissions is vital to ensure permanent storage and account for leakages. Reliable remote sensing solutions are key to establish such CDR methods at a larger scale in carbon markets, especially in compliance markets with high standards for environmental integrity.

Challenges: Remote sensing generates large amounts of data, of which the interpretation can be very challenging. Coupling remote sensing with AI solutions can help to overcome this issue. Data ownership and potentially privacy concerns are further issues associated with remote sensing. Depending on the scale of monitored CDR activities, the spatial resolution of remote sensing data may need to be extrapolated, leading to uncertainty and inaccuracy.

(ii) Artificial Intelligence (AI):

Opportunities: AI can support optimization especially of technical CDR solutions like DACS or BECCS by analysing data in real-time to adjust operating parameters.

Further, AI can play a supporting role in maintenance and monitoring of technical systems. In terrestrial ecosystem-based CDR, AI can be used to identify suitable sites by analysing data on soil, precipitation and solar irradiation, and by optimizing the use of fertilizers and irrigation.

Challenges: Training and functioning of AI to support CDR are challenging due to inconsistent and patchy data, as well as the need to model complex and potentially variable technical (DAC, BECCS) and environmental (ecosystem based, BECCS) systems. Validating the performance of AI models in CDR is crucial for gaining trust in their recommendations. This can be challenging due to the lack of historical data for validation and the long timeframes required to assess CDR outcomes. Overall, a lack of trust in and public opposition against AI could proof challenging for such applications in CDR.

(iii) Blockchain technologies:

Opportunities: Blockchain technology can play a substantial role in the verification process of carbon markets, including emerging CDR certificate markets. Tokenisation of removals could help to avoid double-counting, and will increase transparency, thereby improving trust in the markets and making accounting and reporting easier.

Challenges: A key challenge of using blockchains is the high energy demand of this technical solution. Given the source of energy (renewable vs. fossil), emissions from energy generation required for utilising the technology in carbon markets potentially overcompensate the removals generated through the benefits of utilising it. Even if renewable energy is used to run blockchains, the large-scale use will lead to conflicts over the availability, especially when electrification of several sectors will require increasingly much (renewable) energy. So far, carbon market regulations are not suited well to take up blockchains. The existing frameworks and processes will need to be revised to enable blockchain specifically, and digital MRV in general. Clearly, the EU cannot operate in isolation, particularly given globalised value chains and the flow of capital from international institutions and investors into the R&I space. Here it become more complex to plan effectively due to systemic aspects and the global perspective.

(iv) Examples of other GPTs with the potential to support CDR development:

In addition to the three specific examples above, other GPTs have the potential to support and affect CDR development in a positive manner. They include the following R&I areas:

- New materials are expected to play a role in enhancing the capture efficiency of engineered CDR solutions, e.g., via advanced porous materials like metal-organic frameworks with a high surface area;
- Genetic modifications (bioengineering) can be applied to enhance photosynthetic or (in the case of bioenergy generation) energetic performance of plants and/or microorganisms; and,
- Synthetic biology aims to achieve similar effects, but typically focusses on engineering microorganisms that turn captured CO_2 into chemicals for further use, e.g., in biofuels or chemical industry. This does not always result in a permanent CO_2 removal, but rather in delaying the emission. However, there are also

attempts to use synthetic biology to turn captured carbon into more stable materials.

5. Opportunities and challenges of breakthrough & disruptive GPTs that can be developed and applied for other climate change mitigation purposes

GPTs are innovations that have the potential to significantly impact and transform multiple sectors of the economy and society. These technologies are characterised by their broad applicability, adaptability, and the profound changes they bring about in various industries and aspects of daily life. They often act as catalysts for economic growth, productivity enhancements, and societal progress. They can act as lubricant for transformation across all nexuses as described below.

Importance of GPTs to the mobility-built environment-energy nexus

In terms of **mobility**, the use of GPTs (like AI) as important enablers of autonomous vehicles and advanced transportation systems is reshaping mobility. Self-driving cars, for instance, have the potential to reduce accidents, congestion, and greenhouse gas emissions (the latter being clearly dependent on behavioural factors and usage patterns). Furthermore, the integration of mobility-as-a-service platforms is making transportation more efficient and accessible. GPTs enable the transition to sustainable and interconnected transportation networks, reducing the environmental impact of mobility or even the need for mobility, e.g., for work purposes.

In the **built environment**, the incorporation of GPTs (e.g., datatags and nanotechnology), into construction technologies and energy-efficient building materials are revolutionising the way we design, construct and monitor structures including with end-of-life considerations in mind. Smart cities, equipped with GPT-enabled infrastructure, optimize resource use, improve urban planning, and enhance the quality of life for residents. GPTs also allow for the creation of resilient, sustainable, and energy-efficient cities, reducing the carbon footprint of the built environment.

In the **energy** sector, GPTs are being used to analyse very large datasets generated by smart meters, which in turn have enabled a transformation in the way energy usage is monitored and analysed by both Transmission System Operators (TSOs) and Distribution System Operators (DSOs). This has led to dynamic forecasting and predictions of energy demand (which can help plan RES usage/storage and avoid bringing online fossil-based power stations at peak load times), the optimisation of energy usage (for example, via different types of tariffs to manage demand, especially from industry), and the ability to aggregate load shedding during peak usage periods at the household and industry level (demand response). Specific GPT applications include energy efficiency optimisation, load balancing and predictive maintenance. GPTs are crucial in enabling the transition from fossil fuels to renewable energy sources, reducing GHG emissions and promoting energy efficiency, and facilitating energy sector decarbonisation. GPTs can largely contribute to the development of Energy Communities and Scalable Positive Energy Districts.

The implementation of GPTs has the capacity to enhance the relation between these three thematic areas, through solving the following challenges:

- **Material abundancy, as well as the area of tension between efficient materials vs sustainable materials:** GPTs enable breakthroughs in materials science, leading to the development of new materials that are not only more efficient but also more sustainable/have a lower CO_2 footprint. For example, nanotechnology and advanced composites can produce lightweight yet strong materials for various applications, reducing resource consumption and environmental impact. In addition, GPT-driven technologies like 3D printing and advanced manufacturing processes allow for precise and efficient use of materials. This minimizes waste during production, optimizes resource utilization, and reduces the demand for raw materials.

- **Supply chain sustainability:** GPTs facilitate the monitoring and optimization of supply chains, ensuring that materials are sourced sustainably and transported efficiently. This reduces the environmental impact and GHG emission-intensity associated with resource extraction and transportation.
- **Resource shortages (e.g., due to more pressing needs in other areas or missing recycling solutions):** GPT-driven technologies, such as advanced manufacturing processes and big data analytics, can optimize the use of resources in various industries. These technologies reduce waste, increase production efficiency, and make the most of available resources, helping to alleviate resource shortages. In addition, GPTs enable the transition to a circular economy by facilitating the design of products and systems for reuse, remanufacturing, and recycling. This approach extends the lifespan of resources, reducing the demand for new raw materials.

Importance of GPTs to the circularity-industry-carbon removals nexus

GPTs can affect processes within several core aspects of this nexus. For example:

- **Advanced Materials and Manufacturing Techniques:** GPTs can drive innovations in materials science and manufacturing technologies, leading to the development of more sustainable and recyclable materials. For instance, advanced composites and biomaterials can replace traditional materials in various industries, making products more recyclable and reducing the carbon footprint of manufacturing processes.
- **Circular Economy Technologies:** GPTs enable the implementation of circular economy principles in industries. Advanced data analytics and supply chain optimization tools can help industries design products for longevity, reuse, and recycling. They can also support reverse logistics, making it easier to collect and recycle products and materials at the end of their life cycle.
- **Carbon Capture and Utilization (CCU):** GPTs, particularly those related to chemistry and materials science, can enhance CCU technologies. These innovations allow industries to capture carbon emissions from their operations and convert them into valuable products, reducing the carbon footprint of industrial processes.

Other areas in which GPTs can have an active influence in this nexus include: Energy Efficiency and Electrification; Carbon Removal Technologies; Data Analytics and Optimization; Sustainable Supply Chains; Consumer Awareness and Engagement; and, Policy and Regulatory Support.

Importance of GPTs to the agrifood-carbon removals nexus

GPTs have a strong influence on this nexus as it plays a significant role in addressing the challenges at the intersection of three areas, where the aim is to make agricultural and food production more sustainable, while actively removing CO_2 from the atmosphere. Examples of how GPTs contribute to this objective include:

- **Precision Agriculture and Data Analytics:** GPTs enable precision agriculture by utilising sensors, data analytics, and machine learning. These technologies optimise resource use in farming, leading to higher crop yields, reduced inputs (such as water and fertilisers), and lower greenhouse gas emissions per unit of food produced.
- **Climate-Resilient Crop Varieties:** GPTs in genetics and biotechnology can expedite the development of climate-resilient crop varieties. These crops are more resistant to extreme weather events and require fewer inputs, making agriculture more sustainable and less carbon intensive.
- **Carbon Farming Practices:** GPTs support the adoption of carbon farming practices such as agroforestry, cover cropping, and reduced tillage. These practices sequester carbon in soil and vegetation, reducing atmospheric CO_2 levels while improving soil health and crop productivity.

Other areas in which GPTs can have an active influence over Agrifood-carbon removals are Carbon Capture in Food Production, Supply Chain Traceability, Food Waste Reduction, Alternative Protein Sources, Sustainable Aquaculture, Consumer Awareness and Behaviour and Policy Support.

Opportunities across nexuses

Breakthrough and disruptive GPTs such as AI or big data can provide great opportunities when applied to climate change mitigation purposes:

- GPTs can enable several solutions from different areas to be pushed forward at the same time;
- They can link the various nexuses and adjust for systemic interactions;
- They can support tipping points and corresponding enabling conditions; and,
- GPT development can further accelerate innovation cycles, facilitate the creation of new business models, and cut costs at a faster rate, potentially leading to the triggering of certain tipping points.

Challenges across nexuses

Overall, GPTs can have a positive impact on sustainability and energy efficiency. However, their introduction also requires guidelines or norms to be established to ensure that the challenges they create are identified and mitigated as effectively as possible. First, it is critical to identify the most desirable future narrative for each GPT to ensure sustainable use and avoid potential negative impacts on climate change mitigation efforts. Second, GPTs create new dependencies and highly complex (and sometimes also unexpected) systemic interactions which may have knock-on consequences in other R&I areas; and, finally, GPTs can lead to a rapid and evolving need for suitable regulatory conditions to be considered, particularly in the context of regulated markets, so an important aspect is to identify possible risks related to GPT deployment and ensure that regulatory conditions are adjusted accordingly.

It is also important to consider the negative, unintended consequences these technologies can bring from a technical, societal and governance perspective. In addition to the new dependencies they can create, the adoption of GPTs can affect consumer behaviour by dramatically increasing energy consumption or the systemic changes it entails, by replacing humans with AI and the establishment of massive and power-hungry data centres which may contribute to a rebound effect. These unintended negative consequences of GPTs also have to be targeted in the context of the systemic R&I discussed in this study.

6. Integrating systemic interactions of climate mitigation approaches in the design of R&I agendas

Starting from the limiting factors preventing the adoption of systemic thinking in the design of R&I programmes, one can identify a series of enabling conditions required to progress towards the adoption of systemic thinking:

From…	**… To**
Siloed Mindsets and Structural Barriers	Systemic thinking and collaboration
Inadequate Metrics and Evaluation Tools	Comprehensive tools to assess systemic impacts and interconnections of innovative solutions
Risk-Aversion in Funding Allocation	Forward-looking approach making the most of available, and potentially novel, financial instruments
Misalignment of Stakeholder Interests	Inclusive design processes and pilot programmes which bring together a large variety of stakeholders, building on existing co-creation processes across the Commission and with stakeholders
Lack of Capacity and Expertise to address the required transformation in a systemic way	Systematic integration of multi-disciplinary teams and expertise in the design and implementation of R&I programmes across relevant Commission and Member State R&I supporting institutions
Static programmes	Agile R&I programmes able to cope more dynamically with emerging priorities and fast changing environments.

Based on the above observations on limiting factors and the research completed during this study, notably the detailed case studies (presented in section 6 of the main report) and identifying examples of tipping points and R&I related interventions that can trigger them, the following recommendations were identified to support the integration of systemic interactions of climate change mitigation approaches in the development of R&I agendas.

1. Combine the mission-driven approach with a human need driven agenda and a tipping point framework in the design of R&I programmes, to maximise impact and social benefit

Allows to:

- Remain focused on the full set of human needs that must be addressed in a sustainable way, back casting from 2050 targets and consider various possible end points;
- Move beyond techno-centric approaches and focus on the broader set of enabling conditions required to trigger feedback loops, create the right enabling conditions and eventually reach tipping points leading to systemic change;
- Consider the broader set of R&I interventions required to address the different levers to achieve a tipping point, i.e., economic competitiveness & affordability; performance & attractiveness; accessibility; cultural norms & desirability; capability & information; and, complementarity.
- Focus on the full spectrum of barriers preventing the achievement of enabling conditions; and,
- Provide greater directionality to R&I programmes by focusing on interventions that are likely to have the highest impact (recognising that many will also carry high risk to the public sector funder) while remaining focused on benefits for citizens.

Can be implemented by:

- Identifying and further specifying the appropriate tipping point mechanisms underpinning the required system transformation and the levers that can be activated to create the right conditions for the emergence of large scale, systemic tipping points (building on the detailed case studies presented in section 6 of this report).
- Provide more directionality to the EU missions by clearly linking them to specific tipping points and levers that can be activated, therefore broadening the scope of R&I interventions.
- Systematically considering the societal and social aspects of relevance across the lifecycle of emerging technical solutions (i.e., at the design, planning & development, operation, and end-of-life stages) to anticipate their occurrence and ensure they are properly address through R&I- or other types of interventions.
- Adopting a portfolio approach by bringing instruments like partnerships, missions, innovation and deployment actions together to address a single challenge/goal and activate different levers to trigger the desired tipping points. Ensuring that the existing philosophy of "co-creation" in the programming of R&I Work Programmes, in which all relevant Commission services are involved, is continued and evaluated to identify and resolve any inherent weaknesses, while ensuring that tools such as European Partnerships are also allowing for effective co-creation with industry and other stakeholders (NGOs, RTOs, universities etc.).

2. Adopt comprehensive evaluation frameworks to assess the systemic impacts and interconnections of innovative solutions

Allows to:

- Capture the full potential of transformative solutions;
- Capture a set of insights and data across key criteria that can help achieve a consistent, objective and comparable approach to feed R&I funding decisions by policy makers;
- Prioritise R&I areas within a specific boundary (e.g., considering R&I areas belonging to an established nexus);
- Weight criteria based on the needs and/ or challenges to be addressed in a given context; and,
- Reduce the risk of certain R&I areas (potentially those with the largest incumbent stakeholder groups), from having too much influence in the decision-making process.

Can be implemented by:

- Making use of an evaluation framework (such as the one developed for this study, including the use of visualisation tools such as Power BI) and combining it with a systemic approach examining solutions and their interactions (see below);
- Building the framework by selecting a set of key criteria that are relevant for the need and/or challenges to address building on the latest literature.

3. Take a systemic approach to identify innovative solutions and their interactions within and across nexuses

Allows to:

- Develop future scenarios (through foresight studies) to examine the potential role and impact of individual innovations (which are not only technological, but also social, societal, financial and governance) and their interactions within and across nexuses;
- Identify new R&I areas formed from interactions within and across nexuses;
- Identify important enabling technologies within and across nexuses;
- Avoid constricting effects due to cross nexus effects (e.g. insufficient energy storage which prevents greater RES penetration); and,
- Identify important cross-cutting non-technical barriers and challenges (e.g. regulatory conditions).

Can be implemented by:

- Focusing on goal-oriented R&I, placing less emphasis on individual technologies and solutions (see also recommendation 1 above);
- Leverage new frameworks such as the “positive tipping points” framework to better understand the interdependencies among innovative solutions and the levers that can be actioned to create the enabling conditions required for new solutions to reach scale and commercialisation (see also recommendation 1 above).

- Drawing on scenario-oriented approaches which include per se already a large number of systemic aspects;
- Ensuring that social innovations are not just an “add on”, but are placed high on the agenda when considering societal challenges and the needs of society (see also recommendation 4 below); and,
- Factoring in critical challenges to ensure that social innovations are not restricted to increasing societal acceptance of technological solutions, and that governance innovation is not limited to removing barriers to these technological solutions, but rather considered as R&I areas requiring dedicated focus and specific support (see also recommendation 4 below).

4. Systematically integrate societal considerations in the design of R&I programmes

Allows to:

- Fill funding gaps by addressing societal challenges and solutions that private financiers might not want to finance;
- Avoid possible bottlenecks and negative cascading effects during the deployment of new solutions which arise due to social aspects (e.g., acceptance, behaviour, justice aspects); and,
- Disseminate information and knowledge in a targeted manner to support new solutions (e.g., informing on co-benefits) to improve the education of society.

Can be implemented by:

- Identifying the societal barriers to innovation across different R&I areas that prevent successful commercialisation and market deployment of innovations, while also recognising that societal aspects sometimes may not have a bearing on R&D needs where the sole outcome is focused on technological improvements;
- Using extended life cycle assessments within technical assessments (see section 5) to obtain the full picture of a solution space and its dependencies;
- Putting societal challenges and solutions on an equal footing with technical ones in funding programmes; and,
- Including social needs driven system aspects in a broad range of scenario approaches.

5. Develop pilot projects which bring multiple innovative solutions together at different scales to fully capture the nature of their interactions

Allows to:

- Explore the benefits of systemic thinking and new framework such as the “positive tipping points” framework within a defined environment to identify key learnings and inform how to best scale these up across R&I programmes at different levels;

- Showcase new configurations of innovative solutions which would otherwise not be funded – this includes innovation related to regulations and exploring new business models;
- Move beyond the real-lab approach (already partly explored at either small-, medium- or large-scale through concepts like 'living labs', 'placed-based innovation', and 'incubators') by integrating different technical and societal solutions to help understand social challenges, both in public and/ or commercial settings; and,
- Bring together actors from different areas (academia, research & technology organisations (RTOs), private companies, public administrations including local and regional authorities, regulatory agencies, households, etc.) around common societal challenges and transformations.

Can be implemented by:

- Dedicated funding windows, using a mission-oriented approach, aimed at incentivising the development of relevant projects;
- Deploying regulatory sandboxes to help with more rapid adoption of innovations in the market; and,
- Testing new business models and collaborations, particularly with local and regional authorities given their crucial role as key actors in bringing together the ecosystem of innovators, facilitating collaboration between various stakeholders working on climate mitigation and ensuring wider society is effectively engaged as part of the EU R&I long-term agenda. Regional Innovation Valleys and Hydrogen Valleys, for example, showcase how regions can propel innovation by engaging local and regional R&I stakeholders.

7. Strengthening EU engagement in international fora to facilitate the rapid development and diffusion of breakthrough solutions

Given the global nature of climate change, international cooperation on climate neutrality R&I has the potential to leverage successful R&I efforts to the global level (and vice versa) and support the rapid development and diffusion of breakthrough solutions. Based on the findings presented above and additional dedicated research. Three main interventions that could be implemented by the EU to improve international cooperation on climate neutrality R&I were identified:

Lead efforts to expand the scope of multilateralism to include social innovation.

The EU's Global Approach to R&I seeks to lead by example, promoting multilateralism, openness and reciprocity in its cooperation with the rest of the world, which it hopes will achieve a just green transition. While the EU already supports several regional initiatives that encourage social innovation, this remains a large gap in multilateral R&I initiatives. Many initiatives support the advancement of technical solutions but fail to include critical work on social aspects that complement and support technological efforts accelerating thus the uptake of innovation related to climate change in third countries. For example, social innovation, in the context of cities, could greatly support emission reductions by encouraging behaviour change and acceptance of new low-carbon technologies. The EU should harness its knowledge and skills to promote more social innovation efforts within the scope of existing international sectoral initiative it is part of.

Capitalise on existing bilateral partnerships with key innovation leaders, but also explore new multi-lateral collaborations to maximise learning and scaling opportunities.

Under its Global Approach, the EU has forged and nurtured strong bilateral partnerships with key global leaders on critical cooperation areas, such as technology and trade, compatible with European interests and values and to strengthen the EU's open strategic autonomy. To respond to the urgency of the net zero challenge, the EU should strengthen its collaboration with existing partners, using existing agreements and MoU to also cover strategic R&I areas where there is clear alignment of priorities and efforts, including key technologies to enable the decarbonisation of hard-to-abate sectors (e.g., industry), such as hydrogen and CCUS.

Given the uncertain pathway of R&I efforts globally, and the fact that solutions in the sustainability space may not arise from existing bilateral partnerships, the EU should also embrace multilateralism. This can be done among others through the G7 and G20, as well as Horizon Europe (expanding existing regional initiatives), for building a deeper pool of transformative spaces, i.e. environments and platforms that encourage and facilitate innovative and groundbreaking approaches for addressing sustainability challenges. Additionally, intermediary actors or entities that operate between different parties, facilitating communication, collaboration, and the exchange of knowledge should maximise learning and scaling ideas. In the context of R&I for sustainability, intermediary actors could include research institutions, non-governmental organizations (NGOs), industry bodies, or other stakeholders that play a role in connecting, coordinating, and supporting collaborative efforts. The EU should engage with these players to fully leverage their potential.

Champion more inclusive and diversified cooperation on R&I.

Growing global calls for more inclusiveness in international R&I initiatives opens a space for the EU to build on its leadership role in international and regional initiatives. Additionally, expanding the geographical scope of existing initiatives and facilitating the participation of countries from the Global South should be supported. This will not only complement the EU's technical assistance programmes and support to developing countries, but also contribute to its broader climate diplomacy objectives and outcomes.

The global energy shift is emerging as a significant geopolitical force, altering the power dynamics among regions and nations, and offering the potential of energy independence to various countries.[6] The net zero energy transition creates a new geo-economic era which is fundamentally distinct from conventional 'fossil-fuel centred' geopolitical concepts and frameworks (mainly around competition over access to fossil fuels, tensions over natural gas, and disputes/tensions over oil-rich parts of the world). This transformation will potentially reshape the longstanding political order fuelled by new technologies and declining costs, which are increasingly making renewable energy sources competitive with traditional alternatives. In the long run,

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[6] IRENA, 2019. A new world: The geopolitics of energy transformation. Available at: https://www.irena.org/-/media/files/irena/agency/publication/2019/jan/global_commission_geopolitics_new_world_2019.pdf

innovation potential, cheap capital, ability to set standards and certification norms for products and infrastructures; harnessing digitalisation and cybersecurity; control over supply chains of critical materials as well as ability to manage social costs will lead to new landscapes regarding global politics and affect the geopolitical status quo. Adjusting policies, trade agreements, and regulatory frameworks to accommodate dynamic global energy markets is also recommended to avoid green protectionism[7].

In this context the EU must:

- Prioritise actions with third countries on targeted development of high-risk, high-impact technologies to accelerate the innovation cycle by sharing costs, risks, knowledge and capacities.
- Engage in strategic competition focusing on areas of competitive advantage across the international value chain and using its capacity to set norms and standards and track progress based on the annual European Climate Neutral Industry Competitiveness Scoreboard[8].
- Design actions to support the spread of context-specific zero-carbon innovations in developing and emerging economies (including education, capacity building, technical support, pilots) to advance the global green transition.
- Better integrate R&I policies to the broader framework of external policies including trade and development.

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[7] World Wide Fund for Nature, 2003. Green protectionism: the use of measures for narrow protectionist ends under the guise of addressing legitimate environmental goals. Available at: https://www.wto.org/english/forums_e/ngo_e/wwf_greenprotec_e.pdf

[8] JRC, 2023. European Climate Neutral Industry Competitiveness Scoreboard (CINDECS) - Annual Report 2022. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC134499.

1. Introduction

"We do not have all the answers yet. But this is Europe's man on the moon moment" - Ursula von der Leyen

Transforming Europe into a climate neutral economy and society by 2050 requires extraordinary efforts and the mobilisation of all sectors and economic actors, coupled with all the creative and brain power one can think of. Each sector has to fundamentally rethink the way it operates to ensure it can transform towards this new net-zero paradigm, without jeopardising other environmental and societal objectives both within the EU and globally. In this context, the EU has seen the emergence of a vibrant ecosystem of cleantech innovators and investors over the last decade, supported - among other - by ambitious policy frameworks and research and innovation (R&I) agendas at national and EU level. This is only the beginning: indeed, as stressed by the IEA and the OECD, our ability to meet climate neutrality targets directly depends on our ability to innovate. Half of the greenhouse gas (GHG) emissions that must be achieved by 2050 are deemed to be dependent on solutions that are currently only at the demonstration or prototype stage.[9] The current level of innovation, however, is insufficient to meet the net-zero challenge.[10] To seize its "*man on the moon moment*", the EU must intensify its efforts and revisit its approach to R&I to ensure it is fit for purpose and well equipped to support the next wave of breakthrough innovations that will be required to achieve climate neutrality in the EU and globally by 2050.

How can R&I programmes adopt the requisite systemic and transformative approach? How can they navigate interactions between technological and social innovations? Despite the need for transformation, breakthrough innovations do not fall from the sky, but rather represent step-changes that result from crossing a threshold, which can cause the impression of sudden appearance. In innovation such thresholds often relate to scaling-induced cost-reductions. Continued work on incremental progress on high-potential technologies can eventually unlock transformational leaps.

The climate neutrality objective requires decarbonisation across virtually all of human activity. An R&I programme that is fit for purpose must thus be comprehensive. Any residual emissions need to be countered by dedicated efforts to remove and permanently store CO_2. Efforts can no longer be concentrated solely on replacing some polluting technologies. Innovation and clean technology adoption needs to empower all sectors. Progress on carbon management technology and other multi-purpose technologies may help clean up several industries at once.

An R&I agenda that is fit for purpose recognises the full set of societal objectives and planetary boundaries (illustrated for example by the Doughnut Economics

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[9] IEA, 2021. Net Zero by 2050 A Roadmap for the Global Energy Sector. Available at: https://www.iea.org/reports/net-zero-by-2050

[10] OECD, 2023. DRIVING LOW-CARBON INNOVATIONS FOR CLIMATE NEUTRALITY. OECD SCIENCE, TECHNOLOGY AND INDUSTRY POLICY PAPERS No. 143. Available at: https://www.oecd-ilibrary.org/docserver/8e6ae16b-en.pdf?expires=1701870650&id=id&accname=guest&checksum=BD5A0FA19D9219F2546FC3DD90056DD8

framework[11]) and avoids a narrow climate "tunnel vision". Interrelations between climate and biodiversity crises, and the fact that one cannot be solved without the other (as confirmed by the IPBES IPCC work on biodiversity and climate change[12]) need to inform R&I programmes and synergies among nature-based solutions (NBS) must be unlocked, which can in turn not only contribute to climate neutrality but also to environmental and societal benefits. To do justice to broader objectives, an integrated approach is required regarding innovation in both technological and societal systems – giving room for the continued reflection of applicable economic paradigms and green growth assumptions[13] in keeping with an ever-evolving social, political and technological landscape.

An R&I agenda is about action.[14] Given the dynamic evolution of the social and technological landscape on the way to net-zero, public R&I funding must remain adaptable and agile enough to embrace new paradigms and evolving technology landscapes, thus keeping it relevant and impactful.

Throughout the study a shared set of concepts and terms is used:

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[11] Raworth K., 2017. Doughnut Economics: the doughnut of social and planetary boundaries. Available at: https://www.kateraworth.com/doughnut/

[12] IPBES and IPCC, 2023. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change, Available at: https://files.ipbes.net/ipbes-web-prod-public-files/2021-06/2021_IPCC-IPBES_scientific_outcome_20210612.pdf

[13] Including by the EU institutions themselves, as illustrated by the recent Beyond Growth Conference (https://www.beyond-growth-2023.eu/) and the "Growth without economic growth" report from the EEA (https://www.eea.europa.eu/publications/growth-without-economic-growth)

[14] "Agenda" – in its original Latin meaning – means "things to get done".

Definition of key terms underpinning the study

- **Climate mitigation solution:** Technologies, products, services, business models and societal innovation contributing to climate change mitigation. (Source: Mission Innovation[15])
- **High-risk**: Refers to areas where the current technological maturity level is low, and therefore the interest in the private sector to invest is currently low because the risk-reward ratio is too high and returns too uncertain. (Source: Terms of Reference). Furthermore, at the tech-risk stage, timeframes to commercialisation are uncertain and almost certainly long, which poses problems for the Venture Capital (VC) investment model.
- **High impact:** The level of impact is primarily considered in terms of contributions to GHG emissions abatement. Other environmental and societal objectives are, however, also considered. (Source: Terms of Reference)
- **Disruptive general-purpose technologies**: “A single technology, or closely related group of technologies that has many uses across most of the economy, is technologically dynamic, in the sense that it evolves in efficiency and range of use in its own right and is complementary with many downstream sectors where those uses enable a cascade of further inventions and innovations" (emphasis is of the original authors). (Source: Academia[16])
- **Systemic interaction:** System changes brought about by the interaction of many single technological and non-technological solutions, as well as specific systemic solutions. A good example for systemic interactions of mitigation approaches is provided by the integration of multiple technologies into a coherent approach, e.g., the coordination and integration of different modes of transport, which can establish a concept of mobility as a service. (Source: Terms of Reference)
- **Nexus:** A group of interconnected parts of a system, whereby the study of their interconnections affords important insights that would be missed in an individualized part-by-part analysis.
- **Tipping point:** A critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly. In this report the focus is on socio-techno-economic tipping points and particularly the “positive tipping point” framework, which identifies conditions for their occurrence (see section 5.1).

1.1. Guiding Research Questions

The objective of this report is to contribute to this fresh thinking, with analytical rigour and broad-based stakeholder-involved reflections, to open up the consideration-space beyond narrow and siloed analysis of individual solutions, yet simultaneously also identifies specific high-risk and high-impact innovation areas for climate change mitigation.

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[15] Wilson C., 2019. Towards >60 Gigatonnes of Climate Innovations. 1.5°C Compatibility Pathfinder Framework (CPF). Available at: https://misolutionframework.net/pdf/Net-Zero_Innovation_Module_3-The_1.5_%C2%B0C_Compability_Pathfinder_Framework_(CPF)-v1.pdf

[16] Bekar, C., Carlaw, K., & Lipsey, R., 2018. General purpose technologies in theory, application and controversy: A review. *Journal of Evolutionary Economics*, *28*, 1005-1033

Numerous stakeholders actively contributed to the study, providing inputs and recommendations at three key points: (1) a series of Foresight Workshop designed to identify solutions and R&I areas across multiple Solution Landscapes; (2) an Expert Validation Workshop designed to present the initial findings of the study and test the initial recommendations; and, (3) a final Stakeholder Consultation designed to present the study findings and collect feedback on the recommendations. Overall, more than 100 experts were engaged in the study, which belongs to different sectors and categories. Experts involved in the first two workshops included key professionals covering universities, businesses and consultancies, business and industry associations, financiers, think-thanks, research institutes as well as representative from different Directorate-Generals of the European Commission and the Joint Research Centre (JRC). Additionally, experts involved in the final Stakeholder Consultation included public institutions at national and regional level. The study also benefited from the critical review of a panel of five external reviewers that were involved from the inception stage of the study until its final report.

The study has set out to answer four types of questions: (1) questions pertaining to opportunities in pursuing specific (classes of) mitigation solutions; (2) questions pertaining to systemic interactions between solutions (including social dimensions); (3) the third area of enquiry pertains to how the above considerations may holistically be integrated into an R&I agenda that is fit for purpose; and, (4) the final research questions concern how the EU could integrate these considerations into its international cooperation efforts. The specific questions as formulated in the Terms of Reference are found in Box 2.

Guiding Research Questions

- Which climate mitigation solutions or group of solutions can be identified as both high-risk and high-impact and therefore require public support to reach market maturity in the next 10-15 years?
- Which are the opportunities and challenges of breakthrough & disruptive technologies in:
  - Net carbon removals?
  - General-purpose technologies (GPT) that can be developed and applied for climate change mitigation purposes?
- How can systemic interactions of climate change mitigation approaches be integrated in the development of R&I agendas?
- How can EU engagement in international fora be strengthened to facilitate the rapid development and diffusion of breakthrough solutions to fight climate change in the next 10-15 years?

To address these research questions, an exploratory research approach was adopted. Exploratory research is used to explore new topics or to propose new ideas on already well-developed topics. It does not follow a prescriptive methodology but allows the research team to adapt the approach as the research progresses. Based on this approach the above research questions were addressed from different angles while drawing on various complementary concepts and frameworks. This has allowed to test a set of hypotheses on breakthrough & disruptive technologies for climate mitigation and generate new insights.

This report does not provide definitive answers but should rather be considered a stepping stone towards the design of future R&I programmes. And while the report does not address every innovation area in which incremental progress could potentially result in leaps forward during the relevant time-horizon (to 2050), given the limitations of anticipation, it does focus on innovations that can be foreseen and which are expected to have the highest impact. Overall, the report is designed to help in the formulation of the decision problems at hand and to provide a structure of considerations that may underpin the design of an EU-wide R&I programme that is fit for purpose, as well as provide reflections on potential international cooperation efforts which can complement EU-wide R&I efforts. More specifically, the study informs the second strategic plan of Horizon Europe, the framing of the next EU Framework Programme for R&I (expected to cover the years 2028-2035), as well as other relevant programmes at both EU (e.g., the EU ETS Innovation Fund) and Member State level. To that end, and in view of the Commission's strong mandate to put strategic foresight at the heart of EU policymaking, the study has sought to adopt a holistic, system-level approach to support transformative change.

1.2. Structure of the report

In fitting with the challenge posed by a R&I agenda that is fit for purpose, this final report presents the analyses and findings jointly identified in interaction with stakeholders and experts and building on an extensive literature review at the start of the study. The emphasis is on the plurality of analyses, since each approaches the above research questions from a distinct and complementary angle. **Section 2** introduces the methodology used to inform this research.

Section 3 explores the need for a systemic perspective in the development of a R&I agenda by first asking what the limiting factors preventing a systemic approach in R&I have been to date (2.1); how scenarios may help by providing structure in the particular context of the climate-neutrality objective (2.2); and, then, by outlining how analysis of nexuses[17] can produce crucial insights into innovation synergies and trade-offs (2.3).

Recognising the challenges associated with "picking the winners" (4.1), **Section 4 explores how high-risk and high-impact solutions can be identified while keeping a systemic perspective in mind**. Starting from the results of the scenario analysis, this section introduces a number of Solution Landscapes that were developed to identify solution areas and associated R&I areas to answer to specific needs and challenges (4.2). The common challenges identified across Solution Landscapes are then discussed (4.3), illustrating the need for common solutions and helping with the prioritisation that is essential for public officials to decide on which high-risk, high-impact R&I areas to fund. The comprehensive evaluation framework, developed specifically for this study to systematically assess the identified R&I areas against a fixed set of criteria is briefly introduced and the highest-scoring results covering high risk, high-impact R&I areas are then discussed (4.4). The results of the

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[17] Here a climate neutrality nexus is defined as one representing systemic interactions between R&I areas.

evaluation framework are finally introduced at the nexus level to ensure coherence with the systemic approach underpinning this study (4.5).

Section 5 then presents the results of the analysis of three nexuses and the role of R&I programmes in supporting their transformation with the aim to answer the question: how to integrate systemic interactions in the design of R&I agendas? For each nexus, the following aspects are set out: (a) key challenges toward nexus-transformation; (b) innovation potentials; (c) positive (and potentially negative) spillover effects; and, (d) negative trade-offs. The nexuses presented are: the mobility - built environment – energy nexus (5.1.1); the circularity – industry – carbon removal and capture nexus (5.1.2); and, the agrifood – carbon removal nexus (5.1.3). Together they showcase the necessity for exploring nexuses between otherwise siloed innovation spaces, in order to mobilise their respective potentials and navigate trade-offs holistically. Subsection 5.2 finally examines key lessons, including by pointing out that some technologies may act as general-purpose technologies (GPTs) with potential to accelerate multiple nexuses at once. It also introduces how the combination of a mission-driven approach with a human need driven agenda and a tipping point framework can help address the challenge posed by the integration of systemic perspectives in the design of R&I programmes.

Based on selected case studies across the nexuses, **section 6 presents how this approach can be applied to support different climate neutrality solution reaching the market by 2030-40**.[18] For each case study, various types of barriers, system interactions and opportunities for accelerating progress via different forms of R&I support are highlighted.

Section 7 discusses the need for international cooperation in science-diplomacy, innovation support and technology transfer for mutual benefit to the EU and its allies and to accelerate efforts in meeting the global challenge of reaching climate neutrality. Following an overview of the current landscape in international cooperation (7.1), the challenges and opportunities for strengthened cooperation on R&I toward climate change mitigation are discussed, including some country-specific examples (7.2). Finally gaps and recommendations for further action toward enhanced international efforts under European leadership are identified (7.3).

Our final **section 8 concludes the study and provides the overarching recommendations**.

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[18] The 2030-2040 timeframe for market maturity was chosen to allow for at least a decade of market adoption to reach a meaningful contribution to net-zero by 2050.

2. Overview of the methodology

The exploratory research approach deployed to inform this study consisted of seven sequential steps informing each other. Each of these steps is presented in this section and more details are provided in Annex 3 where relevant and helpful for the reader.

2.1. Literature review

The foundational step of the study consisted in a broad review of the academic and grey literature. This literature was organised in two strands serving different goals:

- **Top-down literature review**: The objective of this review was to contextualise the study and ensure it reflects the latest thinking in the climate neutrality R&I ecosystem. The review adopted a top-down approach and mainly focused on transversal research, seeking to answer the same research questions as this study. It combined a "classic" literature review structured around general key words and search strings, with a more innovative horizon scanning and topic modelling exercise to look beyond the state-of-the-art.
- **Bottom-up literature review**: This literature review was guided by the results of the analysis of different climate neutrality scenarios detailed in section 2.2. Climate neutrality scenarios are key to gather insights on the importance of individual solutions in achieving climate neutrality, on their expected implementation time, on their techno-economic and societal characteristics, as well as on system aspects under which the solutions evolve. The scenario analysis was used to identify the most relevant solution areas based on their expected role in the decarbonisation of our society and their level of maturity. For each of the identified solution areas, a comprehensive literature review was deployed to design Solution Landscapes. The Solution Landscape concept is presented in more detail in section 2.3.

Key implications from the literature review for the scoping of the study

- **Building a flourishing future for all: a global sustainability perspective is vital to stay within planetary boundaries**. Building on the Planetary Boundaries[19] framework and the Doughnut Economics[20] framework, that combine the ecological ceiling associated with the Planetary Boundaries (*outer ring*) with social foundations (*inner ring*), a holistic approach to sustainability was adopted recognising the intrinsic interrelations, co-benefits and trade-off between economic, environmental and societal objectives. Recognising the global nature of the challenges we face; a global sustainability perspective was adopted. This is vital to accommodate equity in the strive for a flourishing and decent life for all people on the planet.

- **Achieving EU-level climate neutrality by 2050 will require technological and societal innovations to be adopted**. The design of climate neutral R&I agendas must recognise the technological bias present in many decarbonisation scenarios and strategies. As detailed in the analysis of climate neutrality scenario, achieving net-zero by 2050 will require a combination of technological and societal innovation and it is crucial to ensure R&I programme do not fall into a techno-centric paradigm, but rather capture the full spectrum of solutions at hand the support they require. It must for example be recognised that smaller and less capital-intensive end-user solutions may achieve much more rapid deployment and GHG abatement impacts than larger engineering solutions.[21] In this context, the role of policy in achieving social tipping points towards more climate-friendly consumption patterns must also be explored.[22]

- **There is a need to combine supply-push and demand-pull interventions to support the emergence of breakthrough innovations**. The linear supply-push innovation pathway approach has now been widely challenged by more open innovation systems approaches that have yielded important societal solutions. Support for R&I can no longer be conducted in a technology supply-side push “vacuum”: demand side feedback mechanisms and socio-economic policy levers are critical aspects of the development and deployment of technologies. R&I agendas must recognise the complex interaction between actors, institutions, and networks as well as changes in regulation, infrastructure, use practices, industrial networks, or symbolic meaning/culture that shape innovations and their success or failure.[23]

- **Spillover effects from public R&I funding can generate much greater returns on investment than originally envisaged**. Innovation spillovers can occur both across different solution areas (so-called knowledge spillovers) and across different applications (so-called application spillovers). At their best, such application spillovers have been called 'general-purpose technologies'.[24] Spillover effects should be considered to help justify a policy intervention in areas where the initial investment case may not justify support. R&I efforts should concentrate on all stages of the deployment of new solutions, from ideation and conceptualisation all the way to large-scale adoption. Particular focus should be put on solutions with the potential to create a “breakthrough effect” across multiple sectors.

- **There is a need to move from a “static problem approach” to a “dynamic solution approach” to achieve the scale of transformation required**. The OECD and Mission Innovation have developed a more holistic approach to look at climate innovation, which delivers the Paris Agreement goal of 1.5°C. This approach goes from a “Static Problem Approach”, focused on reducing resource and carbon intensity of activities in different sectors, mainly via new technologies or technology optimisation, towards a “Dynamic Solution Approach”, which provides solutions based on human needs and falls into an expanded innovation agenda. Overall, the "Static Problem Approach” versus the “Dynamic Problem Approach” aims to focus on generating benefits rather than reducing negative impacts for a sustainable 1.5°C compatible pathway. The main risk with a static approach is that, in some cases, existing unsustainable production and business models are assumed as the default option and smart new solutions that support global sustainability will not be considered.[25]

- **Lessons must be learned from the mission-based R&I programmes to design the next wave of R&I programmes**. While net-zero missions have led to clear improvements (in terms of common objectives and strategic agendas, broader co-ordination of policy plans across silos and higher integration of support instruments across the different stages of the innovation chain), a recent OECD report concluded that they "*will not be sufficient to scale up and deploy these innovations on a massive scale […] To bring about the transformative changes needed to achieve the goal of net-zero (as opposed to simply reducing overlaps and speeding up technological innovation), net-zero missions will require investments of a far greater scale and scope. They will also need to balance, align and accompany the mass deployment of these innovations with solutions to promote social and behavioural changes, which is prerequisite for reducing GHG emissions rapidly and significantly.*"[26] New frameworks must therefore be tested to address these limitations.

2.2. Climate neutrality scenarios analysis

Net-zero scenarios describe pathways leading to a climate neutral economy and society, typically by 2050. Despite a spread in their assumptions and approaches, the analysis and comparison of such scenarios allows the identification of key patterns on the path to climate neutrality. The analysis of net-zero scenarios can therefore provide directionality to R&I efforts leading to climate neutrality. This study is therefore rooted in the analysis of a series of net-zero scenarios developed at global, European or national level and underpinned by a variety of assumptions, i.e., from techno-centric scenarios to scenarios focused on societal and behavioural changes. The combined

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[19] Stockholm Resilience Centre, 2023. Planetary Boundaries. Available at: https://www.stockholmresilience.org/research/planetary-boundaries.html

[20] Barth, J., Lavorel, C., Miller, C., & Hafele, J., 2021. A compass towards 2030: navigating the EU's economy beyond GDP by applying the Doughnut Economics framework. ZOE Institute for Future-fit Economies: Bonn.

[21] IEA, 2020. Special Report on Clean Energy Innovation: Accelerating technology progress for a sustainable future. Available at: https://iea.blob.core.windows.net/assets/04dc5d08-4e45-447d-a0c1-d76b5ac43987/Energy_Technology_Perspectives_2020_-_Special_Report_on_Clean_Energy_Innovation.pdf

[22] Nelson S., Allwood J. M., 2021. Technology or behaviour? Balanced disruption in the race to net zero emissions, Energy Research & Social Science, Volume 78, 2021, 102124, ISSN 2214-6296. Available at: https://www.sciencedirect.com/science/article/abs/pii/S2214629621002176

[23] Markard J., 2020., The life cycle of technological innovation systems, Technological Forecasting and Social Change, Volume 153, 2020, 119407, ISSN 0040-1625. Available at: https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/291404/2/TISDynamicsFinal.pdf & Robert Gross, Richard Hanna, Ajay Gambhir, Philip Heptonstall, Jamie Speirs, How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology, Energy Policy, Volume 123, 2018, Pages 682-699, ISSN 0301-4215. Available at: https://doi.org/10.1016/j.enpol.2018.08.061

[24] Ibidem.

[25] Mission Innovation, RISE, BCG, BCG Green Ventures, 2022. The next generation of climate innovation. Available at: https://misolutionframework.net/pdf/Next_Gen_Climate_Innovation.pdf

[26] OECD, 2023. OECD Science, Technology and Innovation Outlook 2023: Enabling Transitions in Times of Disruption. Available at: https://www.oecd-ilibrary.org/sites/0b55736e-en/1/3/5/index.html?itemId=/content/publication/0b55736e-en&_csp_=b2412cc0600196af8b299a715946ac12&itemIGO=oecd&itemContentType=book#section-d1e16902-e2b3acc2c8

analysis of these scenarios allows to identifying key R&I areas and key nexuses for climate neutrality by 2050, where key nexuses represent systemic interactions between R&I areas. The important interlinkages of the climate and biodiversity crises, which strengthens the rationale for integrated solutions including NBS is also recognised. In section 3 the analysis of key patterns in net-zero scenarios covering worldwide, European and national levels, is used to derive justifications for nexuses in transformation scenarios covering both technological and societal transformations.

2.3. Solution Landscapes

The concept of Solution Landscape was developed as a tool to map climate mitigation solutions in a structured way. Building on the recent literature around the design of low-carbon R&I programmes, the Solution Landscapes combine a “Solution Tree” with a “Challenge Tree” with the objective to:

- Adopt a needs-based approach and ensure all the solutions identified serve a specific purpose and/or address a specific challenge or bottleneck on our way to climate neutrality.
- Structure the study around a broad definition of the concept of ‘solution’ and avoid the pitfall of overfocusing R&I programmes on technological solutions only.
- Consider solutions in their broader context by focusing on both ‘technical’ and ‘social’ challenges preventing our collective progress towards climate neutrality, e.g., what type of solutions are needed to trigger behavioural change and leverage the potential of new technologies or business model?

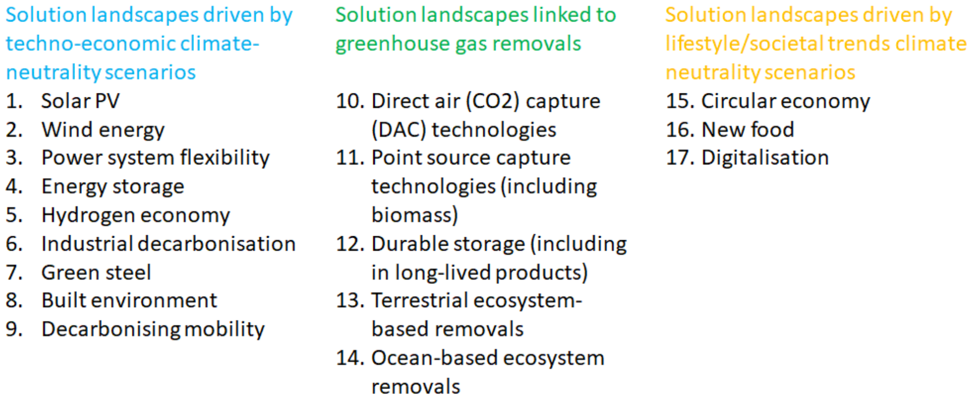
On one hand, the **Challenge Tree** is focused on the end goals, i.e., the desired policy outcomes, which were identified based on the results of the scenarios analysis. These overarching end goals are then broken down into sub-targets and specific challenges linked to these sub-targets. On the other hand, the **Solution Tree** starts from an overarching solution contributing to addressing the overarching goal and then breaks down that solution into different solution areas and then specific R&I areas that have not yet reached full commercialisation and must be addressed to ensure the overarching solution can reach its full mitigation potential. Within each Solution Tree, particular attention was also given to the role of GPT in addressing the identified challenges and supporting the development of new solutions.

By adopting such a design, the study combines a ‘solution-push’ approach (focusing on solution developments) with a ‘demand-pull’ approach (focusing on the enabling environment). The Solution Landscapes allow to clearly articulate the end goals of a particular solution and the challenges to get there. They also provide the necessary context to ensure the ‘solution-push’ side (in this case, the EU R&I agenda) (1) take these factors into account early on in their development process; and, (2) can support bold research efforts which going beyond system optimisation. This approach is also embedded in the Mission-oriented research and innovation approach adopted by the EU in recent years.

Following the approach set out above, 17 Solution Landscapes were designed based on the literature review following the approach described above. Each solution landscape also benefited from the critical review of the Cleantech Group to confront the findings from the literature review with the point of view of innovators. This was followed-up by a critical challenge of the Solution Landscapes during the Foresight

Workshops presented under section 2.4. The results of this work are presented in section 4.2 and the 17 Solution Landscapes and their accompanying narrative are presented in the separate Solution Landscapes Annex. As illustrated in 05, the Solution Landscapes can be clustered by type of scenarios depending on the type of overarching goal they aim to address and the solutions they cover.

Figure 5. Overview of the 17 Solution Landscapes, clustered by type of scenarios depending on the type of overarching goal they aim to address and the solutions they cover. Source: ICF & partners, 2023.



Solution landscapes driven by techno-economic climate-neutrality scenarios

1. Solar PV
2. Wind energy
3. Power system flexibility
4. Energy storage
5. Hydrogen economy
6. Industrial decarbonisation
7. Green steel
8. Built environment
9. Decarbonising mobility

Solution landscapes linked to greenhouse gas removals

10. Direct air (CO2) capture (DAC) technologies
11. Point source capture technologies (including biomass)
12. Durable storage (including in long-lived products)
13. Terrestrial ecosystem-based removals
14. Ocean-based ecosystem removals

Solution landscapes driven by lifestyle/societal trends climate neutrality scenarios

15. Circular economy
16. New food
17. Digitalisation

2.4. Foresight Workshops

Once drafted, the Solution Landscapes were discussed in detail with experts during four Foresight Workshops, structured around 12 sessions (see Table 1 below). These workshops involved 40+ experts from the European Commission and the European Environmental Agency and 70+ external experts (from academia, business, finance and civil society), the full list of consulted organisations is presented in Annex Annex 2.

The objective of the Foresight Workshops was to discuss the following questions:

- Do the Solution Landscapes miss important R&I areas with the potential to strongly contribute to the identified challenge?
- Which R&I areas can be considered as “high-risk/ high impact” and should therefore be analysed in more detail?
- What type of R&I support should be put in place to help these solutions achieve commercialisation in the period 2023-40?
- How should the systemic interactions between Solution Landscapes be integrated into R&I programmes?

Table 1. Overview of the Foresight Workshops

FORESIGHT WORKSHOPS	SESSION FOR DETAILED DISCUSSIONS
Workshop 1: Transform the energy system	Breakout 1.1: Scale-up renewables
	Breakout 1.2: Power system flexibility
	Breakout 1.3: Energy storage
Workshop 2: Transform the industry, built environment and mobility	Breakout 2.1: Hydrogen economy
	Breakout 2.2: Industry decarbonisation
	Breakout 2.3: Built environment
	Breakout 2.4: Decarbonise mobility
Workshop 3: Scale-up GHG removals solutions	Breakout 3.1: Technical solutions
	Breakout 3.2: Nature-based solutions
Workshop 4: Transform our society	Breakout 4.1: Scale-up the circular economy
	Breakout 4.2: Transform the food system
	Breakout 4.3: The role of digitalisation in the transformation towards climate neutrality

2.5. Evaluation framework

The first four steps of the methodology resulted in a long list of more than 150 R&I areas (framed into the R&I landscapes) with the potential to significantly contribute to climate mitigation efforts. A detailed evaluation framework was designed to screen all these R&I areas and identify the ones with both the highest mitigation potential and the highest need of policy support. The evaluation framework, which is presented in detail in Annex 3, was built based on the results of the literature review with the aim to identify R&I areas that:

- Are **not commercially available** yet, but do not face insurmountable obstacles to achieve commercialisation in a 10–15-year timeframe (Pillar 1 – Techno-economic feasibility);
- Have an important **climate mitigation** potential (Pillar 2 – Mitigation potential);

- **Does No Significant Harm to (i.e., negatively impacts) other environmental objectives** (Pillar 3 – Environmental impact)[27];
- Have the potential to generate **socio-economic benefits** and meet social acceptance (Pillar 4 – Socio-economic impact); and,
- Are not already benefiting from extensive **support** from existing R&I programmes in the EU and beyond (Pillar 5 – Current level of support).

To combine these different dimensions into a coherent framework, the evaluation framework relied on five key features:

- 22 **evaluation criteria**, developed according to the pillars, against which each R&I area was assessed. These criteria were identified based on the results of the literature review and in particular the *Harmonised Approach to Assessing Feasibility* developed by the IPCC[28];
- A **qualitative scoring methodology** that could identify between high and poor performers;
- A **data collection methodology** that allowed an educated assessment of each R&I area;
- A **theory of numeric equivalence**, allowing to turn qualitative scores to numeric values that better accommodate the reporting of summary reports – single performance score per R&I area; and,
- An **aggregation methodology** that allowed to summarise results from the lowest level of the framework (criterion) to a highest level (aggregation of criteria using an Index).

Based on this methodology, the 150+ R&I areas were screened against the 22 criteria listed in **Error! Reference source not found.** to create an index of individual s olutions. PowerBI was then used to analyse the index from different perspectives and generate recommendations. While this approach results in an informative index of individual solutions, it does not take into account the systemic interactions between different solution areas, which is a key requirement for this study. This was approached from a different methodological perspective, as described in the next section.

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[27] In line with the EU Taxonomy Regulation

[28] Intergovernmental Panel on Climate Change, 2022. Climate Change 2022: Mitigation of Climate change. Available at: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

Table 2. Criteria of the evaluation framework by pillar

PILLARS	CRITERIA
Techno-economic feasibility	• Simplicity • Scalability potential • Regulatory feasibility • Financial feasibility • Critical material exposure or availability • Institutional feasibility
Mitigation potential	• GHG abatement potential • Contribution to nitrogen and phosphorus pollution • Contribution to atmospheric aerosol loading
Environmental impact	• Climate change adaptation • Sustainable use and protection of water and marine resources • Circular economy and waste prevention and recycling • Pollution prevention and control • Biodiversity and land requirements
Socio-economic impact	• Job creation • Distributional effects • Acceptance / public favourability • Resource security (Water-Energy-Food-Ecosystem Nexus)
Current level of support	• Support at EU level • Support at Member State level • Support beyond EU: US, China

2.6. Systemic perspectives & needs-based approach

Building on the results of the literature review, this strand of the methodology consisted in approaching the research questions from a systemic perspective. To do so the work completed by Mission Innovation and the Net-Zero Compatible Innovations Initiative over recent years, as well as on the learnings from existing mission-oriented innovation policies and adopted a needs-based approach were used as building blocks. This first step consisted in identifying the essential needs that must be addressed in a sustainable manner to allow for more than 10 billion flourishing lives on earth while reaching climate neutrality, i.e.: Shelter, Energy supply, Mobility, Food, Water, Social interaction and participation. Based on these needs and the results of the scenario analysis, the Solution Landscapes were then clustered in three nexuses gathering the set of solutions required to address the identified needs. These nexuses were then used to structure the analysis at different levels:

- **Analysis of the results of the evaluation framework at nexus level** to build a picture of the key R&I needs across the nexuses;

- **In depth-analysis of the three nexuses** to identify (1) the challenges and bottlenecks preventing the transformation of the nexus towards climate neutrality; (2) the solutions emerging to address these challenges and how they interact; (3) the potential spillover effects which could result from these interactions; and, (4) the potential risks and trade-offs that result from these interactions. Across all three nexuses, the general role played by GPTs[29] is also considered, since they present important enabling technologies (e.g., AI, machine learning, big data), which can have a strong impact across all nexuses and also link different areas (i.e., strong systemic aspects).
- **Identification of a series of case studies** to root the analysis and recommendations in concrete examples of innovative solutions. These case studies were selected with the objective to have a variety of technical, social and GPT-related solutions that were analysed in more detail and, among other, used to assess if and how the "positive tipping point" framework could be combined with a mission-driven approach and human needs agenda to give more directionality to R&I programmes. Although the selected case studies typically scored well in the evaluation framework and are part of the set of solutions that should be prioritised by R&I efforts, they should not be considered as the definitive list of top priorities emerging from this study – rather as an illustrative set of R&I areas which exemplify perspectives which are of value to policy makers in considering what to support.

To support this systemic analysis, the "positive tipping point" framework introduced in the Box below was also leveraged.

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[29] General Purpose Technologies (GPTs) are innovations with the potential to significantly impact and transform multiple sectors of the economy and society. They are characterized by their broad applicability, adaptability, and the profound changes they bring about in various industries and aspects of daily life.

How can R&I programmes play a role in triggering positive tipping points?

Changes in complex systems are often non-linear and triggered by multiple intentional and non-intentional interventions, whose cause and effect may not be proportionate. A tipping point represents a critical point in a system beyond which an important and often disproportionate change occurs. Understanding the tipping point mechanisms that will bring about such conversions are important to policy makers, since they can help to achieve important scaling effects, generating greater system impacts from limited available public resources. The positive tipping point framework can be used as a guide to inform the design of R&I programmes, extending them beyond their typical techno-centric focus. The framework identifies different levers that need to be actioned in order to create the right conditions for the emergence of large scale, systemic tipping points.

Levers include: **Economic competitiveness & affordability**: to stimulate demand, proposed solutions must be economically competitive to alternative solutions; **Performance & attractiveness**: proposed alternatives must meet - or outperform - existing solutions on required levels of performance or quality; **Accessibility**: the solutions, or the change in behaviour proposed by the alternatives, can be conveniently accessed by stakeholders; **Cultural norms & desirability**: alternatives are also socially desirable/acceptable and normalised across stakeholders; **Capability & information**: stakeholders have the right information to use the solution, or act on the behaviour; and, **Complementarity**: proposed solutions are surrounded by complementary innovations, including across the whole value chain, allowing their rapid deployment leading to the displacement of the old solution suite.

The framework identifies different "reinforcing feedback loops" to achieve these conditions at scale (e.g., social contagion, increasing returns on adoption, information cascade, etc.) and intervention types that should be implemented to trigger these feedback loops, create the right enabling conditions and eventually tip the system. In designing R&I programmes, the framework puts the broader enabling environment on an equal footing with "innovation and technology" focused interventions.

This part of the research built on further literature review, detailed analysis of particular R&I areas and a stakeholder consultation.

3. How can climate scenarios help develop a systemic perspective for R&I programmes?

3.1. Why is a systemic approach needed in R&I for climate neutrality?

The drive toward climate neutrality and systemic transformation comes with its unique set of challenges for public R&I programmes. Adopting a holistic and systemic approach is vital for delivering transformative innovations across all sectors – as required to achieve the EU's 2050 climate goal (as per the European Green Deal and stipulated in the European Climate Law). Without a systemic perspective it is easy to overlook (1) factors limiting the scaling of clean technology adoption, (2) opportunities for multi-purpose or general-purpose technologies (GPTs), and (3) powerful innovation dynamics, that accelerate or hinder the adoption of solutions.

Our examination of 17 Solution Landscapes (see separate Solution Landscapes Annex) shows the importance of identifying limiting factors that could hold back adoption of an individual solution, an entire technology ecosystem or even multiple ecosystems at once. A prominent example is battery production or sourcing of materials refining as a limiting factor for battery electric vehicle (BEVs) adoption that might simultaneously hold back the roll-out of renewables due to the lack in grid-balancing batteries.

On the flipside, a systemic approach can also help identify the multiple simultaneous opportunities flowing from multi-purpose technologies or GPTs unlocking synergies across a wide range of climate change mitigation solutions.

Exploring the innovation dynamics in specific solution areas has revealed that intimate knowledge of innovation and adoption dynamics is essential to see the whole picture. For example, it is crucial to understand uncertainties in ocean carbon removals in the context of other carbon removal solution areas, as these may compete for limited resources in funding and political attention. Further, in solution areas, intimate knowledge is also required in the projection of cost-reduction (and inversely technology-adoption) curves.[30]

3.2. What are the limiting factors preventing the adoption of a systemic approach?

The transition to a systemic approach is not without hindrances, and R&I programmes have often struggled to incorporate systemic considerations in their structures and funding allocations (Dixson-Declève et al., 2023). This section elucidates key limiting

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[30] For example, discussions regarding the direct air capture (DAC) Solution Landscape revealed that multiple strategies may need to be pursued at once: one which leverages conventional materials for which established supply-chains support rapid scaling, or another, which leverages novel materials for a more energy-efficient approach. The latter strategy will, however, require the establishment of novel supply-chains, which may initially hold back the scale up of DAC, but later enable it to reach a much larger overall scale (given the efficiency gains).

factors[31] that stand in the way of systemic adoption in R&I programmes, which will provide a common thread for the subsequent discussion and recommendations.

1. **Siloed Mindsets and Structural Barriers:** One of the predominant factors lies in the existing structure of many R&I programmes, both public and private. Historically designed to address specific, compartmentalised challenges, they often fail to recognise and integrate interdependencies across sectors. As highlighted by EON Foresight[32], institutional rigidity and deeply embedded sectoral boundaries discourage holistic thinking and impede collaboration.

2. **Inadequate Metrics and Evaluation Tools:** Current metrics and evaluation mechanisms for R&I programmes are often narrowly defined around short-term outcomes or technology-centric benchmarks. According to insights from the OECD[33], there is a lack of comprehensive tools to assess the systemic impacts and interconnections of innovative solutions, leading to a potential undervaluation of truly transformative projects.

3. **Risk-Aversion in Funding Allocation:** Achieving systemic transformation often requires funding high-risk, high-reward projects. However, many R&I programmes, influenced by a need for assured returns and the generation of results/solutions that deliver tangible impact and contribution to policy objectives in the short term, tend to gravitate towards incremental innovations, rather than embracing more radical, systemic solutions driven by fundamental R&I.

4. **Misalignment of Stakeholder Interests:** While the need for systemic change is widely recognised, aligning stakeholders towards a common agenda is challenging. Differences in short-term priorities, risk appetites, and strategic objectives can create friction and slow down the momentum towards adopting a systemic long-term oriented approach.

5. **Lack of Capacity and Expertise:** Systemic thinking demands an integration of multiple disciplines, expertise in complex systems dynamics, and an understanding of socio-economic and environmental interdependencies. Many organisations and institutions lack the internal capacity or the transdisciplinary expertise to guide R&I programmes toward systems transformation.

6. **Pace of Global Change:** The rapidly evolving global R&I landscape, marked by technological advancements, changing political dynamics, and emerging environmental and societal crises, can sometimes outpace the ability of R&I programmes to adapt systemically to effectively address key societal challenges.

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[31] These findings were derived from a combination of expert assessment, workshop discussions and the Dixson-Declève S., et al., 2023. Research and innovation to thrive in the poly-crisis age. Available at: https://op.europa.eu/en/web/eu-law-and-publications/publication-detail/-/publication/6a49758f-d429-11ed-a05c-01aa75ed71a1

[32] Eon, 2023. Cutting the Gordian Infrastructure Knot. Available at: https://www.eon.com/content/dam/eon/eon-com/eon-com-assets/content/innovation/innovation-frontline/opinion/articles/gordian-study-op-ed/230606_gordium-studie_final.pdf

[33] OECD, 2023. The OECD Science, Technology and Innovation Outlook 2023. Available at: https://www.oecd-ilibrary.org/sites/0b55736e-en/1/2/1/index.html?itemId=/content/publication/0b55736e-en&_csp_=b2412cc0600196af8b299a715946ac12&itemIGO=oecd&itemContentType=book

Identifying strategies and methodologies to overcome these barriers can enable R&I programmes to advance systemic and transformative technology and social practice. The subsequent sections will delve deeper and propose recommendations that align with the overarching objective of Europe achieving climate neutrality by 2050.

Public R&I funding can catalyse private investment in development and diffusion of technologies. Research by the Cleantech Group[34] shows that policy prioritization of specific sub-sectors is often followed by VC investment. Moreover, European investors take cues from EU programmes, using grant awards as a quality indicator: "*programmes like Horizon 2020 and EIT [provide] essential support for knowledge and resource heavy ventures, in terms of non-dilutive funding opportunities as they prove their concept and team before approaching venture capital investors*."

Net-zero scenarios point to another systemic R&I requirement: striking the equilibrium between techno-economic solutions and societal lifestyle adaptations, as both of which may be needed to reach net-zero. Scenarios often explore a continuum from full reliance on technology-adoption to full reliance on a fundamental shift in societal behaviours and values. A public R&I program that is fit for purpose must integrate both paradigms. Neither can stand alone; technological innovations might be futile if societal behaviours remain unchanged (given rebound effects in consumption behaviour). And vice-versa: societal behaviour change often flows from new technological alternatives. Therefore, R&I programmes aiming for a systemic mindset must prioritise an integrated approach, emphasising both technological breakthroughs and societal transformations. Additionally, while unforeseen events like geopolitical crises or global pandemics are recognised as game-changers, incorporating such variables into R&I planning remains a formidable challenge. As unpredictable events can significantly alter trajectories R&I agendas need to be flexible, adaptive, and based on broad foresight – ready to pivot in response to changing global landscapes.

Every choice in the R&I landscape inherently contains normative dimensions, reflecting underlying values, societal norms, and ethical considerations. These value judgments influence the direction and depth of research, innovation, and subsequent application. Calls to prioritise techno-economic solutions over lifestyle changes, or vice versa, are rooted in values regarding progress, economic growth, or environmental stewardship. Similarly, prioritization of research areas often intertwines with paradigms of what is deemed 'important' or 'desirable', which can be in conflict with more narrow mission objectives (e.g., net-zero). When official funding institutions, allocate the public resources they are entrusted with, they are to navigate a fine line between pushing the boundaries of innovation and ensuring responsible stewardship of public resources. As a result, their investment choices may often appear excessively conservative, particularly when it comes to high-risk, high-reward projects. This cautious approach, while understandable in the context of public accountability, can hinder transformative innovations that may hold the key to addressing pressing global challenges. This is perhaps best exemplified with the controversial discussion of nuclear energy, which, despite its zero-emissions status

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[34] Cleantech for Europe, 2021. Powering Cleantech in Estonia and Beyond: Meet Beamline Accelerator (5.10.21). Available at: https://www.cleantechforeurope.com/news/estonian-cleantech-meet-beamline-accerator

and potential for breakthrough innovation (e.g., in small and medium sized reactors) is often disregarded in net-zero considerations for dogmatic reasons.

3.3. How can climate scenarios help develop a systemic perspective for R&I programmes?

3.3.1. Net-zero scenarios provide directionality to R&I for climate neutrality

Decarbonising European societies has been defined as a "mission" answering to the large societal challenge of climate change[35]. Professor Mazzucato, in her 2018 report to the European Commission, defines missions as a "*means to focus our research, innovation and investments on solving critical problems, while also spurring growth, jobs and resulting in positive spillovers across many sectors [...] To engage research and innovation in meeting such challenges, a clear direction must be given, while also enabling bottom-up solutions*"[36].

The IEA states in their 2021 report on the contribution of technologies under development to climate neutrality: "*The Faster Innovation Case in Energy Technology Perspectives 2020 explored whether net-zero emissions could be achieved globally by 2050 through accelerated energy technology development and deployment alone: it showed that, relative to baseline trends,* ***almost half of the emissions savings needed in 2050 to reach net-zero emissions rely on technologies that are not yet commercially available***" [37]. The IEA relates "Technologies under development" to the first three of the following four relevant categories: (i) Prototype; (ii) Demonstration; (iii) Market uptake; and, (iv) Maturity. It is important to realise that scenarios do not only take R&I needs into account, but also many other aspects impacting market uptake, related notably to technology diffusion, evolutionary improvement through technology learning and scale effects. These factors are not necessarily a major target for the policies deployed by DG RTD, but rather for policies related to technology diffusion, notably demand policies. Based on an analysis of different climate neutrality scenarios, it can be quite difficult to distinguish between technology developments which still have major R&D challenges to address; and technology developments which are driven by market diffusion.

The OECD report 'Driving low carbon innovation for climate neutrality, Policy Paper 143, March 2023)[38], states that innovation rates are insufficient at the moment and investments on green innovation seems stagnating, contrary to deployment. Therefore, the report urges policy makers to support more balanced R&I programmes.

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[35] European Commission, Directorate-General for Research and Innovation, Mazzucato, M., 2018. Mission-oriented research & innovation in the European Union: a problem-solving approach to fuel innovation-led growth, Publications Office, 2018. Available at: https://data.europa.eu/doi/10.2777/360325

[36] Ibidem.

[37] IEA, 2021. Net Zero by 2050 A Roadmap for the Global Energy Sector. Available at: https://www.iea.org/reports/net-zero-by-2050

[38] OECD, 2023. Driving low-carbon innovations for climate neutrality. Available at: https://www.oecd.org/publications/driving-low-carbon-innovations-for-climate-neutrality-8e6ae16b-en.htm

In addition, there are substantial differences in the pathways to carbon neutrality. Broadly schematised, they fall into two categories:

- Climate neutrality scenarios that operate with a **strong techno-economic focus** to reach the objectives. These scenarios are based on the **hypothesis that the material basis will continue to be in some way a major part of our future world**, though it is used much more efficiently. In that sense, they still present a "(non)linear continuation to the past".
- Climate neutrality scenarios that operate with a **strong focus on changes in societal trends and behaviours**. These scenarios are based on a new definition of what is meant by growth and the **hypothesis that our well-being can be largely decoupled from a material world**. Societal values change considerably in those scenarios and require a new societal compromise on what is acceptable and what is felt as limiting too strongly individual freedoms.

Certainly, this is largely schematised: scenarios with a strong techno-economic focus include substantial elements of lifestyle changes, while scenarios strongly inspired by changing societal needs cannot be totally decoupled from material needs, especially when it comes to a timeframe of ten years and longer. Nevertheless, this separation is useful to explore differences in R&I needs.

In this study, two sets of net-zero scenarios are analysed:

- Scenarios with a strong techno-economic focus, emphasising the need for technological innovations.
- Scenarios focussing on lifestyle changes and new societal trends. These scenarios were added to this analysis following interactions with the external experts of the study. They are premised on a need to fundamentally alter production and consumption patterns. They imply normative disruption and potentially limitations to personal freedom.

Our scenarios reflect decadal trends and ignore possibilities of abrupt shocks and crises (such as the Russian invasion of Ukraine or the COVID-19 pandemic) given their unpredictability. Ambitious climate policy and a fitting R&I agenda may, however, need to build in resilience against such shocks including from import dependencies, energy security, or climate-related migration. Some shock-induced disruption can lead to unexpected medium-term outcomes, as both COVID-19 and the war in Ukraine have rapidly reconfigured global supply chains, briefly altering the course of clean technology adoption.

The scenarios selected for the analysis are presented in Table 3. They all reach climate neutrality at their respective governance level.

Table 3. Net-zero scenarios considered in the analysis. Source: ICF & partners, 2023

LEVEL	SELECTED SCENARIOS
Net zero scenarios focussed on techno-economic developments	
Worldwide	• IRENA (2022) "World Energy Transitions Outlook: 1.5°C Pathway"39 • IEA (2021) "Net Zero to 2050"40 and IEA (2020) "Energy Technology Perspectives 2020"41) • IPCC (2022) (Working Group 3, Net Zero Scenarios)42 • Land-use scenarios (e.g., with IMAGE) as part of SSP for IPCC AR6
EU	• EU Climate Neutrality Scenarios (1.5°C Technical)43 • Scenarios of the EU Scientific Advisory Board on Climate Change44
National	• Germany Climate Neutrality Scenarios (Long-term Scenarios)45 • National Climate and Energy Plans for each EU Member State (to be updated by June 2023)46
Net-zero scenarios emphasising lifestyle/behavioural developments	
Worldwide	• IPCC Special Report: Global Warming of 1.5°C47 • IPCC Scenarios coupled more strongly with lifestyle changes, e.g., the IMP-Ren (renewables) or IMP-LD (low demand) scenarios, compensating for technological limits and barriers48

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[39] IRENA, 2022. World Energy Transitions Outlook: 1.5 degree C Pathway. Available at: https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022

[40] IEA, 2021. Net Zero by 2050. Available at: https://www.iea.org/reports/net-zero-by-2050

[41] IEA, 2020. Energy Technology Perspectives 2020. Available at: https://www.iea.org/reports/energy-technology-perspectives-2020

[42] IPCC, 2022. IPCC Sixth Assessment Report. Available at: https://www.ipcc.ch/report/ar6/wg3/https://www.ipcc.ch/report/ar6/wg3/

[43] European Commission,2018. European long-term strategy – A Clean Planet for all. Available at: https://ec.europa.eu/clima/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

[44] European Scientific Advisory Board on Climate Change, 2023. Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. Available at: https://climate-advisory-board.europa.eu/reports-and-publications/scientific-advice-for-the-determination-of-an-eu-wide-2040/scientific-advice-for-the-determination-of-an-eu-wide-2040-climate-target-and-a-greenhouse-gas-budget-for-2030-2050.pdf/@@display-file/file

[45] BMWK, 2022. Scientific analysis on the decarbonization of Germany. Available at: https://www.langfristszenarien.de/enertile-explorer-de/index.php

[46] European Commission, 2023. National Energy and Climate Plans. Available at: https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps_en

[47] IPCC, 2018. Special Report: Global Warming of 1.5°C. Available at: https://www.ipcc.ch/sr15/

[48] IPCC, 2022. Climate Change 2022. Mitigation of climate change. Available at: https://report.ipcc.ch/ar6/wg3/IPCC_AR6_WGIII_Full_Report.pdf

LEVEL	SELECTED SCENARIOS
EU	• H2020 NewTrends project, which investigates the impact of New Societal Trends such as Shared Economy, Digitalisation, Circular Economy on energy demand49 • EU Climate Neutrality Scenarios (1.5°C LIFE(style))50 • EU bio-economy plans51

Net-zero scenarios describe pathways leading to a climate neutral energy and land system and economy in Europe. As such they provide a space within which to explore interdependencies in climate neutrality pathways. Therefore, they help identify potential R&I areas and nexuses representing systemic interactions between R&I areas.

3.3.2. Systemic innovation needs derived from the scenario analysis

Naturally, there is a large variation among scenarios, regarding the contribution of individual decarbonisation technologies and components, as well as non-technological solutions. Systematic review of the scenarios reveals patterns and prominent decarbonisation technologies and societal solutions most scenarios imply to hold an important role. The highest-potential solutions with relatively low levels of technological and market maturity were identified across scenarios. In contrast, criteria that are more difficult to identify from scenarios – such as the cost of mitigation – were not considered.

The following figures illustrate some of the key patterns across the national, European and global level.

Patterns identified for the **electricity sector** (see Figure 6 below) include:

- A strong increase in electricity demand (by a factor of 2 - 3.4) due to electrification and electricity-based energy carriers such as hydrogen as well as their down-stream products.
- A very high share of renewables in the range 85-100%, with PV and wind being by far the most dominating technologies, above 70%. Some advanced countries such as Germany will already reach such levels by the end of the current decade. This raises the question of public R&I funding on these technologies, which are largely driven by development goals, and the increasing competitive position of renewables (in 2022 83% of all new power generation capacity worldwide was based on renewables) rather than R&I goals. The quickly developing market also provides ample opportunity for steady improvement in technology performance and cost. Nevertheless, hidden in the figures below are systemic aspects such as storage capabilities and sector coupling, limitations in available space (e.g., for solar), and acceptance (e.g. for wind), as well as infrastructure-related aspects

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[49] NewTrends, 2020. 2020 Trends. Available at: https://newtrends2020.eu/

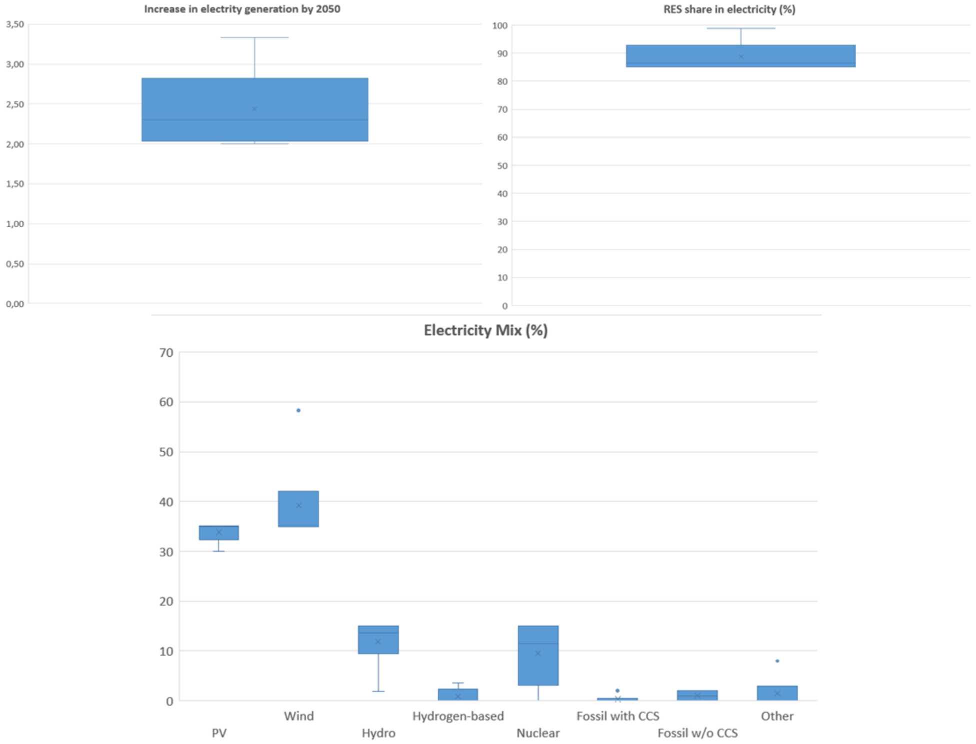
[50] European Commission, 2018. European long-term strategy – A Clean Planet for all. Available at: https://ec.europa.eu/clima/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

[51] European Commission, 2023. Bioeconomy strategy. Available at: https://research-and-innovation.ec.europa.eu/research-area/environment/bioeconomy/bioeconomy-strategy_en

which, due to the fluctuating nature of PV and wind, gain strongly in importance and require additional focus, including from R&I policies and programmes.

- Other technologies for electricity generation, even hydro power, appear as secondary next to wind, though they may play a certain role from a system perspective. There appears to be little role for CCS on fossil fuel power plants.
- A broad range of potentials ascribed to nuclear among the scenarios suggests widely differing views despite the known potential both from current technology, as well as potential breakthrough innovation, such as on Small Modular Reactors (SMR). The EU's energy roadmap for example counts on 15-18% of total energy production from nuclear in 2050.

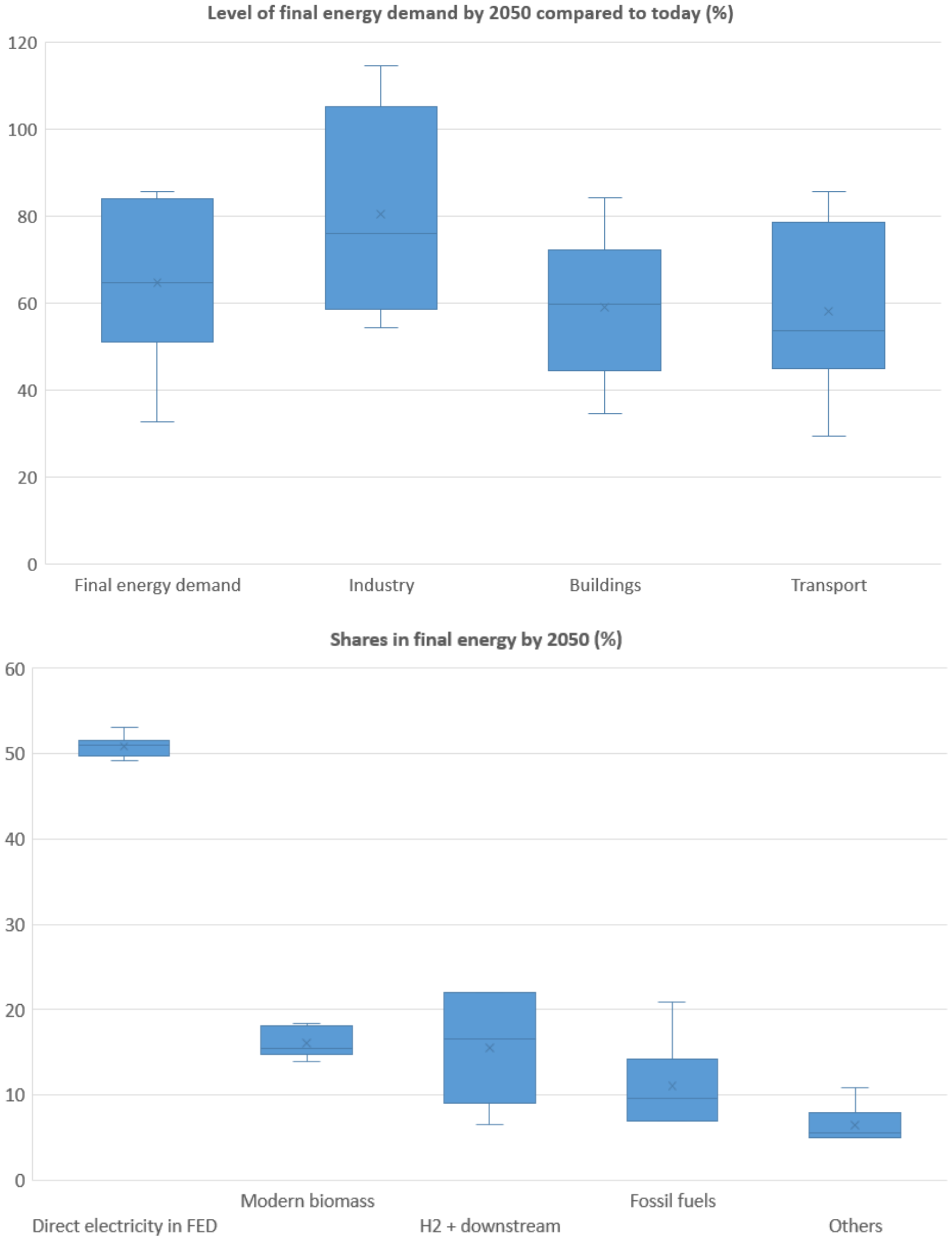
Figure 6. Key patterns in scenarios for the electricity sector. Source: Fraunhofer, ISI. 2023.



Key patterns in the scenarios include for the **final demand sectors** (see Figure 7 below), among others:

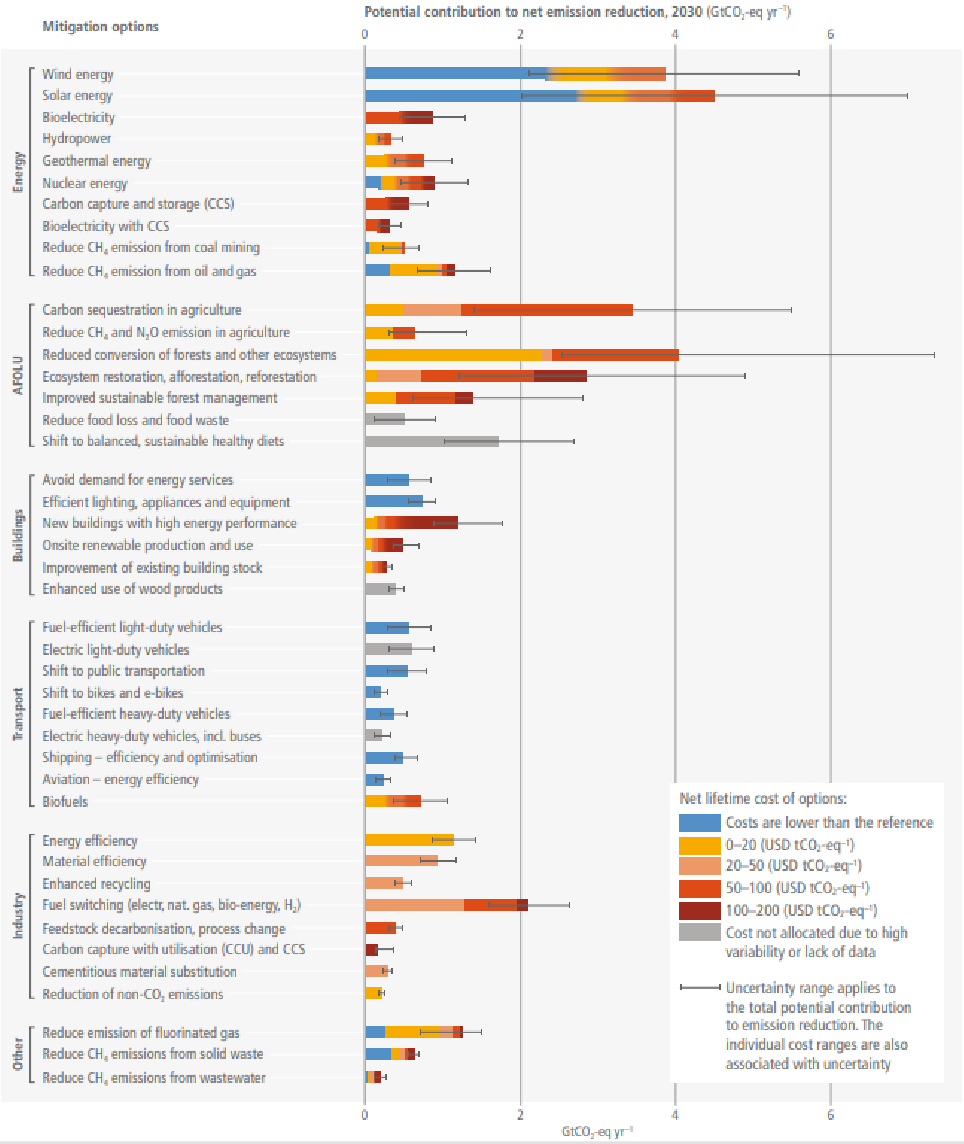
- A strong increase in overall final energy demand (FED) to levels of +60-90% (at worldwide level more the upper bound given the stronger growth in population and the desire for a more decent life).
- This raises tremendous challenges in terms of energy efficiency and carbon neutral solutions in industrial processes, coupled with a circular economy and material efficiency to reduce the amount of highly carbon intensive materials required to support existing and emerging solutions. The challenge is high, given that this is the only sector where energy demand is partly still expected to increase, despite more direct electricity uses.
- A second challenge for energy efficiency relies on the interlinked block of buildings and transport, whose energy demand is expected to decrease on average to 50-70% of today's consumption levels.
- Direct electrification is expected to contribute to at least 50% to the coverage of final energy demand through energy efficiency improvements, consistently across national, European and worldwide levels.
- The role of modern biomass and hydrogen (including downstream products such as synthetic fuels or ammonia) comes second with an average contribution of 15% each. Especially the hydrogen economy has still a broad range across the scenarios which is partly linked to differing views and assumptions where the technologies may best contribute, given the high conversion losses in the value chain of hydrogen.
- Finally, lifestyle-based scenarios suggest the possibility of lower energy demand levels due to reductions in energy services requested. The energy demand is substituted by new societal developments such as reduced living spaces, the digital sharing economy, and behaviour-induced circularity.

Figure 7. Key patterns in Net Zero scenarios for final demand sectors. Source: Fraunhofer, ISI. 2023.



Scenarios in the IPCC AR6 (2023) introduce an additional focus on agriculture, food and CO_2 storage, where mitigation cost appears as specifically high (see Figure 8).

Figure 8. Key patterns in IPCC (AR6) Net Zero scenarios for mitigation options. Source: IPCC AR6 (2023).



The broad comparison of net zero scenarios by the EU Advisory Board on Climate Change (2023) affirms the importance of newer measures. Their three iconic pathways (see Table 4) underline contributions of early-stage technology clusters such as the hydrogen economy, CCS or CCU, as well as CDR technologies, including those based on biomass.

Table 4. Key patterns in Net-zero scenario comparisons of the EU Advisory Board on Climate Change (2023). Source: European Scientific Advisory Board on Climate Change (2023).

		Iconic pathway	
	Demand-side focus	**High renewable energy**	**Mixed options**
Greenhouse gas budget 2030-2050 (Gt CO_2e)			
Intra-EU bunkers only	11.7	13.8	11.1
All bunkers	13.7	16.8	13.2
Greenhouse gas reduction below 1990, including intra-EU bunkers			
By 2040	-91.2%	-90.9%	-90.8%
By 2050	-101.1%	-102.0%	-100.3%
Other key parameters			
Final energy demand (% change in 2040 vs 2015)	-40%	-38%	-23%
Electrification (electricity share of final energy demand in 2040)	45%	50%	45%
Share of electricity production in 2040 (%)			
Non-biomass renewables	90%	87%	72%
Nuclear	3%	7%	23%
Natural gas (with and without CCS)	2%	2%	4%
Net imports			
Fossil fuels in 2040 (EJ)*	6.1	5.8	8.0
% change since 2015	-81%	-82%	-70%
Bioenergy consumption (primary) in 2040 (EJ)	10.3	7.1	5.3

		Iconic pathway	
	Demand-side focus	**High renewable energy**	**Mixed options**
Greenhouse gas budget 2030-2050 (Gt CO_2e)			
Intra-EU bunkers only	11.7	13.8	11.1
All bunkers	13.7	16.8	13.2
Greenhouse gas reduction below 1990, including intra-EU bunkers			
By 2040	-91.2%	-90.9%	-90.8%
By 2050	-101.1%	-102.0%	-100.3%
Other key parameters			
Final energy demand (% change in 2040 vs 2015)	-40%	-38%	-23%
Electrification (electricity share of final energy demand in 2040)	45%	50%	45%
Share of electricity production in 2040 (%)			
Non-biomass renewables	90%	87%	72%
Nuclear	3%	7%	23%
Natural gas (with and without CCS)	2%	2%	4%
Net imports			
Fossil fuels in 2040 (EJ)*	6.1	5.8	8.0
% change since 2015	-81%	-82%	-70%
Bioenergy consumption (primary) in 2040 (EJ)	10.3	7.1	5.3

	Iconic pathway		
	Demand-side focus	**High renewable energy**	**Mixed options**
Hydrogen production in 2040 (EJ)	1.7	1.6	3.5
Carbon capture, utilisation and storage (Mt CO_2 captured per year by 2050)			
Total	145	308	417
of which biomass *	*77*	*234*	*147*
Land sink (net LULUCF Mt CO_2 removed annually)*			
In 2040	351	323	601
In 2050	351	312	669

Table 5. Key solution areas and systemic nexuses stemming from the techno-economic scenarios analysis. Source: ICF & partners, 2023.

CHALLENGES	SOLUTIONS	MITIGATION POTENTIAL*	MATURITY LEVEL	SYSTEMIC NEXUSES IN WHICH SOLUTIONS ARE EMBEDDED
Decarbonise the power & heat sectors	"Power horse" Renewable Energy Sources (RES) (Solar PV & Wind) contributing to the bulk of generation	Very high: main source of renewable electricity across all scenarios.	Commercialised solutions, but require R&I support to make massive scale-up as cost-effective and resource-efficient as possible, considering technology and critical material dependencies.	(1) circularity – industry – carbon removals and capture (2) mobility – built environment – energy
	Other RES (e.g., Hydropower Ocean, Tidal, Geothermal), contributing to system stability	Limited: role mostly linked to complement “power horse” RES (e.g., by contributing to system stability, since they are more dispatchable than Solar PV and Wind), except for the (very) large potential of Geothermal Heat (RES-H).	Varying, depending on technology from very early technology to some first commercial applications – with the exception of Geothermal Heat.	
	Flexibility & grid stability	Very high (at overall systems level): required to transition towards RES-based power sector.	Varying, depending on technology	

CHALLENGES	SOLUTIONS	MITIGATION POTENTIAL*	MATURITY LEVEL	SYSTEMIC NEXUSES IN WHICH SOLUTIONS ARE EMBEDDED
	Storage of electricity and heat	High: required as one important flexibility provider to transition towards RES-based power sector.	Varying, depending on technology	
Decarbonise high emitting sectors	Decarbonised and energy-efficient industrial processes (green steel, green cement, green chemistry (including bio-based materials, …)	Very high: carbon-intensive processes account for the larger part of direct emissions from industry.	Some process steps commercially available; R&I for upscaling required for many processes. A major R&I challenge is to avoid increases in energy demand while decarbonizing.	(1) circularity – industry – carbon removals and capture
	Built environment (including positive energy buildings and urban environment)	Very high: buildings account for the larger part of direct emissions from industry. Energy efficiency strongly to contribute, especially in existing buildings.	Mature technologies available (e.g., direct use of electricity in heat pumps, district heating), but modularity, cost and performance (e.g. superinsulation) are issues for R&I. Urban environment (for example urban greening) and sector-coupling solutions less researched. Lifestyle related R&I concerns notably the Shared Economy.	(2) mobility – built environment – energy

CHALLENGES	SOLUTIONS	MITIGATION POTENTIAL*	MATURITY LEVEL	SYSTEMIC NEXUSES IN WHICH SOLUTIONS ARE EMBEDDED
	Zero-carbon mobility	High: especially for aircraft (long-distance carriers), shipping, goods transport.	Commercial solutions available in passenger transport (notably with electric vehicles). Energy efficiency options (including light-weight materials), circular economy (e.g., on batteries) and modal shift-relevant technologies strongly contribute to low-carbon passenger transport, but also to other transport modes. Big technical hurdles remain for e.g., shipping fuels, alternative aircraft propulsion.	(2) mobility – built environment – energy
	Hydrogen economy	Medium to high: the hydrogen economy as a cross-cutting issue is expected to contribute notably to decarbonise industrial process, aircraft and shipping, potentially part of goods transport.	Commercial solutions available, but new and more electrolyser processes, hydrogen transport and storage, contribution to sector coupling of R&I are needed.	(1) circularity – industry – carbon removals and capture
Provide the supporting efficient and flexible	Smart and flexible electricity grids Hydrogen/gas grids	High: Infrastructure contributes to mitigation by providing flexibility, efficiency and low cost	Infrastructures exist for all five layers, but the interaction between all five layers, notably between the first four energy infrastructures and the energy-	(1) circularity – industry – carbon removals and capture

CHALLENGES	SOLUTIONS	MITIGATION POTENTIAL*	MATURITY LEVEL	SYSTEMIC NEXUSES IN WHICH SOLUTIONS ARE EMBEDDED
infrastructure to transport low-carbon energy carriers decarbonise energy, power and high emitting sectors	Heat grids ("District heating 4th + 5th generation") CO_2 transport infrastructures IT Grids related to the transformation of the energy system	(also at lowering transported volumes due to energy efficiency), while being resilient to intentional and unintentional disturbance.	relevant IT infrastructure is highly complex and requires much more understanding of interactions between the layers. The ability to fully model within each infrastructure 'layer' – such as electricity grids – can be very challenging.	(2) mobility – built environment – energy
Maximise GHG removals solutions, including Nature Based Solutions	Direct Air Capture (DAC) technologies	Medium to high: required for synthetic fuels derived from hydrogen, which include carbon (e.g., synthetic methanol or methane). If those are not used in large amounts, the need for DAC is rather small to medium.	Technology exists in principle but is hardly experienced; cost reduction potentials are largely unknown. Minimising cost, improving performance and reducing environmental impact are challenges.	(1) circularity – industry – carbon removals and capture (3) agrifood – carbon removals
	Point source capture technologies (including biomass)	High for BECCS: essential in achieving negative emissions.	Technology exists in principle but is hardly experienced; cost reduction potentials are largely unknown. Minimising cost, improving	

CHALLENGES	SOLUTIONS	MITIGATION POTENTIAL*	MATURITY LEVEL	SYSTEMIC NEXUSES IN WHICH SOLUTIONS ARE EMBEDDED
			performance and acceptance issues are challenges.	
	Durable storage (including in long-lived products)	Medium to high: essential in assuring a net contribution to carbon removal. Limiting factor is the potential of long-lived products.	Mature technologies exist but minimising cost, and improving performance are challenges.	
	Terrestrial ecosystem-based removal	Potentially high but at risk due to the impact of climate change as well as human activity.	Proven solution group but facing challenges linked to business case and permanence. Early-stage technology group (linked to complexity of terrestrial eco-system)	
	Ocean ecosystem-based removal	Potentially high but with high level of scientific uncertainties regarding their efficacy as well as side effects.	Early-stage solution group linked to the complexity of ocean ecosystem and the uncertainty regarding the effectiveness and costs of ocean-based CDR. Large uncertainties regarding ecosystem effects of various marine CDR applications require further research.	

Table 6. Key solution areas and systemic nexuses stemming from the lifestyle/NewTrends scenario analysis. Source: ICF & partners, 2023.

CHALLENGES	SOLUTIONS	MITIGATION POTENTIAL	MATURITY LEVEL	SELECTED FOR THE NEXT STEP?
Transition to fully circular economic models	Circular economy	High (large contribution to lower industrial emissions for the production) to very high (reducing critical dependencies on materials and technologies).	Varying, depending on technology, materials/product level. It requires also strong changes in the habits of using products.	(1) circularity – industry – carbon removals and capture
Decentralise the energy system	Digitalisation & “prosumaging" (producing, consuming, managing energy at a decentralised level)	High (at systems level): combination of (1) societal trend, i.e., the wish to be an actor in a decentral electricity system; (2) technological solutions (e.g., blockchain technology); and, (3) market arrangements, which include new procedures to exchange electricity (e.g. built on blockchain technology).	Varying, depending on technology, approach. It requires also strong changes in the relation to the commodity electricity and the market arrangements. F&I required for underlying technology.	(2) mobility – built environment – energy
Change the way we feed the world	New agri-food nexus	High: from today’s perspective other sectors appear as larger emitters but the agri-food sector is one of the most difficult to mitigate and the emissions in the whole chain are complex and distributed on a worldwide level.	Varying, depending on technology, approach. It requires also strong changes in the relation to food culture and the related supply chains.	(3) agrifood – carbon removals

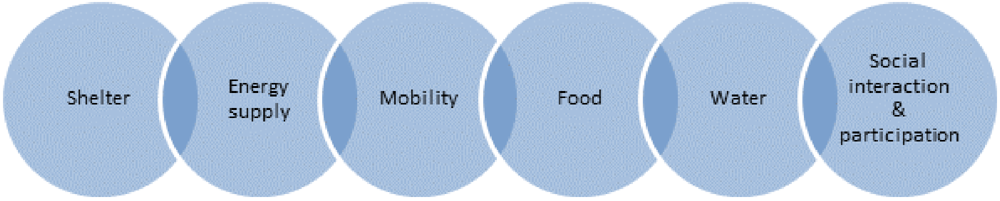
** Note: The mitigation potential refers here to the average of the ranges established earlier in the section from the different scenario studies. The sheer size of the mitigation potential is not alone a measure of importance. Contributing to the "last mile" or GHG reduction may be essential for climate neutrality but may not be expressed in large amounts. This is also, why technologies with smaller contributions, e.g., other renewables than PV and wind, appear in the list.*

The key areas identified through the scenario analysis feed into the development of key R&I nexuses, described in section 3.4.

3.4. A "needs"-based approach to identify systemic nexuses

The following discussions develop around the topic of systemic interactions, exemplified by different needs-based nexuses, which have also been informed by considerations on future societal needs that the net-zero economy needs to meet. When considering the role of specific solutions – as presented also in the separate Solution Landscapes Annex (see also Section 4.2) – it is important to be clear on what needs the solution is meeting. Only with such clarity can the solution be justified, and mission-alignment of future R&I areas be ensured. The needs offer important context for an interdisciplinary examination of how each particular need can most likely be met while also meeting the net-zero condition. A needs-based approach also facilitates the identification of barriers and opportunities.

As stressed by the European Environmental Agency (EEA), the transition towards climate neutrality will not be achieved through incremental changes, but through fundamental transformation of the "*production-consumption systems that meet [our] demand for energy, food, mobility, and shelter*".[52] Overall, the needs that the climate neutral economy will have to meet are:



Meeting these needs in a net-zero economy will require thoughtful measures centred on three nexuses where technological and societal innovation is possible and required:

- **Mobility – built environment – energy**

The decarbonisation of everyday life requires infrastructures that are up to the job. Housing, transport, energy use and RES integration cannot be designed in isolation: urban and rural spaces that we occupy, commuting distances, accessibility of shopping and leisure spaces, housing energy efficiency and the carbon intensity of the power grid determine peoples' carbon footprint almost entirely. This nexus revolves around the interconnections in urban planning, transportation, and energy which are so central for climate-neutral lives. It includes the need for an equitable, accessible and sustainable transport sector (mobility), well-planned living spaces (shelter), and access to zero-emissions, reliable, and affordable energy. Getting the

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[52] European Environment Agency, 2023. Imagining sustainable futures for Europe. Available at: https://www.eea.europa.eu/publications/scenarios-for-a-sustainable-europe-2050

services required to meet the needs of shelter, energy and mobility to net-zero requires technological and societal innovation across these three areas.

- **Circularity – industry – technological removals**

Without industry decarbonisation, which according to the EU 2050 long-term strategy for climate neutrality[53] is also expected to rely heavily on the removal of CO_2, we might risk failing to reach climate neutrality due to significant industrial emissions. The three areas also represent very strong synergies: industry decarbonisation and (re)-utilisation of CO_2 in industrial production (e.g., construction materials) can be done jointly, whereas the carbon management involved in capturing CO_2 from industrial fossil point sources and storing it in geological formations is in synergy with the direct air capture of CO_2 or the capture at biogenic (or mixed fossil and biogenic) industrial point sources and its storage. Adding a circular economy dimension to industrially produced products (that may have been produced by processes involving carbon removals), in particular around re-use and repair, will further enhance the overall sustainability of the production chain. Therefore, this nexus is not only an enabler and important building block to allow a sustainable production of technologies and materials used in the nexus on mobility-built environment-energy but can also improve sustainability of the efforts to address social interaction and participation via a circular economy which is driven by a green industry.

- **Agrifood – natural/ecosystem-based removals**

Food production is usually located in coastal and terrestrial ecosystems. It addresses an essential need which must be managed in a sustainable manner. Combined with ecosystem-based carbon dioxide removal (CDR) methods, the ultimate objective is that it can be turned into a relevant carbon sink with significant synergies, whereby production can over time be enhanced and CO_2 durably removed. There are, however, fundamental challenges surrounding the durability of CDR with food production as well as trade-offs that need to be navigated. These trade-offs include agriculture and CDR methods requiring similar resources, namely areas with fertile preconditions, fertilizers, and water for irrigation. The trade-offs demand a systemic examination to avoid creating unwanted effects, whereby one solution (e.g., biomass utilization toward a removal) adversely impacts on another (biomass availability for other agrifood uses or nutrient losses). While stationary food production systems have been a substantial part of human civilization for millennia, climate change has brought to the fore the vital role that CDR from ecosystems already plays and has alerted policy makers to the extra efforts required to enhance natural CDR processes. Thus, a key task in the nexus between food production and carbon removals is to integrate CDR aspects into existing systems in a way that increases CDR functions without hampering food production. Despite potential conflicts of interest, the integration of CDR into already existing agricultural systems is to be favoured over establishing ecosystem-based CDR into hitherto uncultivated areas. The latter option holds a large potential for negative ecological side effects, including on biodiversity, hydrological cycles, and other ecosystem services. Established intensive agricultural practices

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[53] European Commission, 2018. A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. Avalable at : eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773

often lead to GHG emissions, but there are several approaches to reduce these emissions via altering practices, some of which can increase CDR capability; while increased soil health can also increase crop yields as well as carbon sequestration. While the joint dependence on resources may yield conflicts of interest between food production and CDR, there are also numerous potential co-benefits. Harnessing these co-benefits, while preventing overly high competition for resources, will need to be a key aspect of successful support measures targeting ecosystem-based CDR solutions.

4. How to identify high-risk / high-impact solutions while keeping a systemic perspective in mind?

4.1. The challenge of picking winners

Though an important paradigm of R&I funding, there are significant, and well documented, challenges in *picking winners* when it comes to accelerating solutions toward a particular societal objective – as is the case for achieving the climate neutrality goal. With inherent uncertainty and dynamism in the innovation landscape, and since climate change related R&I is a rapidly evolving field, it is challenging to forecast which competing solutions may reach the greatest potential and be most effective in achieving climate goals – not least because societal factors play into these dynamics in often unexpected ways. With inherent limitations in the anticipatory capacity of R&I funding institutions, one cannot assume that R&I decisions and their outcomes could ever be optimally determined. This raises questions about the prospect of heavily investing in a particular technology or solution, given the risk that it may be surpassed by another, more effective or efficient innovation.

More fundamentally, the focus on selecting winners limits our ability to challenge the status quo and support transformative change. This focus contributes to locking R&I programme in what Mission Innovation defined as a "*Static Problem Approach*" aiming to reduce problems in existing systems rather than questioning them and supporting solution providers that can deliver on human needs in a sustainable way.[54] Recognising this challenge, many countries, and the EU, have opted for mission-oriented innovation policies to address complex challenges such as climate change. The OECD defines these policies as a "*co-ordinated package of policy and regulatory measures tailored specifically to mobilise Science, Technology and Innovation in order to address well-defined objectives related to a societal challenge, in a defined timeframe*"[55]. By providing strategic orientation, this approach allows to move from "picking winners" to "picking willing*", i.e., "those organizations across the economy (in different sectors, including both the public and private sphere) that are "willing" to engage with a societally relevant mission*"[56].

While the design of mission-oriented innovation policies has broader implications of relevance to this study, notably in terms of policy coordination and implementation, this section focusses on what can be learned from this framework to identify high-risk / high-impact solutions, while keeping a systemic perspective in mind. With the objective to move from a Static Problem Approach to a Dynamic Solution Approach,

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[54] Mission Innovation, RISE, BCG, BCG Green Ventures, 2022. The next generation of climate innovation. Available at: https://misolutionframework.net/pdf/Next_Gen_Climate_Innovation.pdf

[55] OECD, 2023. OECD Science, Technology and Innovation Outlook 2023. Available at: https://www.oecd-ilibrary.org/sites/0b55736e-en/1/3/5/index.html?itemId=/content/publication/0b55736e-en&_csp_=b2412cc0600196af8b299a715946ac12&itemIGO=oecd&itemContentType=book#section-d1e15374-e2b3acc2c8

[56] Mazzucato M., 2018. Mission-oriented innovation policies: challenges and opportunities, Industrial and Corporate Change, Volume 27, Issue 5, October 2018, Pages 803–815.Available at: https://doi.org/10.1093/icc/dty034

leading to an expanded R&I agenda, the following approach, described in section 2 and briefly summarised here, was adopted:

- As an initial step, net zero scenarios were analysed to identify and give directionality to our research on the key R&I areas that are expected to play the largest role in supporting climate neutrality. Climate mitigation solutions and R&I areas were mapped in a structured way, developing and using the **Solution Landscapes**, which identified a “Solution Tree” with a “Challenge Tree”. This helped to identify **key high-risk and high-impact R&I areas** and related challenges for different sectors (see section 4.2).
- A transversal analysis of the Solution Landscapes was then completed to identify **common challenges and solutions** with the potential to address multiple challenges simultaneously. This analysis provides a first indication of the type of solutions that should be prioritised by R&I efforts, but it remains high level and can therefore not be considered as a definitive answer to the identification of high-risk / high impact solutions (see section 4.3).
- The **evaluation framework** was developed and applied to each R&I area identified within each Solution Landscape based on different criteria. This gave an initial idea of the most prominent R&I areas belonging to the considered sectors. The evaluation framework also allowed us to assess and rank R&I areas across Solution Landscapes (see section 4.4).
- In parallel, applying a **needs-based** approach and the results of the scenario analysis, the Solution Landscapes were clustered into three nexuses, gathering the set of solutions required to address the identified needs. These nexuses were then used to structure the analysis at different levels, also using inputs deriving from the **evaluation framework applied at nexus level**. This resulted in the identification of key high-risk and high-impact areas related to each nexus (see section 4.5).

4.2. The role of Solution Landscapes

Solutions Landscapes were used to map the climate mitigation solutions and R&I areas in a structured way, based on the results of the scenario analysis. They were built starting from the end goals through the so-called Challenge Tree, that were broken down into sub-targets and specific challenges linked to these sub-targets. On the other hand, the **Solution Tree** starts from an overarching solution contributing to addressing the overarching goal and then breaks down that solution first into different solution areas and, second, into specific R&I areas that have not yet reached full commercialisation.

Thanks to its design, as described in Section 2, the study combined a ‘solution-push’ approach (focusing on solution developments) with a ‘demand-pull’ approach (focusing on the enabling environment). The Solution Landscapes enable the clear articulation of the end goals of a particular solution and the challenges to get there. Within each Solution Tree, particular attention was also given to the role of GPTs in addressing the identified challenges and supporting the development of new solutions.

In the following section, a selection of Solution Landscapes is shown and presented, focusing on key areas which emerged from the scenario analysis: energy, industry, and carbon removals. They cover:

- Industrial decarbonisation;
- Power system flexibility;
- Built Environment; and,
- GHG removals, which represents a suite of five Solution Landscapes, of which three are featured including: (1) industrial removals; (2) land-based removals; and, (3) Terrestrial Ecosystem-Based Removals.

The full set of Solution Landscapes is presented in the separate Solution Landscapes Annex.

Solution Landscape: Industrial decarbonisation

European industry faces a double challenge of being an economic sector that is in dire need of deep decarbonisation, while at the same time, being hard to decarbonise. The principal challenge that leads to the high carbon intensity of industry is in the use of coal (or other fossil fuels) for industrial processes and therefore industry must search for alternatives to coal and fossil fuels for various industrial processes (typically associated with emissions reduction). This, however, has the potential to lead to further material dependencies on the alternatives that are found, which will also necessitate modifications to existing processes to make them compatible with other fuels[57].

The overarching Solution Landscape shown below presents an overview of the principal sectors where further technological R&I might be needed towards a 2050 climate neutrality goal.

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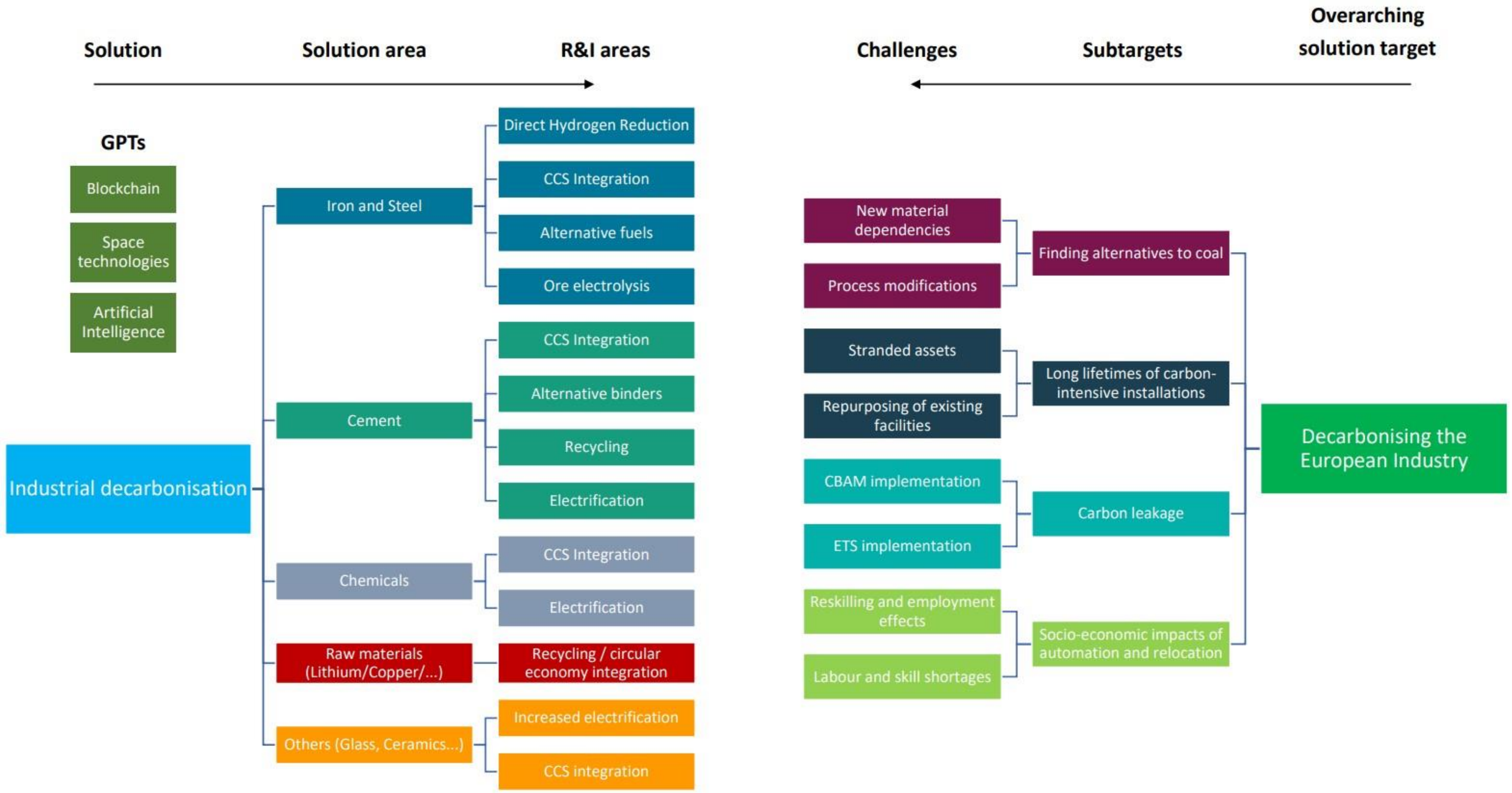
[57] Sovacool, B. K., Geels, F. W., & Iskandarova, M., 2022. Industrial clusters for deep decarbonization. *Science*, *378*(6620), 601-604.

Figure 9. Solution Landscape for Industrial Decarbonisation. Source: ICF & partners, 2023.



The **steel** industry faces particular challenges when it comes to decarbonisation, although several potential solutions are being researched. These can be broadly categorised under hydrogen reduction or CCS integration. When it comes to the **cement** sector, CCS integration, along with improvements in recycling and the search for alternative binders have been noted in the literature as potential research areas for the future[58]. The **chemicals** industry is harder to generalise, due to the wide nature of processes and chemical manufacturing involved, but CCS integration as well as steps towards green chemistry have been discussed in this context. Other sectors such as glass and ceramics have also been noted in the literature as being important in the context of industrial decarbonisation, however, with a smaller role compared to the steel and cement sectors.

While the variety of industrial processes and their individual decarbonisation pathways are hard to summarise, the literature does mention the potentials of increased **electrification** (for heating purposes) and **integration of CCS solutions** as broadly applicable general solutions[59,60]. Finally, as far as other metals (especially those relevant to the energy transition, such as lithium, copper, or cobalt) are concerned, the importance of their integration in a **circular economy** has been specifically noted, which is relevant for the cement and steel sectors as well[61].

Solution Landscape: Power System flexibility

Flexibility in energy systems currently plays - and will continue to play - an important role in enabling the integration of intermittent energy vectors in the energy mix of the EU. Flexibility can be understood in a multi-dimensional manner, involving multiple energy vectors, including electricity, heat, gas, and hydrogen. The overarching Solution Landscape shown below presents three broad solution areas comprising key R&I areas as well as the role of GPTs:

a) Grid efficiency and stability

The infeed of intermittent energy vectors, particularly in the case of renewable electricity, poses important issues of grid stability. This in turn is strategically important, especially to ensure competitiveness of European services and industry. Both the power and gas grids are also strategically important in a geopolitical sense, to ensure energy security. There have been many improvements in demand- and supply-side flexibility, as evidenced by a significant body of literature. Demand-side flexibility will become more important, not only due to an increased flexibility from industry, but also from both the services and residential sectors. Increased technological capabilities, both physical and digital, are necessary to enable higher demand-side flexibility, including intelligent grid management to integrate microgrids and local energy communities, for instance. Increased digitalisation of the grid infrastructure at all levels is a prerequisite for these developments and is dealt with in the Solution Landscape

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[58] Agora Energiewende, 2021. Enabling European industry to invest into a climate-neutral future by 2030, January 2021.

[59] US Department of Energy, 2022. Industrial Decarbonization Roadmap, DOE/EE-2365, US Department of Energy, September 2022.

[60] European Commission, Directorate-General for Research and Innovation, 2022. ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2777/92567

[61] Ibidem.

for Digitalisation (see separate Solution Landscapes Annex). Supply-side flexibility is equally important and would incorporate a combination of technological and market measures (such as the enabling of Virtual Power Plants or of flexibility markets) to ensure an efficient response to demand-side flexibility.[62]

b) Storage

R&I in energy storage will continue to be important to ensure a flexible energy system in the EU. Due to its multi-faceted nature, and increased sector coupling and coupling of energy carriers, research into energy storage is varied and incorporates many technology families, including batteries, hydrogen storage, or thermochemical storage. A crucial aspect is to take into account the material flows of critical materials such as cobalt, nickel, or vanadium[63]. Energy storage has been treated in its own Solution Landscape (see separate Solution Landscapes Annex)

c) Dispatchability

Over the long term, increasing the capacities of dispatchable energy sources is extremely important and is to be considered in conjunction with increased capacities in storage and supply-side flexibility. Research in alternative base load technologies to move away from fossil fuels is important not only from a grid management perspective, but also increasingly from an energy security perspective. In addition, unconventional RES such as deep geothermal or ocean energy, as well as other dispatchable energy sources might be necessary to more efficiently use all available renewable energy potential in the EU[64].

Role of disruptive General Purpose Technologies (GPTs)

Ensuring flexibility in power grids involves better grid management, and **Artificial Intelligence** has been shown in the literature to have applications in better load forecasting as well as in enabling more active consumers (on the grid and on the market)[65]. Similarly, **blockchain technologies** can enable more consumer participation in the grid as well as facilitate transactions of energy between retail consumers that serve to increase flexibility in the power grid and on the power markets[66].

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[62] IRENA, 2018. Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf

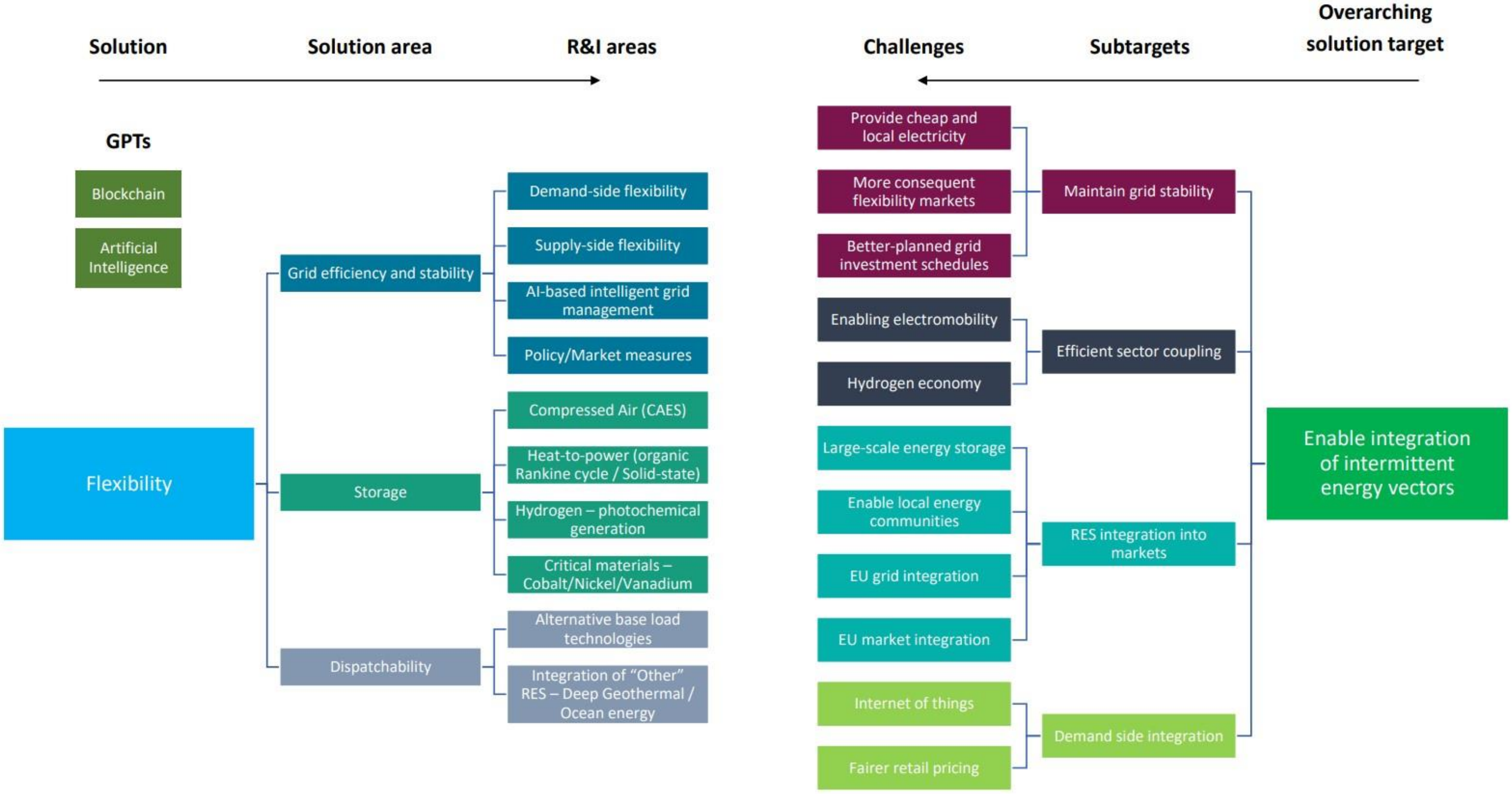
[63] Ibidem.

[64] Pablo del Rio, Alexandra Papadopoulou & Nicolas Calvet, 2021. Dispatchable RES and flexibility in high RES penetration scenarios: solutions for further deployment, Energy Sources, Part B: Economics, Planning, and Policy, 16:1, 1-3, DOI: 10.1080/15567249.2021.1893044

[65] Omitaomu, O. A., & Niu, H., 2021. Artificial Intelligence Techniques in Smart Grid: A Survey. *Smart Cities*, *4*(2), 548–568. MDPI AG. Retrieved from http://dx.doi.org/10.3390/smartcities4020029

[66] Basden, J., & Cottrell, M., 2017. How utilities are using blockchain to modernize the grid. *Harvard Business Review*, *23*, 1-8.

Figure 10. Solution Landscape for Power System Flexibility. Source: ICF & partners, 2023.



Solution Landscape: Built Environment

The built environment presents an important channel of reduction in carbon emissions towards a climate neutral ambition in 2050. Buildings form the central element in this solution landscape, with construction materials being particularly carbon-intensive, but it is also important to consider buildings in active interaction with the wider built infrastructure, its environment as well as with its users, as noted also by the NEXUS expert report on the New European Bauhaus programme[67].

The overarching Solution Landscape shown below presents five broad solution areas comprising key R&I areas as well as the role of GPTs:

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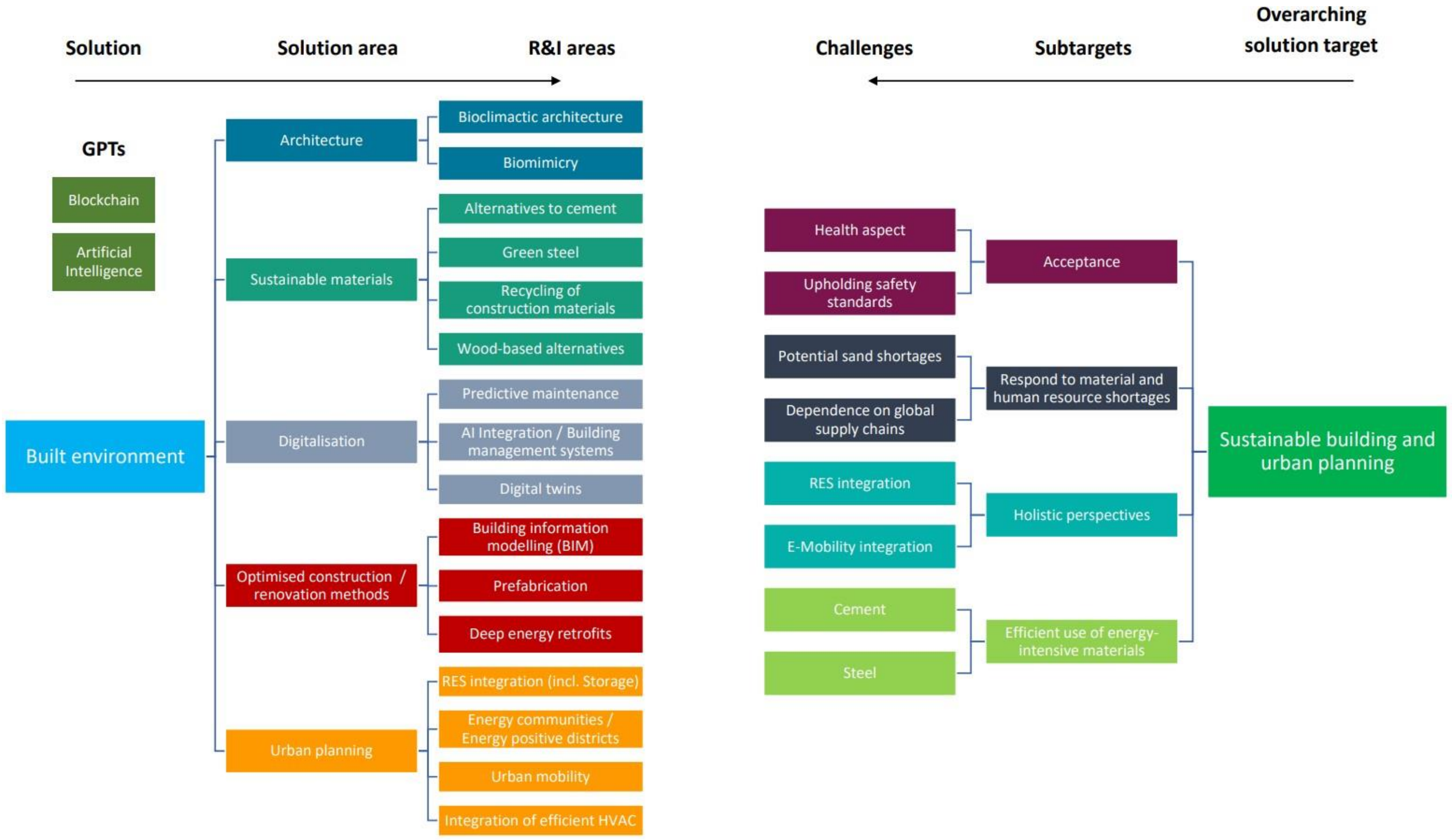
[67] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., 2022. *Horizon Europe and new European Bauhaus NEXUS report : conclusions of the High-Level Workshop on 'Research and Innovation for the New European Bauhaus', jointly organised by DG Research and Innovation and the Joint Research Centre*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/49925

Figure 11. Solution Landscape for the Built Environment. Source: ICF & partners, 2023.



a) Architecture

R&I in architecture (i.e., building design) plays a key role in pushing the building sector closer towards a carbon neutral pathway, due to its long-lasting effects on the energy consumption profile of buildings. Upcoming architectural innovation programmes, such as the New European Bauhaus demonstrates an increased awareness of energy consumption patterns[68]. Further research in architectural improvements in adaptation to changing user patterns, and the integration of nature-based solutions such as biomimicry, or direct integration of trees and nature into buildings, could lead to a more efficient convergence to carbon neutrality ambitions of the new building stocks to be constructed across Europe in the future, while also increasing the quality of life for the citizen and improving resilience to climate change impacts.[69]

b) Use of sustainable materials

The use of sustainable materials in the built environment is an area of active research that will continue to be important. This is due to the large potential to reduce the embedded carbon emissions of various components of a building's structure. In particular, alternatives to both cement and steel have proven absolutely necessary to reduce the amount of embedded carbon in buildings. Reuse and recycling of construction materials, while currently being an active area of research, still requires substantial R&I to be better integrated into a circular economy. Finally, construction elements based on sustainably harvested wood or other organic materials, which can also temporarily store carbon removed from the atmosphere, have been under discussion as areas of further research (as has been discussed under the context of the New European Bauhaus[70]), with several innovative companies pursuing commercial applications. While the materials aspect of the built environment has clear interactions with industry (including steel and cement, covered by the Solution Landscape on Industrial Decarbonisation above), the buildings and built environment sector have a distinct role to play on the demand-side of these materials. To this extent this solution landscape refers to solutions that involve more efficient use of resources (including reuse and recycling, where applicable), while remaining distinct from process innovations inherent to the manufacture of steel, cement, or other building materials.

c) Digitalisation

While digitalisation in general is treated in its own Solution Landscape (see separate Solution Landscapes Annex), specific applications include development of predictive maintenance solutions incorporating elements of AI.[71] This feeds into general, broader applications of building maintenance systems and the integration of energy demand management (through the Internet of Things, for instance), as well as a rising interest

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[68] Ibidem.

[69] Rosado-García, M. J., Kubus, R., Argüelles-Bustillo, R., & García-García, M. J., 2021. A New European Bauhaus for a Culture of Transversality and Sustainability. *Sustainability*, 13(21), 11844. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su132111844

[70] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., 2022. Op. cit.

[71] Cheng, J. C., Chen, W., Chen, K., & Wang, Q., 2020. Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Automation in Construction*, 112, 103087.

in digital twins.[72] Energy management systems (EMS) which include better load forecasting to optimise energy consumption from the grid, as well as systems that integrate generation forecasting for prosumers (for instance, to integrate weather forecasting for those prosumers with rooftop solar PV installations) present interesting use cases for digitalisation in the built environment.

d) Optimised construction / renovation methods

Starting from the building phase and going beyond, Building Information Modelling (BIM) solutions are an area of current active research that ties in with other digital solutions to make the construction process more efficient. Prefabrication of parts of buildings, automatization and industrialisation, which are currently at far lower levels than their true potential, also present enormous opportunities in utilising economies of scale to streamline and optimise construction methods and to making retrofits more affordable. There is also discussion in the literature on the specificities and intersections between "no-tech" construction and "high-tech" construction, both potentially being partial solutions[73]. Finally, deep energy retrofits continue to be an active area of research that focuses on the existing building stock to conserve existing characteristics (particularly in the case of protected or heritage buildings) to make them radically more energy and resource efficient[74,75]

e) Urban planning

As with multiple other Solution Landscapes, the integration of RES into new and existing built environments and making the energy supply to buildings low-emission, while preserving aesthetics (hence fostering acceptability), is both a challenge and an active technological research area at the same time.[76] City planning and design that takes into account the proximity of the citizen to nature, as well as planning that induces citizens to have a lower carbon footprint, are shown in the literature to be in need for further research[77]. Integration with storage solutions, including, but not limited to, electromobility, as well as sector coupling opportunities and low-carbon energy supply such as biomass or district heating. Innovative urban mobility concepts and removing barriers to roll-out of established solutions are, once again, research topics that straddle technological and societal innovation research, not only to introduce tangible low-carbon alternatives to internal combustion engine-based mobility, but also to encourage sustainable mobility solutions. Research on enhancing

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[72] Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmström, J., 2019. Digital twin: vision, benefits, boundaries, and creation for buildings. *IEEE access*, 7, 147406-147419.

[73] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., 2022. Op. cit.

[74] Sardella, A., Palazzi, E., von Hardenberg, J., Del Grande, C., De Nuntiis, P., Sabbioni, C., & Bonazza, A., 2020. Risk Mapping for the Sustainable Protection of Cultural Heritage in Extreme Changing Environments. *Atmosphere*, 11(7), 700. MDPI AG. Retrieved from http://dx.doi.org/10.3390/atmos11070700

[75] Cabeza, L. F., de Gracia, A., & Pisello, A. L., 2018. Integration of renewable technologies in historical and heritage buildings: A review. *Energy and buildings*, 177, 96-111

[76] Mbungu, N. T., Naidoo, R. M., Bansal, R. C., Siti, M. W., & Tungadio, D. H., 2020. An overview of renewable energy resources and grid integration for commercial building applications. *Journal of Energy Storage*, 29, 101385.

[77] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., 2020. Op. cit.

climate resilience is necessary to reduce risks also on climate change mitigation investments.

Role of disruptive General Purpose Technologies

AI and blockchain technologies have the potential to play a role in the built environment, since they touch upon many aspects of the built environment that would benefit from more accurate predictions (such as electricity load forecasting) and safer transactions and more democratic participation in the energy system (such as in peer-to-peer energy transfers). This also extends to applications such as intelligent road traffic management (which has been researched since many decades)[78] as well as predictive building maintenance[79].

Solution landscapes linked to greenhouse gas removals

Given that for climate neutrality residual emissions and removals must be in balance, removals – as a broad category of action – play a particularly relevant role in achieving European climate neutrality and even moving beyond towards a net-negative economy. The IPCC foresees three distinct roles for removals: (1) immediately accelerating the downward slope of net-emissions; (2) achieving climate neutrality in the mid-term; and, (3) achieving net-negative system-wide emissions thereafter.[80]

Rapid development of removal methods also entails a large opportunity for international cooperation by enabling other international partners – through technology cooperation, transfer, international cooperation as per the Paris Agreement, climate finance support or capacity-building exercises – to pursue more mature removal methods.[81]

R&I-related challenges in this space are strongly tied to the public-good nature of most removal methods[82]. Without decisive and tailored R&I support, as well as a clear runway toward long-term policy support, this entire category of action will falter. The five areas covered by this study comprise:

1. Direct air (CO_2) capture (DAC) technologies;
2. Point source capture technologies (including biomass);
3. Durable storage (including in long-lived products);
4. Terrestrial ecosystem-based removals; and,
5. Ocean-based ecosystem removals.

These five Solution Landscapes (SLs) are interconnected both amongst each other as well as with disruptive GPTs. DAC and point source capture (SL1 and SL2) both

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[78] Bielli, M., Ambrosino, G., & Boero, M. (Eds.)., 1994. *Artificial intelligence applications to traffic engineering*. Vsp.

[79] Sacks, R., Girolami, M., & Brilakis, I., 2020. Building information modelling, artificial intelligence and construction tech. *Developments in the Built Environment*, *4*, 100011.

[80] Ibidem.

[81] Lenzi, Dominic; Jakob, Michael; Honegger, Matthias; Droege, Susanne; Heyward, Jennifer C.; Kruger, Tim, 2021. Equity implications of net zero visions. In: Climatic change, 169(3), 1-15.

[82] Maher, Bryan, and Symons, Jonathan, 2022. The International Politics of Carbon Dioxide Removal: Pathways to Cooperative Global Governance. Global Environmental Politics, 22(1), 44-68.

rely on storage in reservoirs or long-lived products (SL3), as well as the availability of sufficient zero-emissions power (and thus are interconnected with renewables and storage solutions. The biomass reliant SLs 4 & 5 are in possible competition with biofuels and timber as a building materials (SL3). Ocean-based ecosystem removals may require highly technological monitoring systems and thus interconnect with developments in AI and robotics. Finally, new information and communication channels could impact on all CDR methods, especially in regard to socio-economic and political aspects of MRV, societal acceptance, and regulation.

In the following section three of these five Solution Landscapes (SL2, SL3, SL4) are elaborated. The Solution Landscape Annex presents all of them in detail.

Point source capture technologies (including biomass)

The point source capture technologies Solution Landscape (Figure 12 below), by its very nature, cuts across industry decarbonisation and CO_2 removals (point source capture of biomass-processing plants can achieve a removal). Point source capture is the first element in CCS. Carbon capture (for later storage including in long-lived products) thus contributes to three objectives:

1. Industry decarbonisation (especially for process emissions, such as in cement, steel or chemicals production);[83]
2. CO_2-removal by capturing CO_2 during biomass processing or storing CO_2 captured directly from the atmosphere (see dedicated Solution Landscape for DAC); and,
3. Decarbonising already committed fossil energy infrastructures (as a last resort sunsetting option).

To mobilise the very significant potential of point source CO_2 capture (covering all relevant point sources, across all sectors, efficiently and without pushing into additional biomass demand), progress ought to be achieved towards increasing capture energy efficiency, achieving higher capture rates, decreasing costs, and achieving versatility and modularity.

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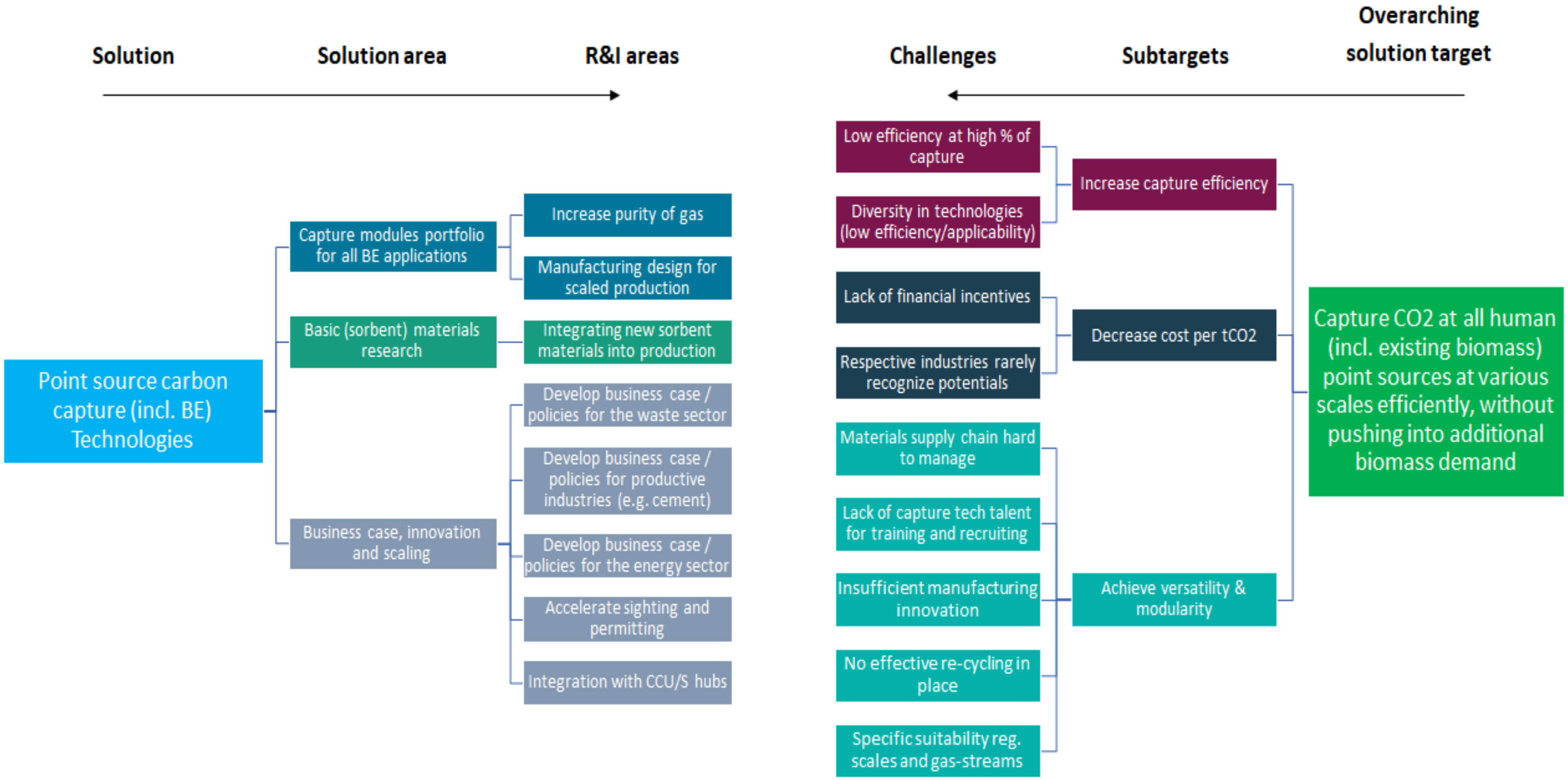
[83] Paltsev, Sergey; Morris, Jennifer; Kheshgi, Haroon; Herzog, Howard, 2021. Hard-to-Abate Sectors: The role of industrial carbon capture and storage (CCS) in emission mitigation. In: Applied Energy 300 (117322).

Figure 12. Solution Landscape for Point source capture technologies (including biomass). Source: ICF & partners, 2023.



Durable storage (including in long-lived products)

The durable storage of CO_2 is a large-scale challenge in and of itself, as it involves the handling of unprecedented volumes of CO_2 gas – a novel waste management industry which needs to be devised as a full socio-economic system from the ground up. The solution landscape is divided into three parts regarding: 1) the vast geological storage capacities required for climate neutrality; 2) the scaling of long-lived CO_2-utilisation products allowing for permanent storage; and, 3) the planning, financing, construction and operation of the transport and storage infrastructures ready to handle millions of tonnes of CO_2 safely and economically (see Figure 13 below). Taking each area in turn:

a) Geological storage capacities – research and piloting of storage hubs

The successful development of new storage sites involves tackling obstacles related to environmental and socio-economic concerns, most notably frequent public resistance. Research may thus accompany the real-world roll-out of storage and utilization hubs and clusters to successfully navigate public perception and trust. R&I towards monitoring of stored CO_2 can help overcome challenges of reliability and long-term observation based on international minimum requirements. Publicly funded research may, furthermore, help make cost structures related to storage (including MRV costs) more transparent and avoid rent-seeking behaviour of storage operator oligopolies, that may otherwise undermine public support and the credibility of results-based incentives. To enable efficient transport and storage of CO_2, research into optimal design of transport, hubs and clusters may facilitate dramatic cost reductions.[84,85]

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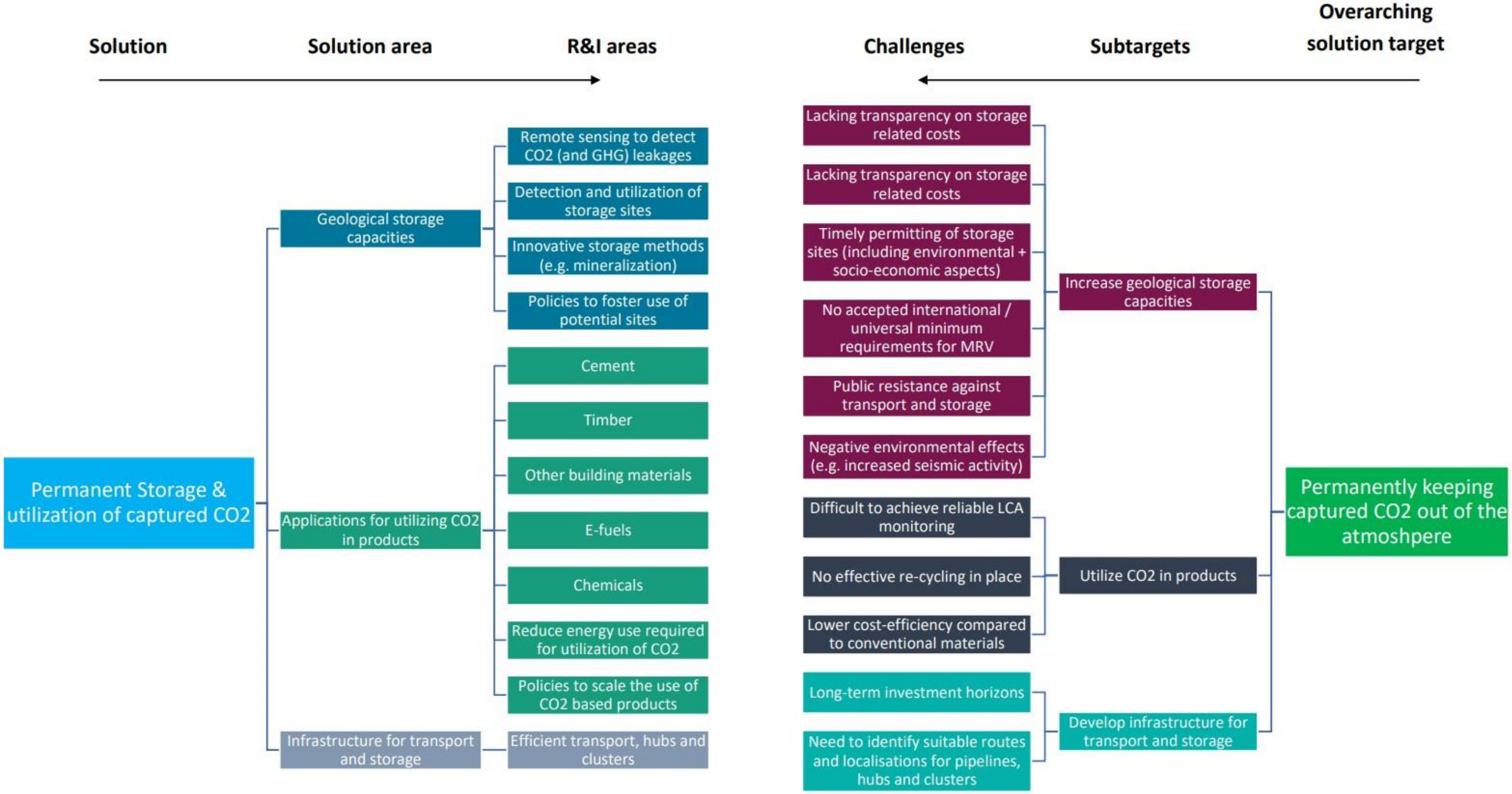
[84] Sun, Xiaolong, et al., 2021.: Hubs and clusters approach to unlock the development of carbon capture and storage–Case study in Spain. Applied Energy, 300, 117418.

[85] Kearns, David; Liu, Harry; Consoli, Chris, 2021. Technology readiness and costs of CCS. Global CCS Institute. Available online at: https://scienceforsustainability.org/w/images/b/bc/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf

Figure 13. Solution Landscape for Durable Storage of CO_2 (including in long-lived products). Source: ICF & partners, 2023.



b) Utilization of CO_2 in products

Carbon dioxide utilization (CCU) is the process of using CO_2 as a raw material for products which range widely from construction materials, plastics[86,87] and other chemicals,[88] food and fuel products. While this represents a form of circular economy, the product lifetime, sector and product properties and use cases, determine the economic and environmental performance of CCU.[89] Only use cases that achieve an overall net flow of CO_2 into durable storage from biogenic or atmospheric source represent a form of carbon dioxide removal.

Various forms of CCU are being researched,[90] but few processes resulting in long-lived products have been successful in the European market to date.[91] Many CCU pathways are not yet economically competitive in comparison to fossil-based processes and technical maturity varies widely.[92] Applications based on biomass carbon tend to be significantly more economical compared to those drawing on DAC.[93] Examples of more developed processes include the production of dimethyl ether and methanol from CO_2,[94] and the use of CO_2 in the construction industry to make inorganic carbonates for building materials.[95]

CO_2 utilization in durable products, such as building materials and plastics, requires innovation in both production systems and applications for CO_2 to become a key feedstock. This may involve the development and standardisation of new materials or the optimisation of existing production methods to incorporate CO_2.[96] Innovation in the design and application can aim to maximise CO_2 utilization and widen the range of

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[86] Nessi, S., Sinkko, T., Bulgheroni, C., Garcia-Gutierrez, P., Giuntoli, J., Konti, A. & Ardente, F., 2021. Life Cycle Assessment (LCA) of alternative feedstocks for plastics production. *Publications Office of the European Union*.

[87] Valderrama, M. A. M., van Putten, R. J., & Gruter, G. J. M., 2019. The potential of oxalic–and glycolic acidbased polyesters (review). Towards CO2 as a feedstock (Carbon Capture and Utilization–CCU). *European Polymer Journal*, *119*, 445-468.

[88] Kätelhön, A., Meys, R., Deutz, S., Suh, S., & Bardow, A., 2019. Climate change mitigation potential of carbon capture and utilization in the chemical industry. *Proceedings of the National Academy of Sciences*, *116*(23), 11187-11194.

[89] d'Amore, F., & Bezzo, F., 2020. Optimizing the design of supply chains for carbon capture, utilization, and sequestration in Europe: a preliminary assessment. *Frontiers in Energy Research*, *8*, 190.

[90] Chauvy, R., & De Weireld, G., 2020. CO2 utilization technologies in Europe: a short review. *Energy Technology*, *8*(12), 2000627.

[91] Patricio, J., Angelis-Dimakis, A., Castillo-Castillo, A., Kalmykova, Y., & Rosado, L., 2017. Region prioritization for the development of carbon capture and utilization technologies. *Journal of CO2 Utilization*, *17*, 50-59.

[92] Bolscher, H., Brownsort, P., Opinska, L. G., Jordal, K., Kraemer, D., Mikunda, T. & Yearwood, J., 2019. High Level Report: CCUS in Europe.

[93] Koytsoumpa, E. I., Magiri–Skouloudi, D., Karellas, S., & Kakaras, E., 2021. Bioenergy with carbon capture and utilization: A review on the potential deployment towards a European circular bioeconomy. *Renewable and Sustainable Energy Reviews*, *152*, 111641.

[94] Nyári, J., Magdeldin, M., Larmi, M., Järvinen, M., & Santasalo-Aarnio, A., 2020. Techno-economic barriers of an industrial-scale methanol CCU-plant. *Journal of CO2 utilization*, *39*, 101166.

[95] Baena-Moreno, F. M., Rodríguez-Galán, M., Vega, F., Alonso-Fariñas, B., Vilches Arenas, L. F., & Navarrete, B., 2019. Carbon capture and utilization technologies: a literature review and recent advances. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *41*(12), 1403-1433.

[96] Naims, H., & Eppinger, E., 2022. Transformation strategies connected to carbon capture and utilization: A cross-sectoral configurational study. *Journal of cleaner production*, *351*, 131391.

suitable product-applications.[97] For example, this may involve the development of new building materials that incorporate CO_2 in their structure, or the creation of plastic products that utilize CO_2 as a raw material. This will require collaboration between engineers, designers, and other experts to develop innovative solutions that effectively utilize CO_2 in these applications.[98]

In order to qualify as contributing to carbon dioxide removal, CO_2 storage through utilization in long-lived products should overall yield a net-negative carbon balance demonstrable through a full cradle-to-grave life cycle assessment.[99]

Overall, the use of CO_2 in durable products requires both technological innovation and creative problem-solving toward effective, sustainable, and economical solutions through collaboration of experts across a range of fields and sectors, including materials science, chemical engineering, and product design.[100] Products based on captured CO_2 often involve a cost-penalty compared to conventional products, which may require for them to be incentivised through carbon markets, policies or regulations.[101,102]

c) Infrastructure for transport and storage development

Storage and utilization of captured CO_2 requires a functioning infrastructure ensemble, which are complex (especially the first time around) and costly to set up. These multi-decadal investment decisions must be approached with a systemic perspective including synergies with various CO_2-sources and storage/utilization hubs and clusters, transport routes (e.g., locations for pipelines [103], ship terminals[104]), compatibility of interfaces, gas compositions, concentrations and pressures, social acceptance and industry actor interests and likely more.[105]

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[97] Mikulčić, H., Skov, I. R., Dominković, D. F., Alwi, S. R. W., Manan, Z. A., Tan, R., & Wang, X. 2019. Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO2. *Renewable and Sustainable Energy Reviews*, *114*, 109338.

[98] Naims, H., 2020. Economic aspirations connected to innovations in carbon capture and utilization value chains. *Journal of industrial ecology*, *24*(5), 1126-1139.

[99] da Cruz, T. T., Balestieri, J. A. P., de Toledo Silva, J. M., Vilanova, M. R., Oliveira, O. J., & Avila, I., 2021. Life cycle assessment of carbon capture and storage/utilization: From current state to future research directions and opportunities. *International Journal of Greenhouse Gas Control*, *108*, 103309.

[100] Gür, T. M., 2022. Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. *Progress in Energy and Combustion Science*, *89*, 100965.

[101] Koytsoumpa, E. I., Magiri–Skouloudi, D., Karellas, S., & Kakaras, E., 2021. Bioenergy with carbon capture and utilization: A review on the potential deployment towards a European circular bioeconomy. *Renewable and Sustainable Energy Reviews*, *152*, 111641.

[102] Tarufelli, B. L., 2020. Overlooked Opportunity: Incentivizing Carbon Capture through Carbon Tax Revenues.

[103] Onyebuchi, V. E., Kolios, A., Hanak, D. P., Biliyok, C., & Manovic, V., 2018. A systematic review of key challenges of CO2 transport via pipelines. *Renewable and Sustainable Energy Reviews*, *81*, 2563-2583.

[104] Kjärstad, J., Skagestad, R., Eldrup, N. H., & Johnsson, F., 2016. Ship transport—A low cost and low risk CO2 transport option in the Nordic countries. *International Journal of Greenhouse Gas Control*, *54*, 168-184.

[105] Nazeri, M., Haghighi, H., Mckay, C., Erickson, D., & Zhai, S., 2021. Impact of CO2 Specifications on Design and Operation Challenges of CO2 Transport and Storage Systems in CCUS. In *SPE Offshore Europe Conference & Exhibition*. OnePetro.

R&I areas to tackle these issues may also include technologies to improve monitoring, e.g., via remote sensing, to meet some of the practical challenges related to MRV during transport[106] and storage. Artificial Intelligence can play a central role in estimating, for example, mass flows in CO_2 transport, trapping of CO_2 during injection, and material interactions in CO_2 utilization.[107]

Interdisciplinary research projects may aid identifying key success factors in the selection of storage sites as well as the design of policies that may foster development of transport and storage infrastructures.

R&I of products suitable for permanent CO_2 storage needs to be promoted. Among promising groups of materials are building materials such as cement, timber, and others, as well as E-fuels and chemicals. Energy use and costs related to these alternatives to conventional materials need to be tackled, and policies incentivising their use must be designed to scale up their application.

Terrestrial Ecosystem-Based Removals

The permanence of CO_2 stored in biomass and soils[108] depends on plants and soils remaining intact. A shift from using biomass in short-lived towards long-lived products play a central role in reducing the short-term re-emission and increases the net carbon stored in wood products[109]. There is significant variability across world-regions regarding both natural and human influence on durability. Natural disasters such as fires, droughts or floods strongly challenge this precondition, with the frequency of extreme events likely increasing due to climate change. Likewise, local and regional conflicts can lead to the re-emission of GHG from terrestrial ecosystems. This challenges the effectiveness of ecosystem-based CDR.

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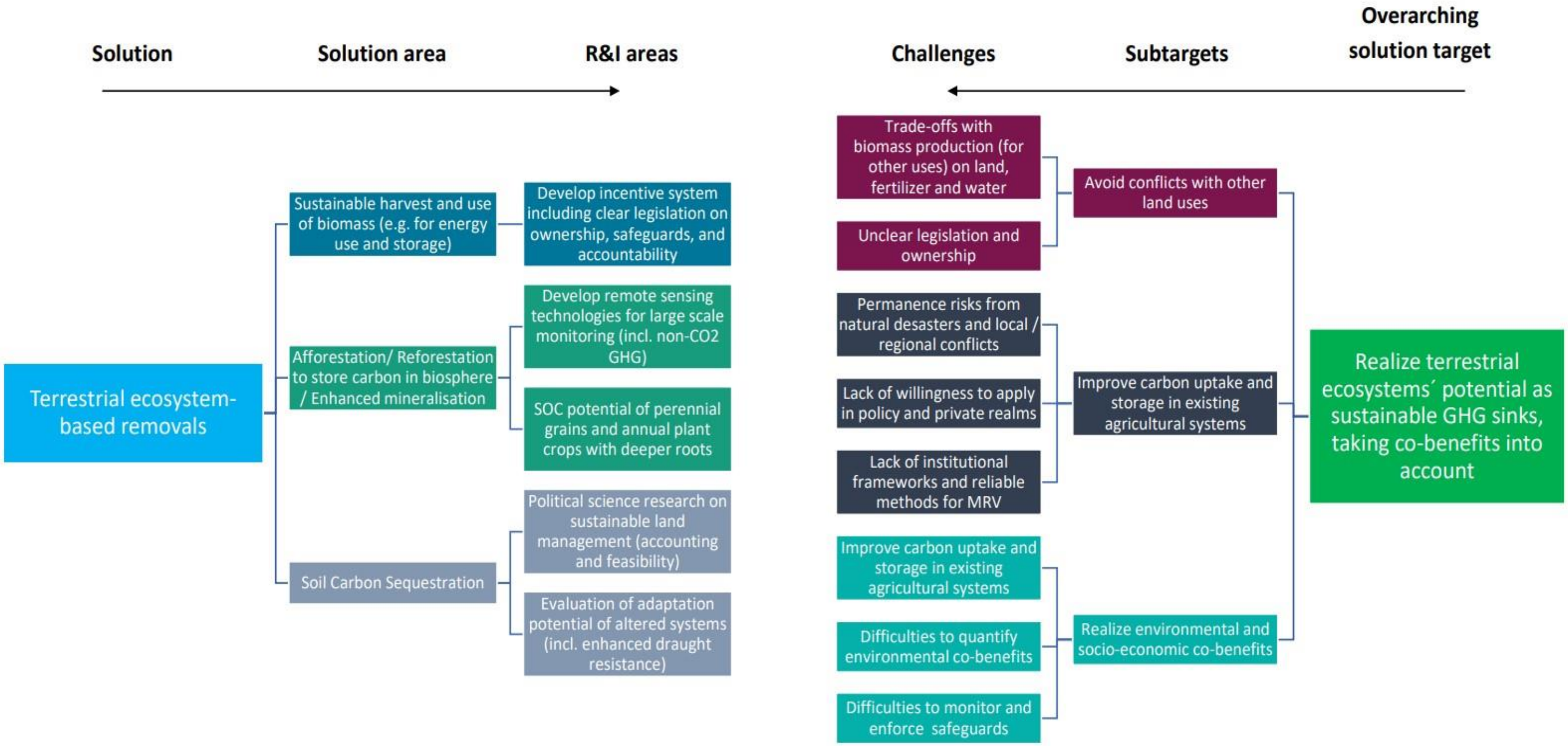
[106] Vitali, M., Zuliani, C., Corvaro, F., Marchetti, B., Terenzi, A., & Tallone, F., 2021. Risks and safety of CO2 transport via pipeline: A review of risk analysis and modeling approaches for accidental releases. *Energies*, *14*(15), 4601.

[107] Yan, Y., Borhani, T. N., Subraveti, S. G., Pai, K. N., Prasad, V., Rajendran, A., & Clough, P. T., 2021. Harnessing the power of machine learning for carbon capture, utilisation, and storage (CCUS)–a state-of-the-art review. Energy & Environmental Science, 14(12), 6122-6157.

[108] Lal, R., Monger, C., Nave, L., & Smith, P., 2021. The role of soil in regulation of climate. *Philosophical Transactions of the Royal Society B*, *376*(1834), 20210084.

[109] Grassi, G., Fiorese, G., Pilli, R., Jonsson, K., Blujdea, V., Korosuo, A. and Vizzarri, M., 2021. Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution, Sanchez Lopez, J., Jasinevičius, G. and Avraamides, M. editor(s), European Commission, 2021, JRC124374.

Figure 14. Solution Landscape for Terrestrial Ecosystem-Based Removals. Source: ICF & partners, 2023.



The solution areas to counter the challenges outlined above cover the whole range of removal methods based on terrestrial ecosystems. Most R&I areas identified are relevant to more than one removal method. Transdisciplinary research to better understand the interplay of carbon uptake and storage, sustainability, and co-benefits is key to all methods to enable responsible and effective large-scale applications. Incentive systems for such applications must be developed to ensure clarity in legislation and ownership, as well as accountability and monitorable safeguards to socio-economic and environmental aspects. Sustainable land-management practices and their application to removal purposes need to be further researched from a political science perspective to ensure co-benefits are sufficiently considered.[110] Co-benefits associated with systems altered to increase carbon uptake and storage (e.g., enhanced draught resistance) need to be analysed, further evaluating the potential for multiple purposes of agricultural systems. Regarding storage in soil carbon, potentials of annual and perennial grains and crops with deeper roots is a promising field of research to increase effectiveness of terrestrial biosphere-based CDR methods. Genome sequencing (and other genetic approaches) can improve CO_2 uptake and storage of plants.[111] To enable reliable MRV, remote sensing technologies for large areas and CO_2, as well as non-CO_2 GHG should be enhanced.

4.3. Common challenges calling for common solutions

Prioritizing high-risk, high-impact R&I areas requires a multi-pronged analytical approach. This includes recognising and working through challenges and barriers identified in the commonalities across Solution Landscapes. Table 7 below provides an overview of these common challenges across the Solution Landscapes. Among these the ones that seem most transversal across the Solution Landscapes, and which should be considered holistically within an overall R&I support planning framework, include:

Material Availability and Circularity

The need to consider availability (supply) of materials holistically, including aspects of circularity, stands out as a pressing challenge spanning diverse Solution Landscapes. This can have knock-on effects that could support or undermine the transition to a climate-neutral economy and such considerations cannot be adequately included when solely examining individual solutions. The implementation of Circular Economy strategies—encompassing sustainable product policy frameworks, increased circularity in production processes, consumer empowerment, and waste minimisation—can significantly mitigate fossil fuel dependence. Beyond circularity, R&I in materials substitution also needs to be done to reduce certain material dependencies. Such strategies, however, need to be developed and tested at the level of nexuses or Solution Landscapes. Policy tools such as regulatory sandboxes and testbeds can be useful in this context.

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[110] Buck, H. J., 2016. Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change*, *139*(2), 155-167.

[111] Zahed, M. A., Movahed, E., Khodayari, A., Zanganeh, S., & Badamaki, M., 2021. Biotechnology for carbon capture and fixation: Critical review and future directions. Journal of Environmental Management, 293, 112830.

Competitive Pricing: The Green Premium Challenge

As RES technologies such as solar photovoltaic (PV), wind energy, and hydrogen production become more affordable, the so-called 'green premium'—the additional cost of choosing RES and other cleaner technologies—decreases and eventually disappears or reverses when such energy generation becomes cheaper than their fossil fuelled alternatives. Financial feasibility hinges, however, not solely on technological advancements, but also on the scaling of sustainable supply-chains (and circular management of materials). Furthermore, financial feasibility is not the sole factor determining overall technology scaling, as adverse regulation can impact very directly on feasibility (e.g., permitting of projects, access to (grid) infrastructures).

Systemic Integration: A Two-Pronged Challenge

The lack of attention to integrating individual solutions into comprehensive systems at the level of product innovation poses another major challenge. On the one hand, technologies like solar, wind, and energy storage must be integrated into an intricate web of other zero-emissions solutions, whereby the interdependency requires engineering attention and innovation to technologically and dynamically manage supply and demand. On the other hand, the socio-economic dimension of technology integration must also not be ignored, whereby the ease of integration of technologies – particularly at the end-consumer level – significantly influences its adoption rate, causing ripple effects on cost-efficiency and long-term potential.

Societal Acceptance and Behavioural Change

Beyond the technical and economic considerations, the human factor – including cultural and risk-benefit perception – remains a key obstacle or opportunity. During adoption, technology applications need to reach societal acceptance beyond the 5% early adopters commonly referred to in adoption curves. For this it can be important to pay close attention to the potential ways in which new technology may weave into the fabric of communities, how newly developed solutions are aligned with society's needs, and how minute design choices may affect the efficient and organic adoption – for example, if congruence between perceived technology-values and societal values is present or not. This may involve engaging citizens (through product designs or upstream engagement in the innovation space) especially when behavioural change is required for adoption.

Table 7. The 17 Solution Landscapes demonstrate common challenges which need to be holistically considered. Source: ICF, 2023.

Nexus	**Mobility-built environment -energy nexus**						**Circularity-industry-carbon removal/capture nexus**							**Agrifood-carbon removal nexus**			**GPT**
Solution Landscapes	Solar PV	Wind Energy	Power System Flexibility	Energy Storage	Built environment	Decarbonising mobility	Hydrogen Economy	Green steel	Industrial decarbonisation	Circular economy	Direct air (CO2) capture (DAC) technologies	Point Source CO2 capture	Durable CO2 Storage	Terrestrial Ecosystem-based CO2-removals	Ocean Ecosystem-based Removals	New food	Digitalisation
Materials availability and circularity (Fossil fuel material dependence). Requisite to upscaling the infrastructure	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓						
Lack of attention for the integration of multiple solutions into complex systems and the role of social solutions in this context	✓		✓	✓	✓	✓	✓	✓	✓								
Competitive price point that allows for obtaining the			✓	✓	✓	✓	✓	✓	✓			✓					

Nexus	Mobility-built environment -energy nexus						Circularity-industry-carbon removal/capture nexus							Agrifood-carbon removal nexus			GPT
most efficient materials while reducing the green premium / Lack of financial incentives																	
Lack of social acceptance and/ or behavioural changes to scale-up existing solutions		✓	✓		✓	✓					✓	✓				✓	✓
Ill-adapted regulatory framework limiting the emergence of new solutions and the scale-up of existing ones		✓					✓			✓	✓	✓			✓	✓	
Lack of skill to allow the development of new solutions and the scale-up of existing ones				✓	✓					✓	✓			✓	✓		✓
Lack of attention for the supply chain and	✓	✓					✓		✓		✓	✓					

Nexus	Mobility-built environment-energy nexus						Circularity-industry-carbon removal/capture nexus							Agrifood-carbon removal nexus			GPT
manufacturing related innovation required to scale-up new solutions																	
Lack of suitable and reliable monitoring, reporting and verification (MRV) systems limiting the emergence of new solutions and the scale-up of existing ones										✓	✓	✓		✓	✓		
Lack of space for building and operating the infrastructure needed or lack of known sites for allowing energy and emission efficiency	✓				✓						✓		✓				
Externalities of building the infrastructure needed (animal		✓											✓	✓	✓		

Nexus	Mobility-built environment-energy nexus						Circularity-industry-carbon removal/capture nexus							Agrifood-carbon removal nexus			GPT
welfare and environment)																	
Lack of capacity to constantly produce energy without considering volatile climate conditions (Grid and energy stability)		✓	✓	✓													
Geopolitical dependency	✓	✓					✓										✓
Efficiency (cost efficiency) in implementation and deployment of the technology											✓	✓	✓				
Lack of capacity to maintain the infrastructure in the long-term	✓	✓								✓							
Lack of adaptation to climate change effects					✓											✓	

4.4. Evaluation framework to help identify high-risk, high-impact R&I areas

4.4.1. The evaluation framework as a supporting tool

To facilitate the identification of high-risk and high-impact R&I areas, a detailed evaluation framework was designed, as summarised in section 2 and more fully described in Annex 3. The framework was used as a supporting tool to screen all the R&I areas (more than 150) identified in the Solution Landscapes, with both the highest mitigation potential and the highest need of policy support, whilst also considering the systemic impact of these areas. The results of the screening provide a composite index of the types of R&I areas that should be prioritised by R&I programmes.

It is important not to regard this approach as a ranking exercise. The selected R&I areas should be seen in a broader context that considers the challenges and interactions between different areas following a more systemic approach – as well as within specific nexuses.

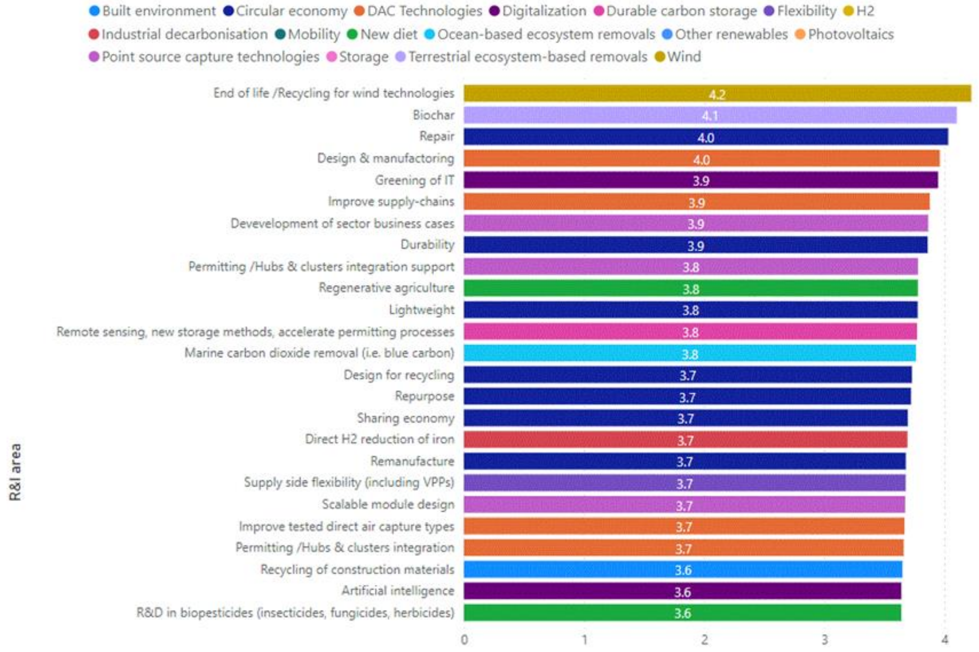
4.4.2. High-risk, high-impact R&I areas requiring public support to reach market maturity in the next 10-15-years

The 15 R&I areas scoring the highest in the evaluation framework are listed below (and shown by Solution Landscape colour coding in Figure 15 below):

- End of life, recycling for wind technologies (belonging to the Wind energy SL)
- Biochar (Terrestrial Ecosystem-Based Removals SL)
- Repair[-ability of products] (Circular Economy SL)
- Design and manufacturing processes and supply chains for scaled production (DAC Technologies SL)
- Greening of information technology (IT) (Digitalization SL)
- Improve Supply Chains (DAC Technologies SL)
- Development of sector business cases (Point Source Capture Technologies SL)
- Durability [of products and designs] (Circular Economy SL)
- Permitting, hubs and clusters integration (Point Source Capture Technologies SL)
- Regenerative Agriculture (New Diet SL)
- Lightweight [product design and manufacture] (Circular Economy SL)
- Remote Sensing, new storage methodology, accessible permitting process (Durable Carbon Storage SL)
- Marine carbon dioxide removal (i.e. blue carbon) (Ocean-Based Ecosystem Removals SL)
- Design for recycling (Circular Economy SL)
- Repurpose (Circular Economy SL)

Beside these 15, the R&I areas that scored the highest are: Sharing economy (Circular Economy SL), Direct H2 reduction of iron (Industrial Decarbonisation SL), Remanufacture (Circular economy SL), Supply side flexibility (Including VPPs) (Flexibility LS), Scalable module design (Point Source Capture Technologies SL), Improve tested DAC type (DAC Technologies SL), Permitting, hubs and clusters integration (DAC Technologies SL), Recycling of construction materials (Built Environment SL), Artificial Intelligence (Digitalization SL), R&D in Biopesticides (insecticides, fungicides, herbicides) (New Diet SL).

Figure 15. 25 highest scoring R&I areas resulting from the evaluation framework, colour coded by Solution Landscape. Source: ICF & partners, 2023.



Although the evaluation framework highlights a precise list of R&I areas, this should be seen as a supporting mechanism for a broader exercise selecting areas to be considered when looking at the nexuses and needs.

4.4.3. KPI framework for impact measurement of high-risk, high impact R&I areas

Just as a set of criteria have been developed to provide an evaluation framework for high-risk / high impact R&I areas, so the adoption of a comprehensive evaluation framework to assess the systemic impacts and interconnections of innovative solutions is important for enable the full potential transformative solutions to be captured.

KPIs could focus on data (backed by qualitative insights) that can help achieve a more consistent, objective and comparable approach to feed R&I funding decisions by policy makers. Such KPIs could also help to prioritise R&I areas within a specific boundary (e.g., considering R&I areas belonging to an established nexus). The criteria could be weighted, based on the needs and/or challenges to be addressed in a given context. Overall, such KPIs could also help reduce the risk of certain R&I areas (potentially those with the largest incumbent stakeholder groups), from having too much influence in the funding decision-making process.

4.5. Using the evaluation framework to identify high-risk, high-impact R&I areas at the nexus level

The results shown in section 4.3 were further developed, focusing on the priority R&I areas emerging from the identified nexuses.

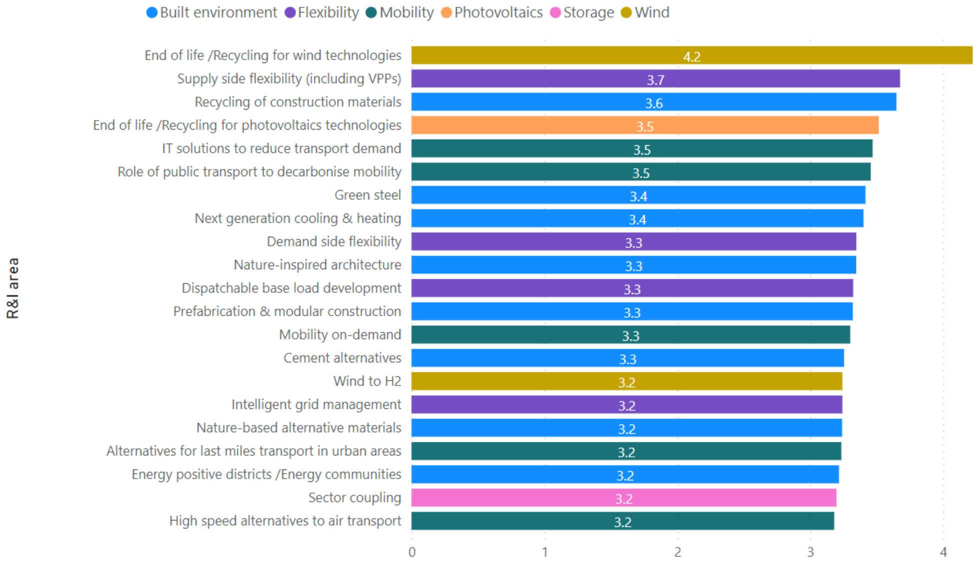
4.5.1. Mobility – Built environment – Energy nexus

Within this nexus (Figure 2), three of the five R&I areas that ranked first are related to **end-of-life treatment** and **recycling**, including those materials used for wind and PV technologies that will start to require recycling as the earliest such developments across Europe reach their end-of-life, and construction materials (e.g., cement, steel) from buildings either renovated or demolished. **Alternative building materials** such as green steel and cement, together with nature-based materials, stand out alongside further R&I efforts towards promoting prefabrication and modular construction methods.

R&I within the **mobility** sector is another theme of importance, with the solutions scoring highest linked to limiting overall transport demand (through IT solutions and mobility-on-demand) and the role of public transport to decarbonise mobility.

R&I efforts in **supply and demand side flexibility** (especially around virtual power plants (VPPs)) score high and can be seen as a key enabler for the transformation of the full nexus. Surprisingly, **energy storage solutions** do not score high, calling for a further investigation of these solutions as they represent a key enabler and an important challenge for the transformation of the nexus overall. The principal reasons for the relatively low scores of energy storage solutions in the evaluation framework comes from the exposure of these technologies to critical raw materials (primarily batteries), as well as a relatively low novelty factor for many storage technologies such as pumped hydro storage or gravity storage. The availability of significant existing R&I funding for storage technologies, particularly batteries, is also a key reason. Therefore, and as highlighted above, this outcome should be interpreted in the context and purpose of the evaluation framework applied. These technologies and solutions still remain critical in reaching the climate neutrality target.

Figure 16. Evaluation Framework results of the mobility, built environment and energy nexus. Source: ICF & partners, 2023.



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4.5.2. Circularity – Industry – Carbon removals and capture nexus

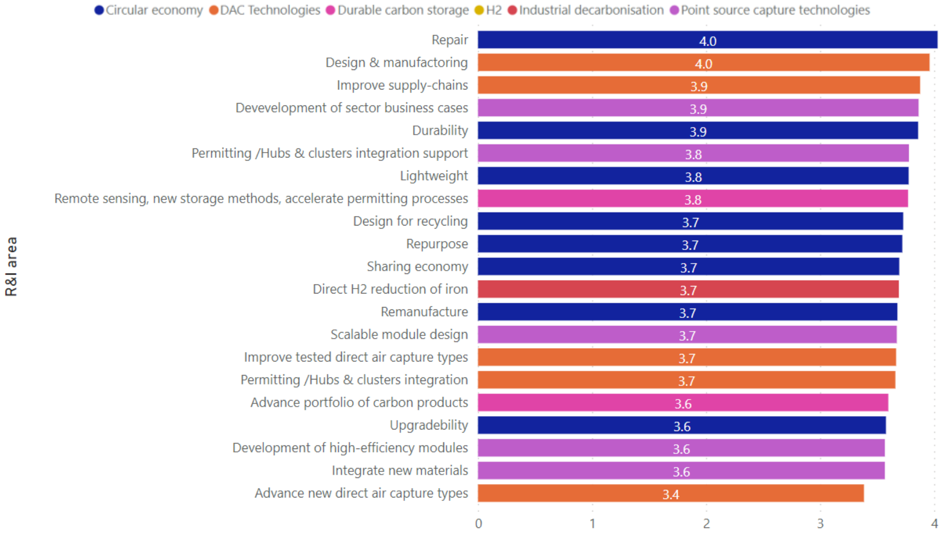
Several R&I aspects of the “**circular economy**” solution landscape score high given their transversal nature, specifically those in relation to industrial decarbonisation (notably steelmaking with direct hydrogen reduction of iron, and cement production), as well as the potential applications of carbon removal/capture in industry. Due to this transversal nature, these R&I areas are not defined very precisely, calling for more refined research to identify specific R&I needs.

This analysis, combined with that from the “Mobility – built environment – energy” nexus represent, however, a strong call to mainstream the 5 Rs of circular economy, i.e., “**Reducing, Reusing, Refurbishing, Repairing and Recycling”** across all R&I efforts, underpinning a need for both technical and societal innovations to be supported.

In addition, decarbonisation efforts of key industrial processes such as steelmaking and cement production might have significant synergies with carbon removal and carbon capture technologies, notwithstanding a fundamental necessity of decarbonisation of these processes even outside a carbon removal/capture framework. A deeper technical integration of **Carbon Dioxide Removal (CDR)/Capture technologies** in the industry will also need to be accompanied by new conceptions of business models in this sector. The CDR R&I areas that scored highest are linked to the Direct Air Capture (DAC) design and manufacturing and supply chains improvements and the need to further refine the business case for point source capture technologies across sectors. These findings dovetail well with the Commission’s November 2022 proposed Carbon Removal Certification Framework

(CRCF) Regulation, which aims to scale up the CDR industry whilst ensuring greenwashing is avoided[112].

Figure 17. Evaluation Framework results of the circularity – industry – carbon removal and capture nexus. Source: ICF & partners, 2023.



4.5.3. Agrifood – Carbon removals nexus

The agrifood-carbon removal nexus covers technologies related to novel and/or improved agricultural techniques and behaviour, as well as terrestrial and marine ecosystem-based CDR methods (see Figure 18). Some of the terrestrial removal technologies which can be integrated into existing agricultural systems have high mitigation potential according to the evaluation framework (e.g., biochar, afforestation/reforestation (A/F), soil carbon sequestration). **Biochar** production is mature, but applications for removals remain underdeveloped. R&I should target durability, MRV requirements, and adoption-related questions regarding business cases and barriers among farmers and communities.

The integration of such removal technologies has high synergies and common practices with approaches related to the science and business of transitioning towards to **regenerative agriculture**, which in turn has links to the development and application of **biopesticides** (replacing chemical pesticides), which could help stimulate new market opportunities in advancing biological pest control. Finally, **consumer behavioural change** also scores high and represents an important mechanism that will be vital in embracing new approaches and business models.

Note that these areas can also have other positive side effects like increased biodiversity, which is a key objective of regenerative agriculture and biopesticides but

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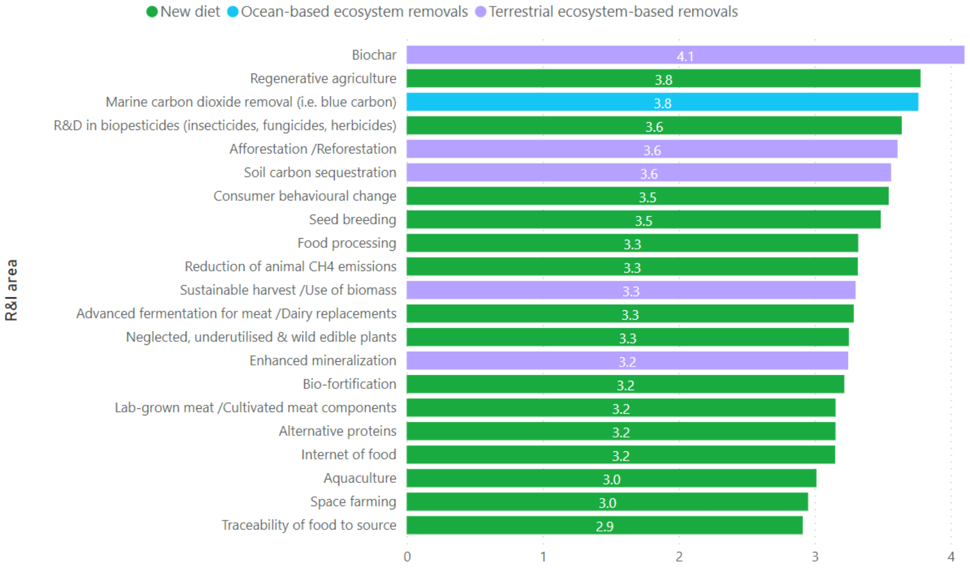
[112] European Commission, 2023. Carbon Removal Certification. Available at: https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/carbon-removal-certification_en

is also typically observed in afforestation/reforestation (A/F). The important connections of these R&I priorities to water availability and use as well as the promotion of NBS are also worth reiterating in the context of overall Green Deal policy objectives.

Similarly, blue carbon solutions (including capture and storage of CO_2 in mangroves, as well as seagrass and kelp farming) have positive GHG mitigation (and biodiversity) implications and can be integrated with many forms of sustainable aquaculture. R&I efforts are however still needed to support their scale up through appropriate implementation and monitoring technologies and practices that track both the carbon flows and ecosystem effects under realistic application scenarios – including remote sensing. Transdisciplinary R&D can also enable resolving regulatory and public acceptance barriers including governance problems of the high seas and domestic law. In addition, R&I funding for ocean-based carbon removals ought to further develop and assess the potentials and risks of currently immature methods (e.g., artificial up-/down welling, ocean alkalinity enhancement (OAE), and micro-nutrient fertilisation). While the theoretical potential of these solutions is potentially very large, they require careful examination to enhance the understanding of how the complexity of marine systems (tipping points; biological and biogeochemical responses under hypoxic and/or anoxic conditions; and, abundances and diversity of phytoplankton) intersects with realistic application scenarios. R&I in MRV systems and regulatory and socio-economic aspects need to be researched in applied transdisciplinary settings.

Figure 18. Evaluation Framework results of the agrifood-carbon removal nexus. Source: ICF & partners, 2023.



5. How to integrate systemic interactions in the design of R&I agendas?

5.1. In-depth analysis at nexus level

In this section, the three nexuses previously introduced are analysed in detail to demonstrate the role that R&I programmes can play in two main ways:

- Identifying and maximizing positive spillovers or cascade spillovers to accelerate the transformation towards climate neutrality; and,
- Navigating trade-offs between different solutions.

Each nexus analysis follows a common structure comprising of four research questions:

- What are the key challenges and bottlenecks preventing the transformation of the nexus towards climate neutrality?
- Which technical and societal innovations are emerging to address these challenges and how do they interact?
- Which potential spillover effects could result from these interactions (and should be targeted by R&I programmes)?
- Which potential risks and trade-offs result from these interactions (and should be taken into account in the design of R&I programmes)?

This section will therefore serve as the basis for answering the research question of how to integrate systemic interactions into the design of R&I programmes.

Each nexus comprises a large number of technical and societal solutions, illustrated in the Solution Landscapes. Across all three nexuses, the general role played by GPTs[113] is also considered, since they present important enabling technologies (e.g., AI, machine learning, big data), which can have a strong impact across all nexuses and also link different areas (i.e., strong systemic aspects). Due to the highly systemic nature of the nexuses and the large number of interdependencies, it is important to examine how these solutions interact. This is not only to identify the common challenges and bottlenecks, but also the risks associated with the failure of some solutions and the impact this might have on several solution areas. This approach also helps to identify where solutions can have positive spill-over effects across several solution areas or act as essential enablers for other solutions.

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[113] General Purpose Technologies (GPTs) are innovations with the potential to significantly impact and transform multiple sectors of the economy and society. They are characterized by their broad applicability, adaptability, and the profound changes they bring about in various industries and aspects of daily life.

It is also important to be able to address possible tipping points in a targeted manner. The positive tipping-points framework[114] identifies six conditions that need to be met to create the right conditions for the emergence of large-scale systemic tipping points:

- **Economic competitiveness & affordability**: The proposed solutions must be economically competitive (e.g., signalled by competitive pricing or business models) to alternative solutions which can stimulate demand.
- **Performance & attractiveness**: The proposed alternatives must meet the required level of performance or quality – or it outperforms existing solutions on essential features such as efficiency and quality.
- **Accessibility**: The solutions, or the change in behaviour proposed by the alternatives, can be conveniently accessed by stakeholders.
- **Cultural norms & desirability**: The alternatives are also socially desirable/acceptable and normalised across stakeholders.
- **Capability & information**: The stakeholders have the right information to use the solution, or act on the behaviour.
- **Complementarity**: The proposed solutions are surrounded by complementary innovations (including the necessary enabling solutions across the whole value chain) allowing their rapid deployment leading to the displacement of the old solution suite.

All of these conditions depend on and are influenced by various systemic interactions, both positively and negatively. In addition, they also show that the consideration of social aspects, such as behaviour or acceptance, is essential to enable tipping points. Therefore, they need to be considered for all technical solutions. Specific examples of systemic tipping points related to the three nexuses discussed below are presented in "The Breakthrough Effect", a report by SYSTEMIQ and the University of Exeter.[115]

5.1.1. Mobility – Built environment – Energy nexus

5.1.1.1. What are the key challenges and bottlenecks preventing the transformation of the nexus?

A set of common challenges has been identified, many of which have linkages between them (as illustrated by the schematic in Table 8 below):

A: Material availability, as well as the area of tension between efficient materials vs sustainable materials: Most technical solutions depend on abundant and efficient materials, which should also be as sustainable as possible. Therefore, improvements in one or more of these aspects (e.g., through more efficient and/or sustainable mining, new recycling/re-use solutions, innovative sustainable materials) will usually address and support several different technical solutions. Important technical

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[114] Cambridge University Press, 2022. Operationalising positive tipping points towards global sustainability. Available at: https://www.cambridge.org/core/journals/global-sustainability/article/operationalising-positive-tipping-points-towards-global-sustainability/8E318C85A8E462AEC26913EC43FE60B1

[115] Systemiq, University of Exeter, Simon Sharpe and the Bezos Earth Fund, 2023. The Breakthrough Effect. Available at: The-Breakthrough-Effect.pdf (systemiq.earth)

solutions of this nexus, which face this challenge and may interact with each other, are e.g., storage solutions (EV, grid, built environment) and RES technologies. In addition, this challenge can also have serious impacts on economic competitiveness & affordability and performance & attractiveness as key conditions for tipping points.

B: **Supply chain sustainability:** Different technical solutions may interact with common supply chains, or at least with the same specific elements of them. Therefore, making a supply chain more secure and sustainable will benefit all technical solutions that interact with that supply chain (e.g., materials for energy storage solutions, which affect all three pillars of the nexus). However, the opposite may also be possible (i.e., potential negative impacts). This is therefore an important lever to address, for example, economic competitiveness & affordability, accessibility or cultural norms and desirability.

C: Resource shortages (e.g., due to more pressing needs in other areas or missing recycling solutions): Different technical solutions may interact if they require the same materials or resources. If such resources (as with critical raw materials (CRMs)) are scarce, it may be necessary to decide to spend more on some solutions than on others, leading to potential resource bottlenecks that slow down the uptake of such solutions. In addition, this can also increase the price for the technologies involved, therefore impacting economic competitiveness and affordability, as well as performance and attractiveness as key conditions for tipping points. A possible example is silver, which is required for PV cells as well as for many other solutions outside this nexus.

D: **Available and suitable storage solutions:** The lack of available storage solutions (at different timescales) – or those that are unsuitable – can risk essential parts of the flexibility solution area, sector coupling or RES integration. Therefore, pushing for available and suitable storage solutions is an essential tool to ensure complementarity for many other solution areas in this nexus.

E: **Grid stability:** This challenge includes for example several strong interactions of the energy part of the nexus with mobility (e.g., EV integration) and the built environment (e.g., decentralisation of the grid, prosumaging). This challenge is closely related to electricity demand but can also have important interactions with areas such as regulatory conditions or cybersecurity. Regarding the enabling conditions for tipping points, especially accessibility and complementarity can be affected.

F: **Energy (electricity) demand management:** Some solutions (e.g., electric mobility and alternative fuels including hydrogen/e-fuels productions) lead to a higher electricity demand. As a result, large interactions can occur with the energy part of the nexus (see E: Grid stability above), as well as RES integration. Therefore, interactions with enabling conditions for tipping points such as accessibility, responsive, real-time demand management or capability and information are possible.

G: **RES integration:** This can have strong interactions with mobility and storage. These can be positive (e.g., enabling more RES integration via new storage solutions or new storage applications, e.g., V2G) but also negative (e.g. too high electricity demands from certain end uses such as mobility). In addition, it has serious interactions with grid stability and the energy demand. However, RES integration is essential to address enabling conditions such as complementarity or desirability for many other solutions.

H: **Pricing and just transition:** Above challenges might lead to higher prices of various solution areas, potentially adding new challenges regarding a just transition and acceptance and therefore create complex and highly relevant new systemic interactions. These may also have possible impacts on nearly all six key conditions for tipping points or even create negative tipping points. Therefore, cross-cutting effects on all other areas are possible.

I: Regulatory conditions, available knowledge, and acceptance: Regulatory frameworks, available knowledge, and acceptance, are (similar to H: Pricing and just transition) relatively broad and cross-cutting issues. However, they are highly dependent on the specific solution under consideration. Nevertheless, these issues are key aspects in addressing enabling conditions such as capability & information, accessibility or cultural norms & desirability. Therefore, cross-cutting effects on all other areas are possible.

Table 8. Important system interactions exist between the challenges in the energy – built environment – mobility nexus. Source: Fraunhofer ISI, 2023.

	A	B	C	D	E	F	G	H	I
A		X	X	X			X	X	
B	X						X	X	
C				X			X	X	
D					X		X	X	
E				X		X		X	
F			X	X	X		X	X	
G				X	X	X		X	
H	X	X	X	X	X	X	X		X
I	X	X	X	X	X	X	X	X	

5.1.1.2. Which technical and societal innovations are emerging to address these challenges and how do they interact?

Various systemic interactions need to be considered if the full potential of R&I support is to be realized over the required timeframe. Relevant innovations which can address one or several of the challenges, as well as their interactions, include:

- **Storage solutions and flexibility:** These elements have several strong interactions between the different parts of this nexus (see challenges D, E, F, G):

  - Storage as an enabler for the flexibility and reliability of the power grid as well as for electric mobility, etc.;
  - Flexibility can be enabled by various solutions (including especially different storage technologies) from all three areas; and,
  - Sector coupling as a central interaction in this nexus (i.e., replacing fossil fuels with renewable energy across end-consumption sectors).
- **Increasing electricity demand:** This is an important and central interaction (see challenges E, F, G, H) resulting from electrification of various areas in this nexus (especially mobility and the built environment) and the corresponding availability of clean electricity (RES integration, grid stability and flexibility). Further development and commercialisation of solutions is required to resolve this tension.
- **Availability of CRMs, including their recyclability** (cross-cutting aspect): This is an important and relevant solution area for all three areas of the nexus. It is therefore essential to research the recycling of CRMs, as well as the use of alternative materials.
- **Sustainability of possible future technical solutions** (see challenges A, B, C) exhibit important interactions and can include the sustainability of the required resources (i.e., via mining, recycling), production of new solutions such as alternative building materials[116]) or the use of such solutions.
- **GPTs** (especially AI), due to their nature, have strong interactions with different solution areas of this nexus. Therefore, they could be an essential part of possible positive feedback loops and spillover effects between different R&I areas, technologies or need-based solutions. Important examples include smart homes and smart grids.
- **Hydrogen** as a possible solution for more flexibility in the energy system, as well as for certain aspects with regard to mobility (not so much for heating/built environment), has various interactions with the different parts of this nexus (see challenges D, G, H). In addition, it has also strong interactions with areas outside this nexus, such as industry, leading to possible resource shortages.
- **New business models and societal solutions** can push new technical solutions or even allow their sustainable implementation and use. Therefore, this aspect can have interactions with almost all solution areas. At the same time, understanding the behaviour of end consumers is essential to enable such positive effects and to prevent possible negative effects (e.g., lack of acceptance for individual solution areas or unexpected effects with regard to energy demand and grid stability). Important examples with regard to this nexus are e.g., overcoming private car ownership, prosumaging, as well as urban planning. Especially the latter is a key factor for climate mitigation in cities with clear adaptation and health co-benefits.

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[116] Here are also strong possible interactions with the industry - circular economy nexus.

- **Module and system design** (Solar PV) can have interactions with the built environment and for example enable new solutions for RES integration (see challenges E, F,G).

5.1.1.3. Which potential spillover effects could result from these interactions (and should be considered as potential outcomes of R&I programmes)?

The combination of systemic interactions with challenges and solutions can lead to different spillover effects. These effects are essential to reach positive tipping points or to advance the respective enabling conditions. However, negative spillovers are also possible and should be avoided. This requires not only a holistic understanding of a nexus and its systemic aspects and spillovers, but also of the interactions between different nexuses. Examples of three different types of spillover effects for the built environment-mobility-energy nexus are presented below. At this point it is important to note that many spillover effects can have an impact in both directions (positive and negative).

General spillover effects:

- Cheap and renewable electricity is pushing e-mobility and new solutions with regard to the built environment (and vice versa).
- Resource shortages and/or other price rising effects can have serious impacts on acceptance issues and a just transition (especially important, because subsequent social interactions with the technical solutions (e.g., acceptance) are essential).
- Interactions due to common supply chains can impact resilience and resource security.
- Recycling of CRMs can have positive impacts on several technical solutions across all areas (e.g., more reliable material availability/less import dependencies).

Knowledge spillover effects:

- The introduction of different smart solutions, as well as the engagement with new technical solutions (e.g., e-mobility, prosumaging), can promote energy awareness, as well as energy knowledge and thus possibly radiate into other areas of daily life.
- As already mentioned, new knowledge on behavioural and acceptance aspects of the different solutions in this nexus is very important. However, it can also have strong spillover effects on other areas and on the acceptance of other technical solutions. In general, such spillover effects are essential for the further integration of such societal aspects in the required R&I.

Application spillover effects:

- Of course, the strongest application spillover effects can be expected for the different GPT (i.e., AI, machine learning, big data) applications, which are relevant to this nexus. Important examples which could even result in spillover effects in the other nexuses could be smart storage solutions or smart energy management systems, cybersecurity applications or big data analysis of energy data.

- Storage solutions can also have strong spillover effects, due to their application in the various fields (such as power grid, mobility, prosumaging, etc.).

5.1.1.4. Which potential risks and trade-offs result from these interactions (and should be considered as potential outcomes of R&I programmes)?

As a result of the different interactions between the different technical and societal solutions, as well as the possible systemic interactions and spillover effects introduced by the common challenges, three major risks can be identified:

- Large competing needs for rare materials can introduce serious resource bottlenecks. This can be amplified by their abundance and (global) supply chain issues. In addition, such bottlenecks can also lead to higher prices, putting even more pressure on more costly sustainable production and mining processes as well as challenging the just transition. Therefore, this risk may even result in possible negative reinforcing feedback loops.
- The strong interactions between solutions that enable electrification (increasing electricity demand), the integration of RES (including grid flexibility and stability) and the resulting reliance on suitable energy storage represent a major risk. All three need to move forward together, otherwise any one of the three lagging behind can seriously hamper the other two and create potential bottlenecks or negative reinforcing feedback loops. In addition, storage solutions are a critical enabler and could, in the worst case, threaten the success of the entire nexus, notably if demand is unmanaged.
- The much less predictable (and often less considered) interactions with social and behavioural aspects (e.g., acceptance of new solutions) can be a major risk. This is particularly with regards to the more technical interactions affecting price and a possible just transition, which can lead to negative reinforcing feedback loops. These in turn may make adoption of the technical solutions in question more or less impossible. Consequently, this can then have an impact on other technical solutions, even if they are not directly linked to the triggering of behavioural/societal systemic interactions (see above).

5.1.2. Circularity – Industry – Carbon removals and capture nexus

5.1.2.1. What are the key challenges and bottlenecks preventing the transformation of the nexus?

A set of three common challenges have been identified, including:

- **Risk of stranded assets:** A significant common challenge in implementing circularity and carbon removal in industry consists of the fate of existing carbon-intensive installations. There might be a risk that existing installations are not integrated into the circular economy and with carbon removal solutions due to high costs – they might well be uneconomical to shut down entirely, resulting in a loss of capacity. Since a widespread implementation of carbon removal solutions would constitute an important tipping point towards climate neutrality goals, addressing this challenge would gain importance.
- **Material dependencies:** An overarching challenge concerns the material dependencies of industry, in particular, the design of products (including the setting of relevant standards), as well as efficient tracking of resource origins, to

enable integration of the industry into the circular economy. Due to the important material flows in the industry, a successful integration of industrial processes into the circular economy would constitute a tipping point.

- **Mutual adaptation of the fields in the nexus:** The mutual adaptation of industry to carbon removal technologies, such that carbon removal is economically feasible, is a challenge faced by both sectors. A significant reduction in the costs of carbon removal would be a tipping point that would enable systemic changes that would accelerate progress towards climate neutrality.

5.1.2.2. Which technical and societal innovations are emerging to address these challenges and how do they interact?

- **Importance of carbon removal technologies:** A significant interaction exists (and will continue to exist) between carbon removal technologies and efforts towards industrial decarbonisation. In industrial processes, where CO_2 is an important effluent that would have otherwise been released into the atmosphere, point-source carbon removal technologies will play a crucial role in removing carbon at source.
- **Resource and material flows:** These currently play and will continue to play an integral role in shaping the future of EU industry due to various factors. The integration of circularity in these flows touches upon many aspects of the reduce-reuse-recycle trinity, notably when it comes to the use of biogenic resources (e.g., biomass), as well as in the recycling and reuse of industrially manufactured products. This is most notable in the cement and steel sectors, which interact with the built environment-mobility-energy nexus.
- **Improvements in the efficiencies of industrial processes:** These will have an impact on the aggregate demand for resources which has a direct connection to the ‘reduce’ aspect of the circular economy.
- **Appropriate pricing of industrial products:** From a socio-economic perspective, an important interaction consists of the effective integration of the costs of carbon removal and circularity in the prices of industrial products. This might have a bearing on the acceptability aspect of the solutions that are part of this nexus.

5.1.2.3. Which potential spillover effects could result from these interactions (and should be considered as potential outcomes of R&I programmes)?

- Positive spillovers of technological progress in this nexus might reach far beyond the technologies involved in this nexus, primarily from knowledge spillovers to other sectors, such as the energy sector where carbon removal solutions might also have a large potential to be implemented.
- A potential negative spillover of the integration of carbon removal solutions in industry might be reduced policy interest to (fundamentally) decarbonise industrial processes in themselves, either by investment in process efficiency improvements, or by searching for alternative fuels.
- The integration of technological solutions for carbon removal and circularity in industry might affect the competitiveness of EU industry in world markets as a

negative spillover. An effective implementation and a price-representative functioning of intra-EU carbon markets, as well as that of the Carbon Border Adjustment Mechanism (CBAM), is of importance in helping to mitigate such impacts.

5.1.2.4. Which potential risks and trade-offs result from these interactions (and should be taken into account in the design of R&I programmes)?

- A significant risk concerning acceptability regards broader economic effects of the integration of carbon removal solutions and of circularity in the industry. To the extent that CO_2 emissions and a lack of circularity represent negative externalities that are resolved by the technological solutions presented in this report, these externalities will be represented by price increases of the end products.
- This nexus is strongly exposed to external factors, notably by the price of carbon and the prevention of carbon leakage to third countries outside of the EU internal market.
- Whereas the development of new technologies can have a positive effect on the demand for skilled labour, the increased involvement of GPTs, such as AI, may have negative (or net-negative) effects on employment levels, particularly of unskilled labour, therefore possibly impacting income and wealth inequality. This might have a negative effect on acceptability.
- An increased focus on carbon removal solutions might hinder investment in process innovations, as well as the search for alternative (carbon-neutral) fuels and heat sources in industrial applications, whereas overreliance on carbon removal alone without reducing the emissions at the same time could prove extremely risky.

5.1.3. Agrifood – Carbon removals nexus

5.1.3.1. What are the key challenges and bottlenecks preventing the transformation of the nexus?

- The central bottleneck to jointly developing agriculture for food production and ecosystem-based CDR is the joint need for **arable land**. As an example, agroforestry (i.e., involving trees/forest into agricultural practices) diminishes the availability of arable land in existing fields/meadows.
- At the same time, the **economic viability** of established agricultural systems is relatively certain (at least in the short term), while changing towards innovative practices holds a financial risk for farmers and communities. This holds true both for practices aiming at avoiding emissions, as well as for practices fostering CDR. The threshold to alter behaviour hinders transformation.
- Similarly, **knowledge** on how to integrate CDR into agricultural systems and apply more climate friendly practices may be lacking, especially in remote rural areas often characterised by agriculture.
- **Regulatory frameworks** may not adequately address the integration of novel approaches within agriculture. There may be legal and policy barriers to adopting innovative practices on agricultural lands, including unclear ownership of land and its outcomes (be it food or carbon removal certificates) and risks related to land

grabbing and geopolitical implications. Regulations for CDR and climate friendly agriculture require a long-term focus, while most agricultural products are being generated in short timescales. Thus, balancing short- and long-term objectives is key. Note that this refers back to the financial uncertainty affecting farmers and communities, as mentioned above.

- **Monitoring, Reporting and Verification (MRV)** of emissions from agricultural areas is far more complex than from point sources. However, is essential to quantify the amounts of avoided and/or removed emissions to create incentives and establish credible projects. Without an effective and efficient MRV system, an effective and efficient transition of the agrifood-carbon removal nexus is unlikely to happen.

5.1.3.2. Which technical and societal innovations are emerging to address these challenges and how do they interact?

- **Arable areas:** The integration of agriculture and CDR on areas already being cultivated is key to avoid public pushback. Technical innovations to address the competition for arable land between agrifood production and CDR aim at combining the two. To make such solutions attractive (for example, interaction with communication and knowledge building, described below), research into optimal combinations of CDR and agriculture is required. Further, integrating agricultural production and suited CDR methods into urban contexts could expand the available area to some degree, although the scalability of such applications is limited. Similarly, shifting towards lab-grown meat could area currently required for pasture. In marine contexts, potential combinations of blue carbon solutions with integrated aquaculture needs to be understood and fostered to avoid conflicts, e.g., between shrimp farming and mangrove forests. The role healthy kelp, farm, and seaweed systems play as a nursery for commercial fish species are increasingly understood. Further research and information on this interlinkage are required.

- **Financial reliability:** The financial viability of innovative practices targeting emission avoidance as well as CDR need to be proven. Both co-benefits and direct financial potentials from different practices need to be quantified. The benefits and challenges of projects combining agriculture and ecosystem-based CDR should be communicated to help lower farmer´s thresholds to establishing them as core practices. Workable solutions should be co-developed with local communities to ensure related policies or initiatives do not face overly strong opposition. These societal approaches interact with the need for transferring technological know-how, as well as the introduction of enabling regulatory frameworks (see below). MRV development (see below) will also be required to prove the financial reliability of CDR methods.

- **Knowledge transfer:** To overcome thresholds to implementation on the community/farmer level, successful communication channels and responsible institutions will need to be built at a large scale. The same channels can serve for technological know-how and financial/regulatory aspects. Dialogues, workshops etc. are already emerging at smaller scale, but further focused action will be needed to scale CDR activities in agricultural spheres. Pilot projects can serve as role models in communities. They utilise existing networks as well as mutual trust and learning on the farmer level. By setting a positive example, they can trigger followers and lead to a local tipping point.

- **Regulatory frameworks:** Regulatory frameworks which embrace ecosystem-based CDR are emerging. The EU´s Carbon Removal Certification Framework (CRCF)[117] has a focus on this type of CDR and is an important starting point. However, the CRCF affects also other agricultural applications, and is thus situated at the heart of this nexus. It interacts especially with the need for credible MRV, which will be required to ensure the financial viability of combined agrifood-CDR approaches.
- **MRV:** Current developments to enable the reliable MRV of land-based emissions include remote sensing, blockchain technology, and digitization of MRV processes in carbon markets in general. Scalable hybrid solutions involving satellite mapping combined with AI and calibrated via physical samples have recently been evolving. Aspects related both to the technological know-how and the risks and opportunities of digitizing MRV need further research.

5.1.3.3. Which potential spillover effects could result from these interactions (and should be targeted by R&I programmes)?

Shaping a regulatory framework that fosters the implementation of combined agrifood-CDR approaches will give certainty to communities and farmers, as well as to developers of technological solutions for improved MRV solutions targeted at avoided and/or removed emissions on land/water, rather than at point sources. At the same time, the availability of such MRV solutions will lower the threshold to apply CDR by farmers or communities, as they can form the basis for reducing financial uncertainties (if accompanied by a credible regulatory framework).

To avoid that the co-existence of agriculture and ecosystem-based CDR is perceived to be dominated by trade-offs, better knowledge on co-benefits and CDR applications actually leading to improvements of agrifood production is needed. As an example, biochar application can positively alter soil characteristics (e.g., water, pH), leading to higher yields per area. Agroforestry has positive effects on microclimate by making soil water available and providing shade to plants and/or animals, often overcompensating for the former agricultural area dedicated to trees in such a solution. Mangroves serve as nurseries for commercial fish species. Research to further identify and optimize such co-benefits will make communication and capacity building easier, lowering thresholds to CDR implementation and avoiding conflicts over land use.

5.1.3.4. Which potential risks and trade-offs result from these interactions (and should be taken into account in the design of R&I programmes)?

If ecosystem-based CDR solutions were adapted at large scale, following the development of reliable frameworks, MRV systems and overcoming reservations to

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[117] European Commission, 2022. Regulation of the European Parliament and of the Council establishing a Union certification framework for carbon removals. Available at: https://climate.ec.europa.eu/system/files/2022-11/Proposal_for_a_Regulation_establishing_a_Union_certification_framework_for_carbon_removals.pdf

implement them at either farmer and/or community levels through extensive capacity building, there is a risk that arable land could be used for CDR rather than for agriculture. This could potentially lead to indirect land-use changes. This risk can probably be avoided if CDR solutions which can be combined with agriculture are favoured. The risk of expanding ecosystem-based CDR into so far unmanaged land seems larger than it replacing agricultural areas.

5.2. Lessons learned from the three nexuses

5.2.1. General Purpose Technologies (GPTs): the lubricant for all system nexuses

5.2.1.1. Introduction

To properly understand the influence of GPTs in all the system nexuses, it is important firstly to define what GPTs cover and what they stand for. GPTs, also known as foundational or transformative technologies, are innovations that have the potential to significantly impact and transform multiple sectors of the economy and society. These technologies are characterised by their broad applicability, adaptability, and the profound changes they bring about in various industries and aspects of daily life. They often act as catalysts for economic growth, productivity enhancements, and societal progress.

Bekar et al. (2018) define GPT as follows:

“A GPT is a single technology, or closely related group of technologies, *that has many uses across most of the economy,* is technologically dynamic in the sense that it evolves in efficiency and range of use in its own right and is complementary with many downstream sectors where those uses enable a cascade of further inventions and innovations" (emphasis is of the original authors)[118].

Overall, GPTs not only revolutionize the sectors in which they are initially applied, but also have far-reaching effects, influencing other industries and enabling new paradigms of economic and societal organization.

The rise of e-commerce, social media, and remote work exemplifies the innovative solutions brought about by GPTs, where these technologies have transformed how individuals communicate, businesses operate, and governments deliver services.

In the fields of genomics, data analytics, and biotechnology, GPTs have revolutionised healthcare. Personalized medicine, driven by genomics and AI-driven diagnostics, promises more effective treatments tailored to individual genetic profiles, improving patient outcomes. GPTs can also improve healthcare access by facilitating telemedicine and remote diagnostics, particularly in underserved areas. Telehealth technologies proved critical in providing medical services during the COVID-19 pandemic.

On the path towards climate neutrality, GPTs may prove important enablers for climate neutrality through numerous – in part, hard to anticipate – use-cases. A recent extensive review[119] of the role of Machine Learning (ML) and Artificial Intelligence (AI)

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[118] Bekar, C., Carlaw, K., & Lipsey, R., 2018. General purpose technologies in theory, application and controversy: A review. *Journal of Evolutionary Economics*, *28*, 1005-1033

[119] Rolnick, D., et al., 2022. In: ACM Computing SurveysVolume 55Issue 2. Available at: https://dl.acm.org/doi/pdf/10.1145/3485128

in tackling climate change identified, for example, more than 30 climate change solution areas that could benefit from a variety of ML solutions. These covered climate mitigation and adaptation, as well as the role of ML and AI in enabling individual action, collective decisions and informing climate-related education and finance.

In the cleantech space, GPTs often need to be combined with a physical / hardware solution to have impact. For example, precision agriculture depends on farm machinery which is capable of deploying / acting on the recommendations generated by an analytics programme. This phenomenon throws up commercial and financial barriers to deployment at scale, even when demand for an innovative solution exists.

In summary, GPTs are transformative innovations that have the potential to reshape multiple sectors of the economy and society, serving as the cornerstone for widespread change and progress towards climate neutrality. To an extent, GPTs highlight the importance of the “twin” green and digital transition.

5.2.1.2. Importance of GPTs to the mobility-built environment-energy nexus

GPTs have been actively supporting the transformation of mobility-built environment-energy innovations.

In terms of **mobility**, the use of GPTs (like AI) as important enablers of autonomous vehicles and advanced transportation systems is reshaping mobility. Self-driving cars, for instance, have the potential to reduce accidents, congestion, and greenhouse gas emissions (the latter being clearly dependent on behavioural factors and usage patterns). Furthermore, the integration of mobility-as-a-service platforms is making transportation more efficient and accessible. GPTs enable the transition to sustainable and interconnected transportation networks, reducing the environmental impact of mobility.

In the **built environment**, the incorporation of GPTs (e.g., datatags and nanotechnology), into construction technologies and energy-efficient building materials are revolutionising the way we design, construct and monitor structures including with end-of-life considerations in mind. Smart cities, equipped with GPT-enabled infrastructure, optimize resource use, improve urban planning, and enhance the quality of life for residents. GPTs also allow for the creation of resilient, sustainable, and energy-efficient cities, reducing the carbon footprint of the built environment.

In the **energy** sector, GPTs are being used to analyse very large datasets generated by smart meters, which in turn have enabled a transformation in the way energy usage is monitored and analysed by both Transmission System Operators (TSOs) and Distribution System Operators (DSOs). This has led to dynamic forecasting and predictions of energy demand (which can help plan RES usage/storage and avoid bringing online fossil-based power stations at peak load times), the optimisation of energy usage (for example, via different types of tariffs to manage demand, especially from industry), and the ability to aggregate load shedding during peak usage periods at the household and industry level (Demand response). Specific GPT applications include energy efficiency optimisation, load balancing and predictive maintenance. GPTs are crucial in enabling the transition from fossil fuels to clean energy sources, reducing GHG emissions and promoting energy efficiency, and facilitating energy sector decarbonisation.

The implementation of GPTs has the capacity to enhance the relation between these three thematic areas, through solving the following challenges mentioned above:

- **Material abundancy, as well as the area of tension between efficient materials vs sustainable materials:** GPTs enable breakthroughs in materials science, leading to the development of new materials that are not only more efficient but also more sustainable/have a lower CO_2 footprint. For example, nanotechnology and advanced composites can produce lightweight yet strong materials for various applications, reducing resource consumption and environmental impact. In addition, GPT-driven technologies like 3D printing and advanced manufacturing processes allow for precise and efficient use of materials. This minimizes waste during production, optimizes resource utilization, and reduces the demand for raw materials.

- **Supply chain sustainability:** GPTs facilitate the monitoring and optimization of supply chains, ensuring that materials are sourced sustainably and transported efficiently. This reduces the environmental impact and GHG emission-intensity associated with resource extraction and transportation.

- **Resource shortages (e.g., due to more pressing needs in other areas or missing recycling solutions):** GPT-driven technologies, such as advanced manufacturing processes and big data analytics, can optimize the use of resources in various industries. These technologies reduce waste, increase production efficiency, and make the most of available resources, helping to alleviate resource shortages. In addition, GPTs enable the transition to a circular economy by facilitating the design of products and systems for reuse, remanufacturing, and recycling. This approach extends the lifespan of resources, reducing the demand for new raw materials.

5.2.1.3. Importance of GPTs to the circularity-industry-carbon removals nexus

GPTs can affect processes within several core aspects of this nexus. For example:

- **Advanced Materials and Manufacturing Techniques:** GPTs can drive innovations in materials science and manufacturing technologies, leading to the development of more sustainable and recyclable materials. For instance, advanced composites and biomaterials can replace traditional materials in various industries, making products more recyclable and reducing the carbon footprint of manufacturing processes.

- **Circular Economy Technologies:** GPTs enable the implementation of circular economy principles in industries. Advanced data analytics and supply chain optimization tools can help industries design products for longevity, reuse, and recycling. They can also support reverse logistics, making it easier to collect and recycle products and materials at the end of their life cycle.

- **Carbon Capture and Utilization (CCU):** GPTs, particularly those related to chemistry and materials science, can enhance CCU technologies. These innovations allow industries to capture carbon emissions from their operations and convert them into valuable products, reducing the carbon footprint of industrial processes.

Other areas in which GPTs can have an active influence in this nexus include Energy Efficiency and Electrification; Carbon Removal Technologies; Data Analytics and Optimization; Sustainable Supply Chains; Consumer Awareness and Engagement; and, Policy and Regulatory Support.

5.2.1.4. Importance of GPTs to the agrifood-carbon removals nexus

GPTs have a strong influence on this nexus as it plays a significant role in addressing the challenges at the intersection of three areas, where the aim is to make agricultural and food production more sustainable, while actively removing CO_2 from the atmosphere. Examples of how GPTs contribute to this objective include:

- **Precision Agriculture and Data Analytics:** GPTs enable precision agriculture by utilising sensors, data analytics, and machine learning. These technologies optimise resource use in farming, leading to higher crop yields, reduced inputs (such as water and fertilisers), and lower greenhouse gas emissions per unit of food produced.
- **Climate-Resilient Crop Varieties:** GPTs in genetics and biotechnology can expedite the development of climate-resilient crop varieties. These crops are more resistant to extreme weather events and require fewer inputs, making agriculture more sustainable and less carbon intensive.
- **Carbon Farming Practices:** GPTs support the adoption of carbon farming practices such as agroforestry, cover cropping, and reduced tillage. These practices sequester carbon in soil and vegetation, reducing atmospheric CO_2 levels while improving soil health and crop productivity.

Other areas in which GPTs can have an active influence over Agrifood-carbon removals are Carbon Capture in Food Production, Supply Chain Traceability, Food Waste Reduction, Alternative Protein Sources, Sustainable Aquaculture, Consumer Awareness and Behaviour and Policy Support.

5.2.1.5. Conclusions on the use of GPTs to support systemic nexuses

GPTs have the potential and capacity to help create transformational solutions for many of the challenges identified across the three nexuses. And in areas such as agriculture, GPTs such as IoT sensors and data analysis software, have already made farming practices more sustainable. Farmers can optimize crop planting, water-efficient irrigation, precision nutrient management, and pesticide use, reducing resource consumption while increasing yields.

Besides facilitating new solutions, it is important to mention that the use of GPTs also brings about new dependencies and can create ‘technological lock-in’. For example, within IT users and businesses become dependent on the technological ecosystem, which can lead to concerns over data privacy, monopolistic practices, and limited alternatives.

Other ways in which GPTs are creating new dependencies are via the ethical and social implications of their deployment. Perhaps one of the most important debates is how automation and AI-driven technologies have led to concerns about job displacement. Industries adopting GPTs for efficiency gains may inadvertently contribute to unemployment or wage disparities, creating societal dependencies on social safety nets. Another critical issue is the widespread adoption of surveillance technologies and data-driven decision-making that can infringe on individual privacy. Dependence on such technologies can erode personal freedoms, necessitating regulations and safeguards to protect civil liberties. Another aspect to consider is the dependence on digital technologies for education, healthcare, and work and how they can exacerbate societal inequalities. Those without access to these technologies may face disadvantages, creating dependencies on equitable access.

Another impact is the extent to which GPT technologies have a direct relation to the increase of digital data usage – and on data storage – which in turn leads to unforeseen costs (mainly via water and energy consumption) for the users due to "lack of transparency and accurate reporting by data service providers" (Farfan, J., & Lohrmann, A. (2023))[120]. A recent study, which uses data from the OECD and The World Bank provides important estimations on how the use of data and OECD-European countries will increase and how as a consequence energy and water usage by these data centres will also increase. Some of the most alarming results are amongst the lines of "the estimated yearly energy consumption for data usage is expected to increase from the average level of 29.8 TWh in 2020 up to around 112.7 TWh by 2030……. similarly, yearly water consumption is projected to increase from the 2020 estimate of 145.2 to 546.7 million cubic meter by 2030" (Farfan, J., & Lohrmann, A. (2023)). Quaranta et al. (2023)[121] have calculated the cost per person per year of these impacts, assuming an average cost of 0.1 EUR/kWh and 3.3 EUR/m^3 of water in the EU, as 19 EUR. These data strongly suggest that the use of water and energy should be included in circularity assessments of data centres and how they can provide reliable and accurate information of their water and energy usage.

The economic benefits that digital solutions can bring to the water sector were also quantified, with a focus on leakage reduction in water distribution networks, reduction of combined sewer overflows and improvement of hydropower generation and operation. Benefits are calculated for each EU Member State and the UK, and then aggregated at the EU scale. These benefits were quantified as 5.0, 0.14 and 1.7 EUR billion per year – or 13.2 EUR per person per year, on average, excluding environmental and social benefits, which may play a non-negligible role (Quaranta et al., 2023).

Although the adverse effects of adopting GPTs can be an important aspect to discuss, there is an apparent and prevalent rhetoric among academic literature that supports all the positive effects of using and enabling the deployment of GPTs. Some authors have theoretically and empirically proven the relation between Industry 4.0 and sustainable development (Fathi et al., 2021). Their argumentation and evidence seem to suggest there actually exists a causal relationship between the adoption of Industry 4.0 technologies and energy sustainability, achieved by "*digitizing the supply side of the energy sector, specifically through reducing operating and maintenance costs of power plants and energy generation facilities, increasing the efficiency and safety of energy delivery networks*" (Fathi et al., 2021). Another important way is for GPTs to

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[120] Farfan, J., & Lohrmann, A., 2023. Gone with the clouds: Estimating the electricity and water footprint of digital data services in Europe. Energy Conversion and Management, 290, 117225.

[121] Quaranta, E., Ramos, H. & Stein, U., 2023. Digitalisation of the European Water Sector to Foster the Green and Digital Transitions, Water 2023, 15(15), 2785. Available at: https://www.mdpi.com/2073-4441/15/15/2785

enable energy efficiency at the factory level by improving production management practices, production planning control, and decision-making processes across manufacturing networks (Fathi et al., 2021).

Overall, GPTs can have a positive impact on sustainability and energy efficiency. However, it is also important to consider the negative, unintended consequences these technologies can bring from a technical, societal and governance perspective. In addition to the dependencies mentioned above, adoption of GPTs can affect consumer behaviour by dramatically increasing energy consumption or the systemic changes it entails, by replacing humans with AI and the establishment of massive and power-hungry data centres which may contribute to a rebound effect.

5.2.1.6. How to integrate systemic interactions between technical solutions in the design of R&I programmes?

An approach that is solely based on a top-down, multi-criteria decision analysis will likely overlook key areas in which progress has to be achieved in order to decarbonise all parts of the economy, while nonetheless delivering on needs. A combination of two complementary analytical approaches is therefore needed: (1) back casting from needs; and, (2) taking the landscape view on solution areas.

Back casting: while recognising that a selection of technologies will most likely continue to be supported in European R&I funding programmes (as part of a portfolio approach), focusing on a societal need that is necessary to be fulfilled in the 2050 climate neutral economy helps ensure that future needs are addressed comprehensively. It also establishes a broader perspective, without overlooking key technology elements or the unexpected application of GPTs. However, an emphasis on back casting will only be required where the case for public investment is strongest and where the private sector is judged not to be better placed to intervene in financing the R&I itself.

Taking a **landscape view** allows the identification of limiting factors, resource-limitation trade-offs, and synergies. This has key benefits: understanding limiting factors allows resources to be focused on where they have the most potential to unlock a ‘Gordian Knot’; while understanding resource-limitation based trade-offs avoids placing reliance on technology combinations that are not going to be scalable alongside each other; and it might also allow technology design alternatives to be identified which avoid the use of limited resources (to prevent supply chains from turning into the limiting factor for example).

It is necessary to combine back casting and taking a landscape view to integrate consideration of systemic interactions between solutions. This is in order to identify which R&I intervention areas may hold the most acceleration potential – by either undoing the blocking power of a limiting factor, side-stepping serious trade-offs and ensuring the mobilization of synergies including from GPTs. This in and of itself, however, may not offer sufficient analysis to pick potential winning technology areas for focused support (which is also required to achieve some of the highest-impact R&I acceleration).

5.2.1.7. How to integrate systemic interactions between technical and societal solutions in the design of R&I programmes?

Widening the scope of the landscape view to include societal and institutional structures allows the inclusion of regulatory, economic and business-case related limiting factors (or synergies) which impact on production scalability, cost-reduction slopes, and availability of necessary financial support in cases of pure climate technologies which would otherwise not offer an economical case for implementation.

As shown above, the integration of societal solutions and investigation of their systemic interactions is essential to address different challenges and enable positive tipping points – such as an acceleration in demand of climate mitigating products (e.g., EVs, solar PV) due to cultural reasons – and potential barriers – from public perception or regulation (e.g. limitations on onshore wind power).

A possible solution to integrate social aspects and give attention to issues such as behaviour and acceptance in the design of R&I programmes are extended life cycle assessments.[122] Here, the aim is to consider all societal and social aspects which may be relevant for new technical solutions in the different nexuses in order to be prepared for possible systemic interactions which may occur.

The following aspects should always be considered when pushing new technical solutions (based on the paper by Kirkegaard et al.):

Table 9. Integrating societal and social aspects which may be relevant for new technical solutions. Source: Fraunhofer ISI, 2023. Based on Kirkegaard et al.

STAGE OF THE LIFE CYCLE	SOCIO-TECHNICAL ASPECTS WHICH SHOULD BE ADDRESSED IN UPCOMING R&I ACTIVITIES IF POSSIBLE
Design	• Achieving co-design where feasible • Engagement of societal actors • Understanding differences and similarities between the respective needs sphere (needs resulting from climate goals) and the social sphere (needs present in society/resulting from our everyday life and expectations)
Planning and development	• Addressing concerns of justice and democracy (distributional effects, participation, etc.) • Addressing social issues with regard to supply chains (sustainability, “social origin” of the needed resources, ethical aspects, etc.)

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[122] Kirkegaard, J.K., Rudolph, D.P., Nyborg, S. *et al.*, 2023. Tackling grand challenges in wind energy through a socio-technical perspective. *Nat Energy* **8**, 655–664. Available at: https://doi.org/10.1038/s41560-023-01266-z

Operation	• Understanding cultural, social and historical contexts • Understanding concerns of everyday life • Understanding systemic interactions of social/behavioural solutions (also with technical solutions)
End-of-life	• Understanding expectations and concerns of the future • Understanding uncertainties with regard to the social/behavioural dimension

Potential examples for the mobility-built environment–energy nexus include:

- Large homes and cars (wanted) vs small ones (needed), as an example for the aspect “Understanding differences and similarities between the respective needs sphere (needs resulting from climate goals) and the social sphere” in the design phase of the life cycle;
- Understanding social impacts of a flexible power grid (and the relevant solutions), as an example for the aspect “Addressing concerns of justice and democracy (distributional effects, participation, etc.)” in the design and implementation phase of the life cycle;
- Understanding social impacts of a shared economy on new technical solutions, as an example for the aspect “Understanding systemic interactions of social/behavioural solutions (also with technical solutions)” in the operation phase of the life cycle;
- “Understanding cultural, social and historical contexts” (operation phase) with regard to new mobility solutions to improve their acceptance and to allow better co-design (design phase of the life cycle); and,
- Expectations on responsibilities for discarding/recollecting and recycling storage solution (e.g., e-mobility and home storage/prosumaging) as an example for the aspect “Understanding expectations and concerns of the future” in the end-of-life (EOL) phase of the life cycle.

5.2.2. How to bring these different systemic perspectives together?

All three analyses – the examination of solution landscapes, the back casting from 2050 needs and the multi-criteria evaluation of individual solutions – are jointly needed to create a sufficiently complex and clear picture of potential priority areas for targeted, yet simultaneously technology-agnostic (and thus competition-friendly), R&I interventions, which yield the most potential to unlock high-impact, high-risk progress toward climate neutrality.

Neither one of the three analytical approaches can individually answer the question of how to prioritize technology areas or specific technologies (or corresponding societal innovations), but jointly they can point to those cases that stand out as a particularly widely applicable contributor (GPT), a particularly severely limiting factor (of both technological or social nature), or simply a technology solution area of particularly large climate change mitigation potential.

6. Combining the mission-driven approach with a human need driven agenda and a tipping point framework in the design of R&I programmes: selected case studies across the nexuses

The following sections provide short case studies for high-risk and high-impact R&I areas under each of the three nexuses. They have been selected following results from the evaluation framework (as described in section 2), taking into account the three nexuses as well as a needs-based perspective with the aim to cover examples including technological solutions, societal solutions, as well as cross-cutting solutions. These case studies illustrate how a mission-driven approach, and a human needs agenda can be combined with the "positive tipping point" framework to give more directionality to R&I programmes. Although the selected case studies typically scored well in the evaluation framework and are part of the set of solutions that should be prioritised by R&I efforts, they should not be considered as the definitive list of top priorities emerging from this study – rather as an illustrative set of R&I areas which exemplify perspectives which are of value to policy makers in considering what to support. An overview of the different case studies is given in Table 10 below:

Table 10. Rationale for selection of case studies based on an assessment of needs and R&I areas that must be addressed to help meet those needs.

NEED TO BE ADDRESSED	**EXAMPLE OF R&I AREAS THAT MUST BE ADDRESSED TO ADDRESS THE IDENTIFIED NEEDS**		
	Technological solutions	**Societal solutions**	**Cross-cutting solutions**
Ensure access to affordable and sustainable buildings	Alternative building materials	Community engagement in energy positive districts & in energy communities	
Ensure access to affordable, reliable and sustainable energy	Recycling of critical raw materials	Understanding behaviour change around prosuming and prosumaging solutions[123]	Role of General Purpose Technologies (GPTs)
Support scalable and sustainable	Direct Air Capture (DAC) Biochar		

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[123] Prosuming refers to production and consumption, while prosumaging covers production, consumption and storage.

NEED TO BE ADDRESSED	EXAMPLE OF R&I AREAS THAT MUST BE ADDRESSED TO ADDRESS THE IDENTIFIED NEEDS		
carbon removal solutions	Marine CDR		

Colour code: Case studies falling under the mobility-built environment-energy nexus; Case studies falling under the circularity-industry-carbon removal nexus; Case studies falling under the agrifood-carbon removal nexus

Each case study follows a common structure, aligned with the evaluation framework, and is used to identify the rationale for R&I support, the various barriers to implementation, and the types of R&I interventions that are most required to help advance each area. For several case studies, the results of value chain analysis carried out by the Cleantech Group have been used to further specify the specific R&I areas required in Europe as well as identifying leading innovative companies at either seed or early-stage. Where appropriate, the system aspects and inter-relationships have also been described, indicating the potential ripple effects and/or complexities arising to enable greater penetration of the R&I area.

6.1. Case studies falling under the mobility-built environment-energy nexus

The case studies under this nexus cover:

- Alternative Building Materials;
- Prosuming and prosumaging; and,
- Community engagement in energy positive districts and in energy communities.

6.1.1. Case study on Alternative Building Materials

Human needs and associated mission

A wide range of options for alternative building materials is encompassed, offering unique advantages for sustainable construction. These materials need to address key aspects of sustainability, such as achieving lower carbon footprints compared to traditional building materials like cement and steel. GHG emissions associated with manufacturing and transportation must be reduced, contributing to climate change mitigation. Additionally, alternatives should be sourced from responsibly managed and renewable sources, promoting resource conservation and reducing dependence on finite resources. The potential to divert waste from landfills through the use of recycled materials is another crucial aspect, providing opportunities for a circular economy. Moreover, alternative materials should possess excellent thermal properties to enhance energy efficiency and reduce reliance on artificial heating and cooling. Lastly, they should support prefabrication and modular construction, improving process efficiency, reducing construction waste, and accelerating project timelines. Embracing alternative building materials offers a holistic approach to sustainable construction, addressing the environmental, social, and economic aspects of the built environment.

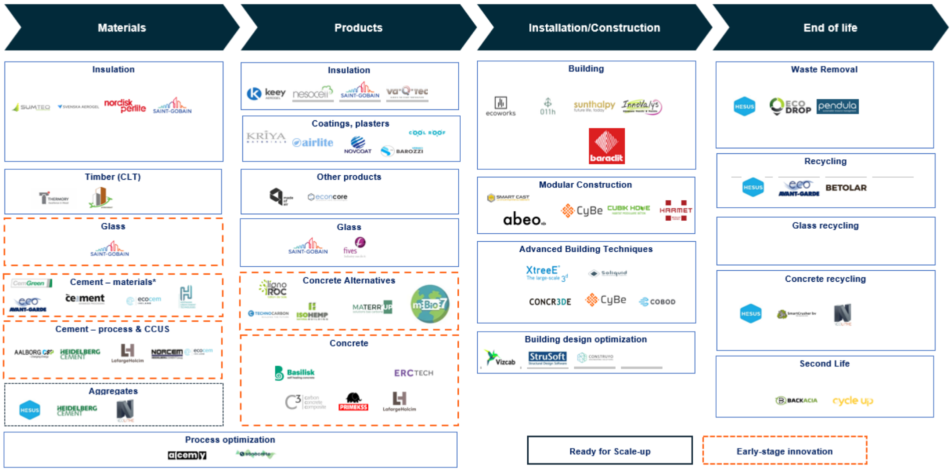
Solution status

Concrete, known as the most widely used man-made material, has significantly shaped urban landscapes due to its strength and versatility. However, the environmental consequences of its production cannot be ignored. Cement, a key ingredient in concrete, is responsible for a staggering 8% of global CO_2 emissions. This highlights the urgent need to address the environmental impact of concrete production and align with the goals of the Paris Agreement. Promising approaches include the use of alternative materials like fly ash, blast furnace slag, or recycled concrete as substitutes for cement. These alternatives not only reduce carbon emissions but also utilize waste materials, contributing to a more circular economy. Sustainable construction practices that focus on reducing concrete demand, optimizing its use, and raising awareness among professionals and the general public are crucial for driving change. Collaboration between policymakers, industry stakeholders, researchers, and environmental organizations is essential to implement low-carbon construction practices, set stricter emissions standards, invest in research and development, and foster innovation and change in the industry. By embracing sustainable alternatives, implementing greener practices, and fostering collaboration, the environmental impact of concrete production can be mitigated, paving the way for a more sustainable future.

Current state of the value chains and existing EU-based innovators

Figure 19 shows the value chain of construction materials, along with relevant R&I fields. As seen from the graphic, cement-related innovations are receiving a lot of interest, with various start-up companies and initiatives from established actors aiming to achieve technological breakthroughs. This could be perceived as a demonstration of the importance of cement alternatives, but also of steel and glass in further innovations in the field.

Figure 19. Innovative construction materials companies in the EU. Source: Cleantech Group, 2023.



*many new cements being developed. Some early stage

** logos are of current EU players in the field

A sample of innovators from the EU, and key insights on grant awards or and fundraising rounds, is listed below:

- **Matterup** is a French company, grant-funded by the EIC, which is developing concrete, and cement made of recycled uncalcined clay, a low-carbon, local, and abundant material. Matterup’s products can be used on construction sites, in roads, and for urban planning applications.
- **Made of Air** is a German company, at seed stage, developing carbon-negative fillers made of biochar. They turn non-food biowaste into elemental carbon to prevent its re-emission into the atmosphere and instead lock it away permanently. This biochar then becomes a filler they can mix with other binders to create carbon-negative building materials.
- **Magsort** is a Finnish company that has developed a technology that can recover all of the metal from slag, including steel slag, and that extracts metal from incinerator bottom ash. This enables the recycling of steel and other metals in the production process and promotes the re-use of remaining materials as aggregates for concrete production, for example. Magsort closed a €15m financing round in November 2021.

Technical barriers along the value chain

Structural performance of the multitude of alternative building materials needs to be demonstrated along with conformity to basic standards (including environmental, energy efficiency, safety, visual, and acoustic), along with the establishing of standards and certification mechanisms to attest to their technical suitability for building applications.

Economic barriers in the present economic eco-system

The current principal barrier would be the low (but increasing) demand for alternative building materials that results in high costs and underdevelopment of supply chains. In addition, due to the multitude of raw materials that come into question, supply bottlenecks of raw (alternative) materials need to be identified and addressed according to the specificities (climate, culture, architecture, availability of material, etc.) in each region.

Societal aspects/acceptance

Visual, acoustic, and safety aspects need to be addressed in addition to the financial attractiveness of alternative building materials to render them societally acceptable. This is in addition to any negative effects on acceptance arising out of purely economic impacts (i.e., high purchase cost).

Policy environment and regulatory barriers/requirements for the R&I intervention area to develop

Setting of environmental, safety, and technical standards is essential to encourage a stable policy atmosphere for the development of alternative building materials. It might be a challenge to encompass a multitude of (physical) environments and institutional structures existing in various Member States. This includes the establishment of certification standards that might need to encompass materials as diverse as synthetic concrete, carbon fibre, biogenic materials (including wood), earth, steel alternatives, etc. While it might be envisageable that certain regulations might be relevant at the EU level (having common market relevance), many aspects of the built environment fall to the municipal levels of administration (or other national and sub-national levels), where new policy precedents might need to develop.

Examples of tipping points and the required interventions to trigger them

The first example of a tipping point could be a supply-side push when builders and renovators start using alternative building materials. This could be triggered in response to a price signal that allows for a more economical integration of these materials, which might be helped by R&I efforts. A supportive regulatory environment that allows for alternative materials to be used more easily throughout the supply chain and across Member States might also make hidden compliance costs more transparent, hence making the financial offer more attractive from the supply-side.

Secondly, a tipping point on the demand-side could involve an increased development of demand beyond the early adopter stage of the innovation curve. This could be triggered not only by reducing costs, but also by positive user experiences concerning the aesthetic and acoustic aspects of the alternative building materials in question. R&I interventions that focus on the acceptability of alternative building materials could contribute to the triggering of this tipping point, as well as pricing mechanisms that take into account embedded carbon in materials.

Conclusions

The exploration of alternative building materials presents a multifaceted approach to addressing the challenges of sustainable construction. To achieve a truly sustainable built environment, it is imperative to consider the environmental, economic, societal, and regulatory aspects surrounding these materials. While the environmental imperative to reduce carbon emissions associated with materials like concrete is clear, overcoming technical barriers, setting and adhering to standards, and establishing certification mechanisms are essential steps in ensuring their suitability for construction. The economic landscape poses challenges in terms of low demand and supply chain development, requiring strategic interventions to make alternative materials economically viable. Societal acceptance hinges not only on the visual, acoustic, and safety aspects but also on affordability. Lastly, a stable policy environment with comprehensive standards and regulations, considering the diversity of materials and regional variations, is vital for fostering innovation and adoption. To drive this transformation, collaboration between all stakeholders, from policymakers to industry players, is paramount in ushering in a more sustainable future for alternative building materials.

6.1.2. Case study on understanding behaviour change around prosuming and prosumaging

Human needs & associated mission

Decentralised self-consumption of renewable electricity, including not only prosuming (production and consumption) but also prosumaging (production, consumption and storage), has become more and more important for electricity markets all over the world. With new upcoming technologies as well as decreasing technology costs, this will increase even further in the future. Therefore, it is essential to understand behaviour and behaviour change in the context of these two concepts and the respective interplay with available and emerging technologies. This not only enables a more targeted promotion of corresponding technologies and regulatory measures, but it also helps to avoid potential negative effects of these concepts. The aim is to sustainably integrate self-consumption of electricity into the future energy system and thereby achieve as many benefits as possible while mitigating the possible negative effects such as distribution effects and new barriers towards a fair and equitable participation in the electricity market for everybody.

Solution status

The future of prosumerism (and prosumaging) depends not only on the respective technologies and regulatory frameworks, but also on the future energy system, the relevant future business models and societal dynamics. Therefore, it must also deal with competing value logics (Brown et al. 2020). To be able to understand possible future pathways and their consequences, the understanding of the respective behaviour and behaviour change is crucial.

The PROSEU project described especially for the last three aspects conflicting value orientations, which can shape future pathways and therefore represent important crossroads in the mainstreaming of prosuming:[124]

- Energy systems: energy islands vs. full system interconnection
- Business models: market logic vs. community logic
- Social dynamics: inclusive prosumerism vs. privileged prosumerism

The development of different behaviour as well as (regulatory) decisions along these different values will shape the future pathway of prosumerism. Accordingly, ten different possible pathways/roadmaps for 2030 and 2050 were identified in the PROSEU project (de Geus, T., Wittmayer, J., Van Berkel, F. 2021), each prioritising different values, system aspects and “key moments”.

Examples of European seed / early-stage innovative companies that are helping to underpin the prosumer and prosumaging market are shown in Table 11. The common feature with these innovations is the strong focus on consumer engagement, directly linked to greater control of household energy production and consumption.

Table 11. European seed / early-stage innovative companies helping to advance the prosumer and prosumaging market with key innovations including GPTs.

energomonitor Czechia. Has developed a cloud platform enabling domestic energy consumers to monitor utility consumption and production. Provides consumers with data and insight needed to adjust energy patterns, reducing energy waste and costs.

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[124] PROSEU, 2021. Charging the future: Roadmaps and value tensions for mainstreaming prosumerism to 2030 and 2050. Available at: [Deliverable Template (proseu.eu)](https://proseu.eu)

meazon measure | monitor | manage

Greece. Has developed a suite of hardware and software technologies to collect real-time energy data. Smart meters, plugs and controllers enable monitoring and delivery of disaggregated energy, predictive maintenance services, multi-tariff billing and flexibility.

AMPERE ENERGY

Spain. Developing smart battery systems with AI-powered software that predicts, manages and optimises consumers' solar energy consumption. An app enables consumers to have full control over their energy patterns.

FLEXTHOR

Belgium. Has developed a battery storage technology and cloud platform for consumers to monitor their energy assets as well as sell or trade energy with other members of their community.

FUERGY

Slovakia. Has developed AI-powered hardware and software technologies aimed at helping energy consumers produce, use, store, and share renewable energy efficiently. Their technology is based on decentralised electricity production and distribution at the local level. Fuergy's brAIn smart battery storage system analyses and manages consumers' energy consumption and autonomously makes the most optimal energy decisions in order to reduce energy and financial wastage.

Technical barriers along the value chain

Since this area is about behavioural aspects and their understanding, there are no direct technological barriers. However, such barriers could arise from the technologies used or needed because of possible behaviour changes. Therefore, a systemic and holistic approach to this research area is always recommended.

Economic barriers in the present economic eco-system

General economic barriers can arise from the market design and the regulatory framework (Lowitzsch 2019; Michaels and Parag 2016; PéRez-Arriaga, I. J., Jenkins, J. D., & Batlle, C. 2017). More individual possible barriers for prosumaging in general are financial attractiveness, profitability and ownership structures.

Societal aspects/acceptance

Consumers have concerns mainly linked to data privacy and security issues (Schill et al. 2019), loss of control and change in comfort level.[125] Besides barriers dealing with acceptance topics, rebound effects can also be a serious challenge (Dütschke et al. 2021; Schill et al. 2019). For both aspects, it is important to gain a better understanding of the respective behaviour and behaviour change. The acceptance of new business models and different energy community solutions should also be investigated and improved (Brambati F, Ruscio D, Biassoni F et al. 2022). Further important issues regarding social aspects of prosuming and prosumaging refer to

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[125] Mengolini, Anna Maria, 2017. Prosumer behaviour in emerging electricity systems. Available at: https://core.ac.uk/download/pdf/84253289.pdf

distribution and participation issues (who is able to participate, who benefits, who has negative impacts) as an important link towards a just transition.

Policy environment and regulatory barriers/requirements for the R&I intervention area to develop

The main legal challenges for collective prosumers include the lack of a possibility to legally establish a renewable energy community, lack of incentives to set up shared renewable self-consumption projects and, in some cases, the reduction or elimination of existing incentives (Inês et al. 2020).

Data privacy and security issues may also be barriers while developing this R&I area (see also acceptance) (Gough et al. 2020). As a consequence, missing data and different regulatory conditions can also complicate the respective research.

Regulatory barriers can also arise around the implementation of new technologies (e.g., around digitalisation) or new business models.

System aspects and infrastructure related issues

Understanding the role of behaviour and behaviour change is essential to understand the dynamic of other more technological related R&I areas related to this behaviour. In this case, a possible key point is the trade-off between a centralised and a more decentralised energy system (Schill et al. 2019) and the respective impacts of different behaviours on the system composition and respective consequences.

Regarding infrastructure related issues, the general ownership infrastructure (i.e., tenant vs. landlord) can heavily impact the behaviour, as well as participation with regard to prosumerism. In addition, different ownership infrastructures with regard to prosumerism projects themselves are possible (European Environment Agency 2022). Expected and unexpected issues can also arise from the energy system infrastructure and its different possible future development (i.e., fully connected grid/centralised energy system vs. energy islands/decentralised energy system).

In addition, the R&I area shows strong interdependencies with other (and also more technological oriented) areas such as renewable grid integration and flexibility (both in terms of possible positive, but also negative impacts), as well as with areas regarding digitalisation (e.g., blockchain for P2P microgrids (Kajaan et al. 2022)) and mobility (e.g. vehicle to grid (Bibak and Tekiner-Moğulkoç 2021)).

Examples of tipping points and R&I related interventions that can trigger them

An important tipping point would be when the uptake of prosumaging is decoupled from home ownership status. R&I interventions focusing on understanding the interdependencies between energy literacy, behaviour, prosumerism and the respective interplay with new technologies, regulatory frameworks and business models might help trigger this tipping point. This will allow not only those barriers already identified to be addressed, but also to identify possible future barriers related to behaviour or required behavioural changes. This is particularly important since this research area is very dynamic and has strong interdependencies and systemic linkages with other (sometimes much more technologically oriented) R&I areas and the regulatory framework. More specific examples for such research topics may include:

- Behaviour and behavioural changes in innovative and new business models and their acceptance.
- Behaviour and acceptance under alternative regulatory and market conditions.
- Behaviour (change) concerning new, forthcoming technologies.
- Putting social and behavioural aspects at the centre (by first examining the behavioural and social requirements to achieve certain scenarios and then looking for the technologies required in each case).

Outlook on non-R&I related actions (e.g., institutional and market-related changes)

A number of non-R&I-related measures, dealing in particular with regulatory aspects and market design, are possible to support the concepts of prosuming and prosumaging and to release the full potential of the related aspects in behaviour and behaviour change. They include:

- Providing easily understandable and accurate information to consumers (Gough et al. 2020).
- Dealing with privacy and data security concerns (Gough et al. 2020).
- Acknowledging the plurality of prosumer initiatives and providing support structures (especially for initiatives with a civic focus) (Horstink et al. 2021);
- Enabling and supporting different model projects and communities, as well as new innovative business models.
- Enabling (fair and just) access to such projects, as well as to the concepts themselves (market design, regulatory framework etc.).
- Regulating and supporting important enabling technologies (especially with regard to digitalisation). Possible examples are blockchain technologies for peer-to-peer transactions, V2G technologies or efficient monitoring and control systems.
- Introducing a stable and generous support scheme that addresses grid feed seems to be a major factor in promoting prosuming (Inderberg et al. 2018).

Conclusions

Just as the future pathways of prosuming and prosumaging are highly dependent on several competing values, the same is true for a possible narrative of this specific R&I area in a post-2030 climate neutrality pathway. Accordingly, it is important to frame the future of prosumers in the intended form of this pathway and the corresponding framework along two competing questions, also giving attention to the systemic aspects:

How can prosuming/prosumaging fit into the desired energy system of the future?

vs.

How can the energy system be tailored to the desired prosuming/prosumaging society of tomorrow?

This should make it possible to formulate a path that enables fair and equitable participation in the energy system of the future for all, and thus also facilitates the realisation of the resulting behavioural potentials.

6.1.3. Case study on Community engagement in energy positive districts and in energy communities

Human needs and associated mission

Community energy is seen as a new form of social movement that aims to create more participatory and democratic energy systems. Previously, community energy lacked a clear legal status, but the European Commission's Clean Energy Package has introduced legal frameworks for certain categories of community energy, referred to as "energy communities."

There are two separate laws within the Clean Energy Package that define energy communities. The revised Renewable Energy Directive covers renewable energy and sets the framework for "renewable energy communities," while the revised Internal Electricity Market Directive introduces roles and responsibilities for "citizen energy communities" in the energy system, encompassing all types of electricity.

Solution status

Energy communities are described as collective citizen actions in the energy system, allowing for different organizational forms such as associations and cooperatives. They are non-commercial market actors that combine non-commercial economic aims with environmental and social community objectives. Both Directives specify certain characteristics of energy communities, including their membership structure, governance requirements, size, and ownership structure. Their aim is to ensure that energy communities operate in the market without discrimination, while also avoiding competition distortion and upholding the rights and obligations applicable to other market parties.

Further R&I in the field of energy communities in the EU is crucial to accelerate the transition to a sustainable and decentralized energy system. By empowering local communities to generate and share renewable energy, energy communities can contribute to reducing emissions and promoting energy self-sufficiency. Continued research can optimize the functioning of energy communities, address regulatory challenges, and foster knowledge exchange, ultimately advancing the EU's climate and energy goals towards climate neutrality.

Technical barriers along the value chain

The integration of energy storage solutions might potentially affect the attractiveness of community energy solutions (including through its effect on prices and price stability). The energy storage solutions can be at the community-level (e.g., through locally produced hydrogen or synthetic fuels that are stored on-site, or batteries) or at the grid-level (pumped hydro solutions or through Virtual Power Plants). Energy storage solutions already exist, but their further development can positively affect the uptake of community energy.

Economic barriers in the present economic eco-system

Prevailing economic barriers are often dependent on the Member State in question, since the economic attractiveness of energy communities often has a strong link to the existing structure and history of the underlying power system. In certain Member States, further economic incentives to establish energy communities might be necessary to further support these actors, particularly to overcome the large capital expenditures necessary for the initial set up of energy generation infrastructure.

Societal aspects/acceptance

The very concept of community energy is based on social and societal innovations and on the inclusion of citizens in both the establishment of the community and the decision-making process. This involves the democratisation of energy generation and an increased usage of the social fabric that involves local socio-political processes, such as addressing socially vulnerable populations. However, the impacts of the establishment of energy communities on the broader grid and its impacts on other users of the grid (through potentially increased network usage costs) might slightly hamper acceptance. These risks might, however, be characterised as low.

Policy environment and regulatory barriers/requirements for the R&I intervention area to develop

While the introduction of the provisions of the Clean Energy Package have facilitated the creation of energy communities in the EU, establishing energy communities often depends on local regulations and local conditions that are essential to enable them to work – or which could act as barriers to implementation. There is also a multifaceted link towards the national-level policy environment, including the interaction with the national grid, as well as with the requirements for skilled labour necessary for the technical implementation of projects.

Examples of tipping points and the required interventions to trigger them

Energy storage solutions and their implementation in community energy constitute a key tipping point. While these solutions are technically available (battery storage, for instance), their operationalisation in an economically feasible manner is as yet not evident. Taking into account that these projects are typically of a smaller scale (compared to the scale of a national grid or a national energy supply and distribution system), the availability of economically feasible small-scale energy storage systems would constitute a veritable tipping point towards a broader spread of community energy solutions. R&I solutions that involve more research in such energy storage solutions can contribute to reaching this tipping point. Closely associated with energy storage solutions is also the energy distribution infrastructure associated with community energy (such as microgrids) and a better understanding of their interactions with the wider national energy system. In addition, while current community energy solutions in the EU typically focus on electricity, both heat and gas are not yet sufficiently studied in the context of community energy. Heat and gas might substantially benefit from R&I efforts that can enable the reaching of a tipping point towards a broader conception of community energy.

Another tipping point concerns the acceptability of community energy solutions. While regulation exists at EU-level, regulation at national levels that enable community energy solutions is not yet evident, in part due to the patchwork of financing mechanisms and regulatory requirements that are in place in different Member States. This in turn might reduce the acceptability from local-level actors (e.g., municipalities, cities) to make the decision to invest in and implement these solutions. Further R&I efforts in better understanding and streamlining the regulatory and institutional enabling factors might contribute towards a tipping point where implementation becomes easier (such as with a one-stop-shop) for local actors.

Conclusions

The introduction of legal frameworks for energy communities in the European Commission's Clean Energy Package has provided a foundation for community engagement in energy positive districts. Energy communities, including both renewable energy communities and citizen energy communities, enable collective citizen actions in the energy system, combining non-commercial economic aims with environmental and social objectives. However, further R&I is required to overcome technical barriers related to energy storage integration, address economic challenges through additional incentives, ensure societal acceptance by minimizing impacts on the broader grid, and navigate the policy and regulatory environment at both the local and national levels. Continued efforts in these areas will be crucial to unlock the full potential of energy communities and accelerate the transition to a sustainable and decentralized energy system in the EU.

6.1.4. Case study on role of GPTs for RES

Human needs & associated mission

The strong integration of renewable energies, but also the significant increase in total electricity demand of 1.8% per year until 2030 (Rossi et al. 2022), pose major challenges for the electricity system in general and the distribution grid in particular. In addition, the share of electricity in the energy mix and the decentralised generation capacity will strongly rise - the latter may exceed half of all installed generation capacity by 2050 (Rossi et al. 2022). This development is accompanied by a probable shift of consumers towards active participants (prosumers) and therefore, in combination with the integration of renewable energies, requires much greater flexibility in electricity distribution while still providing reliable, stable, and just access to energy for all people. Therefore, the respective GPTs, such as AI or big data, will play an essential role in the mobility-build-environment-energy nexus. This is also shown by the results of the evaluation framework, where both AI and big data are among the top ten solutions when analysing this nexus. However, these GPTs will also be important for other areas due to their cross-cutting nature.

Solution status

Rossi et al expect that “decentralised generation capacity could account for more than 30% of all generation capacity by the year 2030 and could easily exceed half of the installed generation capacity by the year 2050” (Rossi et al. 2022).

This will also be accompanied by a sharp increase in the introduction of new Internet of Things (IoT) devices. Rhodes expects around 75 billion of such devices to be used worldwide by 2025 (Rhodes 2020).

One way to deal with these challenges is the introduction of smart grids, involving big data and artificial intelligence (AI) as GPTs (Rossi et al. 2022; Shi et al. 2020;

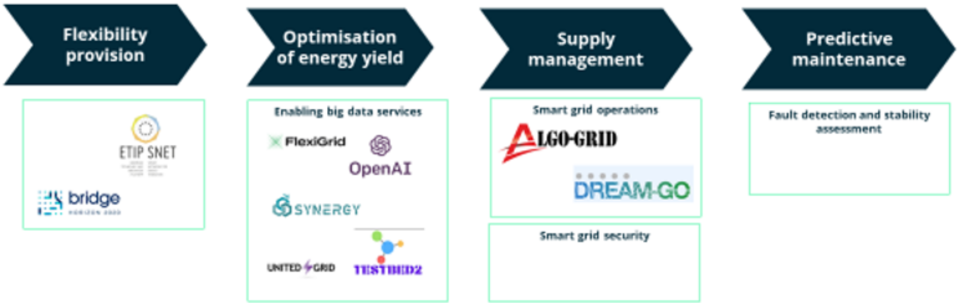
Omitaomu and Niu 2021; Ali and Choi 2020; Abdalla et al. 2021; Zhang et al. 2018). Possible application areas for AI in this regard are among others (Ahmad et al. 2021; Ali and Choi 2020; Omitaomu and Niu 2021):

- Flexibility provision (European Commission et al. 2022).
- Optimizing the energy yield as well as improving the integration of RES (e.g., weather prediction) (Kurukuru et al. 2021).
- Supply management and load demand forecasting.
- Predictive maintenance control.
- Smart grid security.
- Faults detection and stability assessments (Shi et al. 2020).
- Enabling big data services (Barja-Martinez et al. 2021).

In addition to AI, other GPTs such as blockchain technologies may also have various application spaces in the power grid (M. B. Mollah et al. 2021; Teufel et al. 2019; Hasankhani et al. 2021; Foti and Vavalis 2021) or may also be combined with AI solutions (Kumari et al. 2020).

Some illustrative examples of European innovators along this emerging value chain are shown in Figure 27. This also illustrates the gap in capabilities for some areas, such as smart grid security and predictive maintenance, which confirms a need for R&I support.

Figure 22. AI and big data are helping to push smart grids and RES integration. Source: Cleantech Group, 2023.



Technical barriers along the value chain

The use of AI depends heavily on the availability of interoperable high-quality data. Therefore, the appropriate measurement of such reliable high-quality data, as well as its communication, access and transmission (especially in real time) are major barriers. Yet, the simple lack of data can also be an obstacle. An important example is the too slow roll-out of smart electricity meters, which make an important contribution to the digitalisation of the electricity grid and the generation of relevant data. According to current data, an annual increase of 24-5% can be observed in Europe. This would lead to 100% diffusion only close to 2030.[126]

In applications such as weather forecasting for better integration of RES,[127] the reliance on big data can also be a barrier for other reasons. For instance, it can lead to limited forecasting of extreme weather events for which only limited data is available, but which are likely to occur more often and with greater impact in the future (Q. Sun and L. Yang 2019). The unconscious use of incomplete or incorrect data because of large data requirements can also pose serious risks.

Other technical barriers could be, for example, the lack of transparency of AI techniques (Ahmad et al. 2021) or problems of AI systems in the unstructured processing of data (Ahmad et al. 2021).

Finally, the increased flexibility in the power grid as well as the integration of many new IoT devices lead to a complex system becoming even more complex. As a result, the planning and management as well as the modelling and prediction of the system itself is already a major challenge (Q. Sun and L. Yang 2019).

Economic barriers in the present economic eco-system

Two main economic barriers could be identified in the literature: one essential barrier is the availability of the relevant expertise for understanding, implementing and evaluating new solutions within the discussed field. This is even more critical with regard to the second challenge, namely the large investments required to transform the power grid (Ahmad et al. 2021).

According to Rossi et al. (2022) this is additionally accompanied by the observation that “the distribution system operators are facing new sources of uncertainties and have low incentives to innovate due to a strong focus on capital cost return in their regulated revenues. They have to consider bigger financial risks, and it is not always clear how they should calculate costs” (Rossi et al. 2022).

Societal aspects/acceptance

As the use of AI in the power sector but also in general is often based on sensitive or even personal data, new security and privacy risks occur (Thorsen 2022; Ahmad et al. 2021). Consequently, the use of such data can make it quite vulnerable to issues such as data infringements or data identity theft (Ahmad et al. 2021).

Overall, such privacy and security risks can have a strong impact on the acceptance of the implementation of this R&I area and should always be considered from the beginning and with high priority.

Policy environment and regulatory barriers/requirements for the R&I intervention area to develop

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[126] A European Climate Neutrality Observatory. 2023. Electricity. Available at: https://climateobservatory.eu/building-block/electricity

[127] An example is given in Quaranta et al. 2021: A better inflow forecasting for hydropower reservoirs could reduce spills by up to 10% in some cases, and thus increasing annual generation and optimizing water&energy storage.

The different regulatory frameworks of the distribution system operators in Europe as well as the technical differences in the grids and the differences in the organisational structure are major obstacles on the way towards a smart European electricity grid (Rossi et al. 2022). Regarding data as an essential prerequisite for the implementation of reliable AI solutions, these obstacles include the exchange of such reliable data as well as access to it at all relevant levels.

Therefore, a central challenge according to Rossi et al. is to "turn the traditional asset-centric distribution companies into data-centric companies with smarter and more flexible grids" (Rossi et al. 2022). Consequently, this would also require the development and implementation of new business models that enable and support this transition.

System aspects

R&I areas that deal with digital solutions such as AI are very dynamic. Due to their rapid technological progress, their role and potential impact, as well as the possible areas of application, may undergo major changes during their development in the coming decades. It is therefore crucial to keep pace with these developments - especially in terms of regulatory aspects and governance - to ensure a sustainable and secure future for this R&I intervention area while avoiding possible negative impacts (on the environment and society. Furthermore, it is important to address the relatively high barrier to entry for individual participants (companies, consumers, etc.), and the lack of digital resources/competencies, in order not to unintentionally slow down the high dynamics in this solution area. As the R&I areas under discussion are GPTs, strong interlinkages with most other R&I areas also exist. Examples of relevant, more technical areas that are also closely linked to the future power grid include: flexibility, the integration of electric vehicles, and energy storage systems (Rossi et al. 2022; Zame et al. 2018). However, there are also strong interdependencies with more behaviour-oriented areas such as prosuming.

Infrastructure related issues

As mentioned above, the IoT will be a key component of the infrastructure and infrastructure planning of a future smarter grid that can also exploit the potential of AI technologies. It is therefore important to implement the appropriate and harmonized infrastructure that can support tasks such as grid simulation and control, digital twins, asset management or virtual power plants and provide relevant as well as reliable high-quality data (Ahmad et al. 2021). However, in many cases an outdated power system infrastructure, as well as economic pressure (especially in light of high costs and high complexity of the needed modernisation of the system), together with a lack of qualified experts and data science skills, are serious infrastructure related issues (Ahmad et al. 2021).

Further issues involve for example the time synchronisation of data, as well as data volume across both the whole power grid and its respective infrastructure (Zhang et al. 2018). Challenges can also arise in the area of tension between the interconnected grid and potential microgrids (see also prosuming assessment) while striving for the most efficient and resilient system possible.

Examples of tipping points and R&I related interventions that can trigger them

The implementation of AI and smart grids requires the presence and operationalisation of digital infrastructure that can handle the computational needs of these GPTs, including high speed data transfers. An important tipping point towards this direction will therefore consist of the infrastructural aspect – AI and smart grids can only be pervasive in the EU economy when the enabling infrastructure exists (including an appropriate regulatory framework). In addition, the widespread adoption of AI and other identified GPTs might in turn have a substantial role in triggering tipping points in many other sectors, including those presented in section 4.4.

The topic of AI and smart grids incorporates many specific R&I areas which are highly dependent on either the respective use case (power generation, distribution, monitoring, …) or technology (integration of wind, integration of PV, IoT). Nevertheless, some more general fields of action can also be identified which impact, due to their horizontal and enabling nature, also most of the more specific areas, including:

- R&I for better sensors/IoT devices and the respective ICT infrastructure to improve data quality, reliability and real time communication.
- Addressing energy consumption of digital technologies and promote greater efficiency and circularity (European Commission 2022).
- R&I regarding potential security and privacy issues in the implementation of AI-based models and tools in the energy system and how to avoid or solve them.
- Combining AI with better computing systems, robotics, sensors and IoT equipment to optimise potential basic applications or functions of AI. This could allow humans to concentrate on unstructured problems which are more difficult to approach via AI-solutions (Ahmad et al. 2021).
- Developing AI systems, that can correctly identify cost or energy savings for businesses and consumers (Ahmad et al. 2021).
- R&I with regard to the ethical implications of AI and the implementation of corresponding standards and responsibilities (e.g., inclusion in corporate social responsibility) (Ahmad et al. 2021).
- R&I related to the impact of digital solutions (direct and indirect) on GHG and climate relevant aspects.

Outlook on non-R&I related actions (e.g., institutional and market-related changes)

To keep pace with the highly dynamic and rapidly evolving R&I fields that include new digital technologies such as AI, it is crucial that regulators and policy makers consider the impact of AI technologies on the energy system “as a systemic aspect of reducing greenhouse gas emissions rather than as a separate concern” (Ahmad et al. 2021). This should result in stronger links between digital and green policies and can be further supported by relevant horizontal and sector specific KPIs (DigitalEurope 2023).

Since the use of AI heavily relies on reliable and high-quality data, several actions can foster the measuring of data and access to it (DigitalEurope 2023):

- By boosting connectivity and ICT infrastructure, the measurement (e.g., via the use of IoT devices such as smart meters, smart sensors etc.) and communication of data can be supported.
- Enhancing access to high quality sustainable and interoperable data - data cooperation on all levels should be strongly supported (European Data Act, European Data Governance Act).
- In the face of the gigantic amount of relevant data from a large number of different sources, these actions should also be supported by guidelines as well as standards and regulations on big data analytics architecture, platforms and interoperability (Zhang et al. 2018). Examples of recent activities in this area are the EU Action Plan on digitalising the energy system and the planned implementation of a common European Energy Data Space (European Commission 2022).

In addition, it is also important to reach out to different stakeholders to understand their problems and expectations but also to explore the various possible use cases of AI and their limitations (Ahmad et al. 2021) (avoiding an over-regulation but still being able to set the right focus points). This should be accompanied by a drive for digital and green tech skills, fostering the implementation of new and creative AI solutions across all sectors. Owing to the fact that the private sector is an important driver of innovation in AI related technologies, it is also important to mention that not only R&I fundings, but especially international financial agencies, can play a major role in the process of deploying AI solutions in the electricity sector (Ahmad et al. 2021).

Conclusions

As the use of AI solutions in the context of the energy system is a very dynamic area, it is difficult to outline possible narratives in a post 2030 climate neutrality path. This makes it all the more important to be clear about the (common) desired goals and areas of application, as well as their limitations, in order to be able to develop the needed regulatory framework and an appropriate governance. Only through a shared understanding of the challenges ahead and the required intervention areas and KPIs, as well as their realisation, it is possible to identify and push forward the most desired narratives across all nexuses.

6.2. Case studies falling under the circularity-industry-carbon removal nexus

The case studies under this nexus cover:

- Critical raw materials.
- Direct Air Capture (DAC).

6.2.1. Case study on Critical raw materials

Human needs & associated missions

Critical raw materials (CRMs) are economically and strategically important elements, minerals and materials that are considered to be critical for several industries, since they are used in various high-tech and clean energy applications, including batteries, electric vehicles, wind turbines, and advanced electronics.

The EU list of CRMs for 2020 contains 30 materials (COM(2020) 474 final[128]). In general, the list shows a growing trend (14 materials in 2011, 20 materials in 2014, 27 materials in 2017), which underlines the increasing dependence on such materials and emphasizes the need for recycling of such materials (Hofmann et al. 2018; Pommeret et al. 2022). Indeed, the relevance of this topic becomes clear especially when one considers the enormous tasks of the energy transition and the global upscaling of corresponding technologies, in combination with corresponding geopolitical and geological factors. These include not only more competition for the same material supplies (European Commission 2018), but also higher supply risks and import dependencies and thus possible serious bottlenecks and barriers for the energy transition. Therefore, "ensuring secure and sustainable supply of critical raw materials is at the core of EU's political priorities" (COM(2023) 165 final[129]). Therefore, these aspects are included in the challenge part of most solution landscapes. Also in the evaluation framework, solutions related to material recycling or end-of-life of different technologies score highly when the relevant contexts are analysed.

Solution status

Current early-stage innovations in CRM concern many aspects of the industry, specifically the energy and transport (notably EV) industries. This is very evident in the value chain shown in Figure 20, especially as it concerns End-of-Life Recycling and Reuse (on the far right of the diagram), in light of the increased need for energy storage solutions such as batteries and other raw materials that are critical for a successful energy transition. In light of the EU's policy objectives on CRM, there is a clear need to bolster European strengths in the Recycling and Reuse sector, as well as exploring upstream innovations that can support material substitution, processing and refining, as well as component manufacture.

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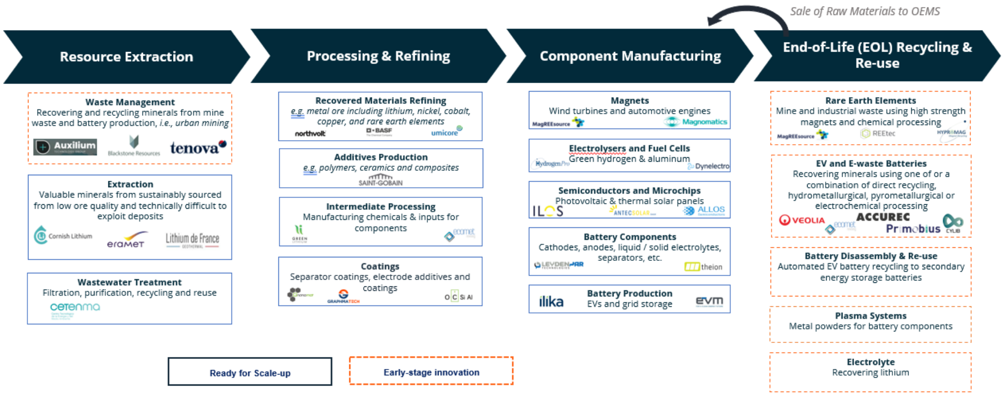
[128] Communication of Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability

[129] European Commission, 2023. COM(2023)165 – Communication on the Secure and sustainable supply of critical raw materials in support of the twin transition.

Figure 20. Europe has several early-stage innovators in the CRM recycling value chain, although there are current gaps in European capability, as shown by empty fields. Source: Cleantech Group, 2023.



While CRMs and their potential recycling are important for most R&I areas and technologies relevant to the energy transition, **the focus of this case study is on CRM recycling with regards to renewable energy generation** (namely wind and solar PV). However, some interdependencies and other highly relevant areas are also touched upon further below.

Given the wide diversity of CRMs and the applications in which they are used, the R&I area assessed here is, of course, very heterogeneous and material-dependent, and includes already well-developed and established recycling technologies. It also includes those technologies that are still at a very early stage of development. Nevertheless, there are also some more systemic and general/cross-cutting barriers in this area, which are addressed below.

Relevant CRMs in the area of renewable energy generation (wind and solar PV) include among others dysprosium, gallium, indium, neodymium, praseodymium and silicon (European Commission 2018). However, other materials such as copper and especially silver could also be of concern given the global climate ambitions and corresponding material demand (Pommeret et al. 2022).

Due to the fact that PV modules have a relative long lifetime (approximately 25 years) the amount of produced waste right now is minimal. However, this changes drastically when one looks at the future potentials: “between 2 and 8 million tonnes of PV waste is estimated to be generated globally in 2030, increasing to at least 60-75 million tonnes by 2050” (European Commission 2018; Chowdhury et al. 2020). Therefore, this issue is less relevant in the short term, but becomes important in the medium and long term. Indeed, just for EU-27, 14.3 - 18.5 Mt PV waste will be generated by 2050 (Kastanaki and Giannis 2022). This directly implies the urgent need for an expansion and/or implementation of respective recycling industries. According to the literature, four Member States (Germany, Italy, France and Spain) could start a viable recycling business by 2024-2032, while eight more Member States (the Netherlands, Belgium, Greece, Austria, Denmark, Portugal, Poland and Hungary) could follow during 2037-2049 (Kastanaki and Giannis 2022). For countries which are unable to operate PV recycling plants until 2050, respective partnerships are required (Kastanaki and Giannis 2022).

A similar picture emerges (less importance in the short term, but of high importance especially in the long term) for wind power (wind turbines, but also wind blades), most of which will be in operation by 2030 (assuming a 30-year lifetime for wind turbines) (European Commission 2018). For the year 2050, for example, 325 kt of wind turbine blade waste has been predicted in Europe (Lichtenegger et al. 2020).

In general, the "enhanced collection and recycling could enable secondary materials to meet 37%–91% of demand for CRMs in low-carbon technologies in 2050" (Karali and Shah 2022). With current global practices, this would amount to less than 15% (Karali and Shah 2022).

The different barriers strongly depend on the specific CRM, as well as on the material source that needs to be recycled or is being investigated. The following section therefore illustrates more specific examples related to solar PV and wind. However, the economic and regulatory barriers in particular are more cross-cutting of the CRM market overall.

Technical barriers along the value chain

Wind turbine blades mainly consist of composite materials, namely glass fibre reinforced polymers or carbon fibre reinforced polymers. These composite materials are, also due to their heterogeneous nature, hard to recycle (Khalid et al. 2023) and the recycling of wind turbine blades is not yet commercialised (Woo and Whale 2022). Most promising are hybrid recycling technologies; however, a significant amount of R&I funding will be required for further deployment of such technologies (Khalid et al. 2023).

Further, the recycling of rare earth metals, e.g., from wind turbine magnets, still faces some technical barriers, especially with regard to low environmental hazards, closed-loop processes and minimal energy consumption as key aspects of a sustainable recycling process (Fujita et al. 2022; Xiao et al. 2023; Delogu et al. 2023).

Likewise, the sustainable and cost-efficient recycling of PV modules is still the subject of research (Deng et al. 2022; Wang et al. 2022; Gahlot et al. 2022). Corresponding barriers could be hazardous materials, emissions and pollution generated during recycling and energy intensive recycling processes.

Economic barriers in the present economic eco-system and regulatory barriers/requirements for the R&I intervention area to develop

Woo and Whale derive a number of barriers that may affect the gap in the circular economy for wind turbines and thus also affect the recycling of respective CRMs (Woo and Whale 2022). These barriers include:

- Insufficient feedstock volumes.
- Inadequate second life markets.
- Lack of policies and regulations that support end-of-life (EOL) management.

- Insufficient stakeholder (e.g., policymakers, industry and wind farm owners) familiarity with end-of-life management options and their associated issues and opportunities.
- Uncertainty of asset Remaining Useful Life (RUL) and quality of second-life products and components.
- Limited end-of-life stage data for LCA calculations.

For PV panels, with the EU Waste Electrical and Electronic Equipment (WEEE) Directive, a strong regulatory framework exists for the EU. It entails all producers supplying PV panels to the EU market to finance the costs of collecting and recycling EOL PV panels in Europe. Nevertheless, also here challenges are faced which could include (Salim et al. 2019):

- Price and profitability of recycling.
- quantity of end-of-life products.
- Poor market confidence in refurbished and recycled products.
- Mass recycling vs. high-quality multi-materials recycling.
- PV panels and batteries are technologies with a potential for material changes.

As can be seen, there are many similar economic and regulatory barriers to recycling both PV panels and wind turbines that may also apply to recycling other technologies or CRMs in general. Some of the most important aspects relate to the amount of recyclable materials/end-of-life products that are available, uncertainties about potential markets for recycled materials, lack of coordination (e.g., collection of materials or relevant products) and regulations, as well as the data available.

Acceptance

In general, acceptance is an essential part of the process to enable a circular economy – including recycling (Badhotiya et al. 2022; Walzberg et al. 2021). For instance, reservations about recycled products (Cristina Calvo-Porral and Jean-Pierre Lévy-Mangin 2020; Polyportis et al. 2022) or intention-behaviour gaps can be observed in many areas (e.g., e-waste recycling (Echegaray and Hansstein 2017)). However, CRM recycling is likely to be less critical in terms of acceptance, as CRMs are much less dominant in the perception of the respective products and are also earlier in the value chain. However, this does not apply to the acceptance of recycling processes and structures themselves, especially if they are associated with a certain degree of public participation (e.g., the collection of EOL products, etc.) and the corresponding waste recovery infrastructure (McCrea et al. 2016).

In addition, appropriate management of dismantling and decommissioning practices, including recycling and waste management, could promote the perception of the respective technology as sustainable and thus support its acceptance (Beauson et al. 2022).

System aspects

The area has strong interdependencies with all R&I sectors that depend on the use of CRMs. Therefore, research and rapid development in this area is also critical to the goal of increased resource security and reduced import dependence, as well as a more circular economy and the uptake of low carbon technologies (Karali and Shah 2022). Given the rapid pace at which new technologies are emerging (including their demand for CRMs) and the highly dynamic geopolitical conditions, this solution area must play a central and important role on the path to climate neutrality as a whole. Therefore, a strong and focused research agenda that drives the relevant technologies, but also a decisive and targeted as well as timely implementation of appropriate regulatory frameworks is an important decision point for the immediate future. Other relevant areas with regard to the energy transition, which are also highly dependent on CRMs are, for example, batteries (Windisch-Kern et al. 2022), hydrogen production (Moschovi et al. 2021), and digital infrastructures.

Infrastructure related issues

The recycling infrastructure of CRM from energy transition technologies is highly complex. This complexity results from factors such as: the large variety of different relevant technologies; the distribution across different geographical locations; and different recycling technologies required due to the large number of different CRMs and relevant products. Together with the different barriers described above, this places large requirements on such requisite infrastructure. Consequently, the establishment of such infrastructure (including collection, pre-treatment and the recycling process) for all relevant technologies and CRMs is a major challenge and heavily dependent on international cooperation.

Examples of tipping points and R&I related interventions that can trigger them

Since the flow of CRM in the EU has substantial interactions with broader geopolitical circumstances, monitoring the inflows of such materials from outside the EU can be a useful indicator of the progress and health of an intra-EU circular economy. A tipping point would then consist of substantially reduced CRM flows from outside of the EU (with a corresponding increase in CRM demand from within the EU). As a second example, a tipping point for a wider implementation of a circular economy in terms of CRM can be the establishment of regulations that implement standards for the use of recycled materials, thereby encouraging their increased use in new products. The latter aspect is highly dependent on the price of such recycled materials. Therefore, a tipping point for the greater use of recycled CRMs must include prices for such recycled materials that are comparable to - or even lower than - the respective non-recycled materials. However, this depends not only on R&I in the European context, but also on global supply chains and the global market/competition.

Specifically pertaining to R&I interventions in energy generation technologies involving CRM, Beauson et al. nicely describe the research needs for EOL wind turbine blades in a European context (Beauson et al. 2022). However, some of these can be adapted for a more general consideration of CRM recycling, also in light of the results described on the previous pages. Possible R&I needs and potential triggers for tipping points therefore include:

- Offering strong support for research and implementation of various sustainable recycling technologies.
- Identifying applications for recycled materials and of standards for the use of recycled materials.
- Designing products for recycling and recycling processes simultaneously.

- Providing a more robust data base (e.g., availability and demand for different materials with an appropriate temporal and geographical solution).
- Developing life cycle assessments of different recycling solutions.
- Supporting research on acceptance and acceptability and its relevant interactions with different EOL disposal solutions.
- Researching new business models for CRMs.

Outlook on non-R&I related actions (e.g., institutional and market-related changes)

As can be seen from the many barriers described above, there is a substantial need not only for R&I measures, but also for non-R&I measures. Again, Beauson et al. 2022 provide some examples related to wind turbine blades in the European context, which also provides a solid basis for the broader discussion on CRM recycling and can be extended by various other generally needed measures:

- Guidelines for design including EOL considerations.
- Standardisation (e.g., regarding the decommissioning of different technologies such as wind turbines).
- Establishing a (second hand) market for EOL products and waste, as well as secondary raw materials and supporting corresponding business models.
- Establishing standards on the use of recovered materials.
- Tracing the amount and location of relevant materials and EOL products, as well as pushing for a sector wide policy development on these issues.
- Enabling recycling across borders by harmonised regulations.
- Providing guidelines for the selection and prioritisation of recycling solutions based on relevant impacts (environmental, economic and social).
- Landfill costs and recycling costs (including possible subsidies) are important regulating levers (Wlazberg et al. 2021).

Conclusions

As the recycling of CRMs has strong interdependencies with all R&I sectors that depend on the use of CRMs, the topic can have strong enabling and cascading effects across all sectors. Therefore, research and rapid development in this area is also critical to the goal of increased resource security and reduced import dependence, as well as a more circular economy and the uptake of low-carbon technologies (Karali and Shah 2022). Given the rapid pace at which new technologies are emerging (including their demand for CRMs) and the highly dynamic geopolitical conditions, this solution area must play a central and important role on the path to climate neutrality as a whole. Therefore, a strong and focused research agenda that drives the relevant technologies, but also a decisive and targeted as well as timely implementation of appropriate regulatory frameworks is an important decision point for the immediate future.

6.2.2. Case study on Direct Air Capture (DAC)

Human needs & associated mission

DAC filters CO_2 from the atmosphere and makes it available for further utilisation or storage. If stored permanently, it is a pure Carbon Dioxide Removal (CDR) technology. The technology is currently among the most expensive CDR approaches, and many criticise DAC for being unnecessary due to the availability of cheaper CDR methods and emission reduction potentials to be realized in the short term. However, the motivation to foster DAC now is to ensure its applicability in the mid- to long-term, when mitigation potentials have been realized and cheaper CDR options have reached barriers, e.g., due to area constraints. DAC is expected to play a central role in a net-negative future, and in reaching the Paris Agreement´s temperature targets. This role is due to the unique characteristics of the technology, including needing very little land area, global applicability, and potential for permanent storage.

Solution status & key barriers

Currently, European DAC start-ups demonstrate both an active early-stage innovation focus and strong interest from private investors. DAC is part of multi-player value chains which, besides the actual manufacturing and building of DAC plants, include CO_2 transport, storage and/or utilization (see Figure 25 below). In these value chains, the capture block (i.e., DAC) is the least developed. While the increasing number of start-ups and pilot sites show investment potentials, DAC business cases rely heavily on private investments and high prices for DAC certificates sold on voluntary carbon markets. Both pillars imply uncertainties and may prove to be insufficient to push the current R+I status into larger scale applications in the mid-term, when DAC is expected to become increasingly important for reaching (global and national) climate targets.

Below, the key barriers to DAC scale-up are presented.

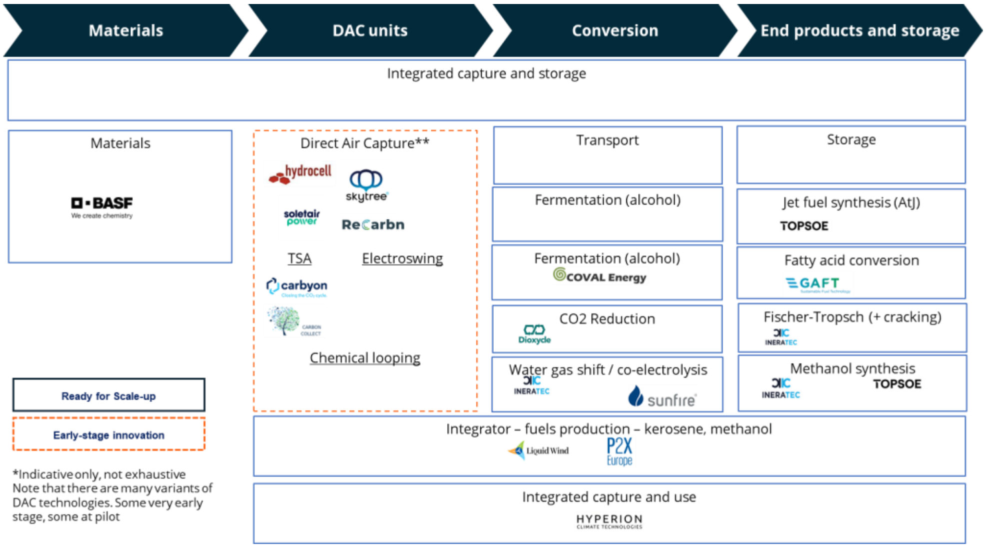
Energy demand

DAC has a high demand for renewable energy, and the related distributional issues and high costs are key issues. Energy efficiency of the technology needs to decrease to enable scale up and avoid energy conflicts. Generally, DAC has higher costs compared to other CDR technologies, but is unique regarding its low land requirements, global applicability, and potential for permanent storage. Some major players, as well as start-ups, work on improving energy efficiency and lowering costs. However, R&I and ‘learning by doing’ need to be supported. Additionally, fostering new technological approaches besides the established liquid and solid swing technologies should be central to any future support.

Manufacturing

DAC plants are novel structures. To be flexible and scalable, the production of modular DAC plants is important; respective processes and facilities also need to be developed and streamlined in tandem with technological developments.

Figure 21. The value chain in Europe for DAC illustrates coverage across some key elements but it remains far from comprehensive and would benefit from further R&I investment. Source: Cleantech Group, 2023.



Economic barriers in the present ecosystem

DAC is highly dependent on carbon prices and/or level of support, because it generates no additional value added other than removing carbon. Currently, revenues stem from voluntary carbon markets (e.g., Microsoft buying credits from Climeworks), public support (e.g. via funds like the EU Innovation Fund) and private finance (e.g. Oxy funding Climate Engineering). All these resources are limited and insufficient for the required scale up. Additional sources will be required to generate sufficient demand, such as compliance markets like the EU ETS or the Paris Agreement´s Article 6.

Utilisation of captured CO_2 (for example, in aviation fuels) might have high abatement potential, but constitute emission reductions rather than removals.

Societal aspects/acceptance

Many perceive DAC as a “last resort”, or even an absurd mitigation technology, which does not need to be implemented and supported now. This view neglects the fact that the technology will not be readily available later if not developed now. At the same time, CDR is increasingly understood as necessary to counterbalance residual emissions. DAC has the advantage over other CDR technologies that it does not require large areas or resources like fertilizers or water. It can be applied in a modular fashion and used to regulate peaks in RES production. Its technological nature implies that scaling DAC could generate technology related jobs. However, to date these aspects have not yet reached public debates to a large extent. In terms of visual disturbance, recent stakeholder engagements in Iceland shows that DAC is accepted if installed without interference with the landscape.

Policy environment and regulatory barriers/requirements for the R&I intervention area to develop

Non-land-based CDR in general is underregulated due to its novelty. The inclusion of DACs into (inter-)national compliance carbon markets is ongoing, but methodologies, guidance and especially practical examples are so far rare. Accounting and reporting issues (e.g., IPCC guidance on national GHG inventories), are not yet fit to include DACs, which impedes DAC targets in concrete national and regional climate policy targets (e.g., NDCs).

Storage capacities are considered a bottleneck for scaling up CDR in general, including DAC, with increased suitable site searches and associated storage permit requirements (including under the CCS Directive, once industrial scale storage occurs). Some guidance on site selection, reporting, reversal risk and liability is available for storage in geological formations, but not for the capture part of the value chain.

Regarding reliable Monitoring, Reporting and Verification (MRV), reversals and re-emissions need to be accurately, reliably and comparably measured over large areas and timeframes to assure the correct calculation of the contribution that DAC activities will make to climate goals.

System aspects

If net-zero targets are to be met, CDR in general will be required at large scales to offset residual emissions, especially from industrial and agricultural sectors where not all GHG emissions can be avoided. DAC has the benefit over other CDR methods to not require large land areas, fertilizers, and water, or depend on certain climatic conditions – it can be applied wherever renewable energy and a connection to transport and/or storage is available. Especially after reaching net-zero, DAC can play a major role in maintaining net-zero or even becoming net-negative (be it regionally, nationally or internationally).

There are clear interdependencies with other R&I intervention areas, especially since the high energy demand of DAC systems makes the availability of large amounts of emission free energy sources imperative if a substantial scale up is to be achieved. DAC could be used to consume excess electricity in times with over supply (e.g., during nights, or when grid capacities are reached).

Realising and fostering public support for DAC as a necessary technology to offset residual emissions and enable a net-zero or net-negative world will help to implement a sustainable governance structure as well as required infrastructure projects for DAC.

Innovative systems approaches are needed, for example for materials (including sorbents/solvents) for DAC modules and their production.

Infrastructure related issues

Three main needs are evident:

- Integration of modular manufacturing and solvent/sorbent production (including for regular replacement of sorbent/solvent materials) into existing industrial processes for an efficient upstream value chain.

- Transport and storage hubs and clusters to enable an efficient downstream value chain.
- Public acceptance of DAC per se, of architectural innovations and associated landscape alterations (visually and acoustically), and energy + landscape trade-offs.

Examples of tipping points and R&I related interventions that can trigger them

Even the most reasonable technological solutions will not be realised at large scale if they are not publicly accepted. Establishing a positive narrative that focusses on DAC´s benefits and its unique role in the large portfolio of climate mitigation actions could legitimate its application and build acceptance in the public. This will be acritical step and could be a tipping point when moving to large scale applications in Europe.

Permanence in storage and utilization, and availability of sufficient sinks are key for establishing a trusted and effective CDR case, especially when it comes to a technical solution like DAC, which has the sole purpose to achieve negative emissions. Enabling sufficiently large storage opportunities and adding the benefits of generating revenues via utilization of captured CO_2 in permanent products will be required to scale up DAC.

DAC developers will need to find ways to increase energy efficiency to avoid conflicts over renewable energy use in a world increasingly relying on sector coupling and the related increased energy demands. Reaching a ratio where energy requirements are low enough to enable large-scale DAC applications without using unacceptable amounts of energy could be a positive tipping point.

The main R&I actions to trigger the tipping points are to improve the process efficiencies of DAC systems, both in terms of energy efficiency and sorbents/solvents, and/or by introducing novel approaches. The exploration of synergies is also important, such as through the integration of DAC into future CCU/S hubs and clusters. Targeted technological and system-related funding for specific DAC solutions is required to speed up the technological development and enable technological readiness for future large-scale applications.

Non-R&I related actions (e.g., institutional and market-related changes) required to trigger the tipping points

A number of key actions are also necessary to trigger tipping points, including:

- Policy attention is required to stimulate technological improvements and alternatives, as well as larger scale demand and thereby wider diffusion.
- Institutional and cultural setting - embedding technological advances within social, economic, industrial, and political systems – is important for such novel systems.
- Creation of an institutional landscape of international cooperation to enable mutual learning, joint frameworks (e.g., on environmental integrity in carbon markets), capacity building and global participation in DAC development and deployment will help more widespread adoption globally.

The market uptake of innovation requires a number of interventions and framework conditions to be in place:

- Integration of DAC into existing policy instruments (e.g., EU ETS).
- Improvements to accounting and reporting guidance/practices.
- Extension of public R&I grants to improve energy efficiency and lower cost.
- Development of tax credits to relieve DAC providers and stimulate adoption e.g., by fossil fuel producers (in line with a carbon takeback obligation).
- Availability of loans to foster private investments in DAC.
- Introduction of policy mechanisms (such as feed-in premia, Contracts for Difference and Power Purchase Agreements (PPAs).
- Improved knowledge sharing (both across the industry and across international stakeholders).

Conclusions

In net-zero and net-negative scenarios, DAC is required to offset residual emissions from hard-to-abate sectors, as it is unique in requiring little area, water, fertilizer (as compared to ecosystem-based CDR solutions like afforestation or bioenergy with carbon capture and storage (BECCS)). Given conflicts of interests to be expected if only the latter CDR technologies were to achieve all negative emissions required in net-zero/net-negative scenarios, DAC is more than likely to play a role in the mid- to long-term. Its relatively easy MRV and potentially high permanence (compared to ecosystem-based CDR solutions) are further advantages over other forms of CDR. However, there is currently minimal acceptance of the technology due to a lack of understanding of its unique role, as well as missing financial incentives and regulations, which together severely limit DAC scale up. In the future, the limited availability of permanent storage options could also become a bottleneck.

6.3. Case studies falling under the agrifood-carbon removal nexus

The case studies under this nexus cover:

- Biochar.
- Marine CDR.

6.3.1. Case study on biochar

Human needs & associated mission

Biochar application to soils – a form of soil carbon enhancement – is a promising CDR method with several co-benefits.[130] It can help not only reaching GHG mitigation via storing carbon in soils for long timespans, but also increase agricultural yields by altering soil characteristics, including increased water availability. It is therefore an important solution area both in terms of CDR and for food security in increasingly arid areas.

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[130] Other reports may focus on other aspects of biochar and consider the removal of CO_2 as a co-benefit rather than as its main function.

Solution status & key barriers

Biochar presents a relatively mature technology with several business cases and pilots at varying scales. However, uncertainties about the durability of storage, associated monitoring needs, and the speed of adoption among farmers and communities have been limiting the pace of scaling to date.

Biochar is produced via pyrolysis of carbon-rich material (e.g., from agriculture and forestry residues). It can be added to soil directly or indirectly, by adding it as a food-additive for cattle to increase soil carbon stocks and fertility (by increasing nutrient and water availability and mitigating soil acidification). Furthermore, biochar may be used as an additive to conventional cement in concrete, reducing the emissions from concrete production and improving concrete properties. Potential negative effects like increased aerosol loading or altering soil pH need to be considered prior to application. Further research on storage permanence in different applications, biochar-soil interactions, reliable monitoring of CO_2 re-emissions from agricultural land, incentives to front-load rewards for biochar application by farmers, and the provision of sustainability and quality guardrails, could allow the scale-up of biochar adoption in an environmentally beneficial manner.

Technical barriers along the value chain

Pyrolysis-biochar technology is relatively mature. Yet, there could be limitations in acquiring sustainably sourced feedstocks. There is also a maximum safe holding capacity of soils, meaning that increased application of biochar does not necessarily lead to increased carbon removal. Further, there is a lack of large-scale trials of biochar application to agricultural soils under field conditions.

Economic barriers in the present economic ecosystem

Revenue streams from farms could be considered, since biochar has positive effects on crop production. The total costs of production and the application of biochar are estimated at between $10 and $345 per ton of CO_2.[131] However, there is insufficient demand from farmers and a lack of investment and financial reward for accelerating the diffusion of biochar.

Societal aspects/acceptance

Compared to CDR in general, and especially BECCS and DACCS, biochar has received more positive and less negative sentiment.[132] However, landowners are often hesitant to change successful production patterns as required for CDR and will need reliable incentives to do so.[133]

Policy environment and regulatory barriers/requirements for the R&I intervention area to develop

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[131] IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

[132] Smith et al., 2023. The State of Carbon Dioxide Removal - 1st Edition. https://www.stateofcdr.org/resources

[133] Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., & Lund, J. F., 2020. Negative emissions and the long history of carbon removal. *Wiley Interdisciplinary Reviews: Climate Change*, *11*(6), e671.

Inclusion into (inter-)national compliance carbon markets is ongoing, however methodologies, guidance and especially practical examples are so far rare. Policymakers in most legislation introduced to date have held back from implementing such incentives and have little motivation to change this pattern: public debate,[134] along with farmer´s reservation towards changing proven practices, makes it challenging to implement concrete incentive schemes.

System aspects

The potential of biochar for reducing CO_2 is dependent on 1) the level of stability of the carbon stored in biochar; and, 2) the conditions of soils. Properties of biochar vary depending on the feedstock, production conditions and treatments after production. If soil is acidic and has a level of fertility with high soil N_2O emissions, the mitigation impact of biochar is maximized. Even if biochar has GHG abatement potential, it might come at the expense of lower levels of energy efficiency compared to biomass combustion.[135]

Infrastructure-related issues

Conflicts with other land uses must be avoided, since fertile land is limited and serves several ecosystem and human services, like food and materials provision, biodiversity, and leisure. Thus, no biomass should be produced solely with the purpose to provide feedstock for biochar production, however residuals or waste should be used, although this potentially limits the technology´s scaling potential.

Coordination with farmers who use biochar for crop production would need to be maintained to ensure effectivity is maximised and knowledge gains from practical applications are disseminated.

Equipment and infrastructure needed for most aspects of the biochar value chain (collection and transport of feedstock to pyrolysis facilities; pyrolysis production; distribution and application of biochar) are still emerging. There are limited large-scale pyrolysis facilities to produce biochar in Europe (in comparison to larger plants in North America). At a small-scale, high production costs occur.

There is a lack of consensus on biochar MRV (monitoring, reporting, and verification) with limited knowledge of quality control and standardisation. Accounting, liability, and obligations for MRV and potential re-emissions of CO_2 need to be clarified. Reversals and re-emissions need to be accurately, reliably and comparably measured over large areas and timeframes to assure correct calculation of activities' contribution to climate goals. Environmental co-benefits are difficult to quantify on different time scales, which further complicates their enforcement.[136] Key questions relate to nutrient and water retaining properties of biochar treated soils and durability of CO_2 in different soils and climate zones.

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[134] Cox, E., Spence, E., & Pidgeon, N., 2020. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nature Climate Change*, *10*(8), 744-749.

[135] Peters, J. F., Iribarren, D., & Dufour, J., 2015. Biomass Pyrolysis for Biochar or Energy Applications? A Life Cycle Assessment. *Environmental Science & Technology*, 49(8), 5195–5202. https://doi.org/10.1021/es5060786

[136] Guillén-Gosálbez, G., Werner, C., Sunny, N., Hamelin, L., Guillén-Gosálbez, G., & Jackson-Blake, L. 2021. Comprehensive sustainability assessment of terrestrial biodiversity NETPs.

Examples of tipping points and R&I related interventions that can trigger them

A potential tipping point to be reached before farmers adopt biochar at a large scale is their acceptance of the positive effects that biochar can have at their respective agricultural production sites. Currently, information on these effects may be available to those farmers actively looking for it, but biochar is not yet established as a standard application to soils in most agricultural settings. Establishing and advertising positive real-world examples in different settings, communities, and climatic zones could lead to an increasing number of farmers integrate biochar into their daily work, until a point is reached where biochar is a standard rather than an exception.

Besides the co-benefit of increasing agricultural yields, a tipping point to establish biochar as a CDR method would be the development of reliable MRV systems for land based GHG emission. So far, the diffuse nature of these emissions, especially in agricultural settings, has put barriers to generating high-integrity carbon certificates for voluntary, let alone compliance markets. If reliable MRV was made available for agricultural land-based emissions, this would enable farmers to make use of biochar´s CDR potentials and generate additional revenues from participating in carbon markets.

Transdisciplinary research to better understand the interplay of carbon uptake and storage, sustainability, and co-benefits. It can help researchers and practitioners learn from one another and overcome obstacles for sustainable terrestrial ecosystem-based carbon removal. R&I should address:

- Enhancing high-carbon ecosystem resilience with limited management.
- Effectiveness of soil carbon enhancements through enhanced mineralization[137], altered soil management, and biochar applications (carbon flows, sustainability and business case)[138];
- Development of practical and reliable monitoring technologies including AI-enabled.
- Permanence assessment not only for storage in soils, but also in other applications like concrete.

Further studies on biochar using Integrated Assessment Models (IAMs) could be done to compare and integrate with other CDR strategies. These should include modelling biochar interacting with other uses of biomass.

Biochar practices and their applications to removal purposes need to be further researched from a political science perspective to ensure co-benefits are sufficiently considered.

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[137] Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., & Banwart, S. A., 2020. Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242-248.

[138] Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., & Hansen, J., 2018. Farming with crops and rocks to address global climate, food and soil security. *Nature plants*, *4*(3), 138-147.

To enable reliable MRV, remote sensing technologies for large areas and CO_2 as well as non-CO_2 GHG should also be enhanced.

Non-R&I related actions (e.g., institutional and market-related changes) required to trigger the tipping points

Regulations and ownership are often unclear when it comes to land-use and agricultural systems. Establishing accountability and monitorable safeguards for socio-economic and environmental aspects are therefore important.

It is necessary to establish standards to guarantee that biochar is produced in a manner that avoids the creation or preservation of harmful levels of toxic containments, and to facilitate regulated deployment approaches.[139]

Policy attention to stimulate wider diffusion includes two broad areas:

- Institutional and cultural setting - embedding technological advances within social, economic, industrial, and political systems.
- Institutional landscape of international cooperation:
  - Integration into existing policy instruments (e.g., EU ETS).
  - Improve accounting and reporting guidance/practice.
  - Public R&I grants.
  - Subsidies to farmers.
  - Tax credits.
  - Loans.
  - Knowledge sharing.

Conclusions

Biochar is unique in offering co-benefits on crop production and quality of water, soil, and air, thereby improving food security and resilience. Biochar indirectly provides adaptation measures for communities to address issues like depletion of soil carbon stocks, land desertification and limited water supply. [140] The cost of the biochar system is also relatively lower than other carbon dioxide removal technologies although it might vary depending on feedstock, location, and process/field conditions. Biochar enjoys a relatively high public acceptance and local support due to its co-benefits and low requirements for natural resources, thereby lowering the threshold. Funding of R&I in biochar by the EU has the potential to have a major impact beyond EU borders, by exporting knowledge and technology to areas with high demand for soil enhancement and high mitigation potential.

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[139] IPCC. 2014. Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter11.pdf

[140] Verde, S. F., & Chiaramonti, D., 2021. *The biochar system in the EU: The pieces are falling into place, but key policy questions remain.* European University Institute. https://doi.org/10.2870/40598

6.3.2. Case study on marine CDR

Human needs & associated mission

Marine CDR describes a group of potential measures which aim to enhance the carbon-uptake of oceans and provide potentially large mitigation potential. They can thus increase the pool of available GHG mitigation methods and contribute to achieving a net-zero or even net-negative emission balance. Besides this primary purpose, some of the methods have significant co-benefits, e.g., in terms of increased biodiversity, costal protection, and local livelihoods.

Solution status & key barriers

There are different types of marine CDR, which achieve increased carbon uptake by (1) altering the chemical composition of surface waters; (2) enhancing the upwelling of deeper water layers (with high nutrient contents); (3) fertilising surface waters to enhance algal growth; (4) farming of kelp, seagrass, or mangroves in coastal waters, or otherwise; and, (5) enhancing biological or chemical carbon uptake. Some of these measures are already well understood and practised, including the reforestation of mangrove forests or other coastal measures. There are, however, also more uncertain, yet potentially highly impactful approaches – in part in the open ocean – the efficacy and potential side effects of which are much less understood and possibly very detrimental. While for coastal applications ("Blue carbon"), socio-economic questions related to management, area-use conflicts, and incentivisation are central, applications in the open seas face a range of uncertainties regarding regulation, MRV, acceptance, and basic research to understand processes of the intervention and environmental responses to it.

The main barriers pertain to the early readiness stage of marine CDR (except of coastal mangrove and kelp restoration) and the associated uncertainty of its suitability. TRLs for marine CDR (except blue carbon) is 1-2.[141]

Economic barriers in the present economic ecosystem

To date, there are no known business cases or sufficient economic incentives for marine CDR. With the exception of mangrove forest restoration (which offers storm protection and allows for coasts to be secured against erosion), marine CDR is not presently expected to create monetizable value-added given the high uncertainty regarding its efficacy. There are, however, potential approaches to this situation. Should marine CDR enable the maintenance - or even enhancement - of outputs from fisheries, this could prove a potential monetizable result. However, given the common pool nature of fisheries, it is unclear how marine CDR could effectively be incentivised through fisheries. In some regions it is conceivable that marine CDR measures would aid the maintenance of beautiful ocean ecosystems and keep them accessible to tourism, which would also offer an indirect monetisation opportunity. However, it would be very difficult also in this case to link the CDR effort with tourism revenues.

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[141] IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

Societal aspects/acceptance

"Blue carbon", such as growing kelp, mangroves, or seaweed, has a number of positive side-effects (including reducing pressure on land area by outsourcing biosphere-based CDR to coastal waters, benefits for biodiversity and climate change adaptation) and are generally well accepted.

Marine CDR in the high seas is less known and viewed as more risky than other approaches; ocean fertilisation is viewed as the riskiest approach, garnering negative sentiment.

Policy environment and regulatory barriers/requirements for the R&I intervention area to develop

Comprehensive regulatory frameworks are not yet in place, neither at the domestic, nor the international level.

In principle, there are no institutional barriers for pursuing marine CDR, although governance and regulation is currently essentially prohibitive. Advances are needed especially regarding governance of the high seas. However, some regulation and permitting innovation is also required to enable scaled up coastal marine CDR in the medium-term. In the long-term, transdisciplinary research will be key to examine potential business cases for marine CDR. This should cover research on various forms of policy and market interventions, including consideration of possible risks of perverse incentives, co-benefits, and safeguards for prevention of harm and other regulatory aspects.

System aspects

The potential of marine CDR for removing CO_2 from the atmosphere and durably storing it over the long-term is dependent on: 1) the physical or biological processes that enhance uptake; 2) on the movement of carbon-enriched waters (including biological residues of dead plankton or plants) into deeper waters; and, 3) the avoidance of the processes themselves generating significant additional GHG emissions (e.g. N_2O and CO_2) in the process.

The desirability of marine CDR is determined by a combination of resulting effects on marine ecosystems, as well as upstream impacts during the sourcing of requisite materials.

Infrastructure-related issues

Issues identified include:

- Upstream mining, milling and transport of material for ocean fertilisation or alkalisation requires significant investment into infrastructure potentially at uncommon locations.
- Infrastructure requirements of various marine CDR methods have barely been examined to date.
- Environmental co-benefits are difficult to quantify on different time scales, which further complicates their enforcement.

Examples of tipping points and the required R&I interventions to trigger them

There is a multitude of potential tipping points in the wide and heterogeneous marine CDR landscape, due to the multitude of methods covered under this umbrella term, and the difference in technological characteristics, readiness, and applicability. Therefore, a few examples are presented here to jointly illustrate the range of tipping points to be considered.

For blue carbon methods (e.g., kelp, mangrove, or seagrass plantation), reliable MRV is required to enable participation in carbon markets with high standards of environmental integrity. The establishment of reliable MRV systems could mark a tipping point in the application of blue carbon projects, as the participation in carbon markets could set incentives for local communities by generating revenues.

Large scale open ocean CDR methods are characterized by uncertainty regarding their potential side effects. Understanding the complex interactions in marine systems resulting from such interventions is a first step towards potential applications, if negative side-effects can be managed and/or avoided. However, reaching this deep understanding is just a first point in a cascade of tipping points. Further crucial steps in this cascade are (among others) establishing robust legal regulations for international waters and related ownership issues; building and/or maintaining offshore infrastructure for related projects (depending on the CDR methods to be used); and developing reliable MRV systems for the potentially wide-spread and diffuse CO_2 flows.

Basic research is needed to understand the feasibility and desirability of marine CDR methods. Transdisciplinary research is also required to examine the potential interplay of carbon uptake, ecosystem and fisheries risks and co-benefits and regional supply implications. R&I should therefore address:

- Opportunities for no-regret interventions in the oceans.
- Minimum requirements regarding the monitoring of carbon flows, as well as the potential impacts on biodiversity.
- Development of technological solutions for monitoring, including remote sensing applications toward practical and reliable monitoring – including perhaps AI and robotics-enabled.
- Remote sensing technologies should also be developed which are suitable for the marine CDR challenges (covering large areas, monitoring broadly for unexpected physical, chemical and biological changes and real-time monitoring for CO_2 and all other relevant GHG emissions).

Non-R&I related actions (e.g., institutional and market-related changes) required to trigger the tipping points

Marine spaces, especially in the high seas, pose complex challenges with regards to rights and obligations with unclear ownership and liability rules. There is a need to establish accountability and monitorable safeguards for socio-economic and environmental aspects.

Standards of desirable outcomes from marine CDR may help guide research programmes to help inform decisions on the suitability of marine CDR methods, as more information on their likely performance becomes available. This may in particular pertain to discerning thresholds for problematic outcomes (e.g., ecosystem, chemical, or physical changes to marine environments) and to channel efforts gradually toward methods and value chains that may be deemed most beneficial overall.

While it is too early to consider potential incentivisation of most marine CDR approaches (other than better-understood coastal approaches), the opportunities and risks of various avenues toward business cases (including use of voluntary carbon markets) may nonetheless need to be monitored to anticipate and potentially prevent fraudulent or otherwise problematic action.

Conclusions

Marine CDR, especially alkalinization, is deemed to potentially offer a very large mitigation potential – should it prove to be feasible and effective. Ocean alkalinity enhancement is estimated at 1-100GtCO_2 annually, while ocean fertilisation potential is estimated at 1-3GtCO_2 annually.[142] As a high-risk, high potential impact method to remove CO_2 with a very different profile to any other emissions-reducing or carbon-removing category, marine CDR requires a very thorough examination and careful R&I efforts to progress its development.

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[142] Ibidem.

7. International cooperation and climate neutrality R&I efforts: key challenges and opportunities for the EU

Climate change is a global challenge that requires global solutions. As an increasing number of countries around the world are committing to net-zero targets, they are faced with similar technological challenges to develop and scale-up the needed solutions that will enable climate neutrality by mid-century while also strengthening adaptation and building resilience across borders.

The European Commission's Global Approach to Research and Innovation outlines the European Union's strategy for international cooperation in a changing world focusing on collaborative, values-driven, and strategic international cooperation to address global challenges and promote progress.

This strategy aims to achieve several key objectives:

1. **Preserve Openness:** It seeks to maintain openness in international research and innovation cooperation. This means fostering an environment where researchers and innovators can collaborate freely, based on principles such as academic freedom, research ethics, and respect for human rights.
2. **Promote Reciprocity and Level Playing Field**: The EU aims to establish a level playing field and reciprocity in its international partnerships, ensuring that cooperation is mutually beneficial and respects fundamental values.
3. **Strengthen Partnerships**: The strategy emphasizes strengthening bilateral and multilateral partnerships to address global challenges in areas like sustainability, digitalization, health, and innovation.

This global approach is implemented through various means:

- **Modulated Bilateral Cooperation:** The EU engages in research and innovation cooperation with partner countries that align with European interests and values, enhancing the EU's open strategic autonomy.
- **Mobilization of Science, Technology, and Innovation:** Bilateral and multilateral efforts are mobilized to address global challenges and promote sustainable development and knowledge-based societies, particularly in low and middle-income countries.
- **Team Europe Initiatives**: These initiatives combine actions by the EU, financial institutions, and Member States to maximize the effectiveness of their collective efforts.

As a part of the strategy, the EU has set out joint commitments with prioritised partners, such as the United States of America (US), Canada, Japan, India, Southern Mediterranean countries, and the African Union, to implement framework conditions designed to secure a level playing field and promote shared values (see more details in Section 5 below).

International cooperation on R&I and innovation policy can greatly accelerate the pace at which critical net-zero innovations are brought to market by: (1) mobilising international expertise and providing platforms for knowledge sharing and policy discussion/ coordination; (2) helping direct resources towards promising technologies; and, (3) setting expectations and providing confidence to stakeholders of what actions can be taken.[143] Critically, it also enables countries to identify key gaps and share risks when funding high-risk and costly technologies e.g. CCUS, clean hydrogen, etc.[144]

This section of the report aims to answer study question 4: How can EU engagement in international fora be strengthened to facilitate rapid development and diffusion of breakthrough solutions in the next 10-15 years at European level, and worldwide?

To further support the EU's R&I priorities identified in the rest of the report, this section explores concrete opportunities to use existing international fora and mechanisms for cooperation – at European and global level – to drive international alignment on R&I priorities and greatly accelerate the development and diffusion of innovative solutions for climate neutrality within the EU and beyond.

The following sections will (1) provide an overview of the current international institutional landscape that supports cooperation in R&I; (2) discuss challenges and opportunities cooperating internationally on R&I; (3) identify gaps in key areas/ sectors that are currently not addressed in existing initiatives, (4) consider opportunities for expanding cooperation in new areas via both bilateral and multilateral initiatives; (5) offer recommendations on routes for the EU to capitalise on existing initiatives and strengthen cooperation to accelerate the development of key net zero solutions.

7.1. Overview of current landscape in international cooperation

In the first instance, the current institutional landscape of international cooperation in R&I was mapped with the aim to provide an overview of the existing international initiatives or institutions that support collaborative clean energy and low-carbon innovation mechanisms and assess their geographical coverage and sectoral scope.

The mapping exercise focused primarily on identifying the major multilateral fora of which the EU and/or its Member States are members and that are active in sectors/ technological areas considered in this study. To paint a comprehensive picture, a broad literature review was conducted including recent peer-reviewed research and grey literature (e.g., reports published by international organisations), complemented by information found on specific initiatives' websites[145]. This preliminary analysis shows that the EU is participating across all key initiatives at both a global and regional level.

The exercise does not aim to provide a comprehensive overview of the broader international climate governance landscape and the full spectrum of institutions and initiatives that support cooperation on climate; in order to keep a laser focus on the key research questions of this study, the scope of this exercise is limited to

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[143] Victor, D.G., Geels, F.W. and Sharpe, S., 2019. Accelerating the Low Carbon Transition: The Case for Stronger, More Targeted and Coordinated International Action. Available from: https://www.energy-transitions.org/publications/accelerating-the-low-carbon-transition/

[144] IEA, 2020. Energy Technology Perspectives 2020 - Special Report on Clean Energy Innovation. Available from: https://iea.blob.core.windows.net/assets/04dc5d08-4e45-447d-a0c1-d76b5ac43987/Energy_Technology_Perspectives_2020_-_Special_Report_on_Clean_Energy_Innovation.pdf

[145] The full list of literature reviewed to inform the mapping is available in Annex 1.

international initiatives that aim to advance cooperation on R&I that supports the development of clean energy technologies (i.e. supply push).

The mapping exercised assessed the core characteristics of each initiative, including:

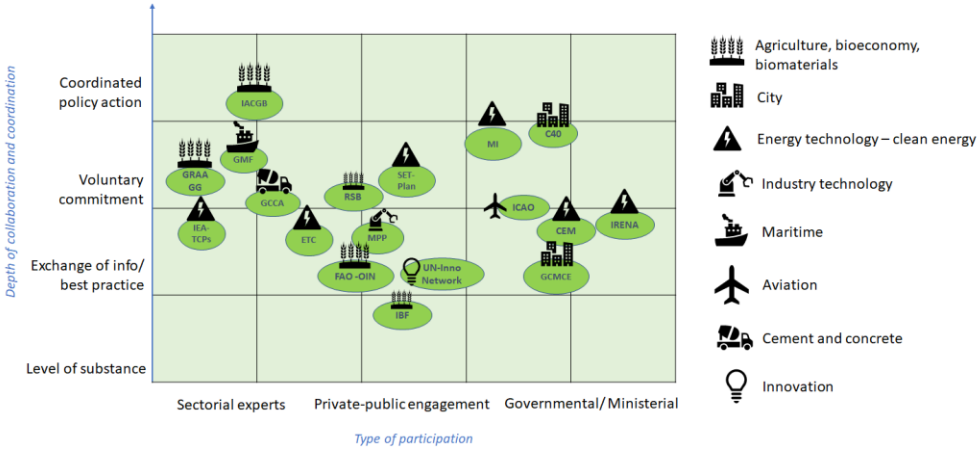
- **Technological scope**: the scope of action and focus areas that the initiatives are covering, which can be broad and encompassing a wide range of technological areas or sectors (e.g., energy innovation), or narrower, focusing on a specific technological area or sector (e.g., aviation).
- **Membership**: the geographical coverage of the initiative emerging from the composition of its official members and access rules (e.g., global/ regional).
- **Governance:** the governance structure and decision-making processes to identify the level of actors involved in setting the strategy and priorities (e.g., from solely working/ technical level to high political level with ministerial involvement).
- **Delivery mechanisms**: the key mechanisms set up by each initiative to deliver on their objectives, ranging from knowledge sharing activities to higher level of commitments through policy coordination.

The full list of initiatives is compiled in Annex 4. To better visualise the complex global landscape, Figure 28 below clusters multilateral initiatives around two key characteristics:

- **the depth of collaboration and coordination**, ranging from low level of coordination (e.g., setting aspirational targets), to medium levels, including members exchanging information and best practices and setting voluntary commitments, to higher levels in which members agree on coordinated policy action; and,
- **the composition of stakeholders** involved at decision-making level in the initiative, from technical experts or sector leaders from the private sector to high-level public officials and ministers.

The clustering shows that the majority of the identified global initiatives cluster around two key characteristics: their governance and operational structure includes both public and private sector stakeholders and the level of collaboration is mostly medium-low, revolving around the exchange of information and best practices.

Figure 23. Clustering of global multilateral initiatives based on type of participation and level of coordination. Source: ICF, 2023.



Note: (*) Acronyms are reported in Annex 4.

7.2. Challenges and opportunities

The scale of the climate and energy challenges that countries face to achieve climate neutrality is unprecedented and requires a concerted effort to deliver clean energy and low-carbon innovation at pace. International cooperation on R&I, through bilateral and multilateral initiatives, is therefore fundamental to ensure a faster roll-out of clean technologies.

While recent literature has argued the necessity to coordinate R&I efforts internationally, a number of challenges have also emerged. However, bringing more clarity to these challenges could help identify approaches to overcome them. Similarly, research has highlighted significant opportunities that cooperation can bring to countries and innovators which reinforce the case for international cooperation across various technological sectors.

This section provides an initial overview of the key challenges and opportunities for international cooperation in clean technology innovation as identified in the literature and by experts' views gathered as part of this study. The discussion aims to improve the understanding of the key benefits of international cooperation as well as evaluate the potential to support the EU's climate ambitions.

7.2.1. Challenges

Several challenges emerge from analysis of the literature and can be clustered in two main groups:

- **Political/economic challenges** (see challenges 1, 2, and 3): challenges or barriers to cooperation in clean technology innovation deriving from political or economic factors that may exacerbate competition and rivalry.

- **Institutional challenges** (see challenges 4, 5, and 6): challenges concerning the current institutional landscape deriving from governance structures and processes that may hinder, instead of facilitating, cooperation.

Each of these challenges is briefly discussed below:

Technological sovereignty

Dependence on third-party providers of key technologies may be a considerable risk that could lead to countries choosing to pursue innovation efforts autonomously, thereby stifling cooperation. While this is an important concern for all countries, a "*desirable level of technological sovereignty*" should be considered and define to allow for efficiency gains in costs/ investments and time that a cooperative approach (e.g., through alliances/ partnerships) may bring[146].

Geopolitical and economic rivalry

The energy and low-carbon transition does not happen in a vacuum, and it is therefore subject to geopolitical and global economic developments that may diminish the willingness of countries to cooperate. As Pasthukova & Westphal note, "*the global environment of great power rivalry and the crises of multilateralism are clearly complicating the global energy transformation*"[147] leading to more power struggles over control of key resources for the transition, whether technological – as pointed out previously – or natural (e.g., minerals).

Major economies vs smaller laggards

Multilateral initiatives based on country-level pledges are often not an effective approach to increase efforts across all members; in fact, as Meckling et al.[148] find, there is an emerging gap between "*innovation leaders and smaller laggards*", where increased efforts are demonstrated only by major economies. This innovation gap could reduce incentives to global cooperation if it does not lead to overall expansion of energy innovation efforts globally.

Complex institutional/ governance landscape

The global landscape of climate governance and international cooperation is rather complex and tends to be structured around countries/ regions rather than around technological sectors which could be more suitable for innovation; in fact, research has highlighted that the current structure make it challenging to identify gaps and potential for further collaboration within existing institutions[149] as well as to convene

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[146] Caravella et al., 2021. Mission-Oriented Policies and Technological Sovereignty: The Case of Climate Mitigation Technologies. Available at: https://www.mdpi.com/1996-1073/14/20/6854

[147] Pasthukova & Westphal, 2020. Governing the Global Energy Transformation. Available at: https://link.springer.com/chapter/10.1007/978-3-030-39066-2_15

[148] Meckling et al., 2022. Energy innovation funding and institutions in major economies. Available at: https://www.nature.com/articles/s41560-022-01117-3

[149] Oberthur et al., 2021. A sectoral perspective on global climate governance: Analytical foundation. Available at: https://www.sciencedirect.com/science/article/pii/S2589811621000082

the key actors in each sector (from both governments and industry) that are best placed to drive collaboration.[150]

Coordination challenges

Complexity can also be a barrier at institutional level as the structure and membership of international cooperation initiatives is often quite large; in fact, as the IEA reported in 2019[151], challenges arising from "*lack of systematic co-ordination processes*" can lead to low engagement and interactions among innovation actors within collaborative mechanisms.

Mismatches in legal structures across innovation processes

Legal structures related to innovation institutions and processes may vary significantly, both across countries, i.e., how national innovation ecosystems are structured and innovation funds disbursed (e.g., national innovation agencies) and across different multilateral initiatives, i.e. how the terms of reference of international organisations/ partnerships have been defined (e.g. governance and decision-making structures, programmatic approaches, etc.). As the IEA finds, these mismatches can make it hard to take forward collaborative project/ activities between countries and exploit synergies across various initiatives.[152]

7.2.2. Opportunities

While a growing body of literature highlights the challenges of engaging in effective multilateral initiatives in the clean technology innovation space, it also positively emphasises the potential opportunities to collaborate more on R&I as well as the benefits that international cooperation can bring to countries and, more broadly, to the sector.

Given the scale of the energy challenges that all countries face to achieve their climate goals, multilateral approaches are critical to accelerate the pace at which new clean energy and low-carbon technologies are developed and deployed; therefore, the "*fundamental question is not whether to collaborate internationally, but rather how best to do it and with whom*"[153].

This section discusses the **opportunities** to further mobilise international expertise and enhance collaborative R&I efforts in specific areas of focus that hold the greatest potential to accelerate technology development. Furthermore, the section presents a brief overview of the **strategic collaboration opportunities** with specific countries

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[150] Victor et al., 2019. Accelerating the Low Carbon Transition. The case for stronger, more targeted and coordinated international action. Available at: https://www.brookings.edu/wp-content/uploads/2019/12/Coordinatedactionreport.pdf

[151] IEA, 2019. Three priorities for energy technology innovation partnerships. Available at: https://www.iea.org/commentaries/three-priorities-for-energy-technology-innovation-partnerships

[152] IEA, 2021. Enhancing Collaboration between Multilateral Initiatives. A handbook for TCPs and other clean energy initiatives. Available at: https://iea.blob.core.windows.net/assets/55bc172a-901e-4718-8f57-8455565c9da2/Enhancingcollaborationbetweenmultilateralinitiatives.pdf

[153] IEA, 2019. Energy Technology Innovation Partnerships. Available at: https://iea.blob.core.windows.net/assets/5809baaa-ebf4-4160-93d3-0f5d29602fad/Energy_Technology_Innovation_Partnerships.pdf

that have established themselves as global innovation leaders and set ambitious targets/ committed resources to developing clean energy technologies.

The overview of opportunities presented below does not cover sector-specific opportunities but rather cross-cutting areas in which international innovation efforts could be focused according to recent research:

Global competition

Technological areas or sectors for which there is strong international competition is a space that offers significant opportunities for accelerating clean energy innovation. As Meckling et al. finds, "*the interplay of RD&D*[154] *cooperation and clean tech competition*" is a cumulative force that can shape and drive changes in international innovation governance and institutions across countries and technologies.[155] Moreover, it provides a strong rationale for collaborating on international regulation to ensure a level-playing field, such as for example, in international aviation and shipping.[156]

Early-transition sectors

The opportunity of working across borders and share R&I efforts is particularly warranted in those sectors where the transition has only just started and new, disruptive technologies are required e.g., energy-intensive industries, heavy road transport, aviation and shipping[157] and where global cooperation can support the creation of "*niches for the first demonstration, testing and deployment of new technologies*"[158].

More importantly, international cooperation could help de-risk R&I investments[159]; in fact, a coordinated approach may help ensure that crucial technologies for the transition do not go underfunded due to the unwillingness of a single country to bear the high financial and market risks typically associated with being "first movers"[160].

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[154] Research, Development and Demonstration (RD&D) refers to the first steps of the technology development cycle, when new technologies are conceptualized, prototypes built and tested in lab and field conditions. These new technologies support both climate change mitigation and adaptation actions. It is a critical phase in the innovation process allowing businesses to explore technologies and ideas as well as collect data and assess feasibility for commercialisation. https://www4.unfccc.int/sites/NWPStaging/News/Pages/Technology-Executive-Committee-compilation-of-good-practices-and-lessons-learned-on-countries-Research-Development-and-Demo.aspx

[155] Meckling et al., 2022. Energy innovation funding and institutions in major economies. Available at: https://www.nature.com/articles/s41560-022-01117-3

[156] Rayner et al., 2021. A sectoral perspective on international climate governance : Key findings and research priorities. Available at: https://www.sciencedirect.com/science/article/pii/S2589811621000094

[157] Ibidem.

[158] Victor et al., 2019. Accelerating the Low Carbon Transition. The case for stronger, more targeted and coordinated international action. Available at: https://www.brookings.edu/wp-content/uploads/2019/12/Coordinatedactionreport.pdf

[159] Meckling et al., 2022. Energy innovation funding and institutions in major economies. Available at: https://www.nature.com/articles/s41560-022-01117-3

[160] IEA, 2020. Clean Energy Innovation. Part of Energy Technology Perspectives. Available at: https://www.iea.org/reports/clean-energy-innovation

Such an approach to R&I collaboration could help fill key project demonstration gaps, whether it is testing of new technologies or existing ones under different operating conditions (e.g., climate and geographical constraints, specific local requirements, etc.)[161], thus leveraging international expertise where local solutions do not currently exist. The design of R&I initiatives and partnerships that support these objectives could help facilitate a faster move towards commercialisation[162] by ensuring that no gaps are left across the value chain.

Data and standards

International cooperation can support coordination of actions not only by exchanging knowledge and learnings, but also by supporting international rule-setting. In fact, collective action to accelerate the development and uptake of low-carbon innovations could be facilitated by the harmonisation of technical standards[163]. Notably, gathering comparable data across countries could help establish effective technology benchmarks and guidelines that ensure global compatibility[164].

For example, the framework of *Article 6* of the Paris Agreement could offer significant opportunities for international cooperation to accelerate emissions reduction and removal efforts. Cooperation is needed not only to advance the development and deployment of carbon removal and storage technologies, but also to support the establishment of innovative approaches to carbon crediting mechanisms aligned around common standards and certifications.[165]

Country collaborations

The study conducted by Meckling et al.[166] provides a useful analysis of the trends in public investments in energy innovation observed in countries (in the 2010-2018 period) with significant levels of RD&D spending. This helps identify clean energy innovation “leaders”. To complement these findings, a recent study by the IEA[167] looks at key policy priorities and commitments to support RD&D efforts in specific technological areas as announced by key countries. The findings from both studies point to a sub-set of countries that have recently ramped up support for new clean

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[161] IEA, 2021. Expanding the Global Reach of the TCPs A handbook for TCPs and other clean energy initiatives. Available at: https://iea.blob.core.windows.net/assets/6352379f-ef19-488c-8e61-b4f2cf5777eb/ExpandingtheglobalreachoftheTCPs_Final.pdf

[162] Meckling et al., 2022. Energy innovation funding and institutions in major economies. Available at: https://www.nature.com/articles/s41560-022-01117-3

[163] Oberthür et al, 2021. A sectoral perspective on global climate governance: Analytical foundation. Available at: https://www.sciencedirect.com/science/article/pii/S2589811621000082

[164] IEA, 2021. Expanding the Global Reach of the TCPs A handbook for TCPs and other clean energy initiatives. Available at: https://iea.blob.core.windows.net/assets/6352379f-ef19-488c-8e61-b4f2cf5777eb/ExpandingtheglobalreachoftheTCPs_Final.pdf

[165] Zakkour, P.D. et al., 2020. Progressive supply-side policy under the Paris Agreement to enhance geological carbon storage. Available at: https://www.tandfonline.com/doi/full/10.1080/14693062.2020.1803039

[166] Meckling et al., 2022. Energy innovation funding and institutions in major economies. Available at: https://www.nature.com/articles/s41560-022-01117-3

[167] IEA, 2022. Clean Energy Technology Innovation. Energy system overview. Available at: https://www.iea.org/reports/clean-energy-technology-innovation

energy RD&D and the specific sectors that they are focusing on. While this analysis focusses on clean energy technology, it is assumed that the key findings are also valid for the broader cleantech innovation space. A summary is provided below:

Globally, three countries account for nearly two-thirds of new clean-energy RD&D:

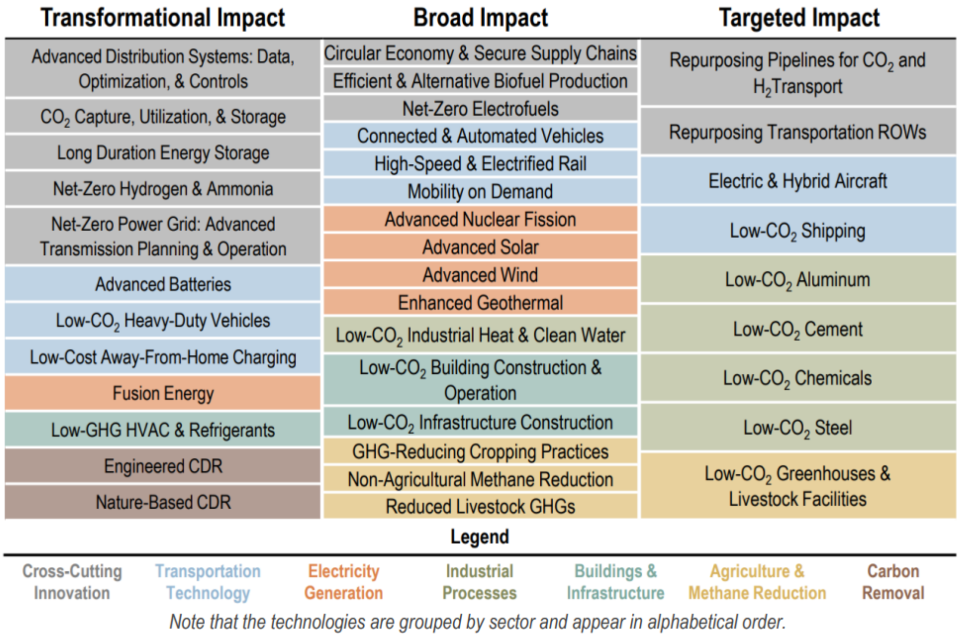
The United States

The growth rate of energy RD&D funding has been maintained at stable levels, including the share allocated to clean energy. Recent policies have highlighted strong support for demonstration projects in the following sectors:

- **Hydrogen:** the *Bipartisan Infrastructure Law* includes about 40% of budgets dedicated to hydrogen demonstrators; and up to USD 13 billion of tax credits for clean hydrogen projects were announced under the *Inflation Reduction Act (IRA)*.
- **CCUS:** while several CCUS projects are already on the way, significant funding for CCUS projects was announced as part of the *Bipartisan Infrastructure Law* (accounting for over 15% of budgets) and increased within the *IRA* including support for retrofits and tax credits for direct air capture projects.
- **Industry decarbonisation:** USD 5.8 billion of funding was announced under the *IRA* to support advanced industrial facilities deployment, including energy efficiency, electrification, low-emission fuels and heat, and CCUS.
- **Biofuels:** the *IRA* includes support for second-generation biofuels and provides close to USD 250 million of grants for the development of low-carbon aviation fuels, as well as dedicated tax credits.

On top of the above key areas, the White House recently published a report identifying emerging technologies that hold promise to change the game on the path to a net-zero economy by 2050. This report, that shows very similar objectives to this study focuses on game changers I the following areas: new technologies; significantly improved technologies; critical enabling technologies; and, multi-objective technologies. The report identifies a portfolio of 37 net-zero game changers as illustrated in Figure 24 below.

Figure 24. Portfolio of 37 Net-Zero Game Changers Identified by the White House. Source: White House, 2022[168].



Transformational Impact	Broad Impact	Targeted Impact
Advanced Distribution Systems: Data, Optimization, & Controls	Circular Economy & Secure Supply Chains	Repurposing Pipelines for CO_2 and H_2Transport
CO_2 Capture, Utilization, & Storage	Efficient & Alternative Biofuel Production	Repurposing Transportation ROWs
Long Duration Energy Storage	Net-Zero Electrofuels	Electric & Hybrid Aircraft
Net-Zero Hydrogen & Ammonia	Connected & Automated Vehicles	Low-CO_2 Shipping
Net-Zero Power Grid: Advanced Transmission Planning & Operation	High-Speed & Electrified Rail	Low-CO_2 Aluminum
Advanced Batteries	Mobility on Demand	Low-CO_2 Cement
Low-CO_2 Heavy-Duty Vehicles	Advanced Nuclear Fission	Low-CO_2 Chemicals
Low-Cost Away-From-Home Charging	Advanced Solar	Low-CO_2 Steel
Fusion Energy	Advanced Wind	Low-CO_2 Greenhouses & Livestock Facilities
Low-GHG HVAC & Refrigerants	Enhanced Geothermal	
Engineered CDR	Low-CO_2 Industrial Heat & Clean Water	
Nature-Based CDR	Low-CO_2 Building Construction & Operation	
	Low-CO_2 Infrastructure Construction	
	GHG-Reducing Cropping Practices	
	Non-Agricultural Methane Reduction	
	Reduced Livestock GHGs	

Legend

Cross-Cutting Innovation	Transportation Technology	Electricity Generation	Industrial Processes	Buildings & Infrastructure	Agriculture & Methane Reduction	Carbon Removal

Note that the technologies are grouped by sector and appear in alphabetical order.

China

While the growth of clean energy RD&D spending decreased in the period 2010–2018, the increase in RD&D funding in the past 20 years has been unparalleled. The IEA estimates that China surpassed the US in public energy R&D spending in 2021 in absolute terms. Additionally, about 35% of total R&D spending by listed companies in 2021 came from companies headquartered in China.

The *14th Five-Year Plan for a Modern Energy System* (2021-2025) focuses on transport, industry, hydrogen, CCUS, power including nuclear (e.g., small modular reactors). Hydrogen, in particular, is an important focus area to support the development of a low-carbon hydrogen supply chain and new technologies, supported by a number of large-scale demonstration projects.

Japan

While the growth in energy RD&D spending stagnated, the share of new clean-energy share saw an increase. The flagship *Green Innovation Fund* offers funding for

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[168] White House, 2022. U.S. Innovation to meet 2050 climate goals. Available at: https://www.whitehouse.gov/wp-content/uploads/2022/11/U.S.-Innovation-to-Meet-2050-Climate-Goals.pdf

business-led decarbonisation projects from R&D to demonstrations in various sectors, including offshore wind, solar PV, hydrogen, CCUS, transport, digital.

Similar to other leaders, the country is dedicating large part of the resources to the development of the **hydrogen** technologies; in fact, 40% of the budgets announced under the *Green Innovation Fund* are for hydrogen projects, followed by about 20% for industry decarbonisation, including hydrogen-based **steelmaking** and hydrogen- and ammonia-powered engines for **shipping**.

Other relevant countries

In addition to the top three clean energy innovation leaders, other countries are demonstrating a significant push to accelerate RD&D efforts. In particular, **Canada** is increasing support for **CCUS** projects, including direct air capture, CO_2 transportation and storage. Through its *Technology Investment Roadmap* (2022-2030), **Australia** is also ramping up efforts to develop **hydrogen** and **CCUS** technologies, with about AUD 2.5 billion already committed to projects. The **United Kingdom** and **India** both saw a decline in the share of clean energy RD&D funding, despite the overall growth in total RD&D, with an increase in fossil fuels and nuclear.

Furthermore, growing opportunities for cooperation on **hydrogen** and **CCS** with the *Gulf Cooperation Council* are emerging due to the convergence of strategic technology and policy objectives and the opening of new dialogues[169] and partnerships[170]. However, issues with technology definition (e.g., blue hydrogen, CCS options) will need to be discussed and clarified to ensure alignment with EU strategies and regulations[171].

While collaboration have typically taken place at national level, there are increasing opportunities for advancing innovation through collaboration at sub-national level, in particular city-to-city cooperation. Cities are responsible for over two-thirds of the global energy consumption, accounting for about 70% CO^2 emissions[172]. From power to mobility, to buildings and industry, cities faced numerous decarbonisation challenges which makes them the perfect testbed for innovative energy solutions. A growing number of initiatives are now driving forward this type of cooperation – a brief overview is provided in the Horizon Europe Work Programme 2023-2024.

Finally, a call for more **inclusivity** in multilateral initiatives for energy innovation is becoming increasingly strong. The inclusion of **emerging and developing countries** in innovation partnerships have often been given little attention, despite the potential

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[169] IRENA, 2022. A Dialogue Between EU and Gulf Cooperation Council on a Regulatory Framework to Develop Green Hydrogen Supply, Demand and Trade. Available at: https://www.irena.org/events/2022/Apr/Dialogue-Between-EU-and-Gulf-Cooperation-Council-on-a-Regulatory-Framework-to-Develop-Green-Hydrogen

[170] European Commission, 2022. A strategic partnership with the Gulf. Available at: https://www.eeas.europa.eu/sites/default/files/documents/Joint%20Communication%20to%20the%20European%20Parliament%20and%20the%20Council%20-%20A%20Strategic%20Partnership%20with%20the%20Gulf.pdf

[171] Heinemann, et al., 2022. Hydrogen fact sheet – Gulf Cooperation Countries (GCC). Available at: https://www.oeko.de/fileadmin/oekodoc/GIZ-SPIPA-hydrogen-factsheet-GCC.pdf

[172] Henrich Boll Stiftung, 2018. Cities: Testbeds for energy innovation. Available at: https://eu.boell.org/en/2018/04/24/cities-testbeds-energy-innovation

opportunities for value creation that these markets could offer. Emerging and developing markets are expected to drive a significant proportion of future energy demand growth as well as for related infrastructures and services[173]. Additionally, as the IEA finds, there is a growing number of locally developed energy innovations as governments increasingly focus on strengthening their domestic innovation capacity.[174]

To conclude, international collaboration and strategic partnerships can support and amplify innovation efforts happening across both advanced and emerging economies and help accelerate the transition to net-zero energy technologies domestically and globally.

7.3. Key gaps and recommendations

7.3.1. Gap analysis

Based on the mapping of the current landscape, a gap analysis was conducted to identify key gaps in the technological and non-technical scope of these initiatives.

Overview of city-to-city cooperation on energy innovation

City-to-city collaboration, though still relatively less diffused, has the potential to deliver significant advantages for cities and, at the same time, accelerate the development and demonstration of innovative technologies to deliver the decarbonisation required to respond to the climate challenge.

Several initiatives are supporting cities within and across regions to cooperate on shared challenges to decarbonise their economic activities while also improving their citizens' wellbeing and creating new job opportunities. A few notable examples are described below:

International Urban and Regional Cooperation (IURC): building on the lessons and results of the International Urban Cooperation, this EU programme aims to lead and develop decentralised international urban and regional cooperation around sustainable urban development and innovation in key partner countries and regions.

24/7 Carbon-Free Energy for Cities: launched by Google and C40, this programme aims to empower cities to develop and implement innovative approaches to decarbonise their energy use, while also create scalable models that could be shared with other cities. London, Copenhagen and Paris are participating in the pilot phase.

Urban Transitions Mission: launched by the European Commission and the Global Covenant of Mayors, in the context of Mission Innovation's Missions programme, this initiative aims to bring together a cohort of 300 cities by 2024 to test and integrate innovative net-zero solutions into an urban transition roadmap framework.

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[173] Quitzow et al., 2019. Advancing a global transition to clean energy – the role of international cooperation. Available at: http://www.economics-ejournal.org/economics/discussionpapers/2019-37/

[174] IEA, 2021. Expanding the global reach of the TCPs. A handbook for TCPs and other clean energy initiatives. Available at: https://www.iea.org/reports/expanding-the-global-reach-of-the-tcps

These initiatives were assessed against the “needs”-based (Section 3) framework to identify key R&I solutions with the aim to understand the extent to which existing international institutions and initiatives address key innovation needs and where key gaps exist. Gaps were then analysed across three categories of solutions identified in this study (see Section 3):

- Technological solutions
- Societal solutions
- GPT solutions

Key findings:

Overall, the analysis showed that, while a significant number of initiatives exists that support and promote international cooperation on energy innovation, a lower number of initiatives and international mechanisms are available in a subset of sectors:

- Food.
- Built environment.
- Resource efficiency (production and consumption).
- Biodiversity.
- CDR.

Additionally, two cross-cutting gaps have been identified across all sectors:

- **Lack of focus on Societal and GPT solutions** – the majority of existing initiatives across all sectors, focus their collaborative efforts almost exclusively on the development of technological solutions. Whilst this is important, including cooperation to support the development of GPT and Societal solutions across all sectors within existing sectoral initiatives can greatly accelerate the achievement of tipping points towards a carbon-neutral economy.
- **Limited geographical coverage** – the participation of countries from the Global South in current international R&I initiatives is very limited with very few regional and bilateral such as OLADE and ECPA. A more systematic inclusion of these countries in global R&I initiatives would help in expanding their local innovation capacity as well as delivering solutions that can better address broader decarbonisation needs.

The detailed analysis helped identify sector-specific gaps where there is currently a lack of attention in existing international initiatives. The findings are summarised in Table 12. Whilst this is not an exhaustive list, the aim is to highlight high-level gaps that could be considered with the view to catalyse international cooperation to support specific R&I areas and/ or the development of specific solutions.

Table 12. Sector-specific gap analysis

SECTOR/NEED	GAPS IDENTIFIED
Built environment	• Limited number of initiatives promoting and supporting affordability and accessibility of cooling technology across the Global North and South for example through price of components (notable examples include The Green Cooling Initiative and Mission Innovation). • Limited scope of initiatives supporting collaboration in sustainable heating technologies. • Limited scope of initiatives like the Global Alliance for Buildings and Construction (GlobalABC) and ECTP that collect data to track and measure the performance of new technologies in an urban context. The focus of initiatives identified is largely on policy development and regulatory compliance. • Lack of cooperation on Building Energy Efficiency Codes (BEECs) to support uniformity across standards and promote market alignment. In particular, encouraging coordination of demonstration and testing of power system flexibility solutions, including long-term storage that is crucial to transition to net-zero power in future years.
Energy	• Limited initiatives providing financial support and other incentives for projects with lower Technological Readiness Levels (TRLs). There is a need to have a more level-playing field in global competitions like the Global Cooling Prize Shell Hackathon, RWE Innovation Competition
CDR	• Although some niche resources on reporting exist for hydropower,[175] there is a lack of a common GHG reporting methodology to align global incentives to invest in removal technologies that deliver real emissions reductions. While initiatives like the GHG Gas Protocol provide guidance and capacity-building, they do not provide a platform for discussion and coordination at the international level. • Nature based Solutions (NBS) are identified to have a variety of environmental, social and economic advantages in addition to CDR potential. While there is an internationally agreed definition and understanding of NBS,[176] insufficient involvement and consultation of relevant stakeholders, such as indigenous groups, has been criticized. This lack of involvement enables the privatisation and commodification of

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[175] Open Hydro, 2022. HydroPower Reporting Guideline: Climate-change mitigation. Available at: https://openhydro.net/resources/

[176] The United Nations Environment Assembly (UNEA-5) and UNEP have defined Nature based Solutions (NbS) as the actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater coastal and marine ecosystems.

SECTOR/NEED	GAPS IDENTIFIED
	nature through market-based mechanisms.[177] The EU initiated the "Network Nature" bringing together local, regional and international stakeholders to cooperation and enhance impact. This initiative could be extended beyond Europe to ensure stronger engagement with the Global South on NBS. • Despite the importance of NBS, the lack of technical expertise prevents it being implemented successfully. The EU is helping scale NBS globally by publishing key guidance on monitoring and evaluation of NBS projects to practitioners by providing resources on evaluating the impact of NBS, public procurement, as well as presenting successful case studies that can be replicated across the world.[178] The introduction of the CEN/TC 465 – 'Sustainable and Smart Cities and Communities' standards will further support the interoperability of digital, societal and nature-based solutions in cities, communities in functional urban, rural and peri-rural areas.
Food	• Limited focus on next-gen technologies[179] like regenerative agriculture and exploring the potential of GPT solutions like usage of AI in filling data gaps and managing nature inventories better.[180]Very few international platforms actively advocate or drive behavioural change (societal solutions) in terms of production and consumption, like the Global Action Platform on Sustainable Consumption and Diets established by the WWF. Smaller initiatives include the SCP South-South.
Mobility	• International cooperation is required to accelerate the development or adoption of innovation.[181] For example, four distinct charging standards have already been introduced worldwide but there is a need to cooperate on the harmonisation of international charging standards including of a) charging plugs, b) protocols used for communication between batteries, charging stations and grid (up to V2G)[182] to drive investment and accelerate adoption of sustainable mobility globally, and to fully benefit of the potential of EVs to maximise the intake of RES and decrease the need to fossil-fuelled generation by peak-shaving. Current initiatives do not address this concern yet. • International cooperation to develop uniform standards on the recyclability of EV batteries and supercharging research. Strong initiatives like the European Battery Alliance are focused on regional developments, but less collaboration is happening at international level.

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[177] IISD, 2021. Seeking common ground for Climate, Biodiversity, and People. Available at: https://www.iisd.org/articles/common-ground-nature

Opportunities to strengthen international cooperation to unlock innovative solutions to key societal challenges

International cooperation is a key tool to support a faster and more equitable development and deployment of solutions to address key decarbonisation challenges. Building on the selected innovation areas in each “nexus” as presented in the earlier sections, key opportunities for enhanced international cooperation have been identified.

In particular, in each nexus R&I areas with the following characteristics were prioritised: high potential to benefit from stronger international cooperation due to the inherent characteristics of the sector and/or solutions, including considerations around trade exposure/ international nature of the value chains; opportunities to address cross-sectoral challenges; and, potential contribution to strengthening the role of the EU in the global innovation landscape we.

1. Mobility – Built environment – Energy nexus

While there are several initiatives tackling these sectors separately, there are clear opportunities for exploiting the synergies and deep interlinkages across these three areas. Adopting a more holistic approach to advancing innovation efforts to develop solutions that realise cross-sector decarbonisation offers clear avenues for international cooperation, among cities:

- **Strengthening multilateral city-to-city cooperation –** looking at cities as naturally interconnected systems can maximise positive spillovers accelerating transformation towards climate neutrality. While the EU has established several strong initiatives, there is high potential for greater cooperation at international level to develop solutions that can be scaled up and replicated across cities facing similar decarbonisation challenges. Successful examples include the EU Cities Mission helping European cities progress in climate-neutrality by offering support for cleaner air, safer transport and less congestion and noise to their citizens. In April 2022, 100 cities of the EU and 12 cities worldwide were associated with Horizon Europe were awarded with the EU Mission Label to achieve climate-neutrality by 2030.[183] Greater cooperation amongst cities globally can

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[178] European Commission, 2023.Nature-based Solutions. Available at: https://rea.ec.europa.eu/funding-and-grants/horizon-europe-cluster-6-food-bioeconomy-naturalresources-agriculture-and-environment/nature-based-solutions_en

[179] IRENA, 2020. International collaboration gap threatens to undermine climate progress and delay net zero. Available at: https://www.irena.org/News/pressreleases/2022/Sep/International-collaboration-gap-threatens-to-undermine-climate-progress-and-delay-net-zero

[180] Connecting Nature Platform. AI enabled tree inventory. Available at: https://connectingnature.eu/cnep-opportunities/ai-enabled-tree-inventory

[181] Chamberlain, K, Al Majeed, S, 2021.Standardisation of UK Electric Vehicle Charging Protocol, Payment and Charge Point Connection https://www.mdpi.com/2032-6653/12/2/63

[182] European Commission, 2018. The need to harmonise technical solutions for charging electric vehicles. Available at: https://www.europarl.europa.eu/doceo/document/E-8-2018-005395_EN.html

[183] European Commission, 2023. Ten European cities awarded with EU Mission Label for their plans to reach climate-neutrality by 2030. Available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4879#:~:text=The%20EU%20Cities%20Mission%20aims,to%20Horizon%20Europe%20were%20selected.

complement and enhance the impact of multilateral efforts on sectoral transitions[184] as well as multiply the impact of local/ national initiatives to deliver global results.[185] City cooperation initiatives like the C40 and the Urban Transition Mission (UTM) under the EU Mission Innovation (with 25 existing initiatives worldwide) can be scaled up to drive more collaborative innovation efforts and support wider international cooperation objectives.

- **Building on successful EU city initiatives –** the EU is a frontrunner in city-level innovation. Exemplary programmes that encourage and reward innovation in European cities[186]the 'European Innovation Partnership on Smart Cities and Communities'[187] and the iCapital award European cities like Bilbao (ES), Bielsko-Biala (PL) and Sofia (BG) have adopted 'smart specialisation strategies'[188]that align the approaches to innovation between regions and cities. There are clear opportunities for the EU to lead efforts globally to scale up and replicate these successful initiatives to include cities in other regions of the world, accelerating the pace of innovation globally and positioning EU cities at a competitive advantage.
- **Enhanced focus on societal innovation** – the interaction between technology and society is apparent in the context of cities, where communities actively use mobility, energy and building technologies in every aspect of their lives. Understanding how new zero-carbon technologies will be taken up by users in urban context is therefore crucial. As noted previously in this study, there are critical issues that have not yet been addressed due to low acceptance, buy-in of the technical solutions from stakeholders including the use of sustainable alternative construction material, adoption of public transport and some EVs. This implies that societal innovation is just as important, if not more than technical solutions. However, several of the identified initiatives fail to address societal innovation and focus exclusively on technical innovation due to factors including misalignment of stakeholders' interests, lack of capacity and enterprise, as well as slow pace of change. This presents an opportunity for the EU to champion increased efforts to address societal innovation in the context of existing international institutions. A successful initiative is of the New European Bauhaus fostering transdisciplinary innovation covering sustainability, aesthetics and inclusion. The initiative has dedicated calls for funding and prizes for projects fulfilling the societal innovation criteria.
- **Increased focus on GPT solutions** – like societal solutions, the potential of GPTs is not yet fully explored and harnessed. For instance, GPTs can be widely

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[184] IEA, 2021. Enhancing collaboration between multilateral initiatives. Available at: https://iea.blob.core.windows.net/assets/55bc172a-901e-4718-8f57-8455565c9da2/Enhancingcollaborationbetweenmultilateralinitiatives.pdf

[185] UNIDO,2019. Bridge for Cities 4.0. Available at: https://www.unido.org/sites/default/files/files/2019-09/Bridge4Cities%20Issue%20Paper_Final.pdf

[186] JRC. Undated. European Innovation Partnership on Smart Cities and Communities. Available at: https://e3p.jrc.ec.europa.eu/articles/european-innovation-partnership-smart-cities-and-communities

[187] European Innovation Council. Undated. European Capital of Innovation Awards. Available at: https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/prizes/icapital_en

[188] European Commission. Undated. Cities as Innovation Hubs. Available at: https://urban.jrc.ec.europa.eu/thefutureofcities/cities-as-innovation-hubs#the-chapter

used in the development of smart mobilities by addressing the need for dynamic country diagnostics[189] using tools like GPT-4.[190] Given the high demand for data that underpins these technologies, there are clear opportunities for knowledge and data sharing at international level to accelerate their development, however, international competition and privacy concerns should be accounted for.

2. Circularity – Industry – Carbon removals and capture nexus

Realising decarbonisation of industry and large-scale carbon removal technologies require significant investments in R&I and careful consideration of competitiveness issues. National industrial strategies present aim to address specific local challenges, capitalise on local strengths and ultimately bring local benefits; hence, international coordination in this matter would be difficult to realise. However, there are opportunities to strengthen **bilateral cooperation** by leveraging already established technological/ trade partnerships to pool resources, skills and expertise of innovation leaders with common R&I objectives.

In particular, there are opportunities for the EU to build new or strengthen existing partnerships in the following R&I areas:

- **Hydrogen** – The EU should leverage its existing channels of cooperation like the Mission Innovation, Clean Energy Ministerial and Clean Hydrogen Partnership to collaborate and coordinate.[191] The need to quickly create global, large-scale demand for low carbon hydrogen requires a collective push for R&I[192]. Specific R&I priority areas emerging from this study, such as the development of technologies for hydrogen production and storage, could be supported by targeted partnerships at bilateral level. In particular, the EU has existing partnerships in the form of MOUs with several countries including US, Japan, and India, amongst others, which have strategic innovation interests around hydrogen technologies that are well aligned with the priority's areas identified in this study. In addition to bilateral collaboration, the EU could leverage its leading role in existing initiatives such as Mission Innovation's Clean Hydrogen Mission to catalyse wider innovation efforts to expand geographical coverage of projects and enhance knowledge-sharing.
- **Carbon Capture Utilization and Storage** – With the potential and relevance of emission reduction technologies like industrial point source capture in combination with utilization and storage (CCUS) increasing, countries like

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[189] World Bank, 2019. Global Roadmap Towards Sustainable Mobility. Available at: https://thedocs.worldbank.org/en/doc/350451571411004650-0090022019/original/GlobalRoadmapofActionTowardSustainableMobility.pdf

[190] Intertraffic, 2023. Smart Mobility with Chat GPT-4: Transport just got even more intelligent. Available at: https://www.intertraffic.com/news/smart-mobility-chatgpt

[191] Lebling et.al. 2023. International governance of technological carbon removal: surfacing questions, exploring solutions. WRI. Available at: https://files.wri.org/d8/s3fs-public/2023-08/international-carbon-removal-governance.pdf?VersionId=zPPNqRqTuljRc7Z7jtlaIolqLq1jW2NZ

[192] IRENA, 2023. Breakthrough Agenda Report 2023. Available at: https://www.irena.org/Publications/2023/Sep/Breakthrough-Agenda-Report

Norway, Canada and US are among the frontrunners in R&I.[193] The development of further utilization and storage opportunities to accommodate CO_2 from (industrial) point source capture could also benefit removal technologies like DAC and BECCS. An existing translanational partnership called Accelerating CCUS Technologies (ACT) advances RD&I in CCUS with the funding and participation of 16 countries/regions including Alberta (Canada), Denmark, France, Germany, Greece, India, Italy, the Netherlands, Romania, Spain, Switzerland, Turkey, UK, USA and the Nordic region.[194] The EU also has existing partnerships with Canada and Japan which can be expanded and strengthened to focus on specific priority areas, with priority ideally given to CCU with long-term CO_2 storage. Furthermore, the US and EU could benefit from shared resources in the early stages of research and development. Aligning on research priorities (materials, chemicals, test beds, pilots, etc.) are needed in key areas. Building on each other's strengths to share/reduce risk, accelerate early-stage innovation and learnings instead of unnecessary duplication. One example could be ARPA-E collaborating with DG RTD to jointly prioritize and fund targeted R&D – in the labs, universities and incubators. This will get the innovation to early-stage companies as fast as possible and with the confidence that as they scale, they can address the largest combined market in the world.

- **Recycling and reuse of industrial products:** A proactive role must be played by governments in encouraging innovation in reuse and recycling of industrially manufactured products including cement and steel. Under the new EU Ecodesign for Sustainable Products Regulation (ESPR) "products passports" could be introduced pushing manufacturers to update their processes and innovate.[195] While there is an existing bilateral agreement with countries like Japan,[196] there is an opportunity for platforms like the European Raw Materials Alliance to expand scope for international collaboration on recycling industrial raw materials and align exports supply chains.

3. Agrifood – Carbon removals nexus

Innovations that support healthy natural ecosystems are critical to ensure not only resilient agricultural and food systems that support our lives, but also to support wider carbon neutrality goals by reducing emissions from these sectors and enhancing nature's carbon removal potential.

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[193] ENGIE, 2021. Northern Lights: Inside Norway's ambitious carbon capture and storage network. Available at: https://innovation.engie.com/en/news/news/new-energies/northern-lights-norway-carbon-capture-storage-project/26502

[194] Stageland, et. Al, 2022. ACT How International collaboration fosters CCUS research and innovation. SSRN. Available at: https://www.zbw.eu/econis-archiv/bitstream/11159/533174/1/EBP089879724_0.pdf

[195] CIDSE, 2023. Joint position paper: EU Critical Raw Material Act. Available at: https://www.cidse.org/2023/07/11/joint-position-paper-eu-critical-raw-material-act/#:~:text=The%20EU%20should%20actively%20reduce,passport%20system%2C%20and%20adopting%20national

[196] European Commission, 2023. Enhancing cooperation with Japan on critical raw materials supply chains through a new Administrative Arrangement. Available at: https://single-market-economy.ec.europa.eu/news/enhancing-cooperation-japan-critical-raw-materials-supply-chains-through-new-administrative-2023-07-06_en

Although the EU defines a strategy for the nexus under the EU Innovation Agenda international initiatives like Agricultural Innovation Mission for Climate (AIM for Climate) and Consultative Group on International Agricultural Research (CGIAR) facilitate innovation in climate-smart agriculture and food systems, here is current a lack of international R&I initiatives and incentives for **agrifood innovation**. Given the increasing importance of this sector, this gap needs to be urgently filled with an opportunity of the EU to promote the scale up of existing initiatives and international for a (e.g., FAO) to include support innovation that reduce food waste, limit emissions from livestock and fertilisers, improve alternative proteins, develop climate-resilient crop and livestock, and protect soil and water resources.[197]

NBS are increasingly identified as salient tools in emission reduction among other co-benefits for the environment, society, and economy, evidenced by 102 nations including them in their Nationally Determined Contributions (NDCs) or climate strategies required by the Paris Agreement.[198] The IPCC has identified three ways in which NBS address climate change: 1) reducing GHG emissions related to deforestation and land use; 2) capturing and storing CO_2 from the atmosphere; and, 3) enhancing the resilience of ecosystems and societies to adapt to climate disasters like extreme weather conditions.[199] However, several countries still lack the know-how to implement successful projects especially those belonging to the global south. It is therefore necessary for the EC to actively expand the reach and scope of its influence through meaningful international cooperation offering both climate mitigation and adaptation co-benefits like terrestrial ecosystem-based removals and ocean ecosystem-based removals. Given the importance of natural ecosystems for biodiversity, economies and societies everywhere, this area presents significant opportunities for expanding participation of countries from the **Global South** in international R&D initiatives.

The EU has demonstrated leadership in advancing initiatives that support innovative solutions that generate economic opportunities while preserving nature and pursuing mitigation efforts. In particular, the Horizon2020 Connecting Nature project (see Case Study 2 below) has been supported and is being delivered by a consortium of 30 partners across 16 European countries. The project developed, among others a platform to bring together private and civil society stakeholders to provide guidance and knowledge-sharing to innovate and scale nature-based solutions in cities to build climate resilience and beyond the urban ecosystem to substantially contribute to CDR. It is a successful EU initiative that the EU could consider scaling up to expand at global

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[197] IEA, 2022. Breakthrough Agenda Report. Available at: https://www.iea.org/reports/breakthrough-agenda-report-2022/executive-summary

[198] Mercer L. 2022. What are nature-based solutions to climate change? Available at: https://www.lse.ac.uk/granthaminstitute/explainers/what-are-nature-based-solutions-to-climate-change/

[199] IUCN. Undated. Nature based solutions. Available at: https://www.iucn.org/our-work/topic/nature-based-solutions-climate#:~:text=Nature%2Dbased%20solutions%20can%20address,carbon%20dioxide%20from%20the%20atmosphere

level, supporting more counties from the Global South to adopt and implement NBS in an optimal manner.

Connecting Nature

The Connecting Nature project is delivered by a consortium of 30 partners within 16 European countries, and with hubs in Brazil, China, Korea and The Caucasus (Georgia and Armenia).[200] The platform engages with local authorities, communities, industry partners, NGOs and academics who are investing in large scale implementation of nature–based projects in urban settings.

The platform is grounded in scientific research ensuring that the NBS proposed are effective and evidence-based through the following:

- **Demonstration Projects:** The platform facilitates the implementation of real-world demonstration projects that showcase the benefits of nature-based solutions, inspiring other cities, and stakeholders to adopt similar approaches for example reflexive monitoring and impact assessment of technical projects.
- **Community Engagement:** By involving local communities and stakeholders, the initiative drives the customisation of NBS to the specific needs and preferences of each city, leading to greater acceptance and support.
- **Capacity Building:** The platform provides resources, training, and knowledge-sharing opportunities, empowering cities to design, implement, and manage nature-based projects effectively.

This is niche platform providing targeted guidance for projects that can be replicated and scaled across the world. Its expansion and promotion can help more countries make use of its resources.

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[200] Connecting Nature, 2023. Bringing cities to life, bringing life into cities. Available at: https://connectingnature.eu/

C40 Cities

The C40 Cities initiative engages mayors from over 100 major cities worldwide to collaborate on climate action. It focuses on implementing practical solutions emphasising on innovation in sustainable practices to enhance urban resilience and reduce greenhouse gas emissions. The initiative encourages sharing best practices, data, and strategies among member cities to accelerate the transition to more sustainable urban environments.

Many cities within the C40 network actively engage their citizens in climate initiatives successfully fostering public support and encouraging behavioural changes that contribute to sustainability. Key factors attributing to its success include the following:

- **Data-driven decisions:** C40 promotes data collection and analysis to inform decisions. Cities can learn from one another's experiences and tailor strategies based on reliable information.
- **Mayoral Leadership:** The involvement of mayors provides strong political will and commitment to sustainability goals, allowing for swift and bold actions.
- **Networking:** C40 provides a platform for cities to network, learn, and exchange knowledge, fostering a sense of community and shared responsibilities.

The initiative is an example of encouraging wider and more inclusive participation from cities across regions and income levels to foster diverse perspectives and solutions. It can be strengthened by prioritising technology transfer and capacity building between the urban centres that are lagging to create a more comprehensive and aligned approach. Finally, a more robust monitoring and reporting framework will enable best practices shared across city networks are translated into conventional planning and urban management processes.[201]

7.3.2. Recommendations

Three main interventions requiring the EU to foster multilateral and bilateral partnerships with key and emerging innovators were identified:

- **Lead efforts to expand the scope of multilateralism to include social innovation.**

  The EU's RTD Global Approach strategy seeks to lead by example, promoting multilateralism, openness and reciprocity in its cooperation with the rest of the world, which it hopes will achieve a just green transition. While the EU already supports several regional initiatives that encourage social innovation, this remains a large gap in multilateral R&I initiatives. Many initiatives support the advancement of technical solutions but fail to include critical work on social aspects that complement and support technological efforts. Societal innovation, in the context of cities, could greatly support emission reductions by encouraging behaviour change and acceptance of new low-carbon technologies. The EU

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[201] Nguyen, T. 2020. Understanding how city networks are leveraging climate action: experimentation through C40. Urban Transformations. https://urbantransformations.biomedcentral.com/articles/10.1186/s42854-020-00017-7

should harness its knowledge and skills to promote more social innovation efforts within the scope of existing international sectoral initiative it is part of.

- **Capitalise on existing bilateral partnerships with key innovation leaders, but also explore new multilateral collaborations to maximise learning and scaling opportunities.**

  Under its RTD Global Approach strategy, the EU has also forged and nurtured strong bilateral partnerships with key global leaders on critical cooperation areas such as technology and trade compatible with European interests and values and to strengthen the EU’s open strategic autonomy. An excellent is the EU’s relationship with the US (see box below). To respond to the urgency of the net zero challenge, the EU should strengthen its collaboration with existing partners, using existing agreements and MoU to cover also strategic R&I areas where there is clear alignment of priorities and efforts, including key technologies to enable the decarbonisation of hard-to-abate sectors (e.g., industry), such as hydrogen and CCUS.

  Given the uncertain pathway of R&I efforts globally, and the fact that solutions in the sustainability case may not arise from existing bilateral partnerships, the EU should also embrace multilateralism, building a deeper pool of transformative spaces and intermediary actors to maximise learning and scaling.

According to Cleantech Group’s report “Transatlantic Cleantech Investment: Towards a Green Transatlantic Marketplace”, bilateral US-EU flows in R&D are the most intense between any two international partners, and there was a substantial increase in cross-border investment between the EU and US over the past decade. From 2012 to 2022, US investors’ participation in EU cleantech deals increased seven times, while EU investors’ participation in US cleantech deals increased three times. This significant growth in investment activity underscores the growing interest in clean technologies and suggests that investors are actively seeking opportunities on both sides of the Atlantic.

One of the key takeaways from this trend is the mutually beneficial nature of transatlantic investment. US investors are providing much-needed growth capital to European cleantech companies that may struggle to secure sufficient funding locally to scale their operations. This infusion of capital not only aids the growth of European companies but also fosters innovation, which is critical for addressing global environmental challenges. On the other hand, European investors are actively supporting US innovators, thus driving demand for their products and further fuelling innovation in the cleantech sector.

Transatlantic investments have a positive impact on the growth trajectories of cleantech companies. Companies with cross-border investments tend to have faster timelines for achieving growth scale and accessing growth funding. This suggests that collaboration and partnership between key innovation leaders on both sides of the Atlantic are instrumental in accelerating the development and adoption of sustainable and innovative technologies. It is important to capitalize on bilateral partnerships in the cleantech sector. Continued collaboration and partnership will help to enhance innovation by leveraging existing strengths and be essential to meet the urgent environmental challenges facing the world.

Bilateral transatlantic cooperative partnerships can enhance innovation for an accelerated energy system transformation. Effective international cooperation through a rules-based system will be essential for collaboration, particularly in early-stage breakthrough cleantech innovation sectors where success often depends on “open” innovation networks, cross-licensing of intellectual property, knowledge-sharing, and cost-sharing.

For example, to expedite the establishment of strong supply chains for lithium-ion and next-generation batteries, including the critical raw materials segments, the European Commission and the US Department of Energy (DOE) declared in March 2022 that they would support a partnership between the European Battery Alliance and the US Li-Bridge Alliance, covering: Researching next-generation, highly efficient, and environmentally friendly battery technologies; speeding up battery recycling and reuse, including the recovery of critical raw materials; investing in the workforce; and guaranteeing the ethical and sustainable sourcing of critical raw materials. This bilateral collaborative partnership demonstrates how cooperation between key innovation stakeholders, including the private sector and research institutions, may support innovation and sustainable development by combining the distinct strengths of these two ecosystem enablers on either side of the Atlantic.

- **Champion more inclusive cooperation on R&I**

  Growing global calls for more inclusiveness in international R&I initiatives opens a space for the EU to build on its leadership role in international and regional initiatives. Additionally, expanding the geographical scope of existing initiatives and facilitating the participation of countries from the Global South should be supported. This will not only complement the EU’s technical assistance programmes and support to developing countries, but also contribute to its broader climate diplomacy objectives and outcomes.

  The global energy shift is emerging as a significant geopolitical force, altering the power dynamics among regions and nations, and offering the potential of energy independence to various countries.[202] The net zero energy transition creates a new geo-economic era which is fundamentally distinct from conventional ‘fossil-fuel centred’ geopolitical concepts and frameworks (mainly around competition over access to fossil fuels, tensions over natural gas, and disputes/tensions over oil-rich parts of the world). This transformation will potentially reshape the longstanding political order fuelled by new technologies and declining costs, which are increasingly making renewable energy sources competitive with traditional alternatives. In the long run, innovation potential, cheap capital, ability to set standards and certification norms for products and infrastructures; harnessing digitalisation and cybersecurity; control over supply chains of critical materials as well as ability to manage social costs will lead to new landscapes regarding global politics and affect the geopolitical status quo. In this context the EU must engage in new partnerships for R&I and foster new alliances and initiatives to promote multilateral cooperation and boost specific renewable technologies especially in R&I by developing accessible funding mechanisms to

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[202] IRENA, 2019. A new world: The geopolitics of energy transformation. Available at: https://www.irena.org/-/media/files/irena/agency/publication/2019/jan/global_commission_geopolitics_new_world_2019.pdf

support a diverse group of researchers and innovators across continents. Adjusting policies, trade agreements, and regulatory frameworks to accommodate dynamic global energy markets is also recommended to avoid green protectionism[203].

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[203] World Wide Fund for Nature, 2007. Green protectionism: the use of measures for narrow protectionist ends under the guise of addressing legitimate environmental goals. https://www.wto.org/english/forums_e/ngo_e/wwf_greenprotec_e.pdf

8. Conclusions & recommendations

As stated at the start of this report, to seize its "man on the moon moment" and become the first climate neutral continent by 2050, the EU must intensify its efforts and revisit its approach to R&I to ensure it is fit for purpose and well equipped to support the next wave of breakthrough innovations that will be required to achieve climate neutrality in the EU and globally. Through an exploratory research approach, the objective of this report was to test different hypotheses to answer four research questions. This section summarises the study's findings and provides a set of recommendations to inform the design of a future climate neutral R&I agenda for the EU.

1. Solution Landscapes (SLs) for climate neutrality

The SLs were used to map the climate mitigation solutions and R&I areas in a structured way, based on the results of the climate neutrality scenarios analysis. Particular attention was given to the role of GPTs in addressing the identified challenges and supporting the development of new solutions. In total, 17 SLs were designed, resulting in a long list of more than 150 R&I areas with the potential to significantly contribute to climate mitigation efforts. The SLs are discussed in more detail in section 4.2.

2. R&I areas to enable climate neutrality

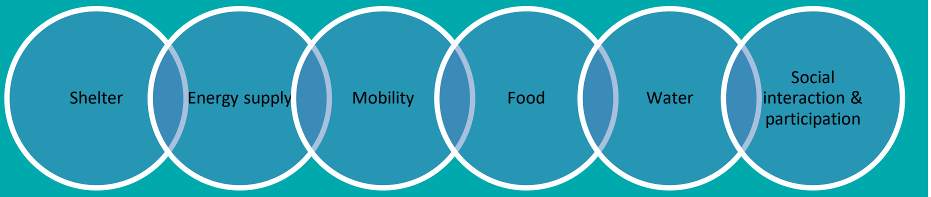
A detailed evaluation framework was designed to screen all R&I areas and identify those with both the highest mitigation potential and the highest need of policy support. The results of the screening provide a composite index which is presented and discussed in section 4.4.

3. A systemic view on societal needs: Three nexuses for climate neutrality R&I actions

The results of the climate neutrality scenarios analysis and the SLs were then confronted with a needs-based approach, which aimed to link specific solutions and R&I areas to broader societal needs that must be met to ensure the successful transformation our economy towards a truly sustainable model.

The transformation of our society towards climate neutrality can be addressed through three nexuses

Overall, the needs that the climate neutral economy will have to meet sustainably to provide a flourishing live for the global population are:



Meeting these needs in a net-zero economy will require thoughtful measures centred on three *nexuses* where technological and societal innovation is possible and required:

- Mobility – Built environment – Energy nexus
- Circularity – Industry – Carbon removals and capture nexus
- Agrifood – Carbon removals nexus

To identify high impact / high risks R&I areas across the three nexuses defined above, the results of the evaluation framework were further developed, focusing on the priority R&I areas emerging from the identified nexuses. The results of this analysis are presented in section 4.5.

4. Challenges and opportunities of breakthrough & disruptive technologies in net carbon removals

Challenges

- Without decisive and tailored R&I support, as well as a clear runway toward long-term policy support, this entire category of solutions could falter;
- The variety of Technology Readiness Level (TRL) profiles calls for different types of interventions, i.e. scientific research vs. regulation and market creation;
- Important challenges are associated with the resource requirements of removals solutions;
- Significant MRV challenges exist across most solutions requiring dedicated R&I efforts; and,
- There is a need to ensure context-appropriate utilisation of this broad cluster of mitigation technologies and practices.

Opportunities

Five SLs were developed to capture the set of R&I areas and the associated opportunities related to net carbon removals. These SLs are presented in detail in a separate Annex containing all 17 SLs. Given the objective to adopt a systemic perspective across the study, these SLs were integrated in the three different *nexuses* described above. It is however important to recognise that net carbon removals SLs are interconnected, both between themselves, as well as with disruptive GPTs. New information and communication channels could for example impact all net carbon removals solution, especially with regards to socio-economic and political aspects of MRV, social acceptance, and regulation.

5. Opportunities and challenges of breakthrough & disruptive GPTs that can be developed and applied for other climate change mitigation purposes

GPTs are innovations that have the potential to significantly impact and transform multiple sectors of the economy and society. These technologies are characterised by their broad applicability, adaptability, and the profound changes they bring about in various industries and aspects of daily life. They often act as catalysts for economic growth, productivity enhancements, and societal progress. They can act as a lubricant for transformation across all nexuses.

Opportunities across nexuses

- GPTs can enable several solutions from different areas to be pushed forward at the same time;
- They can link the various nexuses and adjust for systemic interactions;
- They can support tipping points and corresponding enabling conditions; and,
- GPT development can further accelerate innovation cycles, facilitate the creation of new business models, and cut costs at a faster rate, potentially leading to the triggering of certain tipping points.

Challenges across nexuses

- It is important to identify the most desirable future narrative for each GPT to ensure sustainable use and avoid potential negative impacts on climate change mitigation efforts;
- GPTs create new dependencies and highly complex (and sometimes also unexpected) systemic interactions which may have knock-on consequences in other R&I areas;
- It is necessary to understand the negative, unintended consequences GPTs can bring from a technical, societal and governance perspective and adjust regulatory conditions accordingly; and,
- It is crucial to realise that the adoption of GPTs can affect consumer behaviour and lead to a dramatic increase in energy consumption contributing to a rebound effect.

These unintended negative consequences of GPTs also have to be targeted in the context of the systemic R&I discussed in this study.

6. Integrating systemic interactions of climate mitigation approaches in the design of R&I agendas

Based on the research completed during this study, notably the detailed case studies (presented in section 6) and identifying examples of tipping points and R&I related interventions that can trigger them, the following recommendations were identified to support the integration of systemic interactions of climate change mitigation approaches in the development of R&I agendas.

1. Combine the mission-driven approach with a human need driven agenda and a tipping point framework in the design of R&I programmes, to maximise impact and social benefit

2. **Adopt comprehensive evaluation frameworks to assess the systemic impacts and interconnections of innovative solutions**
3. **Take a systemic approach to identify innovative solutions and their interactions within and across nexuses**
4. **Systematically integrate societal considerations in the design of R&I programmes**
5. **Develop pilot projects which bring multiple innovative solutions together at different scales to fully capture the nature of their interactions**

8. Strengthening EU engagement in international fora to facilitate the rapid development and diffusion of breakthrough solutions

Given the global nature of climate change, international cooperation on climate neutrality R&I has the potential to leverage successful R&I efforts at the global level (and vice versa) and support the rapid development and diffusion of breakthrough solutions. Three main interventions that could be implemented by the EU to improve international cooperation on climate neutrality R&I were identified:

1. **Lead efforts to expand the scope of multilateralism to include social innovation**
2. **Capitalise on existing bilateral partnerships with key innovation leaders, but also explore new multi-lateral collaborations to maximise learning and scaling opportunities**
3. **Champion more inclusive and diversified cooperation on R&I**

In this context the EU must:

- Prioritise actions with third countries on targeted development of high-risk, high-impact technologies to accelerate the innovation cycle by sharing costs, risks, knowledge and capacities.
- Engage in strategic competition focusing on areas of competitive advantage across the international value chain and using its capacity to set norms and standards and track progress based on the annual European Climate Neutral Industry Competitiveness Scoreboard.
- Design actions to support the spread of context-specific zero-carbon innovations in developing and emerging economies (including education, capacity building, technical support, pilots) to advance the global green transition.
- Better integrate R&I policies to the broader framework of external policies including trade and development.

Annexes

Annex 1: Bibliography

Annex 2: Stakeholders Involved

Annex 3: The Evaluation Framework

Annex 4: Detailed Mapping of Initiatives

Annex 5: Solution Landscaping

Annex 1 Bibliography

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Annex 2 Stakeholders Involved

The experts involved in the various consultation phases of this study belonged to different units of the European Commission (DG CLIMA and DG RTD), the Joint-Research Centre (JRC) and its different offices (JRC-ISPRA, JRC Petten), as well as from the European Environment Agency (EEA). Various organisations were also invited to take part in the consultations, as well as national public institutions.

Foresight Workshops

DG RTD and the study team would like to express their gratitude to the European Commission's experts involved in the study, including Enrique Alba, Silvia Bobba, Elisa Boelman, Laurent Bontoux, Marco Buffi, Rene Colditz, Niclas Dzikus , Mathieu Fromentin, Maria Getsiou, Cynthia Latunussa, Paola Lepori, Lorcan Lyons, Alain Marmier, Francesco Matteucci, , Vincenzo Motola, Antonio Pantaleo, Emanuele Quaranta, Rosalinda Scalia, Nicolae Scarlat, Philippe Schild, Frank Smit, and Giulio Volpi; as well as EEA's experts, including Gorka Mendiguren and Mihai Tomescu.

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- Ameresco
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- Bopro
- Breakthrough Energy
- C2CA technology
- Carbon Counts
- Carbon Gap
- Cefic
- Centre for Intellectual Property Policy and Management (CIPPM)
- Chalmers University
- Circular Economy @KTH
- Cleantech Group
- Climate Principles
- Climeworks AG
- Cradle to Cradle Products Innovation Institute
- EIFER
- EIT Food
- Fraunhofer ISI

- Future Food Institute
- Global Maritime Forum
- Hasselt University
- ICF
- IDDRI
- IMI Hydronic Engineering
- KTH – Royal Institute of Technology
- Marble Studio
- Mission Innovation/ Department for Business, Energy and Industrial Strategy
- MVP
- Naked Innovations
- Planet A
- Polytechnic of Turin
- Rocky Mountain Institute
- Rubio
- SITRA
- SNAM
- Trinity College Dublin & Horizon Nua
- University of Bremen
- Utrecht University
- Verkor
- World Fund
- Wuppertal Institute

Final Stakeholder Consultation

The Final Stakeholder Consultation to present the study also saw the participation of some national public governments and institutions, such as the government of France with the Ministry of Higher Education and Research, the government of Ireland with the Department of the Environment, Climate and Communications, the government of Romania with the Ministry of Research, Innovation and Digitalisation, and the government of Spain with research institutions from the Ministry of Science, Innovation and Universities. Also, the Permanent Representation of Belgium to the European Union joined the conference. Additional stakeholders involved in this phase belonged to the following organisations:

- Breakthrough Energy

- CIEMAT
- CSIC
- Eurofer
- European Regions Research and Innovation Network (ERRIN)
- Europeum
- IDAE
- JPI Climate
- Negative Emissions Platform

External reviewers

Overall, the work was developed with the contribution of five external reviewers:

- Marlene Arens (Heidelberg Materials)
- Jan Cornillie (3E)
- Elena López Gunn (ICATALIST)
- Dennis Pamlin (RISE & Mission Innovation NCI)
- Johan Schot (Utrecht University & Deep Transitions Lab)

Annex 3 The Evaluation Framework

Evaluation criteria & qualitative scoring

Each R&I area is assessed against a set of 22 criteria, which are distributed across five pillars reflecting the objectives of the framework. Each criterion is clearly defined and associated with a qualitative scoring methodology distinguishing between poor, average and good performers. An uncertain category was also included in the rating process to reflect the inherent lack of information available about some R&I areas (i.e., Red-Amber-Green-Uncertain rating). The box below provides more details about the process we went through to define these criteria and their rating. below provides a detailed overview of the overall framework.

Key remarks on the design of the evaluation framework

Criteria were developed considering various aspects that were deemed important based on the objective of the study, for the selection of an R&I area: techno-economic, mitigation potential, environmental and socio-economic impact as well as the current level of support. This resulted in developing criteria considering the following five key pillars:

- Techno-economic feasibility: captures how far the R&I area is from being introduced to the market
- Mitigation potential: describes how beneficial the R&I area is in terms of mitigation of key pollutants
- Environmental impact: documents the environmental footprint of the R&I area
- Socio-economic impact: reports the socio-economic footprint of the R&I area
- Current level of support: records the extent to which a given R&I area receives support at the level of Member State, European Union or international

The evaluation framework and the attribution of scores to each R&I area is based on experts judgment. Although the assessment was reviewed by different experts, there is a level of subjectivity to be considered.

The lack of data in some R&I areas related to a specific criterion may challenge the quantitative attribution of a score.

- Not all the criteria are applicable to a certain R&I area.
- The evaluation framework assigned the same weights to all the criteria identified, however a weighting or a prioritisation exercise could be introduced.

Data collection

For the purpose of this evaluation exercise, the authors of the Solution Landscape assessed each of the R&I areas identified within them against the set of 22 criteria discussed above. This assessment was based on a review of the literature and should be considered as an “educated assessment” that could be further refined based on additional research. Following the initial assessment, other experts from the broader study team were asked to review the ratings for each R&I areas.

Numeric value assignment

Following the individual assessment of the R&I areas, a numeric value was assigned to the different ratings to be able to aggregate the assessment of the R&I areas at varying level of details, i.e., criterion, pillar and index level. The following table provides an overview of the numeric values used for that purpose.

Table 13. The rating framework: numeric value assignment

RATING	CONCEPTUAL EQUIVALENT	NUMERIC VALUES
Green	**Reward:** An opportunity for further investment in research has been identified or the R&I area does not benefit from significant support.	5
Amber	**Weak reward**: A barrier to further investment in research has been identified, which may be addressed in the future.	3
Red	**Penalisation**: A significant limiting factor to further investment in research has been identified or the R&I area already benefits from significant support.	1
Uncertain	**Weak reward**: A barrier to further investment in research has been identified, which may be addressed in the future.	2

Aggregation

The evaluation framework performs two steps of aggregation, from Criterion to Pillar, and from Pillar to Index:

- **Criterion to Pillar**: a linear additive aggregation method (sum of criteria) is used for the summation of all criteria under each pillar. This choice of aggregation method allows the assessment of the marginal contribution of each criterion separately from the other criteria included in the same pillar. The implicit assumption that follows the use of this aggregation method is that there is preferential independence – no synergies or conflicts exist between the criteria.
- **Pillar to Index**: A geometric aggregation method (product of criteria) is used for the summation of all pillars to a single score that describes an R&I area. The geometric aggregation is a relatively less compensatory approach, which recognises the existence of synergies and conflicts between pillars. The use of a geometric aggregation has substantial consequences for R&I areas with poor performing pillars. The pillars are given equal weight in the aggregation from pillar to index.

Table 14. Structure of the evaluation framework

CRITERIA	DEFINITION	RAG RATING
Pillar 1 – Techno-economic feasibility: captures how far the R&I area is from being introduced to the market		
1. Simplicity	Is the solution technically simple to operate, maintain and integrate?	• G: The solution is easy to operate, maintain and integrate. • A: The solution demonstrates a limited degree of complexity in terms of operation and/or maintenance but displays ease of integration. • R: The solution is technically complex to operate, maintain and integrate.
2. Scalability	Can the solution technically be scaled up at global level?	• G: There is evidence of realistic potential scale up • A: There is no/ limited evidence of realistic potential scale up • R: There is evidence of no realistic potential scale up
3. Regulatory feasibility	Does the solution face insurmountable regulatory barriers?	• G: Regulatory framework explicitly allowing the deployment of the solution • A: Regulatory framework that does not prevent the deployment of the solution • R: Regulatory framework explicitly preventing the deployment of the solution
4. Financial feasibility	Is there a credible business model for the solution in the long-term?	• G: Demonstrated business model • A: Business model is expected to be demonstrated in the near future • R: Business model has not been demonstrated yet

CRITERIA	DEFINITION	RAG RATING
5. Critical material exposure or availability	Is the solution relying on critical material?	• G: Low resource requirement. • A: Medium resource requirement. • R: High resource requirement.
6. Institutional feasibility	Can the solution be implemented in the existing institutional framework (administrative capacities, ecosystem, etc.)?	• G: Institutional framework explicitly allowing the deployment of the solution • A: Institutional framework that does not prevent the deployment of the solution • R: Institutional framework explicitly preventing the deployment of the solution – risk of carbon lock-in
7. Novelty	How far is the solution from commercialisation?	• G: The solution is at early stage of development (TRL less or equal to 4) • A: The solution is being tested at scale (TRL between 5 and 7) • R: The solution is nearing commercialisation (TRL greater than 7)
Pillar 2 – Mitigation potential: describes how beneficial the R&I area is in terms of mitigation of key pollutants		
8. GHG abatement potential	How important is the GHG abetment potential of the solution?	• G: High abatement potential • A: Medium abatement potential • R: Low abatement potential
9. Contribution to nitrogen and phosphorus pollution	The solution positively or negatively contributes to the nitrogen and phosphorus flows to the biosphere and oceans	• G: Beneficial • A: No significant harm • R: Harmful

CRITERIA	DEFINITION	RAG RATING
10. Contribution to atmospheric aerosol loading	The solution positively or negatively contributes to atmospheric aerosol loading	• G: Beneficial • A: No significant harm • R: Harmful
Pillar 3 – Environmental impact: documents the environmental footprint of the R&I area		
11. Climate change adaptation	The solution positively or negatively contributes to the process of adjustment to the actual and expected climate change and its impacts	• G: Beneficial • A: No significant harm • R: Harmful
12. Sustainable use and protection of water and marine resources	The solution positively or negatively contributes to the environmental status of bodies of water, including marine waters.	• G: Beneficial • A: No significant harm • R: Harmful
13. Circular economy and waste prevention and recycling	The solution positively or negatively contributes to waste prevention and recycling.	• G: Beneficial • A: No significant harm • R: Harmful
14. Pollution prevention and control	The solution leads to a significant increase in the emissions of pollutants into air, water or land	• G: Beneficial • A: No significant harm • R: Harmful
15. Biodiversity and land requirements	The solution requires extensive land use for its implementation	• G: Beneficial • A: No significant harm • R: Harmful
Pillar 4 – Socio-economic impact: reports the socio-economic footprint of the R&I area		

CRITERIA	DEFINITION	RAG RATING
16. Job creation	The solution shows important job creation potential	- G: High job creation potential - A: Medium - R: Low job creation potential
17. Distributional effects	Equity and justice across groups, regions, and generations	- G: Fair and just - A: Not explicitly disadvantageous for certain groups - R: Explicitly disadvantageous for certain groups
18. Social acceptance / public favourability	Extent to which the public supports and understands the consequence of the solution and its implementation	- G: High social acceptance expected - A: Unclear social acceptance - R: Low social acceptance expected likely to prevent the deployment of the solution
19. Resource security (Water-Energy-Food-Ecosystem Nexus)	The solution positively contributes to resource security with a focus on Ecosystem Nexus resources.	- G: The solution positively contributes to Water or Energy or Food security (no negative impacts) - A: The solution does not negatively impact Water, Energy and Food security - R: The solution negatively impacts Water, Energy or Food security
Pillar 5 – Current level of support: records the extent to which a given R&I area receives support at the level of Member State, European Union or internationally		
20. Support at EU level	Level of support provided to the solution in existing R&I programmes	- G: No expressed support, showing a gap in the R&I support landscape - A: Only minor support and/ or supported as a side topic - R: Expressed support, showing the solution is already well covered by existing R&I areas

CRITERIA	DEFINITION	RAG RATING
21. Support at Member State level	el of support provided to the solution in existing R&I programmes	• G: No expressed support • A: Only minor support and/ or supported as a side topic • R: Expressed support
22. Support beyond EU: US, China	el of support provided to the solution in existing R&I programmes	• G: No expressed support • A: Only minor support and/ or supported as a side topic • R: Expressed support

Annex 4 Detailed mapping of international initiatives

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
International Energy Agency (IEA) Technology Collaboration Programmes (TCPs)	Energy Technology - Focus on activities such as research, development, demonstration and analysis, capacity building and dissemination of energy technology.	Global Each TCP is established by at least two IEA member countries. IEA has 30 member countries.	Each TCP has an Executive Committee which consists of representatives designated by participants. The committee oversees decisions on management, participation and implementation. The IEA provides legal advice on processes, procedures and TCP legal structure, but does not provide any direct financial support. The IEA Secretariat provides guidance, advice and support, facilitating the relationship between TCPs and policymakers.	Cooperation between technical experts on specific energy topics.
Mission Innovation (MI)	Energy Technology - MI governments pledged to double their public clean energy research, development and demonstration investment between 2015 - 2020. MI Innovation Challenges cover the entire spectrum of research, development and demonstration from early-stage research needs assessment to technology demonstration projects. Development of strategies for clean energy innovation funding based on	Global 23 countries and the European Commission	Secretariat led by member governments' ministries which are responsible for clean energy innovation and rotating steering committee. Annual Ministerial meeting.	Cooperation between public funders of research and development. Operates through Innovation Challenges (ICs) - global calls to action which are aimed at accelerating the research, development and demonstration in specific technology areas. MI participants have set 8 ICs: Smart grids, off grid access to electricity, carbon capture, sustainable biofuels, converting sunlight, clean energy materials, affordable

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
	individual national resources, needs, and circumstances.			heating and cooling of buildings and renewable and clean hydrogen.
Clean Energy Ministerial (CEM)	Energy Technology - Promote the deployment of clean energy technologies and solutions, share lessons learned, and encourage the transition to a global clean energy economy. Primarily focused on deployment, energy technology innovation is part of the activities of some of the 14 initiatives and 8 campaigns operating today	Global 25 countries and the European Commission	Annual meeting of ministers. CEM Steering Committee- a rotating set of CEM Member Countries providing guidance on the direction and workstreams. Co-chairs are the last and upcoming host of the annual meeting.	Ministers gather to establish clean energy priorities to facilitate clean energy investments and funding in R&D. Members also engage with other ministries which influence the clean energy space, such as ministries of science and technology. Three main mechanisms: high-level policy dialogue, public-private engagement to build cooperation between stakeholders, initiatives and campaigns focusing on clean energy to increase deployment. Example initiative: biofuture platform.
Mission Possible Partnership	Industry - An alliance of climate leaders focused on accelerating efforts to decarbonise seven industrial sectors.	Global Four core partners: the Energy Transitions Commission, RMI, We Mean Business Coalition and the World Economic Forum	Mission Possible Partnership Board and team	Industry-backed, net zero strategies for seven sectors; engagement with policymakers on a 1.5’C future; bring together stakeholders to agree and act on the necessary steps to bring low-carbon products and services to the market at an accelerated pace; engagement with the financial sector to support the role of finance in decarbonisation

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
Energy Transitions Commission	Energy - Committed to achieving net zero emissions by 2050, in line with the Paris climate well below 2'C objective.	Global	Commissioners from a range of organisations (energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs), supported by core and regional teams and Knowledge Partners.	Aiming to inform the decisions of public and private decision makers and support the leaders at the forefront of climate action. Work is focused on three types of programmes: regional programmes, energy programmes and sector decarbonisation programmes.
Global Maritime Forum	Shipping - International not-for-profit organisation committed to shaping the future of global seaborne trade to increase sustainable long-term economic development and human wellbeing.	Global	Governed by a Board of Directors, supported by an Advisory Council of senior stakeholders and leading experts advising the board on the strategic direction, activities, topics, and outcomes and heightens its profile and resources. Also supported by Strategic Partners, Partners, and Project and Knowledge Partners.	Aiming to build a community of leaders and a platform for public and private collaboration to shape the future of global seaborne trade and to make positive change through a high-level meeting annually, alongside working groups and taskforces, exploratory workshops and reports including key findings and recommendations.
International Civil Aviation Authority (ICAO)	Aviation - Its core function is to maintain an administrative and expert bureaucracy (the ICAO Secretariat) supporting these diplomatic interactions, and to research new air transport policy and standardisation innovations as directed and endorsed by governments through the ICAO Assembly, or by the ICAO Council which the assembly elects.	Global 193 national governments	Secretariat consisting of five bureaus: the Air Navigation Bureau, the Air Transport Bureau, the Technical Co-operation Bureau, the Legal Affairs and External Relations Bureau, and the Bureau of Administration and Services	Convenes panels, taskforces, conferences and seminars on priority topics to explore their technical, political, socio-economic and other aspects. It then provides governments with results and advice as they collectively and diplomatically establish new international standards and recommended practices for civil aviation internationally. It also

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
				conducts educational outreach, develops coalitions, and conducts auditing, training, and capacity building activities worldwide per the needs and priorities governments identify and formalise.
Global Cement and Concrete Association (GCCA)	Cement and Concrete - Mission is to position concrete to meet the world's needs for a material that can build and support growing, modern, sustainable and resilient communities.	Global 38 members - Members are producers of Portland cement clinker and other natural cementitious clinkers for the manufacture of cement.	Led by a Board of Directors elected from and by its member companies.	Developed the GCCA Sustainability Charter and Sustainability Guidelines, which underpin the sustainability activity of member companies, setting out what they need to abide by what they measure and how they report their sustainability performance.
UN Innovation Network	Sustainable development - Collaborative community of UN innovators interested in sharing their expertise and experience with others to promote and advance innovation within the UN system.	Global UN Organisations	Chaired by the United Nations Development Programmes (UNDP), UNICEF, and the World Food Programme (WFP)	Hosts regular knowledge sharing sessions to review and discuss the application of new innovation trends and how they can contribute to achieving the SDGs. It also helps Entities share tools, resources and best practices for innovating in the UN. Also engages with senior UN leaders and advises them on how to build structures to promote innovation, activate innovation partnerships and create a culture of innovation in their organisations.

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
Global Covenant of Mayors for Climate and Energy	Local transition - Assists cities and local governments in their transition to a low carbon economy and demonstrate their global impact	Global 7100+ cities	Currently co-chaired by the European Commission Executive Vice President for the European Green Deal and the UN Secretary-General's Special Envoy for Climate Ambition and Solutions. Supported by a Board of regional representatives and the Global Secretariat	A central platform bringing together data on cities' energy and climate actions allowing comparison across other regions and cities
C40	Local transition - Halve the emissions of its member cities within a decade	Global Nearly 100 world leading cities	Led by the C40 chair, an elected leader. Supported by a Steering Committee and a Board of Directors	Operates on performance-based requirements for membership- members must meet the Leadership Standards which set minimum requirements. Hosts annual C40 summit.
Strategic Energy Technology Plan (SET Plan)	Energy Technology - Two key objectives: reduce the cost of clean energy within Europe and Involve EU industry at the forefront of energy technology innovation	EU Member states and other participating countries (Iceland, Norway, Switzerland and Turkey)	Energy Union (launched in 2015- modernising the European economy, converting it to low carbon and increased energy efficiency)	The European Commission established European Industrial Initiatives (EIIs) as public-private partnerships to implement research agendas under the SET plan
European Technology and Innovation Platforms (ETIPs)	Energy Technology - Support the implementation of the SET Plan by providing strategic advice on technical and non-technological areas.	Regional EU Member states and other participating countries (Iceland, Norway, Switzerland and Turkey)	Part of the E-SET (Strategic Energy Technologies) Plan, an Energy Union initiative coordinating low carbon research and innovation activities	Industry-led communities to develop and implement the SET-Plan, aiming to foster innovation in low carbon energy technologies.

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
European Energy Research Alliance (EERA)	Energy Technology - Central role in implementing the SET Plan, acting as an independent advisor.	Regional 250 research centres and universities across 30 countries	President and Vice-President supported by an Executive Committee	Works with industry stakeholders to coordinate research and innovation priorities
European Energy Research Alliance (EERA)	Energy Technology - Central role in implementing the SET Plan, acting as an independent advisor.	Regional 250 research centres and universities across 30 countries	President and Vice-President supported by an Executive Committee	Works with industry stakeholders to coordinate research and innovation priorities
SET Plan Implementation Working Groups (IWGs)	Energy Technology - Implementing the SET Plan's research and innovation activities	Regional SET Plan members. Representatives of the SET Plan countries also attend IWG meetings	Each group governed individually	Working Group meetings to work together to optimise the use of national R&I funding programmes to implement activities
European Research AREA-Net (ERA-Nets)	Energy Technology - Designed to support public-private partnerships in implementation and activities of joint initiatives, aiming to increase the share of funding that Member States dedicate on research and innovation agendas	Regional EU Member states and other participating countries (Iceland, Norway, Switzerland and Turkey)		Networking and other joint activities
Joint Undertaking (JUs)	Energy Technology - Established for the efficient execution of EU, technological development and demonstration programmes	Regional EU and industry-led associations, and other partners	JUs each have their own research agenda	Calls for Proposals defining what funding is awarded to. Also, specifically Joint Technology Initiatives JUs (JTI-JUs) to

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
				implement part of the research agenda for the JTI
International Renewable Energy Agency (IRENA)	Energy Technology - Lead global intergovernmental agency for energy transformation that serves as the principal platform for international cooperation, supports countries in their energy transitions, and provides state of the art data and analyses on technology, innovation, policy, finance and investment.	Global 167 countries and the EU	The Assembly is the main decision-making authority, consisting of one representative from each member. Convenes annually to discuss and decide upon work programme, budget, adoption of reports, applications for membership and potential amendments to agency activities.	Annual assembly brings together 100+ ministers from 170 countries and facilitates ministerial and C-suite level roundtables on specific policy challenges
Global Research Alliance on Agricultural Greenhouse Gases	Food and agriculture - Research into technologies for enhancing carbon stocks	Global 66 members including most of the largest producers and consumers, CGIAR	Governed by the GRA Council, led by the Council Chair and Vice-Chair who are nominated on an annual rotating basis from members	Charter acts as a framework for members to increase cooperation and research investment with the goal of reducing emissions intensity of agricultural practices. Also works on Flagship Projects.
International Advisory Council on Global Bioeconomy	Bioeconomy - Facilitate international collaboration and mutual exchange in all aspects of global relevance for sustainable bioeconomy development.	Global Top level experts on bioeconomy-related policies	Top level experts are elected by the Nominations Committee recommended to the Steering Committee	Members serve for at least 4 years. Develop recommendations and involvement in coordinating regional and national bioeconomy developments.
Food and Agriculture Organisation (FAO)	Food and agriculture - Leads efforts to defeat global hunger	Global 195 members- 194 countries and the EU	Director-General supported by a leadership team, an assistant Director-General and Regional Representatives	While FAO is active across a range of areas, in 2019 the organisation set up the Office of Innovation (OIN). The OIN consolidates FAO's innovation work across

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
				technological, social, policy, institutional and financial innovations. OIN operates through three units: the Secretariat of the Global Forum on Agricultural Research and Innovation (GFAR), the Research Extension Unit (OINR) and the Innovation in Digital Agriculture Unit.
International Bioeconomy Forum (IBF)	Bioeconomy - Launched in November 2017 by the European Commission, a platform aimed at facilitating international cooperation on research and innovation priorities crucial for developing a global, sustainable bioeconomy	Global Canada, European Commission, New Zealand, USA, Argentina, China, India and South Africa	Co-chaired between the European Commission and Canada	A multilateral platform where global research and innovation partners can discuss, coordinate and act on common challenges in the bioeconomy. Currently shaped around four working groups: Plant Health, Information and Communication Technology in Precision Food Systems, the Forest Bioeconomy, and Microbiome. These allow policy makers, researchers and program developers to discuss key issues, common challenges, and potential opportunities in the bioeconomy. IBF activities on bioeconomy indicators are led by FAO, in partnership with the European Commission's Joint Research Centre.
Roundtable on Sustainable	Bioeconomy - Global membership organisation that drives the just and	Global Members are from businesses,	Governed by the Assembly of Delegates, elected by members	Operates innovation programmes through collaboration to support sustainable feedstock production,

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
Biomaterials (RSB)	sustainable transition to a bio-based and circular economy	academia, NGOs, governments and UN agencies		unlock regional potential and advance policy. Framework developed by the multi-stakeholder members, supporting innovative solutions to the climate crisis
Latin American Energy Organisation (OLADE)	Energy - Supports regional and sub-regional energy integration, sustainable development and energy security	Regional 27 member countries from Central and South America and the Caribbean	Executive Secretary elected by the Meeting of Ministers of Energy of Latin America and the Caribbean. Meeting of Ministers is the highest authority body- formulating institutional policy and approval of work plans, budgets, activity reports, balance sheets and financial statements. Council of Experts is responsible for providing technical assistance.	Crafted many partnerships with regional institutions, including with universities such as the University of Chile, to develop and implement research programmes. Also collaborates with other countries bi-laterally such as with GIZ and the Institute of Energy Economics (Germany), IEEJ (Japan, and other regional/international organisations such as IDB, EU and UN
Energy and Climate Partnership of the Americas (ECPA)	Energy - Promotes regional energy co-operation for a clean energy future, with a focus on achieving greater sustainable energy access in Latin America and the Caribbean region. Energy research and innovation is a key priority.	Regional 7 countries in the Americas	Steering Committee to advance EPCA activities. Supported and financed by Organisation of American States members	Focus on R&I. One initiative was the Energy Innovation Centre, financed by the Inter-American Development Bank (IDB), the US Development of Energy (DoE) and other North American partners such as Canada
African Union - European Union Partnership on Climate Change and	Energy - Supports renewable energy and energy efficiency initiatives as well as cross-cutting issues related to climate change and sustainable energy such as human capital	Bilateral African Union and European Union		Operates across 2 pillars: 1) Adapting to and mitigating climate change – Generating and translating climate-related data and applying technological and system solutions that support information

NAME OF INITIATIVE	SCOPE	MEMBERSHIP	GOVERNANCE	DELIVERY MECHANISMS
Sustainable Energy	development, capacity-building, open data and open access			management and dissemination, as well as developing an integrated knowledge approach to climate action. 2) Renewable energy (including developing and integrating renewable energy in the energy system, planning and modelling sustainable energy systems, and strengthening basic research and technological development) and energy efficiency (increasing efficiency of production, promoting energy savings).
Agriculture Innovation Mission for Climate (AIM)	AIM for Climate aims to enhance and expedite investment and assistance for climate-resilient agricultural innovation in three key areas: Advancing fundamental agricultural research at national government and academic institutions to achieve scientific breakthroughs. Supporting applied research in both public and private sectors, including international research centres and laboratories. Facilitating the development, demonstration, and implementation of practical and innovative solutions, knowledge, and services for farmers and market stakeholders, leveraging national agricultural research extension systems.	Joint initiative by the US and UAE – launched at COP 26. Participation is voluntary, there are over 100 members including governments, and private sector stakeholders.		Show strong commitment to boost climate-smart agricultural innovation investment from 2021-2025. Create frameworks for global and national technical collaboration to enhance the impact of investments. Set up structures for collaboration between Ministers, chief scientists, and relevant stakeholders to foster shared research priorities in climate-related agricultural innovation.

Annex 5 Solution Landscapes

A5.1 Solution landscapes driven by techno-economic low-carbon scenarios

This section presents the main findings from the literature review related to R&I areas driven by low carbon techno-economic scenarios. The main goal targeted by the solution landscapes is the future energy system, in particular renewable energy and its grid integration. The latter is also addressed by the R&I areas related to storage and flexibility, thus forming a complicated and highly interconnected solution space to address all relevant techno-economic, but also socio-economic, challenges that need to be addressed towards the stated goal of achieving European climate neutrality.

Furthermore, solution landscapes for the hydrogen economy, green steel, buildings and mobility are also included to obtain a complete picture of the energy system of tomorrow. The combined analysis of these different areas and their respective challenges should make it possible to explore the required long-term research solution space for climate neutrality. In addition, this should also identify possible barriers or unaddressed challenges and enable a mission oriented and strategic research agenda towards climate neutrality.

A5.1.1 Solar PV

A5.1.1.1 Goals and challenges

In most low carbon scenarios, PV and wind will serve as the main renewable energy sources (RES) for affordable and sustainable electricity.[204] To achieve this goal, several challenges must be overcome. In detail, these challenges can be structured according to three sub targets, namely “system integration”, “upscaling”, and “efficiency and price”.

a) System integration

The system integration of RES into the power grid is an important sub-goal and a challenge that cannot be solved by RES technologies alone. Therefore, this goal is also addressed in other solution landscapes such as flexibility, storage and digitalization. This clearly shows the strong interdependencies of the different technologies and solution areas that need to be addressed if any of them are to succeed on the path to a low-carbon future. However, system integration refers not only to the integration of PV and other renewables into the power grid, but also to the integration into our daily lives and infrastructure. It therefore includes besides technical also socio-economic challenges, such as the attractiveness of PV for building owners as well as other flexible use cases (e.g., vehicle integrated PV) - depending on the available technologies.

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[204] VDMA, International Technology Roadmap for Photovoltaics: Results 2021 - 13th Edition 2022.

b) Upscaling

The second sub target is the upscaling of the application of PV technologies to be able to meet future energy demand.[205] This is especially rooted in the increasing electrification which can be seen in most low carbon scenarios and therefore needs a fast and strong upscaling of RES. It is estimated, that by 2050, installed solar panels must reach up to 100 TWp (globally) to have a tangible impact on carbon emissions and our energy mix.[206] Therefore, for a 100% renewable energy economy, a key challenge is to increase the annual production of PV modules to 3–4 terawatts annually by 2040.[207]

To get there, several strongly interlinked challenges have to be addressed: one challenge is the space demand which will be necessary to deploy PV to meet the targeted capacities. This is also part of the challenge of regional constraints, which includes spatial policies, but also geographical constraints.[208] Dependencies can represent a major challenge as well, in terms of resources and materials,[209] but also in a geopolitical context (e.g., import dependencies for various products, parts, or materials). Therefore, the development of appropriate recycling technologies and circular resource flows is also an essential and closely related challenge (see also solution landscape for circular economy). Currently, most of the main PV technologies are restricted by material or resource availabilities.[210] The last important challenge related to upscaling is the availability of skilled workers able to install and maintain the required technologies.[211]

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[205] Kougias, Ioannis; Taylor, Nigel; Kakoulaki, Georgia; Jäger-Waldau, Arnulf (2021): The role of photovoltaics for the European Green Deal and the recovery plan. In: Renewable and Sustainable Energy Reviews 144, S. 111017. DOI: 10.1016/j.rser.2021.111017.

[206] Tao, Meng; Hamada, Hiroki; Druffel, Thad; Lee, Jae-Joon; Rajeshwar, Krishnan (2020): Review—Research Needs for Photovoltaics in the 21st Century. In: ECS Journal of Solid State Science and Technology 9 (12), S. 125010. DOI: 10.1149/2162-8777/abd377. & VDMA, International Technology Roadmap for Photovoltaics: Results 2021 - 13th Edition 2022.

[207] Wilson, Gregory M.; Al-Jassim, Mowafak; Metzger, Wyatt K.; Glunz, Stefan W.; Verlinden, Pierre; Xiong, Gang et al. (2020): The 2020 photovoltaic technologies roadmap. In: Journal of Physics D: Applied Physics 53 (49), S. 493001. DOI: 10.1088/1361-6463/ab9c6a.

[208] Sahoo, Somadutta; Zuidema, Christian; van Stralen, Joost N.P.; Sijm, Jos; Faaij, André (2022): Detailed spatial analysis of renewables' potential and heat: A study of Groningen Province in the northern Netherlands. In: Applied Energy 318, S. 119149. DOI: 10.1016/j.apenergy.2022.119149.

[209] European Commission, Joint Research Centre, Alves Dias, P., Pavel, C., Plazzotta, B., et al., *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system*, Publications Office, 2020, https://data.europa.eu/doi/10.2760/160859

[210] Tao, Meng; Hamada, Hiroki; Druffel, Thad; Lee, Jae-Joon; Rajeshwar, Krishnan (2020): Review—Research Needs for Photovoltaics in the 21st Century. In: ECS Journal of Solid State Science and Technology 9 (12), S. 125010. DOI: 10.1149/2162-8777/abd377.

[211] Kabir, Ehsanul; Kumar, Pawan; Kumar, Sandeep; Adelodun, Adedeji A.; Kim, Ki-Hyun (2018): Solar energy: Potential and future prospects. In: Renewable and Sustainable Energy Reviews 82, S. 894–900. DOI: 10.1016/j.rser.2017.09.094.

c) Efficiency and price

The last sub target is to provide a technical solution which is as efficient and affordable as possible, while still achieving planned deployment targets.[212] This includes not only the efficiency of the energy conversion but also efficient material and resource usage, as well as the profitability of the technologies, which are all necessary for a successful upscaling as described above.[213] Therefore, this is linked to the challenge of finding the most efficient materials, which are also sufficiently abundant to satisfy required market demands and at a reasonable, cost-effective price point. Another challenge is the competition between efficient and sustainable materials. This is because materials used in (early) R&D phases to achieve the best efficiency in energy conversion and functionality may not necessarily be the most sustainable materials (e.g., the use of lead (Pb) in perovskite PV cells).

A5.1.2 Solution and R&I areas

By changing the perspective from the mission/target-oriented view to a technological and solution-oriented view, three different (and broader) solution areas were identified that relate to PV technologies, in the context of achieving an affordable and sustainable electricity source for the future (further solution areas, linked to the same mission/goal are presented in the following chapters). However, the field of photovoltaics is a well-funded topic with numerous research projects already underway.[214] In addition, PV industries still have a learning rate of 24.1%.[215]

a) Cell and module technologies

The first solution area (cell and module technologies) covers the various R&I areas associated with the different cell types that are likely to play an important role in the future. The most important area is still silicon PV cells, the technology that was commercialized the earliest, with a market share of 95% in 2020.[216] Thin film technologies, in contrast, have a market share of only approximately 5% (higher cost and lower efficiency as silicon PV).[217] Therefore, one important aspect is the need to further improve silicon PV technologies (lifetime, price, and further efficiency improvement). A roadmap by Wilson et al. for silicon solar cell development suggests the introduction of passivating contacts to the mainstream high-volume production of PV

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[212] VDMA, International Technology Roadmap for Photovoltaics: Results 2021 - 13th Edition 2022.

[213] Benda, Vítězslav; Černá, Ladislava (2020): PV cells and modules – State of the art, limits and trends. In: Heliyon 6 (12), e05666. DOI: 10.1016/j.heliyon.2020.e05666.

[214] Chatzipanagi, A., Jaeger-Waldau, A., Cleret de Langavant, C., Letout, S., Latunussa, C., Mountraki, A., Georgakaki, A., Ince, E., Kuokkanen, A. and Shtjefni, D., Clean Energy Technology Observatory: Photovoltaics in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/812610, JRC130720.

[215] VDMA, International Technology Roadmap for Photovoltaics: Results 2021 - 13th Edition 2022.

[216] Fraunhofer Institute for Solar Energy Systems, Photovoltaic Report (2022).

[217] Ibidem.

devices, then a possible switch to n-type material and, finally, the introduction of tandem cells (see below).[218]

However, due to material and resource constraints, silicon PV has to be either further developed using sustainable materials,[219] or accompanied by other technologies, such as different thin film technologies or the emerging perovskite cells (see below). Thin film technologies (mainly cadmium telluride (CdTe) and copper indium gallium selenide (CIGS)) are already commercialised. However, they require further research and improvements for increasing their market competitiveness and meeting the required upscaling of capacities. As such, they therefore represent a second important R&I area. In addition, they could also support other areas like building integrated PV.[220] Here, it is important to mention, that several studies have indicated that CdTe PV manufacturing has the lowest environmental footprint compared to other technologies.[221] Further, tellurium (Te) reserves could support up to 10 TW; and the semiconductor materials are well suited for recycling.[222]

As well as the technologies already available on the market, emerging PV technologies could also play an important role in tomorrow's energy system. The most promising are perovskite PV cells, which can also be easily integrated into tandem PVs (see below).[223] Despite the fact that research into perovskite PV is well funded,[224] this technology is rather recent and still has to overcome some major challenges, such as further necessary improvements in stability, but also the toxicity of the materials used (Pb).[225] However, the market success of perovskite and other promising and emerging

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[218] Wilson, Gregory M.; Al-Jassim, Mowafak; Metzger, Wyatt K.; Glunz, Stefan W.; Verlinden, Pierre; Xiong, Gang et al. (2020): The 2020 photovoltaic technologies roadmap. In: Journal of Physics D: Applied Physics 53 (49), S. 493001. DOI: 10.1088/1361-6463/ab9c6a.

[219] Tao, Meng; Hamada, Hiroki; Druffel, Thad; Lee, Jae-Joon; Rajeshwar, Krishnan (2020): Review—Research Needs for Photovoltaics in the 21st Century. In: ECS Journal of Solid State Science and Technology 9 (12), S. 125010. DOI: 10.1149/2162-8777/abd377.

[220] Wilson, Gregory M.; Al-Jassim, Mowafak; Metzger, Wyatt K.; Glunz, Stefan W.; Verlinden, Pierre; Xiong, Gang et al. (2020): The 2020 photovoltaic technologies roadmap. In: Journal of Physics D: Applied Physics 53 (49), S. 493001. DOI: 10.1088/1361-6463/ab9c6a.

[221] Ibidem.

[222] Ibidem.

[223] Commercialization: A Perspective from the United States Solar Energy Technologies Office. In: ACS Energy Letters 7 (5), S. 1728–1734. DOI: 10.1021/acsenergylett.2c00698.; Zhang, Pengyu; Li, Menglin; Chen, Wen-Cheng (2022): A Perspective on Perovskite Solar Cells: Emergence, Progress, and Commercialization. In: Frontiers in Chemistry 10. Online verfügbar unter https://www.frontiersin.org/articles/10.3389/fchem.2022.802890.

[224] Chatzipanagi, A., Jaeger-Waldau, A., Cleret de Langavant, C., Letout, S., Latunussa, C., Mountraki, A., Georgakaki, A., Ince, E., Kuokkanen, A. and Shtjefni, D., Clean Energy Technology Observatory: Photovoltaics in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/812610, JRC130720.

[225] Wilson, Gregory M.; Al-Jassim, Mowafak; Metzger, Wyatt K.; Glunz, Stefan W.; Verlinden, Pierre; Xiong, Gang et al. (2020): The 2020 photovoltaic technologies roadmap. In: Journal of Physics D: Applied Physics 53 (49), S. 493001. DOI: 10.1088/1361-6463/ab9c6a.

technologies such as copper zinc tin sulphide, organic PV, dye-sensitised solar cells or colloidal quantum dot PV is uncertain and, in any case, highly unlikely to take place on a relevant scale in the near future.[226] Therefore, the optimisation of the mature technologies listed above is one major challenge, because they will at least dominate the market over the next three decades.

The fourth R&I area is the development of low-cost, mass market tandem PV technologies. Tandem technologies can increase performance beyond the single junction theoretical limit by the combination of the different (also above mentioned) materials.[227] Therefore, tandem PV can play an important role in the cost reduction of PV through an increase in efficiency.

b) Applications

The second solution area includes various PV applications that could address challenges such as flexibility and space requirements. Here, one important area is the further development of non-traditional module and system designs for applications such as building integrated PV, vehicle integrated PV, floating PV or agrivoltaics.[228] Such applications could contribute to the challenges of upscaling and space demands (e.g. floating PV for countries with high land costs).[229] While some of these applications are already being deployed (floating PV) or well developed across the EU (agrivoltaic), others are still facing challenges, such as a lack of (regulatory) codes and standards for building integrated PV. In addition, there also applications like space-based PV (SBP) for which efforts exist today to deploy first demonstrators and production prototypes by 2040.[230] However, the upscaling of SBP would be a major challenge, so that there have to be doubts as to whether it could have a global impact during this century.[231]

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[226] European Commission, Joint Research Centre, Alves Dias, P., Pavel, C., Plazzotta, B., et al., *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system*, Publications Office, 2020, https://data.europa.eu/doi/10.2760/160859

[227] Wilson, Gregory M.; Al-Jassim, Mowafak; Metzger, Wyatt K.; Glunz, Stefan W.; Verlinden, Pierre; Xiong, Gang et al. (2020): The 2020 photovoltaic technologies roadmap. In: Journal of Physics D: Applied Physics 53 (49), S. 493001. DOI: 10.1088/1361-6463/ab9c6a.

[228] Chatzipanagi, A., Jaeger-Waldau, A., Cleret de Langavant, C., Letout, S., Latunussa, C., Mountraki, A., Georgakaki, A., Ince, E., Kuokkanen, A. and Shtjefni, D., Clean Energy Technology Observatory: Photovoltaics in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/812610, JRC130720.

[229] Tao, Meng; Hamada, Hiroki; Druffel, Thad; Lee, Jae-Joon; Rajeshwar, Krishnan (2020): Review—Research Needs for Photovoltaics in the 21st Century. In: ECS Journal of Solid State Science and Technology 9 (12), S. 125010. DOI: 10.1149/2162-8777/abd377.

[230] Space Based Solar Power - Space Energy Initiative, Space-Based Energy solutions to address global energy challenges

[231] Dotson, David L.; Eddy, Jerry; Swan, Peter (2022): Climate action and growing electricity demand: Meeting both challenges in the 21st century with space-based solar power delivered by space elevator. In: Acta Astronautica 198, S. 761–766. DOI: 10.1016/j.actaastro.2022.05.029.

The second part of this solution area is grid integration/management and storage, to integrate the required large, new and distributed capacities of RES into our energy system.[232] This could include, for example and in combination with other technologies, multiyear storage and storage for regional and global trade of solar electricity but also new applications for in situ or real time consumption.[233] However, they are also addressed in other solution landscapes (e.g. flexibility, storage) as they represent an overarching R&I area with additional challenges, as already described above (in the challenges).

c) Materials/Resources

The third and final solution area deals with materials and resources.[234] Due to the need for a large-scale expansion of PV technologies, combined with the depletion of rare materials, whilst also addressing the sustainability of materials and resources and their usage, this area is essential for climate neutrality.[235]

Given the ambitious goals for photovoltaic growth, it is essential to use sustainable materials that are also abundant on Earth in the quantities needed. Therefore, research is required to replace or avoid costly, rare or unsustainable materials (e.g. for silver, if we want to reach 100 TWp with silicon panels, we have to find five times more silver reserves globally) or at least drastically improve their efficiency.[236] However, sustainability will also become a significant issue for the fabrication of cells and modules (e.g. direct reduction of energy use and decrease of the amount of energy-intensive materials such as crystalline silicon).[237]

According to the International Renewable Energy Agency (IRENA), there will be 6 Mt/year (million metric tons per year) of waste panels in 2050.[238] However, according to

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[232] David, Thamyres Machado; Silva Rocha Rizol, Paloma Maria; Guerreiro Machado, Marcela Aparecida; Buccieri, Gilberto Paschoal (2020): Future research tendencies for solar energy management using a bibliometric analysis, 2000–2019. In: Heliyon 6 (7), e04452. DOI: 10.1016/j.heliyon.2020.e04452.

[233] Tao, Meng; Hamada, Hiroki; Druffel, Thad; Lee, Jae-Joon; Rajeshwar, Krishnan (2020): Review—Research Needs for Photovoltaics in the 21st Century. In: ECS Journal of Solid State Science and Technology 9 (12), S. 125010. DOI: 10.1149/2162-8777/abd377.

[234] European Commission, Joint Research Centre, Alves Dias, P., Pavel, C., Plazzotta, B., et al., *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system*, Publications Office, 2020, https://data.europa.eu/doi/10.2760/160859

[235] Tawalbeh, Muhammad; Al-Othman, Amani; Kafiah, Feras; Abdelsalam, Emad; Almomani, Fares; Alkasrawi, Malek (2021): Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. In: Science of The Total Environment 759, S. 143528. DOI: 10.1016/j.scitotenv.2020.143528.

[236] Tao, Meng; Hamada, Hiroki; Druffel, Thad; Lee, Jae-Joon; Rajeshwar, Krishnan (2020): Review—Research Needs for Photovoltaics in the 21st Century. In: ECS Journal of Solid State Science and Technology 9 (12), S. 125010. DOI: 10.1149/2162-8777/abd377.

[237] Wilson, Gregory M.; Al-Jassim, Mowafak; Metzger, Wyatt K.; Glunz, Stefan W.; Verlinden, Pierre; Xiong, Gang et al. (2020): The 2020 photovoltaic technologies roadmap. In: Journal of Physics D: Applied Physics 53 (49), S. 493001. DOI: 10.1088/1361-6463/ab9c6a.

[238] International Renewable Energy Agency, End-of-Life Management-Solar Photovoltaic Modules (2016).

other sources, by 2050, waste panels are likely to exceed 10 Mt/year.[239] Together with the limited availability of many materials, this underscores the importance of end-of-life PV and recycling of critical materials from PV technologies as R&I areas.[240] One important area is, for example, an efficient and affordable separation of the different materials which have to be recycled.[241]

A5.1.3 Role of disruptive General Purpose Technologies

Artificial Intelligence, as a GPT, has shown to be applicable in multiple aspects of solar energy, such as operation and maintenance (fault detection**)[242],** load forecasting, and weather forecasting to optimise output.[243] Similarly, Blockchain technologies can enable a better integration of solar PV in the grid and in the power markets, by enabling easier determination of proofs of origin, further opening up opportunities for ”green” Power Purchase Agreements (PPAs) at the retail level, and by facilitating energy transactions between end-use consumers. Quantum technologies, such as quantum dot solar cells have been under research for many decades, but are still not commercialised yet- with the progress in quantum research, this might change, however[244]. While also discussed in a previous paragraph, space technologies can prove to further aid solar energy on Earth, not merely by better satellite-based weather forecasting, but also through improvements in solar technologies that are being developed for space applications that might find applications to benefit Earth[245].

A5.1.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

Meng et al stated 2020, that “it is ironic that while we pursue solar photovoltaics for sustainability, almost all of the photovoltaic technologies we have today are unsustainable one way or another. Sustainability requires not only a sustainable energy source but also a sustainable technology to utilize that energy source. The latter has

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[239] Tao, Meng; Hamada, Hiroki; Druffel, Thad; Lee, Jae-Joon; Rajeshwar, Krishnan (2020): Review— Research Needs for Photovoltaics in the 21st Century. In: ECS Journal of Solid State Science and Technology 9 (12), S. 125010. DOI: 10.1149/2162-8777/abd377.

[240] Ibidem.

[241] Ibidem.

[242] Abubakar, A., Almeida, C. F. M., & Gemignani, M. (2021). Review of Artificial Intelligence-Based Failure Detection and Diagnosis Methods for Solar Photovoltaic Systems. *Machines*, *9*(12), 328.

[243] Mellit, A., & Kalogirou, S. (2021). Artificial intelligence and internet of things to improve efficacy of diagnosis and remote sensing of solar photovoltaic systems: Challenges, recommendations and future directions. *Renewable and Sustainable Energy Reviews*, *143*, 110889.

[244] National Renewable Energy Laboratory (NREL), Quantum Dots Promise to Significantly Boost Solar Cell Efficiencies, NREL/FS-6A42-59015, August 2013

[245] Gibney, E., ”Could solar panels in space supply Earth with clean energy”, Nature News Explainer, 2023

been largely overlooked in the 20th century."[246] This sets an important focus for research needs for new solutions to be brought to market by 2040, especially when the technology itself (e.g., photovoltaics) is already relatively mature and widely commercially available. Accordingly, it is extremely important, especially in view of the large capacity build-up of PV, to ensure the sustainability of the technologies and solutions used in this context.

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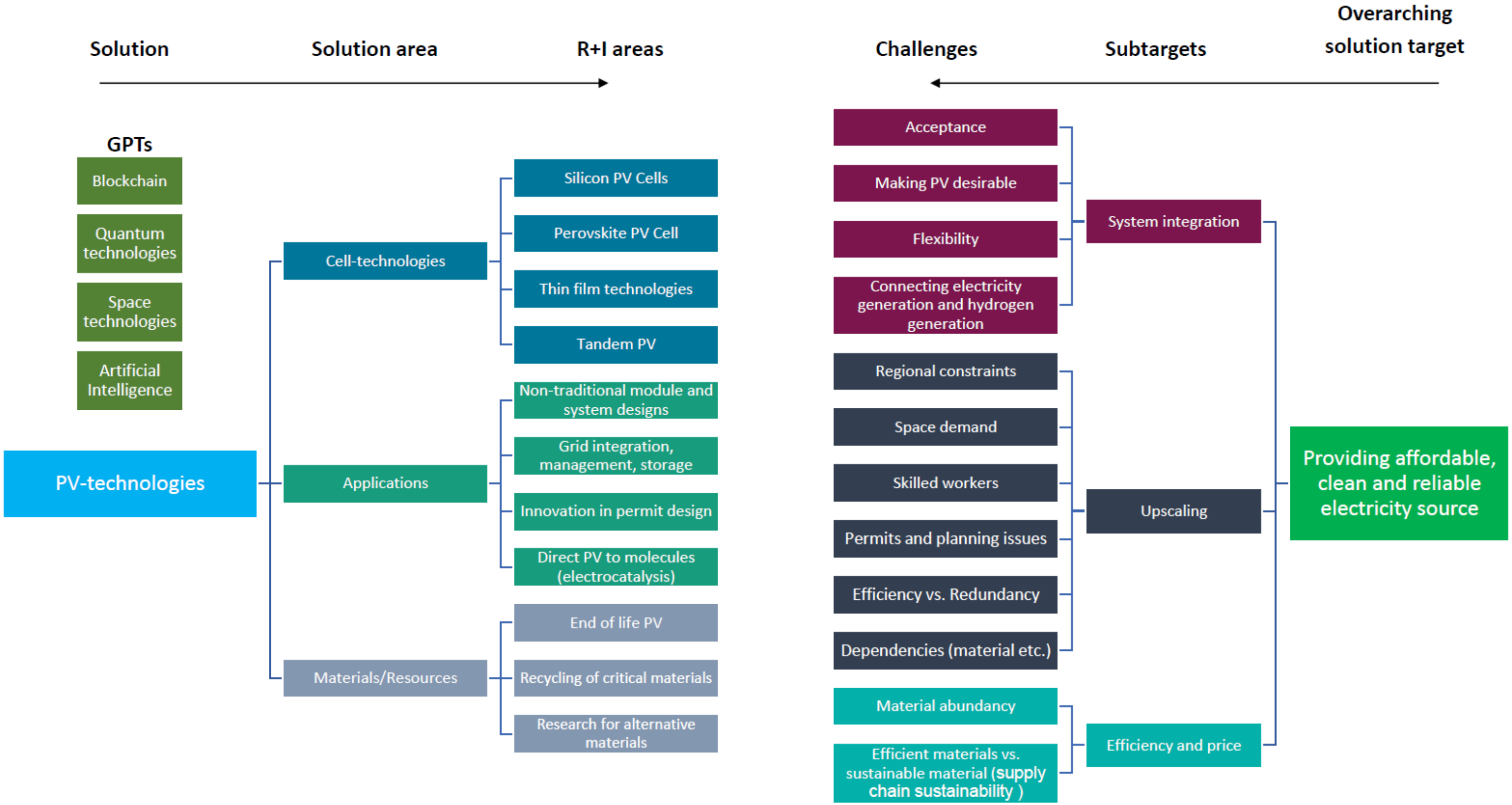
[246] Ibidem.

Figure 1 Solution Landscape Solar PV. Source: ICF & partners, 2023.



A5.1.5 Wind Energy

A5.1.5.1 Goals and challenges

Electricity generated through wind energy has made huge strides in reaching grid parity over the past twenty years, with many wind power installations now becoming competitive without state support[247]. Despite being a mature technology, scientific literature in the field has identified certain goals and challenges.

a) Reaching higher capacity factors

While there is a theoretical limit on the efficiency of wind turbines (59%), many existing wind power generation systems, especially onshore, have not reached this limit. Offshore wind power generation systems fare better in this regard, due to more predictable wind patterns. Adaptation to intermittent wind patterns, especially onshore, is therefore a challenge. The placement of offshore wind turbines is also a challenge to increase efficiency, since the theoretically optimal positioning might be impractical due to other constraints of offshore wind placement (anchoring, maintenance, etc.). Added to this is the challenge of an efficient power transmission system to sub-stations onshore.

b) Structural reliability

Ensuring structural reliability of onshore and offshore wind power installations continues to be a current challenge, especially with active discussions around different anchoring mechanisms of offshore wind platforms, especially floating wind platforms. Resistance of turbine blades to high-speed winds, especially in offshore contexts is also a significant challenge, particularly in the context of maintenance and replacement.

c) Negative environmental externalities

Wind energy continues to face certain negative externalities, particularly when it comes to impacts on birds and marine wildlife. The use of materials for blades, foundations, and masts that do not necessarily have zero embedded carbon continues to be a challenge towards integration into a circular economy involving the recycling and sustainable use of materials, such as cement and steel. However, this does not preclude the possibility of the installation, as a whole, being carbon neutral or even carbon negative.[248]

d) Acceptance

Public acceptance of wind energy, both onshore and offshore, continues to be a barrier to more widespread implementation of wind electricity systems. Concerns about infrasound, as well as the visual impact on the landscape, are important factors. In

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[247] Jansen, M., Staffell, I., Kitzing, L. *et al.* Offshore wind competitiveness in mature markets without subsidy. *Nat Energy* 5, 614–622 (2020). https://doi.org/10.1038/s41560-020-0661-2.

[248] Carrara, S., Alves Dias, P., Plazzotta, B. and Pavel, C., Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, EUR 30095 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-16225-4 (online), doi:10.2760/160859 (online), JRC119941

addition, these concerns are slightly different for offshore and onshore installations, even though they share much in common.[249]

A5.1.5.2 Solution and R&I areas

a) Wind power generator design

Unexpected strong wind speeds can pose structural issues to the functioning of wind turbine blades. Turbine blades hence need to be designed in an optimal way to suit the needs of the particular location, as well as use better weather prediction models (potentially using AI). With the likelihood of extreme weather events due to climate change increasing, this aspect might gain in importance[250].

Wind speeds generally increase exponentially with altitude, and wind power generators are often designed to capitalise on this effect (GE's Haliade-X, the world's first 14MW offshore wind turbine, already operating for two years in Rotterdam, has a rotor diameter of 220m[251]). Innovations are being discussed, however, to take further advantage of this fact by eliminating the solid mast from the wind turbines, hence ending up with airborne wind turbines[252]. On the other hand, akin to biomimicry designs, research is looking at mimicking the capacity of certain trees to withstand high wind speeds and create wind turbine ideas from leaf arrangements[253].

Offshore wind generators have certain advantages, such as being able to be exposed to constantly higher wind speeds than their onshore counterparts. However, stabilising the mast of the wind turbine on the seafloor presents certain challenges. Floating wind turbines have been in development since the past decade, and many designs are at an advanced stage of development, with large-scale demonstration projects already in a commercial, operational phase (e.g. Kincardine Offshore Wind Farm in Scotland uses five WindFloat® units, each with a Vestas 9.5 MW turbine[254]). However, certain designs, such as tension leg platforms (TLPs) are still in early stages of research. Since offshore wind power plants are exposed to rougher conditions than onshore wind plants, research is also going on into finding more optimal maintenance strategies. In addition,

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[249] Langer, K., Decker, T., Roosen, J., & Menrad, K. (2018). Factors influencing citizens' acceptance and non-acceptance of wind energy in Germany. Journal of Cleaner Production, 175, 133-144.

[250] New York State Energy Research and Development Authority (NYSERDA). 2021. "Offshore Wind Climate Adaptation and Resiliency Study," NYSERDA Report Number 21-04. Prepared by ICF International, Inc., Fairfax, VA. nyserda.ny.gov/publications

[251] https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine

[252] Bechtle, P., Schelbergen, M., Schmehl, R., Zillmann, U., & Watson, S. (2019). Airborne wind energy resource analysis. *Renewable energy*, *141*, 1103-1116.

[253] Carré, A., Gasnier, P., Roux, É., & Tabourot, L. (2022). Extending the operating limits and performances of centimetre-scale wind turbines through biomimicry. *Applied Energy*, *326*, 119996

[254] https://www.principlepower.com/projects/kincardine-offshore-wind-farm

transporting and assembling the individual parts of the wind turbine are being optimised, as well as ensuring better grid connection[255].

b) Sustainable Construction

Environmental impacts of wind power generation are, while far lower than fossil fuel sources, not zero. Collaborations of technology researchers with ornithologists and marine biologists, for instance, are already present to assess the impacts, and these may need to be further strengthened[256]. In addition, wind power turbines and generators involve construction of robust sub- and superstructures that share many similarities with the buildings sector (see Solution Landscape for the Built Environment) when it comes to embedded carbon emissions and material criticality[257]. Offshore wind turbines that are in shallow waters still share a public acceptance problem, which has been raised in many other Solution Landscapes[258]. Repowering initiatives for wind turbines might help in a better integration of wind power in the circular economy, as well as in increasing acceptance among the public due to lower noise levels of newer wind turbines, for instance.[259]

c) Grid integration

Wind energy shares some commonalities with other RES, in that they are both intermittent and very location-specific. Therefore, this may result in inefficiencies in the design of the grid around wind turbine or wind farm locations. This requires a flexible grid infrastructure to compensate for the possibility that the major load centres are not necessarily in high wind speed areas. With the advent of the hydrogen economy, research is underway to test the possibility of producing hydrogen through wind energy on-site, which would link it to potential challenges raised in the Solution Landscape on Hydrogen, such as transport and distribution of hydrogen[260].

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[255] Díaz, H.; Serna, J.; Nieto, J.; Guedes Soares, C. Market Needs, Opportunities and Barriers for the Floating Wind Industry. *J. Mar. Sci. Eng.* 2022, *10*, 934. https://doi.org/10.3390/jmse10070934.

[256] Eichhorn, Marcus, et al. “Model-Based Estimation of Collision Risks of Predatory Birds with Wind Turbines.” Ecology and Society, vol. 17, no. 2, 2012. JSTOR, http://www.jstor.org/stable/26269028. Accessed 14 Dec. 2022.

[257] Psomopoulos, C.S.; Kalkanis, K.; Kaminaris, S.; Ioannidis, G.C.; Pachos, P. A Review of the Potential for the Recovery of Wind Turbine Blade Waste Materials. Recycling 2019, 4, 7. https://doi.org/10.3390/recycling4010007

[258] Rand, J., & Hoen, B. (2017). Thirty years of North American wind energy acceptance research: What have we learned?. Energy research & social science, 29, 135-148

[259] Kitzing, L., Jensen, M.K., Telsnig, T. et al. Multifaceted drivers for onshore wind energy repowering and their implications for energy transition. Nat Energy5, 1012–1021 (2020). https://doi.org/10.1038/s41560-020-00717-1.

[260] Schrotenboer, A. H., Veenstra, A. A., uit het Broek, M. A., & Ursavas, E. (2022). A Green Hydrogen Energy System: Optimal control strategies for integrated hydrogen storage and power generation with wind energy. Renewable and Sustainable Energy Reviews, 168, 112744.

A5.1.5.3 Role of disruptive General Purpose Technologies

According to the literature, Artificial Intelligence has the potential to affect multiple aspects of wind energy generation, from the production and maintenance phase of wind turbines[261][262], to better wind forecasting[263], as well as optimised infeed of generated power into the grid based on grid conditions and market prices (load forecasting)[264]. In complement, Blockchain technologies have been mentioned in the literature as a technology that can have wide ranging applications in the wind energy sector, particularly in enabling its integration into the power grid through democratisation of Power Purchase Agreements (PPAs), through a better certification of power sourced by wind energy[265]. And finally, the design of wind turbine blades shares certain aspects in common with technologies commonly used in the aerospace industry (aerodynamics, vibration and fault resistance, etc.). Certain spillovers from improvements in space technology might be very relevant for the wind energy sector[266].

A5.1.5.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

There are two important research areas that might be crucial for wind energy to better contribute to ambitions of climate neutrality. The first concerns the use of sustainable materials for construction, especially the alternatives to cement and steel, so that the construction phase is more sustainable. The second concerns the grid integration of electricity produced by wind turbines, especially those that are offshore. Research is needed, particularly as it concerns integration into the hydrogen economy.

A5.2 Power System Flexibility

Flexibility in energy systems currently plays - and will continue to play - an important role in enabling the integration of intermittent energy vectors in the energy mix of the EU.

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[261] Chatterjee, J., & Dethlefs, N. (2021). Scientometric review of artificial intelligence for operations & maintenance of wind turbines: The past, present and future. Renewable and Sustainable Energy Reviews, 144, 111051.

[262] Marugán, A. P., Márquez, F. P. G., Perez, J. M. P., & Ruiz-Hernández, D. (2018). A survey of artificial neural network in wind energy systems. Applied energy, 228, 1822-1836.

[60] Zhao, E., Sun, S., & Wang, S. (2022). New developments in wind energy forecasting with artificial intelligence and big data: A scientometric insight. Data Science and Management.

[264] Omitaomu, O. A., & Niu, H. (2021). Artificial intelligence techniques in smart grid: A survey. Smart Cities, 4(2), 548-568.

[265] J. Bao, D. He, M. Luo and K. -K. R. Choo, "A Survey of Blockchain Applications in the Energy Sector," in IEEE Systems Journal, vol. 15, no. 3, pp. 3370-3381, Sept. 2021, doi: 10.1109/JSYST.2020.2998791

[266] How a Vibration Problem in a Rocket Could Cut the Cost of Off-Shore Wind Power, , NASA Spinoff Publication, Accessed 07.02.2023, Archived under: https://web.archive.org/web/20230207112026/https://www.nasa.gov/directorates/spacetech/Vibration_Problem_in_Rocket_Could_Cut_the_Cost_of_Off_Shore_Wind_Power/

Flexibility can be understood in a multi-dimensional manner, involving multiple energy vectors, including electricity, heat, gas, and hydrogen.

A5.2.1 Goals and challenges

a) Maintain grid stability

The main objective of flexibility in energy systems and markets is to maintain the stability of the grid so that energy can be supplied in a reliable manner to end consumers. To ensure stability of supply, markets and investment incentives need to be optimised so that actors on the grids receive the right market signals to invest in innovation.[267]

b) Efficient sector coupling

Flexibility also contributes to ensuring the coupling of the power, gas, heat, and hydrogen sectors. This is particularly important in enabling electromobility, for instance, with many applications of peak shaving on power markets involving the charging of electric vehicle batteries, for instance.[268]

c) RES integration into markets

Energy storage continues to be a significant barrier to integrate intermittent RES into the energy system in an optimal manner. Having more capacities for flexibility can help in balancing times of high energy production with periods of low infeed of renewable energy. In addition, the presence of flexibility technologies is essential for the enabling of local energy communities.[269] In addition, enabling flexibility would lead to a better integration of various energy markets throughout the EU, leading to a stronger energy union.

d) Demand side integration

The integration of the demand-side flexibility into energy systems and markets continues to be a significant challenge, since the inflexibility of the demand side, particularly in the residential sector, is partly due to behavioural aspects of end consumers. Integration of the Internet of Things, along with the social acceptance issues it comes with, remains a challenge. In addition, this debate is also associated with questions of energy justice and fairer retail pricing that needs to be kept in perspective.

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[267] Makolo, P., Zamora, R., & Lie, T. T. (2021). The role of inertia for grid flexibility under high penetration of variable renewables-A review of challenges and solutions. *Renewable and Sustainable Energy Reviews*, 147, 111223

[268] Arabzadeh, V., Mikkola, J., Jasiūnas, J., & Lund, P. D. (2020). Deep decarbonization of urban energy systems through renewable energy and sector-coupling flexibility strategies. *Journal of environmental management*, 260, 110090.

[269] Backe, S., Zwickl-Bernhard, S., Schwabeneder, D., Auer, H., Korpås, M., & Tomasgard, A. (2022). Impact of energy communities on the European electricity and heating system decarbonization pathway: Comparing local and global flexibility responses. *Applied Energy*, 323, 119470.

A5.2.2 Solution and R&I areas

Three main solutions in relation to the above challenges are set out in the Solution Landscape (see figure below):

a) Grid efficiency and stability

The infeed of intermittent energy vectors, particularly in the case of renewable electricity, poses important issues of grid stability. This in turn is strategically important, especially to ensure competitiveness of European services and industry. Both the power and gas grids are also strategically important in a geopolitical sense, to ensure energy security. There have been many improvements in demand- and supply-side flexibility, as evidenced by a significant body of literature. Demand-side flexibility will become more important, not only due to an increased flexibility from industry, but also from both the services and residential sectors. Increased technological capabilities, both physical and digital, are necessary to enable higher demand-side flexibility, including intelligent grid management to integrate microgrids and local energy communities, for instance. Increased digitalisation of the grid infrastructure at all levels is a prerequisite for these developments, and is dealt with in Solution Landscape for Digitalisation. Supply-side flexibility is equally important and would incorporate a combination of technological and market measures (such as the enabling of Virtual Power Plants or of flexibility markets) to ensure an efficient response to demand-side flexibility.[270]

b) Storage

Research and innovation in energy storage will continue to be important to ensure a flexible energy system in the EU. Due to its multi-faceted nature, and increased sector coupling and coupling of energy carriers, research into energy storage is varied and incorporates many technology families, including batteries, hydrogen storage, or thermochemical storage. A crucial aspect is to take into account the material flows of critical materials such as cobalt, nickel, or vanadium. Energy storage has been treated in its own Solution Landscape (see section **Error! Reference source not found.**)[271].

c) Dispatchability

Over the long term, increasing the capacities of dispatchable energy sources is extremely important and is to be considered in conjunction with increased capacities in storage and supply-side flexibility. Research in alternative base load technologies to move away from fossil fuels is important not only from a grid management perspective, but also increasingly from an energy security perspective. In addition, unconventional renewable energy sources such as deep geothermal or ocean energy, as well as other

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[270] Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers, International Renewable Energy Agency, Abu Dhabi.

[271] Ibidem.

dispatchable energy sources might be necessary to more efficiently use all available renewable energy potential in the EU[272].

A5.2.3 Role of disruptive General Purpose Technologies

Ensuring flexibility in power grids involves better grid management, and Artificial Intelligence has been shown in the literature to have applications in better load forecasting as well as in enabling more active consumers (on the grid and on the market)[273]. Similarly, blockchain technologies can enable more consumer participation in the grid as well as facilitate transactions of energy between retail consumers that serve to increase flexibility in the power grid and on the power markets[274].

A5.2.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

Increasing capacities for flexibility in energy systems is of extreme importance to attain carbon neutrality, as well as from an energy security perspective. Flexibility has been a subject of intense research in the past decades. However, important gaps exist, particularly when it comes to enabling large- and long-term energy storage (especially in light of limited pumped hydroelectric capacities in different parts of Europe). Better integration of local energy communities, as well as better integration of demand-side flexibility, need further research to contribute fully to carbon neutrality ambitions. Finally, research into more efficient uses of critical materials, and perhaps their alternatives, are absolutely essential to avoid bottlenecks in supply chains that might have far-reaching consequences.

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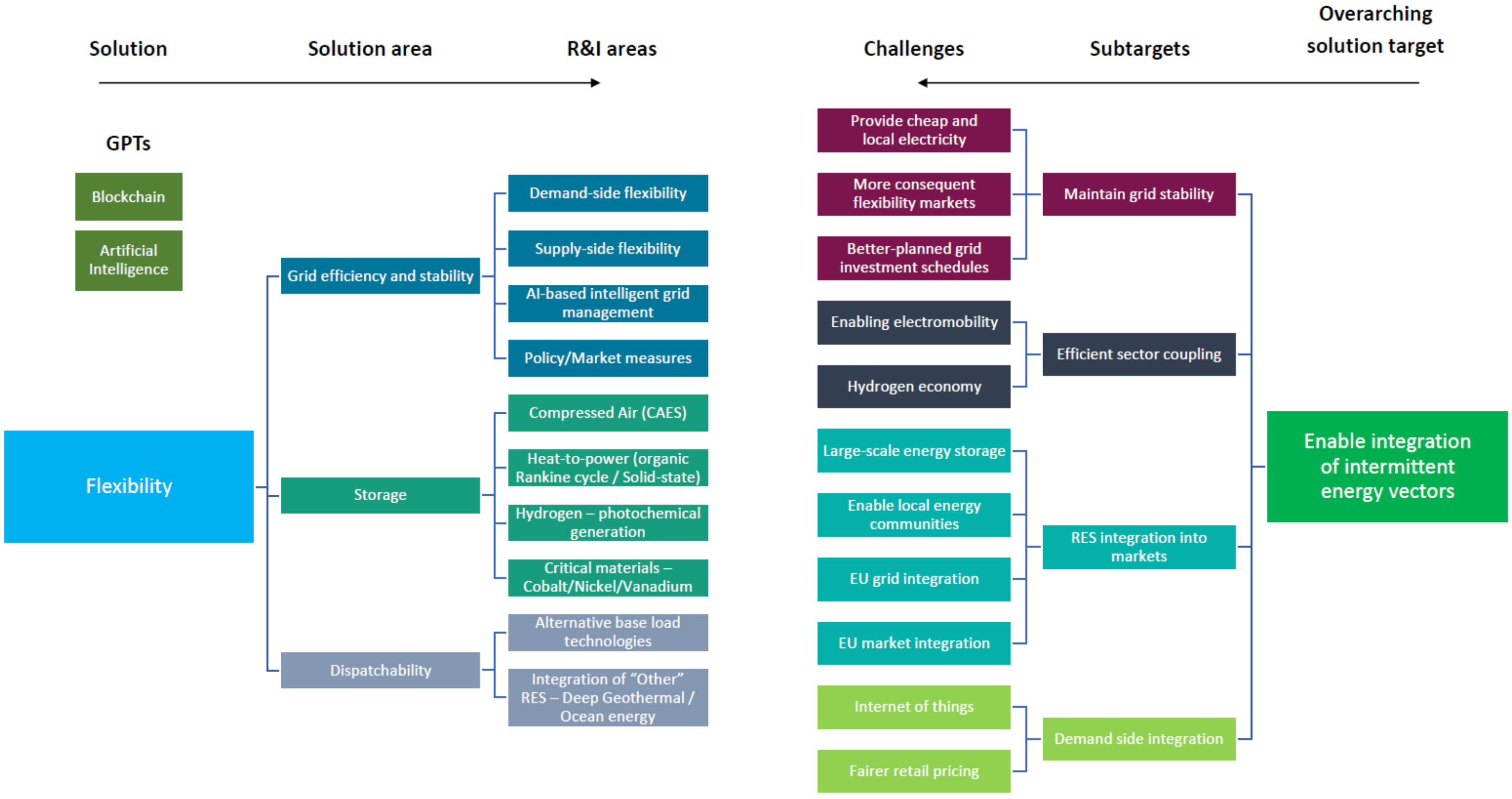
[272] Pablo del Rio, Alexandra Papadopoulou & Nicolas Calvet (2021) Dispatchable RES and flexibility in high RES penetration scenarios: solutions for further deployment, Energy Sources, Part B: Economics, Planning, and Policy, 16:1, 1-3, DOI: 10.1080/15567249.2021.1893044

[273] Omitaomu, O. A., & Niu, H. (2021). Artificial Intelligence Techniques in Smart Grid: A Survey. *Smart Cities*, *4*(2), 548–568. MDPI AG. Retrieved from http://dx.doi.org/10.3390/smartcities4020029.

[274] Basden, J., & Cottrell, M. (2017). How utilities are using blockchain to modernize the grid. Harvard Business Review, 23, 1-8.

Figure 2 Solution Landscape Flexibility. Source: ICF & partners, 2023.



A5.3 Energy Storage

A5.3.1 Goals and challenges:

A major goal to succeed on the path to a European climate neutrality is to enable short- and long-term integration of RES to our energy system. Here, energy storage and other backup solutions are an essential part for the successful management of such[275]. Therefore, this solution landscape is also highly intertwined with other areas, such as flexibility and digitalisation.

However, in the context of this goal, there are also some sub targets and corresponding challenges. While three of these sub targets are more related to grid integration itself (grid stability, integration of renewables, integration of the demand side), the last one (respond to resource shortages) relates to the desired sustainability of the technologies and materials used to achieve the overall target.

a) Maintain grid stability

An important sub target is to maintain grid stability while integrating RES and a more decentralised demand side. Therefore, important challenges are well integrated long-term storage solutions, flexibility markets, as well as grid investment schedules.

b) RES integration into markets

Challenges with regards to the integration of RES are the required large-scale energy storage and the enabling of local energy communities. In addition, the international (European) aspect of this sub target also implies several challenges and a high importance of appropriate governance.

c) Demand side integration

To enable demand-side integration, it is important to address the challenge of flexibility and decentralization, and thus the integration of digital solutions, such as the IoT (see also Solution Landscape for digitalization). In addition, pricing and enabling the participation of all customers (e.g., as prosumers)[276] is also an important aspect.

d) Respond to resource shortages

An overarching sub target for all future technological developments is the appropriate handling of possible resource shortages. Here, an essential challenge is the question of efficient materials vs. sustainable materials. In addition, it is important to avoid self-

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[275] Koskela, Juha; Penttinen, Sirja-Leena; Vesterinen, Taimi; Holttinen, Hannele; Konttinen, Jukka; Järventausta, Pertti et al. (2021): Chapter 5 - The role of energy storage and backup solutions for management of a system with a high amount of variable renewable power. In: Pami Aalto (Hg.): Electrification: Academic Press, S. 105–124. Online verfügbar unter https://www.sciencedirect.com/science/article/pii/B9780128221433000019 .

[276] Prosumagers_Lukas-Kranzl.pdf (newtrends2020.eu)

defeating utilisation of materials and to consider geopolitical constraints (e.g., resource flows and dependencies). European strategic autonomy is wanted.

A5.3.2 Solution and R&I areas

The general solution part for storage can be structured around five different solution areas.

a) Power-to-X

The first solution area, Power-to-X (P2X), includes research, development and deployment of chemical energy storage technologies (CEST).[277] P2X will be a key element for the transition of energy systems towards carbon neutrality, where renewable energy production has to be stored both over a long period of time (seasons) and in large volumes.[278] Therefore, an overarching goal for P2X is to decrease the capital costs and improve process efficiencies to overcome barriers to successful commercialisation.[279] Potential important areas are power-to-fuel and hydrogen storage.[280] However, more specific R&I topics are dependent on the technology chosen (see e.g., Solution Landscape for Hydrogen economy for more specific R&I areas related to hydrogen storage).

Furthermore, P2X also faces some general challenges. These include a significant variety of pathways, uncertainty about the economic drivers, inconsistent policies, as well as spatial and temporal distribution.[281] Therefore, studies on the dynamic behaviour of various P2X pathways, as well as research on more flexible process chains, could be helpful.[282]

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[277] Davies, J., Dolci, F., Klassek-Bajorek, D., Ortiz Cebolla, R. and Weidner Ronnefeld, E., Current Status of Chemical Energy Storage Technologies, EUR 30159 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-17830-9, doi:10.2760/280873, JRC118776. & Daiyan, Rahman; MacGill, Iain; Amal, Rose (2020): Opportunities and Challenges for Renewable Power-to-X. In: ACS Energy Letters 5 (12), S. 3843–3847. DOI: 10.1021/acsenergylett.0c02249.

[278] Frontier Economic (2018): International aspects of a power-to-X roadmap. A report prepared for the World Energy Council Germany. Hg. v. World Energy Council.

[279] Rego de Vasconcelos, Bruna; Lavoie, Jean-Michel (2019): Recent Advances in Power-to-X Technology for the Production of Fuels and Chemicals. In: Frontiers in Chemistry 7. Online verfügbar unter https://www.frontiersin.org/articles/10.3389/fchem.2019.00392.

[280] Arsad, A. Z.; Hannan, M. A.; Al-Shetwi, Ali Q.; Mansur, M.; Muttaqi, K. M.; Dong, Z. Y.; Blaabjerg, F. (2022): Hydrogen energy storage integrated hybrid renewable energy systems: A review analysis for future research directions. In: International Journal of Hydrogen Energy 47 (39), S. 17285–17312. DOI: 10.1016/j.ijhydene.2022.03.208.

[281] Dahiru, Ahmed Rufai; Vuokila, Ari; Huuhtanen, Mika (2022): Recent development in Power-to-X: Part I - A review on techno-economic analysis. In: Journal of Energy Storage 56, S. 105861. DOI: 10.1016/j.est.2022.105861.

[282] Ibidem.

b) Thermal energy storage

Another possibility for energy storage is thermal storage. This could include research for organic Rankine cycles, but also thermochemical storage[283] or compressed air energy storage (CAES).[284] A further possible R&I area here are (flexible) phase change materials (PCMs), especially the emerging class of flexible PCMs which could provide high potential for various smart applications.[285]

c) Batteries

Although the current predominant chemistry of Li-ion batteries (LFP, NCA and NMC622) is the dominant technology and will continue to be so well beyond 2030 (LFP, NMC811+), the parallel development of new battery types is also important. Important technologies which may have a significant increase in importance are sodium-ion, flow batteries and sodium-based technologies.[286] Continued research on different battery technologies is also important, due to the fact that the broad range of possible applications for batteries and energy storage also requires different fit-to-purpose batteries to successfully tackle possible challenges on the pathway to European climate neutrality.[287] Therefore, research into totally new battery types can also contribute to new solutions and applications. Here, a JRC report detected several weak R&I signals concerning possible emerging battery types. Namely, these are: aqueous aluminium ion batteries, calcium batteries, dendrite-free zinc batteries, magnesium metal batteries, potassium metal batteries, sodium CO_2 batteries, zinc CO_2 batteries, and zinc organic batteries.[288]

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[283] Castro Oliveira, Miguel; Iten, Muriel; Matos, Henrique A. (2022): Review of Thermochemical Technologies for Water and Energy Integration Systems: Energy Storage and Recovery. In: Sustainability 14 (12). DOI: 10.3390/su14127506.

[284] Zhou, Qian; Du, Dongmei; Lu, Chang; He, Qing; Liu, Wenyi (2019): A review of thermal energy storage in compressed air energy storage system. In: Energy 188, S. 115993. DOI: 10.1016/j.energy.2019.115993. & Rosa, Mattia de; Afanaseva, Olga; Fedyukhin, Alexander V.; Bianco, Vincenzo (2021): Prospects and characteristics of thermal and electrochemical energy storage systems. In: Journal of Energy Storage 44, S. 103443. DOI: 10.1016/j.est.2021.103443.

[285] Shi, Jinming; Qin, Mulin; Aftab, Waseem; Zou, Ruqiang (2021): Flexible phase change materials for thermal energy storage. In: Energy Storage Materials 41, S. 321–342. DOI: 10.1016/j.ensm.2021.05.048.

[286] Bielewski, M., Pfrang, A., Bobba, S., Kronberga, A., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D., Joanny Ordonez, G., Eulaerts, O. and Grabowska, M., Clean Energy Technology Observatory: Batteries for Energy Storage in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets, EUR 31220 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-56961-9, doi:10.2760/808352, JRC130724.

[287] Lebedeva, N., Ruiz Ruiz, V., Bielewski, M., Blagoeva, D. and Pilenga, A., Batteries - Technology Development Report 2020, EUR 30507 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-27288-5, doi:10.2760/37255, JRC123165.

[288] European Commission, Joint Research Centre, Eulaerts, O., Joanny, G., Fragkiskos, S., et al., Weak signals in science and technologies in 2021: technologies at a very early stage of development that could impact the future, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2760/700257.

An overarching and important aspect for the development of new battery technologies is to ensure the abundance and sustainability of the used materials. In this regard, also R&I for the end-of-life of batteries (e.g., repurposing, recycling) is important, to enable a sustainable and more circular economy in the future.

In addition to battery technologies, this area can also include research into new applications of batteries that support the integration of renewable energy into the power grid. An example of this is the vehicle-to-grid area.

d) Grid integration

The grid integration solution area addresses the challenge of integrating different (new) types of storage into the grid, with the aim of also enabling the integration of RES. The goal is therefore to make the grid more flexible for new use cases (e.g., prosumaging) and to maintain a reliable 24/7 energy supply, while increasing the share of "non-baseload" energy generation. Because of this objective, the solution area is highly intertwined with the other areas of storage, but also with the solution landscapes for flexibility and digitalisation. One example here would be the combination of storage with the IoT and smart (AI) solutions (smart grid) to match demand and supply side. Possible R&I areas can be to implement demand response/demand-side management (DSM) or the topic of seasonal storage. In addition, the development of new business models for energy storage is an important aspect, which also links to the other solution areas.[289]

A5.3.3 Role of disruptive General Purpose Technologies

The role of Artificial Intelligence and Blockchain technologies as applied to energy storage is similar to that covered under the Flexibility Solution Landscape. In addition, there is significant potential of spillovers from research in space technologies towards energy storage (on Earth) since the requirements for energy storage in space are much more stringent, and the learnings from these applications can be used to inspire improvements in electric mobility or electric aviation through lightweight and compact batteries, for instance[290][291]. In addition, improvements in high temperature materials destined for space applications may help energy storage applications such as energy storage in salts that might be limited due to temperature constraints.

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[289] Baumgarte, Felix; Glenk, Gunther; Rieger, Alexander (2020): Business Models and Profitability of Energy Storage. In: iScience 23 (10), S. 101554. DOI: 10.1016/j.isci.2020.101554.

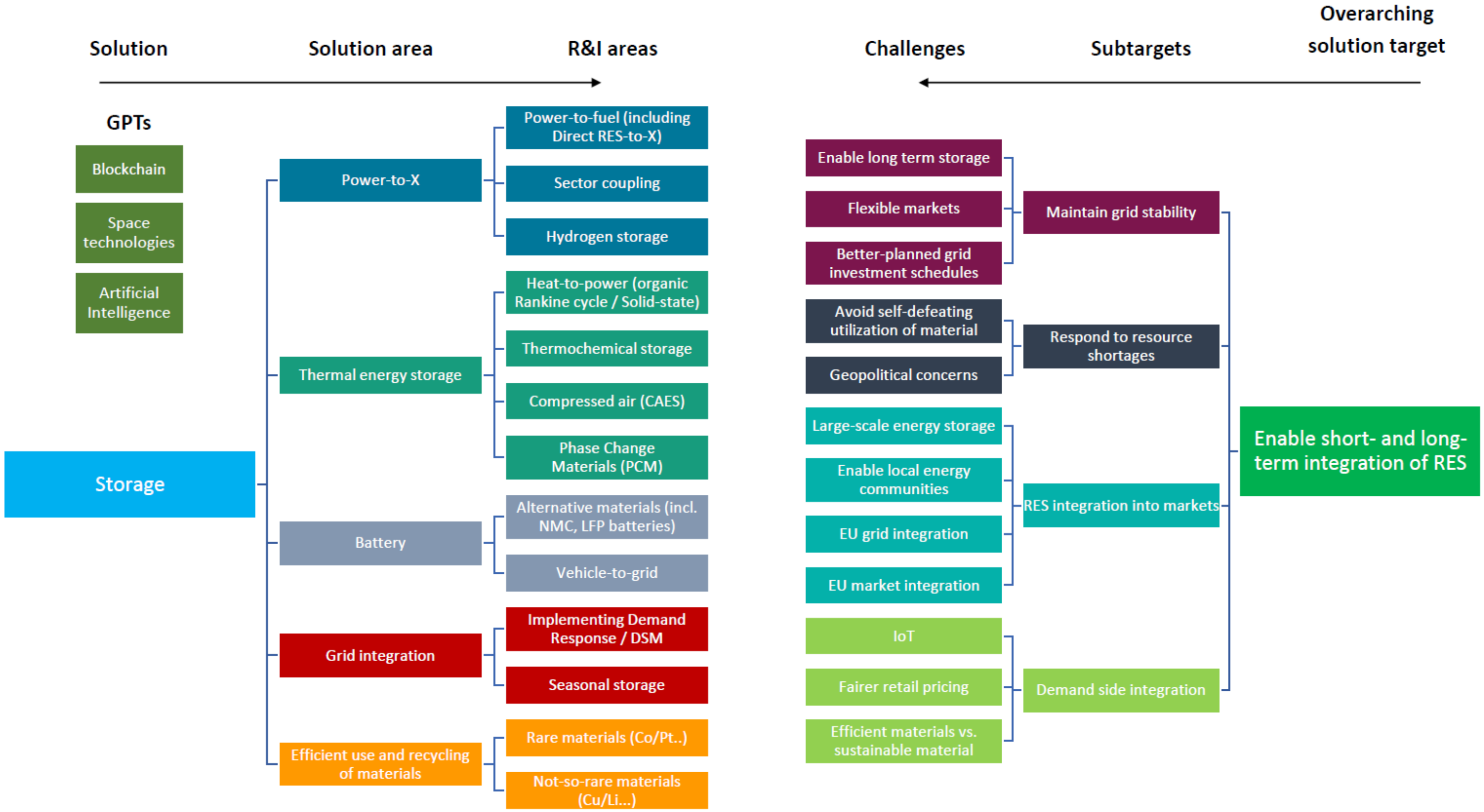
[290] European Commission, ”A tiny battery solution with huge potential for Europe”, MONBASA Project, 2019. Web: https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/tiny-battery-solution-huge-potential-europe.

[291] NASA, ”NASA’s Solid-State Battry Research Exceeds Initial Goals, Draws Interest”, NASA, 2022. Web: https://www.nasa.gov/aeroresearch/nasa-solid-state-battery-research-exceeds-initial-goals-draws-interest.

A5.3.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

The integration of storage solutions into the power grid and their combination with other solution areas (e.g. flexibility, digitalisation) are the most important tasks to enable the integration of renewable energies on a large scale into our future energy system. As also seen in most other solution landscapes, parallel research into more efficient uses of critical materials, and perhaps their alternatives, are absolutely essential to avoid bottlenecks in supply chains that might have far-reaching consequences.

Figure 3 Solution Landscape Storage. Source: ICF & partners, 2023



A5.4 Hydrogen Economy

A5.4.1 Goals and challenges

Even if hydrogen will not be the dominant final energy carrier,[292] it will play a significant role in a climate neutral European energy system of tomorrow.[293] The REPowerEU plan set the ambitious target of 10 million tonnes of renewable hydrogen imports by 2030.[294] Therefore, the establishment of a European hydrogen economy, including all the necessary R&I, as well as an appropriate regulatory framework, is an important task for the next 20 years.

To reach this goal, several relevant sub targets have to be achieved, which are strongly dependent on each other:

a) Upscaling

Upscaling of the hydrogen economy (e.g., production of green hydrogen and replacing grey hydrogen with green hydrogen[295]) is the most important aspect if the above-mentioned European goals are to be achieved. Upscaling depends, in particular, on the appropriate infrastructure; it also implies two more general and overarching challenges that should not be underestimated. These are, first, the cost of CO_2-neutral hydrogen and, second, the regulatory aspects. The rapid diffusion of the hydrogen economy requires a reduction of prices for the desired solutions and an appropriate regulatory framework that facilitates and enables the necessary (long-term) investments.[296]

b) Infrastructure

A major aspect in the scale up is a reasonable infrastructure. One of the mechanisms for achieving this is the European Hydrogen Valleys Partnership, which seek to deploy, in a coordinated manner, entire systems across the value chain, will impact the EU future competitiveness by proving the technical and economic readiness of a hydrogen

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[292] Riemer, M.; Zheng, L.; Pieton, N.; Eckstein, J.; Kunze, R.; Wietschel, M. (2022): Future hydrogen demand: A cross-sectoral, multiregional meta-analysis. HYPAT Working Paper 04/2022. Karlsruhe: Fraunhofer ISI (ed.).

[293] ”Communication COM/2020/301: A hydrogen strategy for a climate-neutral Europe,” 2020.

[294] European Commission (2022): “REPowerEU: Joint European Action for more affordable, secure and sustainable energy,” [Online]. Available: https://eur-lex.europa.eu/legalcontent/EN/TXT/?uri=COM%3A2022%3A108%3AFIN.

[295] Kakoulaki, G.; Kougias, I.; Taylor, N.; Dolci, F.; Moya, J.; Jäger-Waldau, A. (2021): Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. In: Energy Conversion and Management 228, S. 113649. DOI: 10.1016/j.enconman.2020.113649.

[296] Yue, Meiling; Lambert, Hugo; Pahon, Elodie; Roche, Robin; Jemei, Samir; Hissel, Daniel (2021): Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. In: Renewable and Sustainable Energy Reviews 146, S. 111180. DOI: 10.1016/j.rser.2021.111180. & IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen, Licence: CC BY 4.0 & Cleantech Group (2021): Green Hydrogen An industrial leadership opportunity for the EU, https://s3.amazonaws.com/i3.cleantech/uploads/additional_resources_pdf/31/231/Cleantech_for_Europe_-_Green_Hydrogen_Factsheet.pdf

ecosystem, including production, distribution and storage, and final use.[297] Going beyond Hydrogen Valleys to a pan-EU network is also being considered. For example, the cost of constructing a European hydrogen network by 2040 is estimated by the European Hydrogen Backbone project at €80-143 billion.[298]

In addition, this target comes with several urgent challenges. These are the transport itself[299], as well as safe and secure storage solutions.[300] Both are also closely related to the challenge of leakage and potential hydrogen emissions.[301] Here, it is important to mention that the underinvestment in hydrogen infrastructure is a significant source of concern for potential investors[302]

c) Targeted distribution and applications

Given the limited amount of green hydrogen available in the medium term, it is critical to direct the distribution and use of green hydrogen to the most important use cases (for which there are no alternative solutions), in order to maximize the potential impact of the emerging hydrogen economy. This includes, for example, competition between industrial demand and potential use cases in heating and mobility. In all cases, however, it is important to create the appropriate markets.

d) Sustainability

As in other technology-driven solution areas, it is vital to ensure the sustainability of the technological solution itself. This includes, for example, avoiding the use of rare or expensive materials in order to reduce costs and/or dependencies (see below).

e) Energy security and sovereignty

The final sub target is the preservation of energy security and sovereignty. Here, in particular, the EU's competitiveness on global markets and its dependence on critical raw materials or energy imports must be taken into account in all deployment strategies.[303]

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[297] https://s3platform.jrc.ec.europa.eu/hydrogen-valleys

[298] Estimated Investment & Cost | EHB European Hydrogen Backbone.

[299] Ortiz Cebolla, R., Dolci, F. and Weidner Ronnefeld, E., Assessment of hydrogen delivery options, EUR 31199 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-56421-8, doi:10.2760/869085, JRC130442.

[300] IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen, License: CC BY 4.0.

[301] Arrigoni, A. and Bravo Diaz, L., Hydrogen emissions from a hydrogen economy and their potential global warming impact, EUR 31188 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-55848-4, doi:10.2760/065589, JRC130362.

[302] Qazi, Umair Y. (2022): Future of Hydrogen as an Alternative Fuel for Next-Generation Industrial Applications; Challenges and Expected Opportunities. In: Energies 15 (13). DOI: 10.3390/en15134741.

[303] Dolci, F., Gryc, K., Eynard, U., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D., Joanny, G., Eulaerts, O., Grabowska, M., Clean Energy Technology Observatory: Water Electrolysis

A5.4.2 Solution and R&I areas

The general solution part for a future hydrogen economy can be structured along the three solution areas of production, storage and distribution, as well as possible applications. Given the tight timeframe for achieving climate neutrality, the overarching goal of scaling as quickly and efficiently as possible should be kept in mind when selecting and ranking potential areas of R&I.

In addition, Yue et al. have shown, that *“the current status on the system capital cost and hydrogen production cost are still not competitive for the hydrogen’s wide introduction to the industrial deployments and the consumption of water and rare materials have limited the development from the aspect of sustainability”*.[304]

Therefore, it may be important to focus on more advanced technologies, in terms of reducing cost, while also increasing efficiency and stability, to address the various challenges that need to be overcome for the hydrogen economy to have a significant impact on potential climate neutrality pathways. However, a comprehensive summary of the different (emerging) technologies and their TRLs in the context of hydrogen economy is provided in: IEA (2022), Global Hydrogen Review 2022, OECD Publishing, Paris, https://doi.org/10.1787/a15b8442-en.

a) Production

The production of CO_2-neutral hydrogen is strongly linked to other solution landscape areas. For example, a possible increase of the production of green hydrogen is dependent on the capacities of RES (see e.g., Solution Landscape for Solar PV), while blue hydrogen is dependent on the solution areas of CCS (see relevant Solution Landscape). Owing to the urgent scale up, a focus on the improvement of already more mature production technologies and the development of low-cost, high-efficiency electrocatalysts is important to support such efforts.[305]

These are Akaline electrolysis, Polymer Exchange Membrane (PEM) electrolysis, and Solid Oxide electrolysis (SOE). These solutions also provide different advantages and disadvantages: Alkaline electrolysis is well-established but has a lack of flexibility, PEM is more flexible but costly and has issues regarding the durability, while for SOE more R&I actions are required for deploying it at large scale.[306] However, besides these main

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and Hydrogen in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/7606, JRC130683.

[304] Yue, Meiling; Lambert, Hugo; Pahon, Elodie; Roche, Robin; Jemei, Samir; Hissel, Daniel (2021): Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. In: Renewable and Sustainable Energy Reviews 146, S. 111180. DOI: 10.1016/j.rser.2021.111180.

[305] Qazi, Umair Y. (2022): Future of Hydrogen as an Alternative Fuel for Next-Generation Industrial Applications; Challenges and Expected Opportunities. In: Energies 15 (13). DOI: 10.3390/en15134741.

[306] Dolci, F., Gryc, K., Eynard, U., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D., Joanny, G., Eulaerts, O., Grabowska, M., Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/7606, JRC130683.

solutions, there are also some upcoming technologies with a lower Technology Readiness Level.[307] Here, one example is Anion Exchange Membrane electrolysers, which currently has a Technology Readiness Level of 3-5.[308] In general, investment costs for electrolyser plants can be reduced by 40% in the short term and 80% in the long term[309] Two other points which are worth pointing out in the solution area of hydrogen production are the possible optimisation of electrolysers for specific applications in different industries and the importance of learning rates.[310]

b) Storage and distribution

Storage and distribution are two of the main drawbacks for the scale up of the hydrogen economy.[311] Therefore, substantial R&I efforts are required in these areas.

The delivery of compressed hydrogen by pipeline is the most interesting option from an energetic point of view. Furthermore, with respect to cost effectiveness, pipelines will play an important role in many cases.[312] Therefore, R&I for potential materials and technologies is required which are best suited for the expected build up in pipeline infrastructure or the repurposing of the existing one. This solution area also includes possible R&I on different hydrogen carriers (ammonia, methanol, liquid organic hydrogen carriers) and their respective conversion (to or from hydrogen). An example which is already part of the Horizon Europe Framework Programme is low temperature ammonia cracking (TRL 4).[313]

Also, the storage itself has various possible research topics with still lower TRLs. An example are the different types of underground storage.[314]

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[307] IEA (2022), Global Hydrogen Review 2022, OECD Publishing, Paris, https://doi.org/10.1787/a15b8442-en.

[308] Dolci, F., Gryc, K., Eynard, U., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D., Joanny, G., Eulaerts, O., Grabowska, M., Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/7606, JRC130683.

[309] IRENA (2022): Innovation Trends in Electrolysers for Hydrogen Production, International Renewable Energy Agency, Abu Dhabi. online available under: https://www.irena.org/publications/2022/May/Innovation-Trends-in-Electrolysers-for-Hydrogen-Production

[310] IRENA (2020): Green hydrogen cost reduction, International Renewable Energy Agency, Abu Dhabi. online available under: https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

[311] Rasul, M. G.; Hazrat, M.A; Sattar, M. A.; Jahirul, M. I.; Shearer, M. J. (2022): The future of hydrogen: Challenges on production, storage and applications. In: Energy Conversion and Management 272, S. 116326. DOI: 10.1016/j.enconman.2022.116326.

[312] Ortiz Cebolla, R., Dolci, F. and Weidner Ronnefeld, E., Assessment of hydrogen delivery options, EUR 31199 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-56421-8, doi:10.2760/869085, JRC130442.

[313] IEA (2022), Global Hydrogen Review 2022, OECD Publishing, Paris, https://doi.org/10.1787/a15b8442-en.

[314] IEA (2022), Global Hydrogen Review 2022, OECD Publishing, Paris, https://doi.org/10.1787/a15b8442-en.

c) Applications

Hydrogen as an energy carrier has been extensively researched as an alternative to other liquid or compressed energy carriers such as oil and gas, particularly in the mobility sector. Hydrogen therefore can play a significant role in ensuring better sector coupling. As energy carrier, hydrogen is currently estimated to be more adapted to the goods transport sector (or heavy-duty trucks) rather than for personal transport.[315] However, technological change coming from research into hydrogen storage and fuel cells might change these usage patterns, particularly as it concerns aviation or shipping applications.[316] Hydrogen can also play a versatile role in ensuring flexibility in the EU energy system, particularly when it comes to energy storage uses. Widespread industrial use of hydrogen as a replacement of fossil fuels is currently not envisaged (with initial signs being seen in the green steel sector, for instance), but direct use of hydrogen as a reduction agent needs to be studied further to apply to more industrial sectors.

A5.4.3 Role of disruptive General Purpose Technologies

The role of the General Purpose Technologies Blockchain and Artificial Intelligence in enabling a hydrogen economy is similar to the role in providing grid flexibility and storage solutions, as detailed in the respective Solution Landscapes.

A5.4.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

For the hydrogen economy to have a significant impact on the path to climate neutrality in Europe, its scale-up is the most important challenge. Therefore, R&I should focus on advancing solutions for storage and distribution, as well as low-cost and effective production of green hydrogen. This should also facilitate stronger future investments in the hydrogen economy and thus accelerate its expansion.

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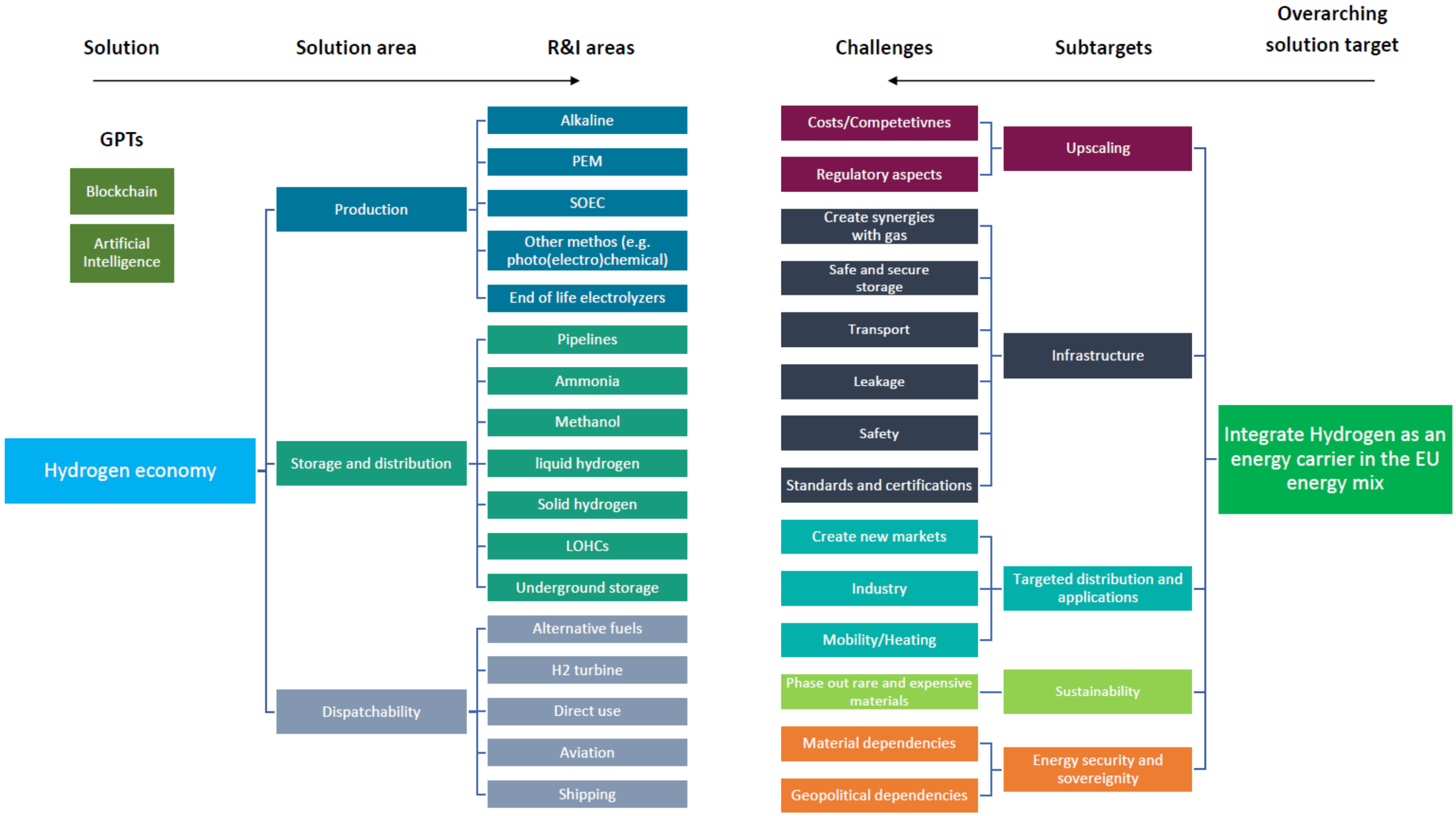
[315] Plötz, P. Hydrogen technology is unlikely to play a major role in sustainable road transport. *Nat Electron* 5, 8–10 (2022). https://doi.org/10.1038/s41928-021-00706-6.

[316] de las Nieves Camacho, M., Jurburg, D., & Tanco, M. (2022). Hydrogen fuel cell heavy-duty trucks: Review of main research topics. *International Journal of Hydrogen Energy*.

Figure 4 Solution Landscape Hydrogen Economy. Source: ICF & partners, 2023.



A5.5 Industrial Decarbonisation

The industry faces a double challenge of being an economic sector that is in dire need of deep decarbonisation, but at the same time, is hard to decarbonise. The principal challenge that leads to the high carbon intensity of the industry is in the use of coal (or other fossil fuels) for industrial processes.

The principal challenge for the industry is therefore the search for alternatives to coal and fossil fuels for various industrial processes (typically associated with reduction). This, however, has the potential to lead to further material dependencies on the alternatives that are found. This will also necessitate modifications to existing processes to make them compatible with other fuels[317].

Due to various improvements in process efficiencies over the years and standardisation of processes, many industrial capital investments are destined for use over long periods of time. These investments might end up as stranded assets that need to be considered when suggesting technical modifications to processes. The question of how and to what extent existing installations and facilities can be repurposed remains relevant.

A third challenge concerns the potentially reduced competitiveness of European industry on the world market as a consequence of increased costs accrued due to decarbonisation of industrial processes. As of 2022, the response of the European Union so far to this question has centred around the implementation of an Emissions Trading System (ETS) in conjunction with a planned rollout of a Carbon Border Adjustment Mechanism (CBAM) to act against carbon leakage. Efforts to decarbonise European industry will undoubtedly be affected by the effectiveness of the ETS and the CBAM, in addition to other policies aimed at strategic ‘net zero’ sectors.

A further challenge concerns the socio-economic impacts (or fallouts) of efforts to decarbonise the industry, namely the labour market impacts. The literature notes that the nature of newly created jobs in sectors destined to be carbon neutral is likely to be more skill-intensive[318], which raises the question of the management of the socio-economic fallouts as far it concerns increasing wage inequalities and the risk of widening existing social inequalities[319]. In addition, the need for new skilled employees, while surely related to the variations in the business cycles, might also prove to be a strategic need in the path towards carbon neutrality.

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[317] Sovacool, B. K., Geels, F. W., & Iskandarova, M. (2022). Industrial clusters for deep decarbonization. *Science*, *378*(6620), 601-604.

[318] Saussay, A., Sato, M., Vona, F., & O'Kane, L. (2022). Who’s fit for the low-carbon transition? Emerging skills and wage gaps in job and data. Working Paper Series, Fondazione Eni Enrico Mattei (FEEM).

[319] Rao, S., Grover, D., & Charlier, D. (2022). Local economic development through clean electricity generation–an analysis for Brazil and a staggered difference-in-difference approach (No. 2022.01). FAERE-French Association of Environmental and Resource Economists.

The overarching solution landscape presented above therefore aims to present an overview of the principal sectors where further technological research might be needed towards a 2050 climate neutrality goal. Following the overview, a specific solution landscape deals with the subject of green steel, and the research needs and opportunities in the cement sector is further elucidated in the solution landscape dedicated to the built environment.

The **steel** industry faces particular challenges when it comes to decarbonisation, but also several potential solutions are under research. They can be broadly categorised under hydrogen reduction or CCS integration. When it comes to the **cement** sector, CCS integration, along with improvements in recycling and the search for alternative binders have been noted in the literature as potential research areas for the future[320]. The **chemicals** industry is harder to generalise, due to the wide nature of processes and chemical manufacturing involved, but CCS integration as well as steps towards green chemistry have been discussed in this context. Other sectors such as glass and ceramics have also been noted in the literature as being important in the context of industrial decarbonisation, however, with a smaller role compared to the steel and cement sectors. While the variety of industrial processes and their individual decarbonisation pathways are hard to summarise, the literature does mention the potentials of increased **electrification** (for heating purposes) and **integration of CCS** solutions as broadly applicable general solutions[321][322]. Finally, as far as other metals (especially those relevant to the energy transition, such as lithium, copper, or cobalt) are concerned, the importance of their integration in a **circular economy** has been specifically noted, which is relevant for the cement and steel sectors as well[323].

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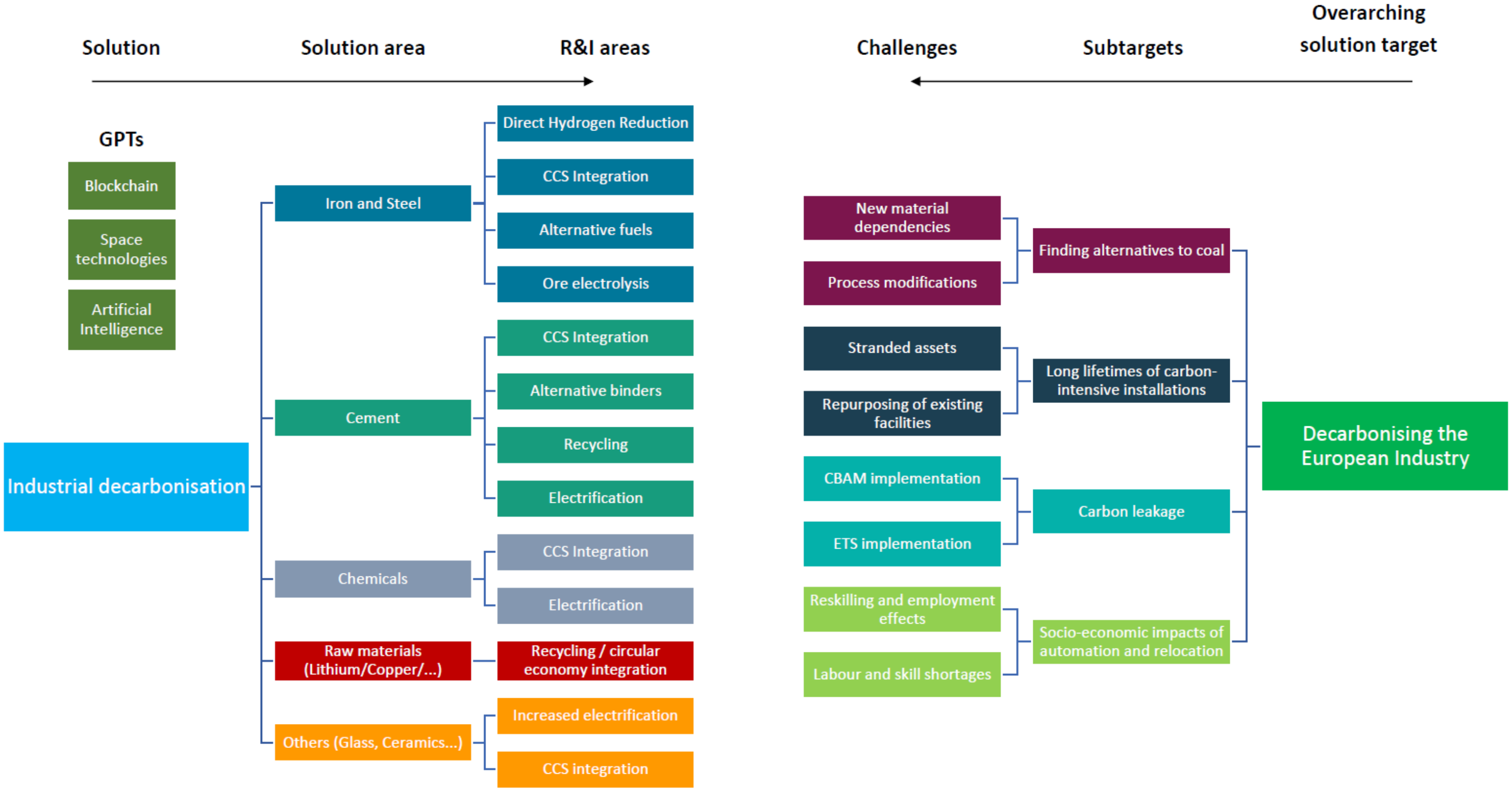
[320] Agora Energiewende, Enabling European industry to invest into a climate-neutral future by 2030, January 2021

[321] Industrial Decarbonization Roadmap, DOE/EE-2365, US Department of Energy, September 2022

[322] European Commission, Directorate-General for Research and Innovation, *ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/92567.

[323] European Commission, Directorate-General for Research and Innovation, *ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/92567.

Figure 5 Solution Landscape Industrial Decarbonisation. Source: ICF & partners, 2023.



A5.6 Green Steel

The steel sector is a significant contributor to industrial GHG emissions, not least due to the importance of steel in the building sector, as well as in other industrial sectors. Decarbonising the sector is therefore identified as a priority towards a carbon neutral future in Europe.[324] Alternatives to steel to reduce consumption (and hence needing to produce less of it) can include wood and other biogenic (i.e. of biological origin) materials as well as other low-carbon materials as alternatives to steel, as has been recognised by efforts to promote the New European Bauhaus, discussed further under the Solution Landscape dedicated to the built environment[325].

A5.6.1 Goals and challenges

a) Reduction of dependence on coke/coal

The main challenge as it pertains to sustainable steel production continues to be the embedded carbon in steel production due to the use of fossil fuels (coke) to reduce iron ore, as well as for the production of high-temperature heat. Developing alternatives to fossil fuels, such as by the use of green hydrogen is the principal challenge in green steel.

b) Integration into the hydrogen economy

Hydrogen, so far, seems to be the most promising candidate to achieve a carbon-free reduction of iron ore, but steelmaking processes need to be adapted in order to integrate hydrogen into the process. This not only involves refitting of furnaces but also ensuring proximity to the hydrogen network.

c) CCS integration

Integration of CCS is also an important way through which steel production could potentially be made carbon neutral. However, it is still unclear in what way and at what cost CCS could be integrated, even though there is an increasing amount of research in this direction.[326]

d) Competitive pricing

A big concern in decarbonising the steel sector concerns the price of the measures that need to be undertaken for carbon neutrality to be achieved. This is particularly relevant

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[324] Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150

[325] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., *Horizon Europe and new European Bauhaus NEXUS report : conclusions of the High-Level Workshop on 'Research and Innovation for the New European Bauhaus', jointly organised by DG Research and Innovation and the Joint Research Centre*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/49925

[326] Griffin, P. W., & Hammond, G. P. (2021). The prospects for 'green steel'making in a net-zero economy: A UK perspective. *Global Transitions*, 3, 72-86.

due to the global nature of iron and steel flows and a strong competition by steelmakers outside the EU, hence putting into question the resilience of the European steel sector to external market and macroeconomic shocks. Ensuring competitiveness, both with traditionally-produced steel as well as with steel from outside the EU might be of strategic importance to the EU, despite measures such as the Carbon Border Adjustment Mechanism (CBAM) being introduced.[327]

A5.6.2 Solution and R&I areas

a) Alternative methods of reduction

A critical step in the steelmaking process is the reduction of iron ore, which is most often done using coke, creating CO_2 as a by-product. A major challenge, therefore, is to decouple the steelmaking process from the use of coke, and fossil fuels in general. Alternative ways of achieving the reduction process are in their initial stages of research or demonstration. The use of hydrogen to reduce iron ore has been one of the major directions that the literature has identified over the past few years. However, there are significant challenges to be overcome, even at the research stage, for hydrogen-reduced-steel to be competitive on the market. The integration of the steel industry in the broader hydrogen economy is of utmost importance for the progress of the steel industry on this pathway - therefore evoking crucial linkages and dependencies on the development of the hydrogen economy in the EU. Infrastructural and logistical issues arising out of integration into the hydrogen economy might risk seeping into the steel sector. Since the transport of compressed hydrogen shares synergies with the transport of natural gas, integration of natural gas in the reduction process of iron ore is also a research area explored by existing literature. Biomass, being a carbonaceous fuel, but having net zero carbon emissions, is also being explored. Finally, an alternative method of reducing iron ore is the (direct) electrolysis of iron oxides in their molten form or in an (alkaline) aqueous form[328]. This eliminates the need for a reduction agent in the process, which could reduce the dependence on hydrogen, which might also face a high demand from other sectors.. A significant challenge in this process, however, are the elevated temperatures that are needed for the electrolysis, which require the R&D of suitable electrolyser and furnace materials.[329]

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[327] Rübbelke, D., Vögele, S., Grajewski, M., & Zobel, L. (2022). Hydrogen-based steel production and global climate protection: An empirical analysis of the potential role of a European cross border adjustment mechanism. *Journal of Cleaner Production*, 380, 135040.

[328] Lopes, D. V., Quina, M. J., Frade, J. R., & Kovalevsky, A. V. (2022). Prospects and challenges of the electrochemical reduction of iron oxides in alkaline media for steel production. Frontiers in Materials, 9, 1010156.

[329] Wiencke, J., Lavelaine, H., Panteix, PJ. *et al.* Electrolysis of iron in a molten oxide electrolyte. *J Appl Electrochem* 48, 115–126 (2018). https://doi.org/10.1007/s10800-017-1143-5

b) Carbon Capture and Storage (CCS) based solutions

A second avenue of research in decarbonising the steel sector is the integration of CCS processes in the traditional steelmaking process. An initial possibility is the direct removal and sequestration of CO_2 emitted from a traditional coking process of iron ore. From the perspective of steel manufacturers, this method would either involve no or minimal adaptations to the input of the steel manufacturing process. Variations include the integration of biomass at the input stage, as well as mineral sequestration of CO_2 integrated in the process.[330] The use of CCS technologies towards carbon neutrality in the EU is set out in detail in section A5.9.

c) Improvements in process efficiency

A third avenue of possible developments in steelmaking are improvements in process efficiency that optimise furnace design or the composition of feedstock to achieve lower overall CO_2 emissions.[331] Research in paired, straight-hearth furnaces indicates that significant cost and efficiency gains might be achieved using pelletised feedstock with coal, and a binder in a bed, with a moving refractory hearth (as an alternative to a traditional rotary hearth process). A further area of research has been in designing more efficient waste heat recovery by thermochemical reformation of the input fuel to increase its calorific value (whereas traditional waste heat recovery stops at the use of heat exchangers to preheat the air input). Plasma direct steel production is also present as an upcoming area for research that involves the use of a hydrogen plasma to directly reduce iron ore by avoiding pre-processing of iron ore feedstock. Another possibility for the improvement of process efficiency lies in the possibility of using scrap steel as feedstock in the steelmaking process. This relates to the broader concept of circular material flows, explored in more detail in a dedicated Solution Landscape for Circular Economy.

A5.6.3 Role of disruptive General Purpose Technologies

Another GPT relevant for the steel sector would be in space technologies that deal with materials in high-temperature applications, since space-based applications often need such materials to withstand extreme temperatures in space as well as upon re-entry to Earth. The potential of research in this field to be applicable to industries such as the steel industry, that might also benefit from high-temperature-resistant materials, has been recognised in the literature[332].

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[330] European Commission, European Research Executive Agency, Vu, H., Cecchin, F., Iacob, N., *Climate-neutral steelmaking in Europe : decarbonisation pathways, investment needs, policy conditions, recommendations*, Stroia, C.(editor), Iacob, N.(editor), Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2848/96439.

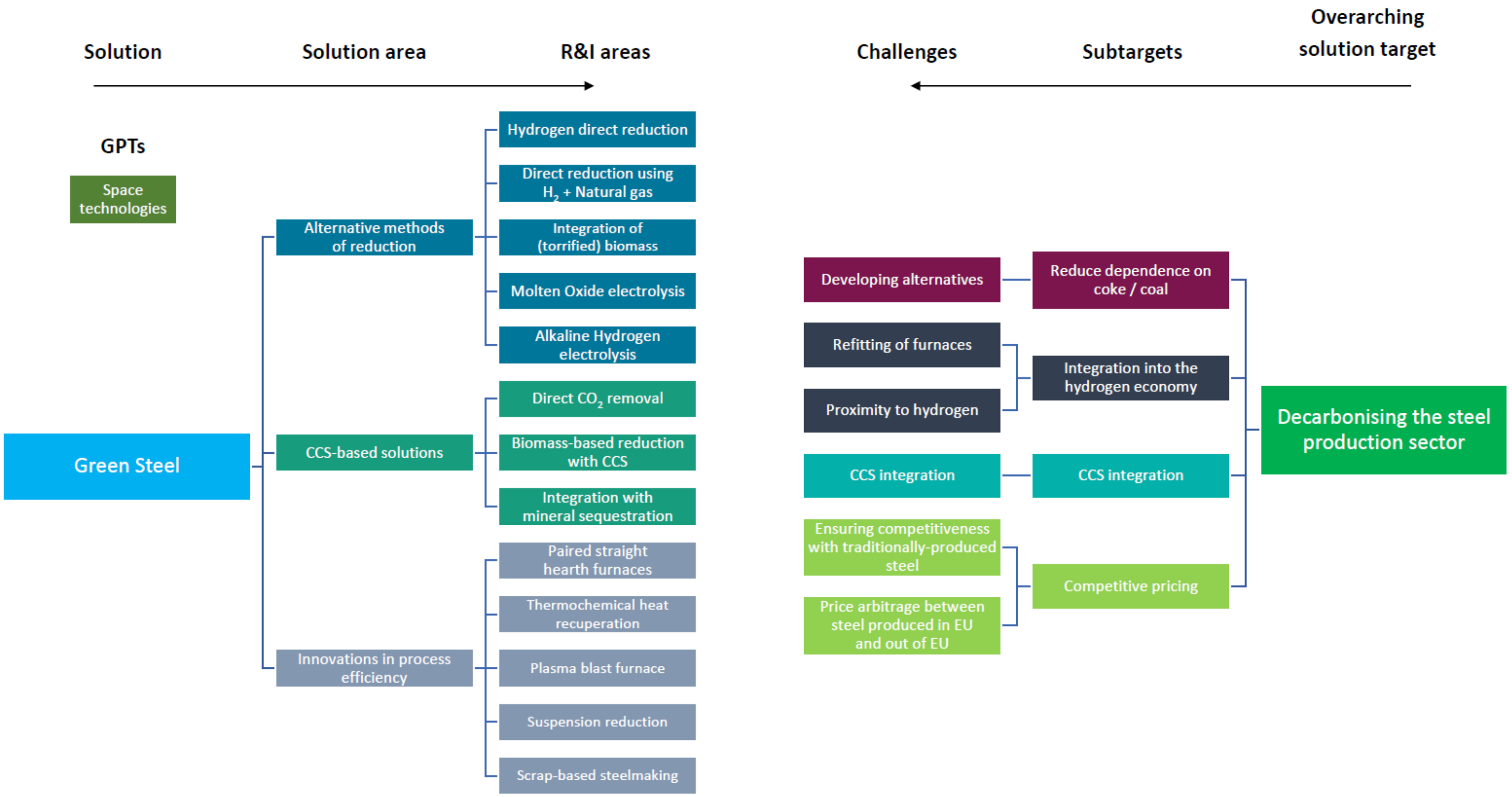
[331] Kim, J., Sovacool, B. K., Bazilian, M., Griffiths, S., Lee, J., Yang, M., & Lee, J. (2022). Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. *Energy Research & Social Science*, *89*, 102565.

[332] Bouslog, S., "High-Temperature Materials", NASA Johnson Space Center, 2021. Web: https://ntrs.nasa.gov/api/citations/20210018710/downloads/High-Temperature%20Materials%20Overview-2021RevA.pdf

A5.6.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

Hydrogen-based reduction of iron ore appears to be the most prominent trend in the steelmaking sector as far as decarbonisation is concerned. Important challenges remain in the integration of the steel sector with the broader hydrogen economy (such as ensuring stable hydrogen supplies through infrastructure and market developments), with significant technological innovation required for green steel to reach market competitiveness, especially as it concerns process improvements. This is particularly considering the geopolitical aspects of steel flows in the world and the increasing strategic importance of the sector to the EU.

Figure 6 Solution Landscape Green Steel. Source: ICF & partners, 2023.



A5.7 Built Environment

The built environment presents an important channel of reduction in carbon emissions towards a climate neutral ambition in 2050. Buildings form the central element in this solution landscape, with construction materials being particularly carbon-intensive, but it is also important to consider buildings in active interaction with the wider built infrastructure, its environment as well as with its users, as noted also by the NEXUS expert report on the New European Bauhaus programme[333]. However, there are several challenges and barriers that currently exist that prevent technological and non-technological innovations from reaching its full potential[334], which are detailed below.

A5.7.1 Goals and challenges

a) Adaptation to climate change effects

Dealing with the direct physical effects of climate change poses a challenge to various aspects of the built environment. Health and safety aspects of buildings and the built environment, particularly in response to more likely climate extremes, are gaining more in importance.[335]

b) Respond to material and human resource shortages

The criticality of materials and resources involved in building construction is an important challenge to address in the built environment. The use of cement, sand, and steel, in particular, is increasingly associated with questions of resource availability and shortages, and is even more critical when associated with supply chains outside the EU. In addition, a higher renovation rate of buildings, likely necessitated by efforts to make them more energy efficient might require increased resource inputs as well as human labour. The supply of both of these might be subject to and sensitive to external shocks.

c) Need for integration of renewable energy solutions

With an objective for carbon neutrality, there is increased focus on the integration of renewable energy sources in the built environment. While the integration of solar PV, for instance, has been already discussed in detail in public and political discourse, other RES technologies such as wind energy are less discussed. In addition, attention needs to be paid to integration of storage solutions including electromobility solutions.

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[333] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., *Horizon Europe and new European Bauhaus NEXUS report : conclusions of the High-Level Workshop on 'Research and Innovation for the New European Bauhaus', jointly organised by DG Research and Innovation and the Joint Research Centre*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/49925.

[334] Sun, Z., Ma, Z., Ma, M., Cai, W., Xiang, X., Zhang, S., Chen, M., et al. (2022). Carbon Peak and Carbon Neutrality in the Building Sector: A Bibliometric Review. *Buildings*, 12(2), 128. MDPI AG. Retrieved from http://dx.doi.org/10.3390/buildings12020128.

[335] Stojanov, R., Duží, B., Daněk, T., Němec, D., & Procházka, D. (2015). Adaptation to the Impacts of Climate Extremes in Central Europe: A Case Study in a Rural Area in the Czech Republic. *Sustainability*, 7(9), 12758–12786. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su70912758.

d) Efficient use (and alternatives to-) of energy-intensive materials

Cement and steel figure not only among the challenges concerning resource shortages, but also when it comes to the relatively high amounts of embedded carbon from the fabrication processes of these materials. Finding alternatives to these materials or finding low-carbon ways of obtaining these (raw) materials is essential to ensuring a low-carbon built environment.

A5.7.2 Solution and R&I areas

a) Architecture

Research and innovation in architecture, i.e. building design, play a key part in pushing the building sector closer towards a carbon neutral pathway, due to its long-lasting effects on the energy consumption profile of buildings. Upcoming architectural innovation programmes, such as the New European Bauhaus demonstrate an increased awareness of energy consumption patterns[336]. Further research in architectural improvements in adaptation to changing user patterns,and the integration of nature-based solutions such as biomimicry, or direct integration of trees and nature into buildings, could lead to a more efficient convergence to carbon neutrality ambitions of the new building stocks to be constructed across Europe in the future, while also increasing the quality of life for the citizen and improving resilience to climate change impacts.[337]

b) Use of sustainable materials

The use of sustainable materials in the built environment is an area of active research that will continue to be important. This is due to the large potentials to reduce the embedded carbon emissions of various components of a building's structure. In particular, alternatives to both cement and steel have proven absolutely necessary to reduce the amount of embedded carbon in buildings. Reuse and recycling of construction materials, while currently being an active area of research, still requires substantial research and innovation to be better integrated into a circular economy. Finally, construction elements base on sustainably harvested wood or other organic materials , which can also temporarily store carbon removed from the atmosphere, have been under discussion as areas of further research, as has been discussed under

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[336] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., *Horizon Europe and new European Bauhaus NEXUS report : conclusions of the High-Level Workshop on 'Research and Innovation for the New European Bauhaus', jointly organised by DG Research and Innovation and the Joint Research Centre*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/49925

[337] Rosado-García, M. J., Kubus, R., Argüelles-Bustillo, R., & García-García, M. J. (2021). A New European Bauhaus for a Culture of Transversality and Sustainability. *Sustainability*, 13(21), 11844. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su132111844.

contexts of the New European Bauhaus[338], with a number of innovative companies pursuing commercial applications. While the materials aspect of the built environment has clear interactions with the industry (including steel and cement, see Solution Landscape concerning Industrial Decarbonisation), the buildings and built environment sector have a distinct role to play on the demand-side of these materials. To this extent this solution landscape refers to solutions that involve more efficient use of resources (including reuse and recycling, where applicable), while remaining distinct from process innovations inherent to the manufacture of steel, cement, or other building materials.

c) Digitalisation

While digitalisation in general is treated in its own Solution Landscape (see section 4.3.3**Error! Reference source not found.**), specific applications include development o f predictive maintenance solutions incorporating elements of AI.[339] This feeds into general, broader applications of building maintenance systems and the integration of energy demand management (through the Internet of Things, for instance), as well as a rising interest in digital twins.[340] Energy management systems to include better load forecasting to optimise energy consumption from the grid, as well as systems that integrate generation forecasting for prosumers (for instance, to integrate weather forecasting for those prosumers with rooftop solar PV installations) present interesting use cases for digitalisation in the built environment.

d) Optimised construction / renovation methods

Starting from the building phase and going beyond, Building Information Modelling (BIM) solutions are an area of current active research that ties in with other digital solutions to make the construction process more efficient. Prefabrication of parts of buildings, automatisation and industrialisation, which are currently at far lower levels than their true potential, also present enormous opportunities in utilising economies of scale to streamline and optimise construction methods and to making retrofits more affordable. There is also discussion in the literature on the specifities and intersections between “no-tech” construction and “high-tech” construction, both potentially being partial solutions[341]. Finally, deep energy retrofits continue to be an active area of research that focuses on the existing building stock to conserve existing characteristics (particularly in the case of

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[338] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., *Horizon Europe and new European Bauhaus NEXUS report : conclusions of the High-Level Workshop on ‘Research and Innovation for the New European Bauhaus’, jointly organised by DG Research and Innovation and the Joint Research Centre*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/49925.

[339] Cheng, J. C., Chen, W., Chen, K., & Wang, Q. (2020). Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Automation in Construction*, 112, 103087.

[340] Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmström, J. (2019). Digital twin: vision, benefits, boundaries, and creation for buildings. *IEEE access*, 7, 147406-147419.

[341] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., *Horizon Europe and new European Bauhaus NEXUS report : conclusions of the High-Level Workshop on ‘Research and Innovation for the New European Bauhaus’, jointly organised by DG Research and Innovation and the Joint Research Centre*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/49925

protected or heritage buildings) to make them radically more energy and resource efficient[342].[343]

e) Urban planning

As with multiple other Solution Landscapes, the integration of RES into new and existing built environments and making the energy supply to buildings low-emission, while preserving aesthetics (hence fostering acceptability), is both a challenge and an active technological research area at the same time.[344] City planning and design that takes into account the proximity of the citizen to nature as well as planning that induces citizens to have a lower carbon footprint are shown in the literature to be in need for further research[345]. Integration with storage solutions, including, but not limited to, electromobility, as well as sector coupling opportunities and low-carbon energy supply such as biomass or district heating. Innovative urban mobility concepts and removing barriers to roll-out of established solutions are, once again, research topics that straddle technological and social innovation research, not only to introduce tangible low-carbon alternatives to internal combustion engine-based mobility, but also to encourage sustainable mobility solutions. Research on enhancing climate resilience is necessary to reduce risks also on climate change mitigation investments.

A5.7.3 Role of disruptive General Purpose Technologies

Artificial Intelligence and blockchain technologies have the potential to play a role in the built environment since they touch upon many aspects of the built environment that would benefit from more accurate predictions (such as electricity load forecasting) and safer transactions and more democratic participation in the energy system (such as in peer-to-peer energy transfers). This also extends to applications such as intelligent road traffic management (which has been researched since many decades)[346] as well as predictive building maintenance[347].

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[342] Sardella, A., Palazzi, E., von Hardenberg, J., Del Grande, C., De Nuntiis, P., Sabbioni, C., & Bonazza, A. (2020). Risk Mapping for the Sustainable Protection of Cultural Heritage in Extreme Changing Environments. *Atmosphere*, 11(7), 700. MDPI AG. Retrieved from http://dx.doi.org/10.3390/atmos11070700

[343] Cabeza, L. F., de Gracia, A., & Pisello, A. L. (2018). Integration of renewable technologies in historical and heritage buildings: A review. *Energy and buildings*, 177, 96-111

[344] Mbungu, N. T., Naidoo, R. M., Bansal, R. C., Siti, M. W., & Tungadio, D. H. (2020). An overview of renewable energy resources and grid integration for commercial building applications. *Journal of Energy Storage*, 29, 101385.

[345] European Commission, Directorate-General for Research and Innovation, Schellnhuber, H., Widera, B., Kutnar, A., et al., *Horizon Europe and new European Bauhaus NEXUS report : conclusions of the High-Level Workshop on 'Research and Innovation for the New European Bauhaus', jointly organised by DG Research and Innovation and the Joint Research Centre*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/49925

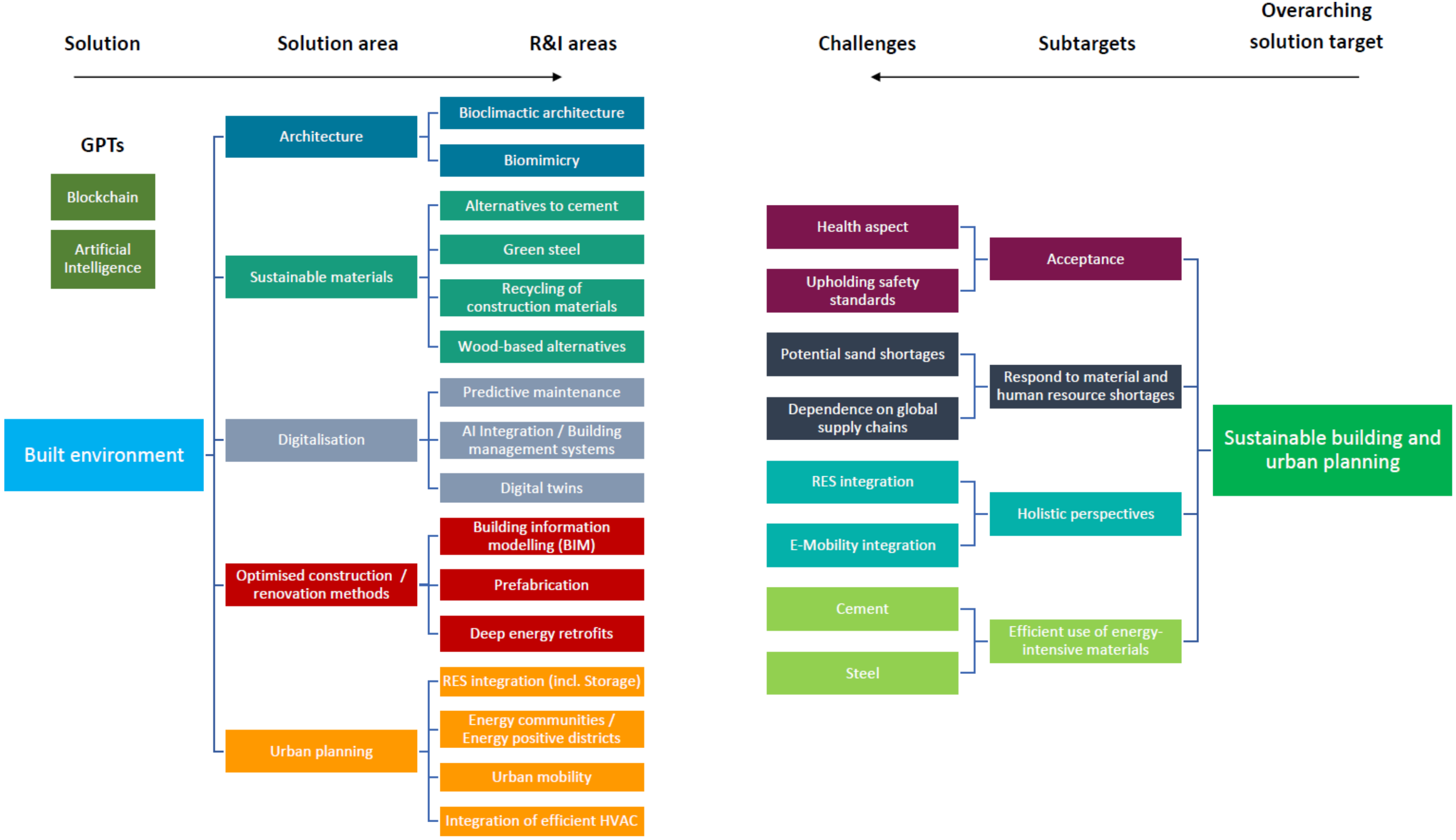
[346] Bielli, M., Ambrosino, G., & Boero, M. (Eds.). (1994). *Artificial intelligence applications to traffic engineering*. Vsp.

[347] Sacks, R., Girolami, M., & Brilakis, I. (2020). Building information modelling, artificial intelligence and construction tech. Developments in the Built Environment, 4, 100011.

A5.7.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

The most important research area in the built environment sector remains the research into ways to make renovations faster, cheaper, better and more convenient for the buildings' users, thus bringing down the CO2 emissions of the building stock. Another important research area is alternative, climate-friendly construction materials. Caution needs to be exercised, however, to ensure that additional resource dependencies do not exacerbate tensions in (global) supply chains, which might particularly be the case for the integration of RES or flexibility technologies.

Figure 7 Solution Landscape Built environment. Source: ICF & partners 2023.



A5.8 Decarbonise mobility

A5.8.1 Goals and challenges

Transport represents 27% of the EU's GHG emissions. It is the only major sector which saw its emission grow in the EU since 1990. Decarbonising the transport sector is therefore a priority for the EU to reach its climate goal.[348] It is also a challenge globally as the amount of goods and people transported around the globe keeps increasing and will continue to do so in the future. Alongside this expected demand growth other factors will impact global transportation patterns including challenges related to demographics, urbanisation, pressure to minimise and dislocate emissions outside urban centres, congestion of aging transport infrastructure and growth in fuel demand.[349] The lack of access to public transport and active mobility infrastructure (for example, cycling infrastructure in cities reduces individual vehicle emissions) and transport services is also a major source of social inequalities reinforcing the need to support a comprehensive transition of the transport sector towards safe, low-carbon solutions for the transport of goods and individuals. This is the overarching target of this solution landscape. For the purpose of this report, this overarching target is broken down in three sub targets, reflecting the Avoid-Shift-Improve framework.[350]

a) Reduce (avoidable) transport (Avoid)

“Avoid" strategies are directed towards reducing the number of trips or trip length.[351] Here we focus on the goal to reduce avoidable vehicle and air travel by:

- Providing safe and well designed infrastructure, coupled with information campaigns, financial incentives, safe parking, and appropriate signage, that will enable readily available alternatives to be more easily and widely adopted for short distance travel (e.g., bike/e-bikes instead of car; cargo bikes instead of vans, etc.).
- Drastically reducing the need for short haul flights (e.g. train instead of plane).
- Improving connectivity between different transport modes (e.g., facilitating multimodal transport information, management and payment or by improving urban planning).

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[348] https://www.transportenvironment.org/challenges/

[349] https://www.worldenergy.org/assets/downloads/wec_transport_scenarios_2050.pdf

[350] https://www.eea.europa.eu/publications/transport-and-environment-report-2021/download

While the Avoid strategies should start by focusing on reducing unnecessary trips, the question about the need to limit overall transport across the globe should also be raised alongside the potential role of R&I in this context.[352]

b) Shift to public, shared and/or non-motorized transport (Shift)

Improving the performance of current transport modes fuelled by fossil fuels will only allow us to address part of the mobility challenge ahead of us (i.e., it will for example not solve issues linked to congestion in urban centres). Across many EU Member States, significant action has already occurred to promote a shift in transport modes, embracing cycling, electro-mobility solutions and walking, which in turn can provide significant health and social benefits. Indeed, there has been a surge in e-bike ownership in the EU, with sales since 2009 of 26 million e-bikes (and 5 million in 2021 alone)[353]. But there is still more that could be done to help enable a more wholesale shift from cars to alternative, low-emission or zero emission transport modes. In many cities/regions of the EU, for this shift to happen, obstacles to roll-out of existing solutions such as improvements in cycling and walking infrastructure must be overcome to enable even greater adoption of micro-mobility solutions, coupled with the development of new solutions, e.g., in terms of IT solutions to facilitate shared ownership (including of autonomous vehicles) or app-based on demand mobility services. For electro-mobility solutions, investment in R&I, including on batteries, is needed as much as any other sector. Important behavioural challenges must be addressed with this set of solutions to make alternatives to individual, motorised transport affordable, attractive, safe and practical compared to individual ownership.[354]

c) Decarbonise existing transport modes (road, air, water) (Improve)

While electric vehicles (EVs) are now being commercialised at scale in Europe and the decision to phase-out of fossil fuel cars by 2035 was enacted earlier this year, this is only part of the story. Looking at private vehicles first, the transition to e-mobility must be underpinned by a green, ethical and world-leading battery supply chain in Europe. This requires advancements in battery technology and recycling to ensure the amount of raw materials required for this transition can be massively reduced. In parallel the supporting charging infrastructure and shared use of vehicles (which will lead to reductions in both resource use and urban space needs) must deployed at scale and solutions must be identified to further diminish the charging time of batteries. This will require the further development and roll-out of strategically located, smart and interoperable infrastructure. At the same time, established alternatives to individual motorized transport like (e-)bikes (including cargo-bikes) need to be rolled out and further developed, together with their infrastructure. For other transport modes, low-carbon alternatives are not commercialised at scale yet (far from it) and R&I efforts must be reinforced to accelerate this transition. This requires looking into alternative fuels (e.g. sustainable aviation fuel,

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[353] https://www.conebi.eu/

[354] https://institute.global/sites/default/files/articles/Planes-Homes-and-Automobiles-The-Role-of-Behaviour-Change-in-Delivering-Net-Zero.pdf and https://www.iea.org/articles/do-we-need-to-change-our-behaviour-to-reach-net-zero-by-2050

hydrogen, e-ammonia) or low-carbon planes (i.e., powered by clean electricity or hydrogen produced using renewable energy) and vessels.[355]

Two challenges requiring particular attention as they span across the different elements listed above are linked to: (1) ensuring the attractiveness of the new low-carbon solution to the end users (e.g., by design, business model or by regulation); and, (2) ensuring the availability of resources required to transform mobility at scale globally.

A5.8.2 Solution and R&I areas:

Decarbonisation presents several challenges, some of which may be overcome with strategic R&I support.[356]

a) Decarbonise individual mobility

Before turning to the need to further support the uptake of electric mobility, R&I efforts linked to the avoidance of individual transport (e.g. by providing alternative to physical travel by for example facilitating online meetings) and modal shift (e.g. by facilitating the shift to existing low-carbon mobility solutions such as walking, bike/ e-bikes, cargo-bikes, etc.) should also be investigated. While these solutions often rely on existing technologies, R&I efforts linked to their uptake and accessibility should not be forgotten, especially as they are often linked to broader question such as urban planning and digitalisation.

Accelerating the electrification of individual mobility requires the development of next-generation charging infrastructure standardised and widely available. The challenge is not only to ensure that charging stations are widely available, accessible and easy to use, but that this infrastructure is meaningfully embedded in the electricity grid of the future.[357] To drastically accelerate the deployment of the charging infrastructure, innovation will be required in areas such as: electrical hardware, controls software, permitting, load management on the grid, wireless or robotic charging, bidirectional and vehicle-to-vehicle charging or battery swapping.[358] Options such as the inclusion of inductive charging embedded in the roadway should also be investigated.

Additionally, the rapid scaling in battery production, including the mining of battery materials, presents significant challenges, as these materials are often extracted in environmentally damaging ways. Research into lower-impact mining processes, as well

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[355] https://www.transportenvironment.org/challenges/planes/ and https://www.transportenvironment.org/challenges/cars/

[356] Grosso, M., Ortega Hortelano, A., Marques Dos Santos, F., Tsakalidis, A., Gkoumas, K., & Pekár, F. (2020). *Innovation Capacity in the Transport Sector: A European Outlook: An Assessment Based on the Transport Research and Innovation Monitoring and Information System (TRIMIS)* (No. EEUR 30326 EN).

[357] Das, H. S., Rahman, M. M., Li, S., & Tan, C. W. (2020). Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. *Renewable and Sustainable Energy Reviews*, *120*, 109618.

[358] https://www.whitehouse.gov/wp-content/uploads/2022/11/U.S.-Innovation-to-Meet-2050-Climate-Goals.pdf

as less harmful battery chemistries, is key.[359] This is discussed in more details under the Solution Landscape for Storage.

b) Decarbonise local and regional transport of goods

To encourage modal switch and the transition away from individual ownerships, solutions in the field of mobility-on-demand and automated & connected vehicles must be further developed and made more attractive to the end users. This concerns both public and private transport. The type of R&I efforts it requires are linked for example to the design of eco-routing algorithms to facilitate on-demand solutions or the development of digital and interoperable infrastructure to facilitate the deployment of automated vehicles.[360]

Another challenge is the electrification of local[361] and long-distance road-based transport of goods.[362,363] This requires the development of high-voltage charging options for electric trucks, properly integrated in the electricity grid.[364] It remains to be seen, whether road-based long-distance ground transport of goods can also make a rapid switch to long-distance electric trucking. Given that battery electric trucks coming onto the market deliver real-world ranges of 800km, this might solely depend on the pace of adoption and the practicality (which again depends on high-voltage charging infrastructure). Minor improvements to battery energy density, driving energy efficiency (tires) and charging speeds (voltage and cooling) could make a big difference in the pace of adoption. The suitability of hydrogen powertrains alongside battery-electric needs to be critically evaluated with a full energy-systems perspective.[365] R&I efforts should also be deployed to develop alternatives to the last miles transport in urban areas.

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[359] Alves Dias, P., Bobba, S., Carrara, S., & Plazzotta, B. (2020). The role of rare earth elements in wind energy and electric mobility. *European Commission: Luxembourg*.

[360] https://www.whitehouse.gov/wp-content/uploads/2022/11/U.S.-Innovation-to-Meet-2050-Climate-Goals.pdf

[361] Gkoumas, K., Stepniak, M., Cheimariotis, I., Marques dos Santos, F., Grosso, M., & Pekár, F. (2022). *Research and Innovation in Urban Mobility and Logistics in Europe: An Assessment Based on the Transport Research and Innovation Monitoring and Information System (TRIMIS)* (No. EUR 31197 EN).

[362] Seemungal, L., Arrigoni, A., Davies, J., Weidner, E., & Hodson, P. (2021). *Decarbonisation of Heavy Duty Vehicle Transport: Zero Emission Heavy Goods Vehicles* (No. JRC125149).

[363] Burges, K., Kippelt, S., & Probst, F. (2021). Grid-related challenges of high power charging stations for battery electric long haul trucks.

[364] Walz, K., Rudion, K., Moraw, C. M., & Eilers, M. (2022, October). Probabilistic Impact Assessment of Electric Truck Charging on a Medium Voltage Grid. In *2022 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)* (pp. 1-6). IEEE.

[365] Martin, J., Neumann, A., & Ødegard, A. (2022). *Sustainable Hydrogen Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Dynamic Cost Model*. Tech. rep. WP 2022-010. Cambridge, MA: MIT CEEPR. URl: https://ceepr. mit. edu/sustainablehydrogen-fuels-versus-fossil-fuels-for-trucking-shipping-and-aviation-adynamic-cost-model/(visited on 07/27/2022).

c) Decarbonise maritime and inland waterways transport

Decarbonising maritime and inland waterways transport is another significant challenge as the shipping industry currently relies almost exclusively on fossil fuels.[366] The main challenge here is associated with cost[367] and the high energy density required to cover long maritime distances. Alternative fuels, such as biofuels, synfuels, ammonia or hydrogen,[368,369] and carbon capture technologies at motor engine point sources appear to be the most promising avenues for decarbonising long distance maritime transport, while electric ferries and fuel cells could be the solution for short distance shipping. However, to decarbonise the shipping sector, a system-wide thinking is required and the three value chains that are central to steering the sector's decarbonisation must be involved. These include: the fuel chain; the shipbuilding chain; and the operations chain.[370] Key R&I interventions across these value chains should be considered together. R&I efforts linked to sail propulsion technologies (e.g. use of sails, rotors and kites as an auxiliary propulsion source) should also be investigated, especially as performance gains could be important but are still uncertain and these solution require a rethink of the mode of navigation (e.g. modification of sear routes, reduction of speed, etc.).[371]

d) Decarbonise air transport

Decarbonising long-distance air transport presents a significant challenge, since energy density is an absolute necessity in aviation. While advances in battery energy density are on the cusp of making battery-electric propulsion feasible for short-distance small aircraft application[372] the first pure battery-electric airplane models are currently being

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[366] Grosso, M., Marques dos Santos, F. L., Gkoumas, K., Stępniak, M., & Pekár, F. (2021). The Role of Research and Innovation in Europe for the Decarbonisation of Waterborne Transport. *Sustainability*, *13*(18), 10447.

[367] Camargo-Díaz, C. P., Paipa-Sanabria, E., Zapata-Cortes, J. A., Aguirre-Restrepo, Y., & Quiñones-Bolaños, E. E. (2022). A Review of Economic Incentives to Promote Decarbonization Alternatives in Maritime and Inland Waterway Transport Modes. *Sustainability*, *14*(21), 14405.

[368] Tan, E. C., Dutta, A., Iisa, K., & Mukarakate, C. (2022). *Sustainable Biofuels for Low-Carbon Maritime Transportation* (No. NREL/PR-5100-84535). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[369] Watanabe, M. D., Cherubini, F., Tisserant, A., & Cavalett, O. (2022). Drop-in and hydrogen-based biofuels for maritime transport: Country-based assessment of climate change impacts in Europe up to 2050. *Energy Conversion and Management*, *273*, 116403.

[370] https://unctad.org/news/decarbonizing-maritime-sector-mobilizing-coordinated-action-industry-using-ecosystems-approach

[371] https://www.polytechnique-insights.com/en/braincamps/energy/low-carbon-innovations-for-maritime-freight/sailing-merchant-ships-utopia-or-reality/#note-1; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815666/economic-opportunities-low-zero-emission-shipping.pdf.

[372] Viswanathan, V., Epstein, A. H., Chiang, Y. M., Takeuchi, E., Bradley, M., Langford, J., & Winter, M. (2022). The challenges and opportunities of battery-powered flight. *Nature*, *601*(7894), 519-525.

tested.[373] For long-distance commercial aviation the economics may remain challenging for some time to come though. Breakthrough innovations in this space could nonetheless make a serious difference for battery-powered aviation by 2040. Developing economies of scale in high speed rail systems could be a further alternative to some air travel routes in Europe.[374] Breakthrough innovations in hydrogen-based aviation could be key.[375] Efficiency improvements in synfuels production may be crucial to otherwise decarbonise long-distance aviation.[376] As concluded by the White House report: "*Improvements in engineering, materials, energy storage, performance, safety, and costs are needed for viable commercial electric, hybrid, and fuel cell aircraft at scale*"[377].

e) Connectivity and supporting infrastructure

Finally, it will be key to invest R&I efforts into the infrastructure required to support this mobility of the future. This implies on one hand looking at how the different transport options can best be integrated into an efficient system; but also considering the full set of implications of individual options in terms of broader environmental and social impact. This is particularly important for this Solution Landscape given the expected growth in transport demand globally.

A5.8.3 Role of disruptive General Purpose Technologies (GPTs)

The advent of Artificial Intelligence solutions in the mobility sector has been widely documented in the literature – while AI can lead to optimisations in traffic management and control and has been used for this application since many years[378,379], the role of AI in integrating mobility solutions into a more flexible energy system as a whole to leverage

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[373] https://thedriven.io/2022/09/20/electric-planes-are-coming-short-hop-flights-could-be-running-on-batteries-in-a-few-years/

[374] Avogadro, N., Cattaneo, M., Paleari, S., & Redondi, R. (2021). Replacing short-medium haul intra-European flights with high-speed rail: Impact on CO2 emissions and regional accessibility. *Transport Policy*, *114*, 25-39.

[375] Huete, J., Nalianda, D., Zaghari, B., & Pilidis, P. (2022). A Strategy to Decarbonize Civil Aviation: A phased innovation approach to hydrogen technologies. *IEEE Electrification Magazine*, *10*(2), 27-33.

[376] Marques dos Santos, F., Gkoumas, K., Stepniak, M., Tsakalidis, A., Grosso, M., Ortega Hortelano, A., & Pekár, F. (2021). *European Research and Innovation in Aviation Emissions Reduction: An Assessment Based on the Transport Research and Innovation Monitoring and Information System (TRIMIS)* (No. JRC124895).

[377] https://www.whitehouse.gov/wp-content/uploads/2022/11/U.S.-Innovation-to-Meet-2050-Climate-Goals.pdf

[378] Agarwal, P. K., Gurjar, J., Agarwal, A. K., & Birla, R. (2015). Application of artificial intelligence for development of intelligent transport system in smart cities. *Journal of Traffic and Transportation Engineering, 1(1)*, 20-30.

[379] Okrepilov, V. V., Kovalenko, B. B., Getmanova, G. V., & Turovskaj, M. S. (2022). Modern Trends in Artificial Intelligence in the Transport System. Transportation Research Procedia, 61, 229-233.

the storage capacities of batteries or other energy storage solutions is still the subject of ongoing research[380].

A5.8.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

- Battery breakthroughs across all forms of transport including e-bikes;
- Charging infrastructure breakthroughs – linking with smartgrids (charging to balance the grid);
- Behaviour challenges: how to avoid rebound effects (increasing mobility in response to lower cost and accessibility); and,
- Drone-based, last-mile delivery.

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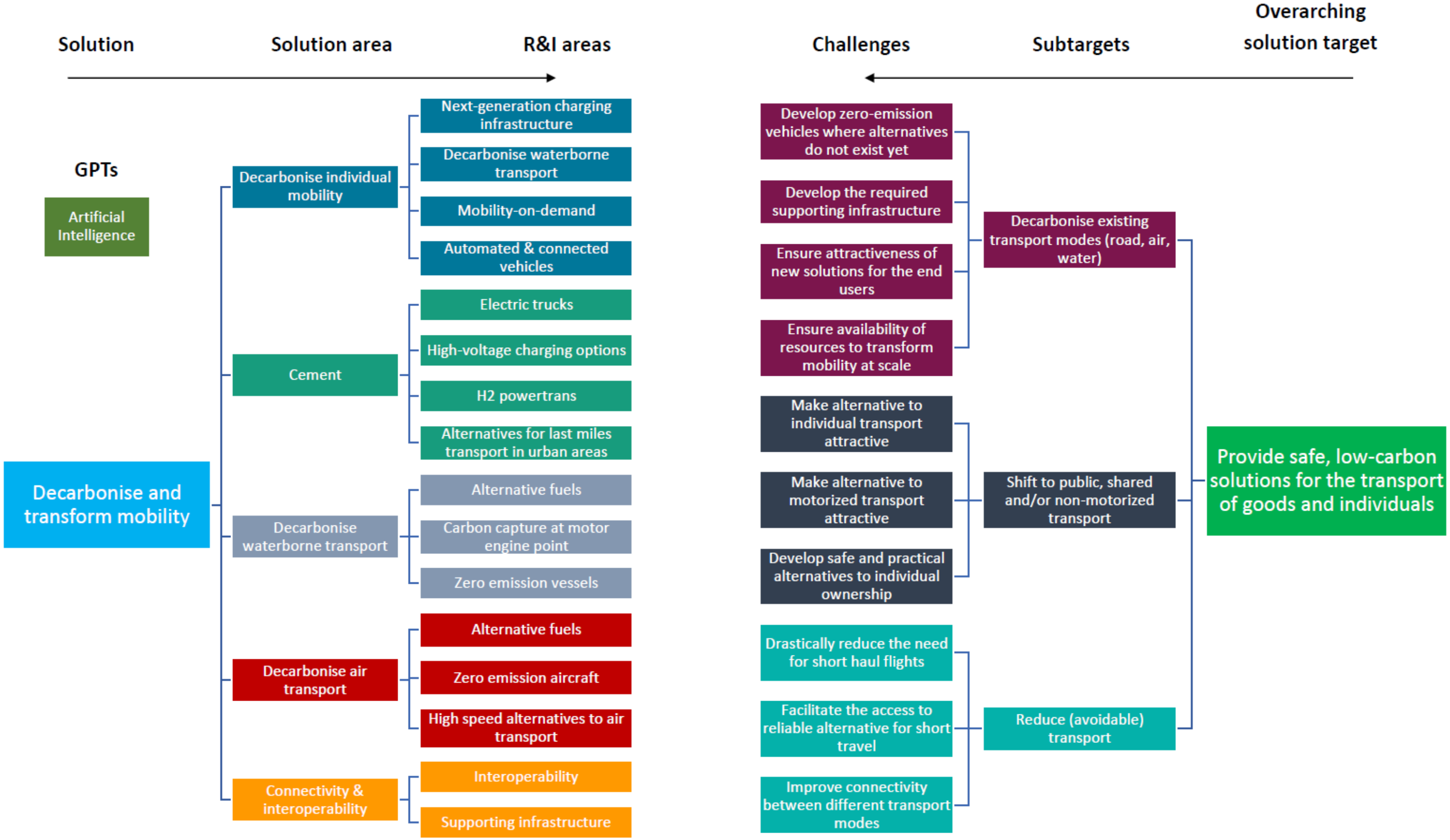
[380] Ahmed, M., Zheng, Y., Amine, A., Fathiannasab, H., & Chen, Z. (2021). The role of artificial intelligence in the mass adoption of electric vehicles. Joule, 5(9), 2296-2322.

Figure 8 Solution Landscape Decarbonise and transform mobility. Source: ICF & partners, 2023.



A5.9 Solution landscapes linked to greenhouse gas removals

This section outlines the key insights gained through the literature review with regards to the field of GHG removal. This includes particularly – but not exclusively – carbon dioxide removal (CDR). The section starts by outlining key challenges in this field in and presents the five solution landscapes answering these key challenges.

Clarification of removals and negative emissions related terms and concepts

We use the terms *carbon dioxide removal(s)*, *net carbon removals* and *greenhouse gas removals* interchangeably, although the latter also includes greenhouse gases other than CO_2 such as methane. GHG removal represents mitigation action that goes beyond full decarbonisation, to achieve a GHG flow from the atmosphere into durable storage.[381] In line with IPCC terminology, we refer to *GHG removal methods* to mean individual technologies and practices that can achieve removal.

To achieve system-wide net-negative emissions (beyond climate neutrality) the annual volume of removals must exceed the volume of residual emissions within an economy.[382] This is what the IPCC refers to as *net-negative emissions*.[383]

A5.9.1 Challenges associated with carbon dioxide removals

Given that for climate neutrality residual emissions and removals must be in balance, removals – as a broad category of action – play a particularly relevant role in achieving European climate neutrality and even moving beyond towards a net-negative economy. The IPCC foresees three distinct roles for removals: (1) immediately accelerating the downward slope of net-emissions; (2) achieving climate neutrality in the mid-term; and (3) achieving net-negative system-wide emissions thereafter.[384]

Rapid development of removal methods also entails a large opportunity for international cooperation by enabling other international partners – through technology cooperation,

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[381] IPCC (2022): Annex II: Glossary [Möller, Vincent; van Diemen, Renee; Matthews, J.B. Robin; Fuglestvedt, Jan S.; Mendez, Carlos; Reisinger, Andy; Semenov, Sergey (eds)]. In: IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.020.

[382] Allen, Myles. R.; Friedlingstein, Pierre; Girardin, Cecile A.; Jenkins, Stuart; Malhi, Yadvinder; Mitchell-Larson, Eli; Rajamani, Lavanya (2022): Net Zero: Science, Origins, and Implications. In: Annual Review of Environment and Resources, 47, https://doi.org/10.1146/annurev-environ-112320-105050.

[383] IPCC (2022): Annex II: Glossary [Möller, Vincent; van Diemen, Renee; Matthews, J.B. Robin; Fuglestvedt, Jan S.; Mendez, Carlos; Reisinger, Andy; Semenov, Sergey (eds)]. In: IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.020.

[384] Ibidem.

transfer, international cooperation as per the Paris Agreement, climate finance support or capacity-building exercises – to pursue more mature removal methods.[385]

Research and innovation related challenges in this space are strongly tied to the public-good nature of most removal methods[386]. Without decisive and tailored R&D support, as well as a clear runway toward long-term policy support, this entire category of action will falter.

Each removal method has its own profile of opportunities, challenges and limitations, including notably in relation to resource requirements, such as for: a) biomass; b) water; c) heat; d) power; and, e) land.[387] Such resource constraints, limited maturity and high costs of CDR have been cause for concerns over excessive reliance on CDR in IPCC scenarios.[388] Removals, which rely on natural sinks in the oceans or on land, furthermore, face significant MRV challenges.[389] Successful mobilisation of removals toward net-zero thus demands a tailored portfolio approach.[390]

Carbon dioxide removal methods are sometimes categorized into 'nature-based solutions' and other (more technology-reliant) approaches. These are, however, not well-defined technology categories. Following the definition of the IUCN[391], whether or not a removal application is a *nature-based solution* depends on the form and context of its use in each specific case (rather than representing a technology-inherent characteristic). This points to the challenge of ensuring context-appropriate utilization of this broad cluster of mitigation technologies and practices.

Another key challenge lies in the early Technology Readiness Level (i.e., TRL 1-2) of many removal methods.[392] This indicates that there is substantial potential for

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[385] Lenzi, Dominic; Jakob, Michael; Honegger, Matthias; Droege, Susanne; Heyward, Jennifer C.; Kruger, Tim (2021): Equity implications of net zero visions. In: Climatic change, 169(3), 1-15.

[386] Maher, Bryan, and Symons, Jonathan (2022): The International Politics of Carbon Dioxide Removal: Pathways to Cooperative Global Governance. Global Environmental Politics, 22(1), 44-68.

[387] Honegger, Matthias, Michaelowa, Axel, & Roy, Joyashree (2021): Potential implications of carbon dioxide removal for the sustainable development goals. Climate policy, 21(5), 678-698.

[388] Pamlin, D. (2019). Towards >60 Gigatonnes of Climate Innovations: A Three-Step Solution Framework for Net-Zero Compatible Innovations. Mission Innovation. Retreaved from https://misolutionframework.net/pdf/Net-Zero_Innovation_Module_1-A_Three-Step_Solution_Framework_for_Net-Zero_Compatible_Innovations_(TSF)-v1.pdf on February 9th 2023.

[389] Smith, Pete et al. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global Change Biology, 26(1), 219-241.

[390] Rueda, O., Mogollón, J. M., Tukker, A., & Scherer, L. (2021). Negative-emissions technology portfolios to meet the 1.5° C target. Global Environmental Change, 67, 102238.

[391] The International Union for the Conservation of Nature (IUCN) defines nature based solutions as: "Actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature." (See https://www.iucn.org/our-work/nature-based-solutions).

[392] Möllersten, Kenneth (2022): Assessment of classes of CDR methods: Technology Readiness, Costs, Impacts and Practical Limitations of Biochar as Soil Additive and BECCS. Energy, 2004, 2965.

development and disruption to the market within a time-horizon of 10-15 years. To realise this potential, large scale private and public investments are required.

At the same time there are several removal methods, which are technologically fully mature, the mobilisation of which, however, requires innovation in incentivisation through regulation, policy and carbon markets.[393] Capturing carbon emissions from point sources – including those combusting (some) biomass – is being piloted in several European countries (e.g. in Sweden[394], Iceland[395], and the Netherlands)[396] and should be scaled through a combination of adequate incentives to unlock attractive business models and immediate development of necessary transport and storage infrastructures (hubs and clusters). R&I interventions are needed to identify opportunities and limiting factors for such business models and infrastructure developments.

Review articles in the interrelated fields of carbon removal and CCS,[397,398,399] already offer a broad-based, interdisciplinary overview of the CDR landscape. And much of the CDR challenge is in the sphere of political adoption.[400] Yet research and innovation does have an important role to play in bringing down cost, resolving resource challenges through more efficient processes and facilitating adoption of smart MRV approaches. There are, however, gaps in the academic literature when it comes to newer technological approaches; and R&I interventions should be carefully designed to not lock-out newer (and yet undiscovered) innovation spaces, including new sorbent materials or thermodynamic processes for capturing and releasing CO_2.

A5.9.2 Solution landscapes on carbon dioxide removal

This section summarises the literature review and outlines the five solution landscapes of carbon dioxide removals and details specific solution areas in each – type of research and development, the challenges they could address as well as the potentials and limits of each toward net-zero emissions. The solution landscapes cover:

- Direct air (CO_2) capture (DAC) technologies .

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[393] Bellamy, Rob, Geden, Oliver, Fridahl, Mathias, Cox, Emily, & Palmer, James (2021). Governing carbon dioxide removal. Frontiers in Climate, 172.

[394] https://www.stepwise.eu/project/pilot/ https://www.stepwise.eu/project/pilot/

[395] https://www.carbfix.com/

[396] https://www.avr.nl/en/co2-installation/first-tons-of-co2-captured-from-residual-waste-supplied-to-greenhouse-horticulture/

[397] Raza, A., Gholami, R., Rezaee, R., Rasouli, V., & Rabiei, M. (2019). Significant aspects of carbon capture and storage–A review. Petroleum, 5(4), 335-340.

[398] Martin-Roberts, E., Scott, V., Flude, S., Johnson, G., Haszeldine, R. S., & Gilfillan, S. (2021). Carbon capture and storage at the end of a lost decade. *One Earth*, *4*(11), 1569-1584.

[399] Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., ... & Mac Dowell, N. (2018). Carbon capture and storage (CCS): the way forward. Energy & Environmental Science, 11(5), 1062-1176.

[400] Honegger, M. (2023). Toward the effective and fair funding of CO_2 removal technologies. *Nat Commun* 14, 534.

- Point source capture technologies (including biomass) .
- Durable storage (including in long-lived products)
- Terrestrial ecosystem-based removals .
- Ocean-based ecosystem removals .

The five solution landscapes are interconnected both amongst each other as well as with disruptive general-purpose technologies. DAC and point source capture (solution landscapes 1 and 2) both rely on storage in reservoirs or long-lived products (solution landscape 3), as well as the availability of sufficient zero-emissions power (and thus are interconnected with renewables and storage solutions. The biomass reliant solution landscapes 4 and 5 are in possible competition with biofuels and timber as a building materials (solution landscape 3). Ocean-based ecosystem removals may require highly technological monitoring systems and thus interconnect with developments in AI and robotics. Finally, new information and communication channels could impact on all CDR methods, especially in regards to socio-economic and political aspects of MRV, social acceptance, and regulation.

A5.9.3 Direct air (CO2) capture (DAC) technologies

DAC technology captures CO_2 from ambient air and makes it available for permanent storage and/or utilisation.

A5.9.4 Goals and challenges

Currently, several forms of DAC technology are being developed and tested in pilot projects.[401] However, there are numerous barriers towards scaling: high costs and high energy demands; a lack of transport and storage infrastructure; and an absence of a successful business case due to a lack of dedicated voluntary or political support. Furthermore, scalable production processes will be needed – likely based on modules allowing for flexibility in plant size.[402]

Specific challenges are related to: (1) developing efficient DAC modules designed for rapidly scaling production; (2) driving down costs and identifying new technological approaches to DAC with lower energy demands; and, (3) increasing the potential for large-scale production, including by finding suitable sites which enable energy- and emission-efficient DAC applications (i.e., sites with abundant emission-free energy production at hand), as well as establishing efficient supply chains, enhanced manufacturing processes and recruiting the required expert personnel.

In the DAC solution landscape, we identify three solution areas to meet these challenges:

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[401] Ozkan, M., Nayak, S. P., Ruiz, A. D., & Jiang, W. (2022). Current status and pillars of direct air capture technologies. *Iscience*, 103990.

[402] International Energy Agency (IEA) (2022): Direct Air Capture - A key technology for net zero. Available online at: https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf (accessed November 22, 2022).

1. development of DAC modules and their production.
2. continued research on materials (including sorbents).
3. developing business cases, innovations and scaling – as follows:

a) DAC module (hardware) development and production

The first solution area pertains to developing optimized DAC modules (e.g., which have the least number of moving parts, least energy intensive materials, and only the necessary quantities of materials). The modular design of DAC plants can be leveraged as a key enabler of dramatic economies of scale in production.[403] To bring costs down further, standardisation in identification and permitting of potential sites may be aided through the modular design.[404] In addition to optimising the modules themselves, designing enhanced production processes allowing for scalability is key. The objective should be to move the industry towards a highly scalable production ecosystem which can be automated. General improvements to production processes, in terms of engineering, manufacturing design and supply chains, will be important for reaching every subsequent next stage in scaling DAC plant sizes.[405]

b) Basic (sorbent) materials research

DAC is fundamentally plagued by two challenges: thermal and electrical energy requirements and the need to regularly replace sorbent materials. Both are related to the sorbent materials utilised and the cycles these go through.[406] While some of the most established processes involve temperature-swing cycles,[407] other approaches should also be further advanced for their potential for lower energy demands.[408] Ongoing R&D suggests potential for dramatic reductions in energy requirements (through alternative capture-and-release cycles) and possible reductions in sorbent material aging.[409] Basic research into various alternative materials, including advanced materials like carbon

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[403] Lackner, K. S., & Azarabadi, H. (2021). Buying down the cost of direct air capture. *Industrial & Engineering Chemistry Research*, *60*(22), 8196-8208.

[404] McQueen, Noah; Vaz Gomes, Katherine; McCormick, Colin; Blumenthal, Katherine; Pisciotta, Maxwell; Wilcox, Jennifer (2021): A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. In: Progress in Energy 3 (3), DOI 10.1088/2516-1083/abf1ce.

[405] Izikowitz, D. (2021). Carbon Purchase Agreements, Dactories, and Supply-Chain Innovation: What Will It Take to Scale-Up Modular Direct Air Capture Technology to a Gigatonne Scale. *Frontiers in Climate*, *3*, 24.

[406] Azarabadi, H., & Lackner, K. S. (2019). A sorbent-focused techno-economic analysis of direct air capture. *Applied Energy*, *250*, 959-975.

[407] Zhao, R., Liu, L., Zhao, L., Deng, S., Li, S., & Zhang, Y. (2019). A comprehensive performance evaluation of temperature swing adsorption for post-combustion carbon dioxide capture. *Renewable and Sustainable Energy Reviews*, *114*, 109285.

[408] Shi, X., Lin, Y., & Chen, X. (2022). Development of sorbent materials for direct air capture of CO2. *MRS Bulletin*, 1-11.

[409] Kong, F., Rim, G., Song, M., Rosu, C., Priyadarshini, P., Lively, R. P., ... & Jones, C. W. (2022). Research needs targeting direct air capture of carbon dioxide: Material & process performance characteristics under realistic environmental conditions. *Korean Journal of Chemical Engineering*, *39*(1), 1-19.

nitride[410], and both adsorption and desorption processes[411] can potentially dramatically improve DAC efficiency (and thereby diminish the currently high costs). Research and innovation which targets both existing sorbents and novel approaches is therefore warranted.[412]

c) Business case, innovation and scaling of research

Besides technical improvements and innovations, incentives, infrastructures and political frameworks need to be developed which foster the scaling up of DAC. In short, a landscape to make DAC operations financially attractive is required.[413] This may include facilitating permitting processes, energy (e.g. integration with smart grids to maximise utility of intermittent energy availability[414]), and synergies (e.g. through integration of DAC into future CCU/S hubs and clusters). Furthermore, frameworks for DACs participating in voluntary and compliance-based carbon markets need to be established, where the comparably high costs related to DACs can be met with sufficiently high carbon prices. Blockchain technologies could alter carbon revenues and, consequently, attractiveness for private investments into DAC projects, to the extent they find their way into carbon market interactions. There is ongoing research[415,416] as well as real world examples[417] for such blockchain applications. Last, but not least, intellectual property (IP) must be managed in a way that stimulates ongoing innovation and investments rather than over-proportionally rewarding "early-bird" approaches.

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[410] Talapaneni, S. N., Singh, G., Kim, I. Y., AlBahily, K., Al-Muhtaseb, A. A. H., Karakoti, A. S., ... & Vinu, A. (2020). Nanostructured carbon nitrides for CO2 capture and conversion. Advanced Materials, 32(18), 1904635.

[411] Leonzio, G., & Shah, N. (2022). Innovative Process Integrating Air Source Heat Pumps and Direct Air Capture Processes. *Industrial & Engineering Chemistry Research*, *61*(35), 13221-13230.

[412] Sabatino, Francesco; Grimm, Alexa; Gallucci, Fausto; van Sint Annaland, Martin; Kramer, Gert Jan; Gazzani, Matteo (2021): A comparative energy and costs assessment and optimization for direct air capture technologies. In: Joule 5 (8), p. 2047-2076.

[413] Meckling, Jonas; Biber, Eric (2021): A policy roadmap for negative emissions using direct air capture. In: Nature Communications 12 (2051).

[414] Breyer, C., Fasihi, M., & Aghahosseini, A. (2020). Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitigation and Adaptation Strategies for Global Change*, *25*(1), 43-65.

[415] Al Sadawi, A., Madani, B., Saboor, S., Ndiaye, M., & Abu-Lebdeh, G. (2021). A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. Technological Forecasting and Social Change, 173, 121124.

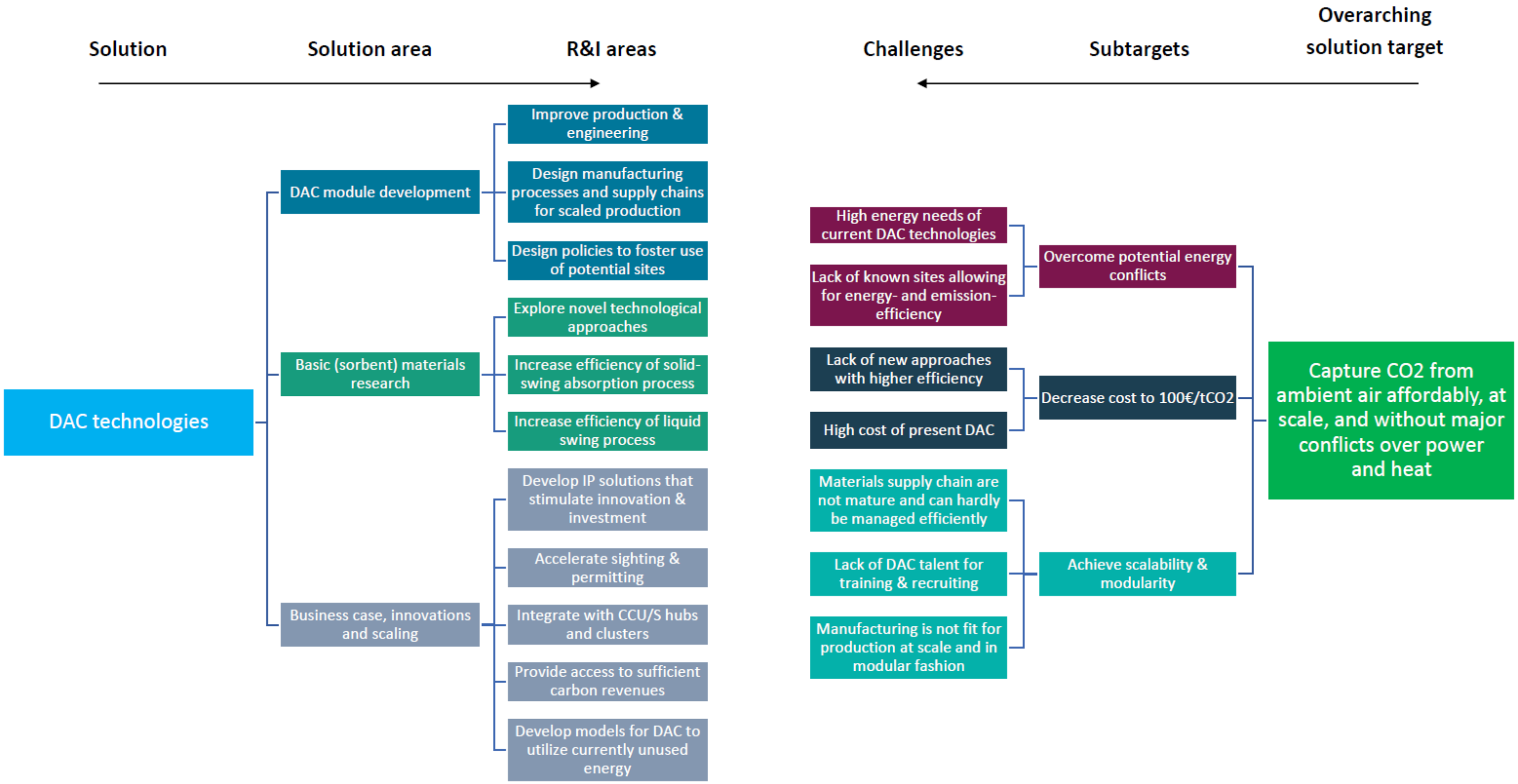
[416] Pan, Y., Zhang, X., Wang, Y., Yan, J., Zhou, S., Li, G., & Bao, J. (2019). Application of blockchain in carbon trading. Energy Procedia, 158, 4286-4291.

[417] Jiang, T., Song, J., & Yu, Y. (2022). The influencing factors of carbon trading companies applying blockchain technology: evidence from eight carbon trading pilots in China. Environmental Science and Pollution Research, 1-13.

A5.9.5 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

In short, smart R&D funding plays an important role for advancing DACCS to maturity and market by 2040 through breakthroughs in DAC module design and production scalability, continued research on next generation materials and efficient processes, and facilitating the mobilization of business cases, innovation ecosystems and scaling.

Figure 9 Solution Landscape DAC technologies. Source: ICF & partners, 2023.



A5.10 Point source capture technologies (including biomass)

The solution landscape of point source capture technologies, by its very nature, cuts across industry decarbonisation and CO_2 removals (point source capture of biomass-processing plants can achieve a removal). Point source capture is the first element in CCS. Carbon capture (for later storage including in long-lived products) thus contributes to three objectives:

1. Industry decarbonisation (especially for process emissions, such as in cement, steel or chemicals production);[418] .
2. CO_2-removal by capturing CO_2 during biomass processing or storing CO_2 captured directly from the atmosphere (see dedicated Solution Landscape for DAC).
3. Decarbonising already committed fossil energy infrastructures (as a last-resort sunsetting option).

A5.10.1 Goals and challenges

To mobilise the very significant potential of point source CO_2 capture (covering all relevant point sources, across all sectors, efficiently and without pushing into additional biomass demand), progress ought to be achieved towards increasing capture energy efficiency, achieving higher capture rates, decreasing costs, and achieving versatility and modularity.

Point source capture technologies are challenged primarily in three ways (as outlined in the figure below): (1) the relatively high cost of necessarily tailor-made hardware with limited standardisation; (2) significant cost and energy penalties especially for high capture rates; and, (3) the absence of a reliable business case and credible scaling trajectories across industry-, energy-, and waste applications.[419]

In response, the *point source capture technologies* solution landscape entails three solution areas: (a) focussed on R&D of capture modules; (b) focussed on basic materials research; and (c) research focussed on business case, innovation and scaling of deployment.

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[418] Paltsev, Sergey; Morris, Jennifer; Kheshgi, Haroon; Herzog, Howard (2021): Hard-to-Abate Sectors: The role of industrial carbon capture and storage (CCS) in emission mitigation. In: Applied Energy 300 (117322).

[419] Yang, F.; Meerman, J.C.; Faaji, A.P.C. (2021): Carbon capture and biomass in industry: A techno-economic analysis and comparison of negative emission options. In: Renewable and Sustainable Energy Reviews 144 (111028).

a) Capture modules portfolio R&D

A key feature of point source carbon capture is its modularity and adaptability to many different post-combustion emission streams.[420] While gas streams in various types of incineration processes have various concentration levels of pollutants other than CO_2 and contain various levels of water vapor, they can in principle be addressed largely by the same CO_2-capture modules in various combinations with specific pre-treatments to bring concentrations of other substances to acceptable levels.

A condition for wide adoption of post-combustion, point-source CO_2 capture is the availability of low-cost and variously combinable modules for the pre-treatment and CO_2-capture that is adaptable to various volumes and compositions of flue gas streams. The goal of the first solution area is thus the development of a hardware ensemble of capture modules (and complementary pre-treatment modules), which are jointly capable of addressing a wide range of industry-, energy- and waste sector applications to achieve both emissions reductions (when capturing fossil or process emissions) and removals (when capturing biogenic carbon).[421]

b) Basic materials research

The holy grail in point source capture is achieving high capture rates with a low energy penalty. Pushing the envelope on this requires continued R&D into materials and ad-/desorption processes in applied settings.[422,423] Much progress has already been made, but further improvements appear possible[424]; and much of that progress is expected to come from advanced sorbent and membrane materials.[425] Even small percentage changes in capture rates can have dramatic implications on the decarbonisation and carbon removal potential of point source capture technology. Machine learning

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[420] Kárászová, M., Zach, B., Petrusová, Z., Červenka, V., Bobák, M., Šyc, M., & Izák, P. (2020). Post-combustion carbon capture by membrane separation, Review. *Separation and Purification Technology*, *238*, 116448.

[421] Wilberforce, Tabbi; Olabi, A.G.; Sayed, Enas Taha; Elsaid, Khaled; Abdelkaree, Mohammad Ali (2021): Progress in carbon capture technologies. In: Science of The Total Environment 761 (143203).

[422] Hussin, F., & Aroua, M. K. (2020). Recent trends in the development of adsorption technologies for carbon dioxide capture: A brief literature and patent reviews (2014–2018). Journal of Cleaner Production, 253, 119707.

[423] Khandaker, T., Hossain, M. S., Dhar, P. K., Rahman, M. S., Hossain, M. A., & Ahmed, M. B. (2020). Efficacies of carbon-based adsorbents for carbon dioxide capture. *Processes*, *8*(6), 654.

[424] Ahmed, R., Liu, G., Yousaf, B., Abbas, Q., Ullah, H., & Ali, M. U. (2020). Recent advances in carbon-based renewable adsorbent for selective carbon dioxide capture and separation-A review. Journal of Cleaner Production, 242, 118409.

[425] Hou, R., Fong, C., Freeman, B. D., Hill, M. R., & Xie, Z. (2022). Current status and advances in membrane technology for carbon capture. *Separation and Purification Technology*, *300*, 121863.

approaches can improve both molecular and process related performance of capture materials, e.g. via modelling thermodynamic sorbent properties or process settings.[426,427]

c) Business case, innovation and scaling of deployment

Point source carbon capture for storage represents an activity solely pursued for its climate benefit.[428] There is no other value-added and accordingly any investments into capture capabilities have to rely on carbon incentives, either from dedicated policies (including sufficiently high and stable carbon pricing) or regulatory requirements. As in DAC, the impact blockchain technologies have on future carbon markets may alter influence business models for point source carbon capture. [429,430] Business model uncertainty can be reduced in plant designs.[431] Given the very limited experience in mobilising CCS capabilities on the basis of conventional climate policy instruments at the global level, there is currently a very large uncertainty as to the scalability of carbon capture in response to particular levels of carbon pricing.[432] The industry response and bankability of carbon capture investments should be examined in the context of diverse sector applications,[433] in order to avoid pursuing policies that remain ineffective at mobilising point source capture for storage (as has been the case to date under the EU Emissions Trading System).

Appropriate design of incentives for biomass-point-source CCS needs to account for potential biomass resource conflicts with an economy-wide systemic perspective.[434] Heavy prioritisation should be given to incentivising the capture from biomass-processing installations that are virtually certain to be irreplaceable. These installations

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[426] Rahimi, M., Moosavi, S. M., Smit, B., & Hatton, T. A. (2021). Toward smart carbon capture with machine learning. Cell reports physical science, 2(4).

[427] Yan, Y., Borhani, T. N., Subraveti, S. G., Pai, K. N., Prasad, V., Rajendran, A., ... & Clough, P. T. (2021). Harnessing the power of machine learning for carbon capture, utilisation, and storage (CCUS)–a state-of-the-art review. Energy & Environmental Science, 14(12), 6122-6157.

[428] Honegger, M., & Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. *Climate policy*, *18*(3), 306-321.

[429] Al Sadawi, A., Madani, B., Saboor, S., Ndiaye, M., & Abu-Lebdeh, G. (2021). A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. Technological Forecasting and Social Change, 173, 121124.

[430] Pan, Y., Zhang, X., Wang, Y., Yan, J., Zhou, S., Li, G., & Bao, J. (2019). Application of blockchain in carbon trading. Energy Procedia, 158, 4286-4291.

[431] McGrail, B. P., Freeman, C. J., Brown, C. F., Sullivan, E. C., White, S. K., Reddy, S., ... & Steffensen, E. J. (2012). Overcoming business model uncertainty in a carbon dioxide capture and sequestration project: Case study at the Boise White Paper Mill. International Journal of Greenhouse Gas Control, 9, 91-102.

[432] Herzog, Howard J. (2011). Scaling up carbon dioxide capture and storage: From megatons to gigatons. Energy Economics, 33(4), 597-604.

[433] Leeson, D., Mac Dowell, N., Shah, N., Petit, C., & Fennell, P. S. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control*, *61*, 71-84.

[434] Fajardy, M., Chiquier, S., & Mac Dowell, N. (2018). Investigating the BECCS resource nexus: delivering sustainable negative emissions. *Energy & Environmental Science*, *11*(12), 3408-3430.

include waste incineration, the chemical industry, and other productive industry plants that, for example, co-fire biomass if locally available in excess or as waste.[435]

A5.10.2 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

In short, R&D funding can play an important role in broadening and deepening the potential of CCS to market by unleashing progress towards increasing capture energy efficiency, achieving higher capture rates, decreasing costs, and achieving versatility and modularity for use across an increasingly broad spectrum of industry sectors, applications and scales of point sources of CO_2.

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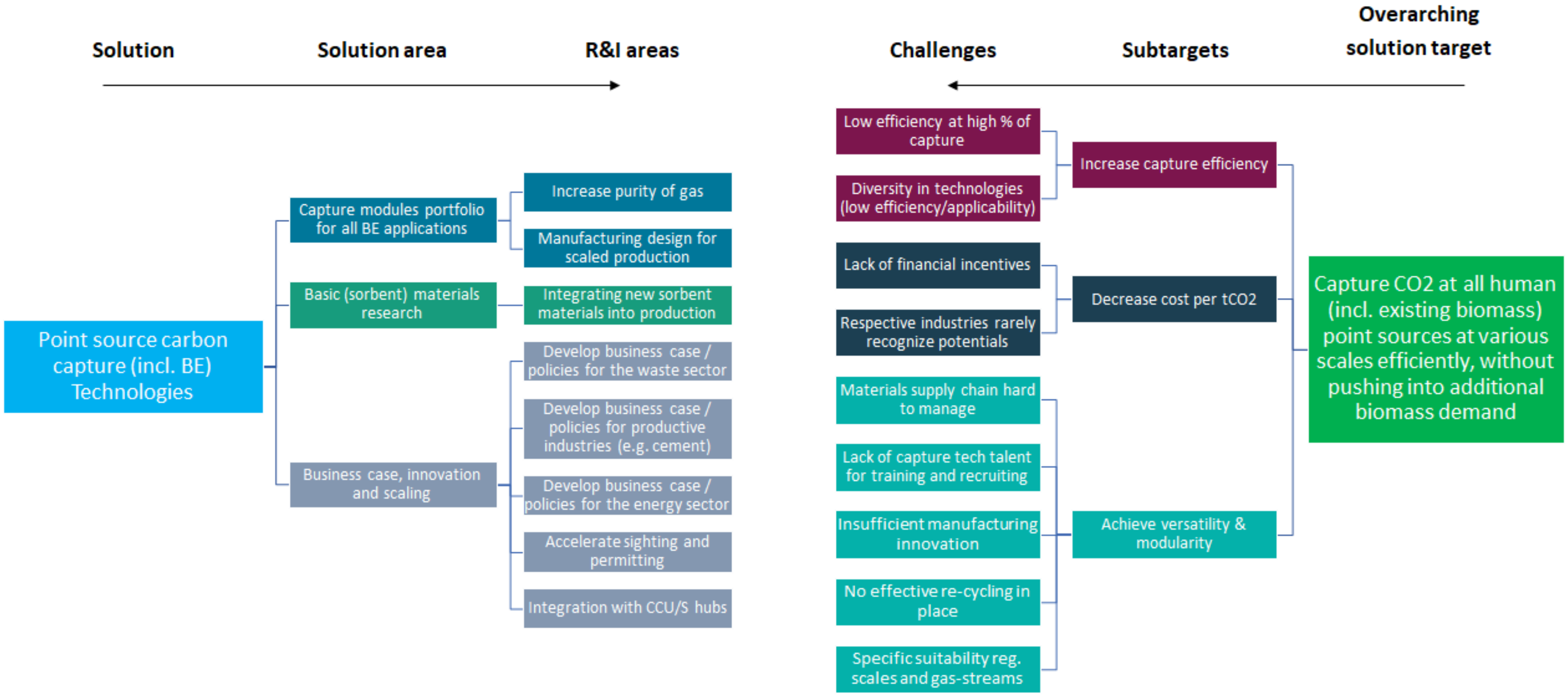
[435] Rosa, L., Sanchez, D. L., & Mazzotti, M. (2021). Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. *Energy & Environmental Science*, *14*(5), 3086-3097.

Figure 10 Solution Landscape Point source carbon capture technologies. Source: ICF & partners, 2023.



A5.11 Durable Storage (including in long-lived products)

A5.11.1 Goals and challenges

The durable storage of CO_2 is a large-scale challenge in and of itself, as it involves the handling of unprecedented volumes of CO_2 gas – a novel waste management industry which needs to be devised as a full socio-economic system from the ground up. The solution landscape is divided into three parts regarding: 1) the vast geological storage capacities required for climate neutrality; 2) the scaling of long-lived CO_2-utilisation products allowing for permanent storage; and, 3) the planning, financing, construction and operation of the transport and storage infrastructures ready to handle millions of tonnes of CO_2 safely and economically (see figure below).

Permanent and/or temporal (100 yrs time perspective) storage of CO_2 is a vital component of many (mainly non-ecosystem-based) CDR methods. Increasing geological storage capacities, as well as utilisation in long lasting products, are key sub-targets to achieve large-scale storage, as is the development of infrastructures for (international) cooperation on CO_2 transport and storage.

a) Geological storage capacities – research and piloting of storage hubs

Regarding storage sites, several specific challenges need to be tackled. The successful development of new storage sites involves challenges across a multitude of practical and theoretical realms including obstacles related to environmental and socio-economic concerns, most notably frequent resistance from the public. Research may thus accompany the real-world roll-out of storage and utilization hubs and clusters to successfully navigate public perception and trust. Research and innovation toward monitoring of stored CO_2 can help overcome challenges of reliability and long-term observation based on international minimum requirements. Publicly funded research may furthermore, help make cost structures related to storage (including MRV costs) more transparent and avoid rent-seeking behaviour of storage operator oligopolies, that may otherwise undermine public support and the credibility of results-based incentives. To enable efficient transport and storage of CO_2, research into optimal design of transport, hubs and clusters may facilitate dramatic cost reductions.[436,437]

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[436] Sun, Xiaolong, et al. (2021): Hubs and clusters approach to unlock the development of carbon capture and storage–Case study in Spain. Applied Energy, 300, 117418.

[437] Kearns, David; Liu, Harry; Consoli, Chris (2021): Technology readiness and costs of CCS. Global CCS Institute. Available online at: https://scienceforsustainability.org/w/images/b/bc/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf (accessed December 09, 2022).

b) Utilization of CO_2 in products

Carbon dioxide utilization (CCU) is the process of using CO_2 as a raw material for products which range widely from construction materials, plastics[438,439] and other chemicals,[440] food and fuel products. While this represents a form of circular economy, the product lifetime (see Box 4), sector and product properties and use cases, determine the economic and environmental performance of CCU.[441] Only use cases that achieve an overall net flow of CO_2 into durable storage from biogenic or atmospheric source represent a form of carbon dioxide removal.

Clarification of the relationship between carbon utilization in short-lived versus long-lived products

Carbon utilization can play a role in mitigating climate change, both in cases of short-lived and long-lived products, although their contribution is different. Short-lived products, such as synfuels, have the potential to lower emissions by displacing other more carbon-intensive alternatives (to be demonstrated through full cradle-to-grave lifecycle analysis). Carbon utilization in long-lived products can be considered a form of durable storage and thus contribute to CDR (if the overall LCA balance indicates a net flow of CO_2 into durable storage).[442]

Various forms of CCU are being researched,[443] but few processes resulting in long-lived products have been successful in the European market to date.[444] Many CCU pathways are not yet economically competitive in comparison to fossil-based processes and technical maturity varies widely.[445] Applications based on biomass carbon tend to be significantly more economical compared to those drawing on DAC.[446] Examples of more

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[438] Nessi, S., Sinkko, T., Bulgheroni, C., Garcia-Gutierrez, P., Giuntoli, J., Konti, A., ... & Ardente, F. (2021). Life Cycle Assessment (LCA) of alternative feedstocks for plastics production. *Publications Office of the European Union*.

[439] Valderrama, M. A. M., van Putten, R. J., & Gruter, G. J. M. (2019). The potential of oxalic–and glycolic acidbased polyesters (review). Towards CO2 as a feedstock (Carbon Capture and Utilization–CCU). *European Polymer Journal*, *119*, 445-468.

[440] Kätelhön, A., Meys, R., Deutz, S., Suh, S., & Bardow, A. (2019). Climate change mitigation potential of carbon capture and utilization in the chemical industry. *Proceedings of the National Academy of Sciences*, *116*(23), 11187-11194.

[441] d'Amore, F., & Bezzo, F. (2020). Optimizing the design of supply chains for carbon capture, utilization, and sequestration in Europe: a preliminary assessment. *Frontiers in Energy Research*, *8*, 190.

[442] Cuéllar-Franca, R. M., & Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO2 utilization*, *9*, 82-102.

[443] Chauvy, R., & De Weireld, G. (2020). CO2 utilization technologies in Europe: a short review. *Energy Technology*, *8*(12), 2000627.

[444] Patricio, J., Angelis-Dimakis, A., Castillo-Castillo, A., Kalmykova, Y., & Rosado, L. (2017). Region prioritization for the development of carbon capture and utilization technologies. *Journal of CO2 Utilization*, *17*, 50-59.

[445] Bolscher, H., Brownsort, P., Opinska, L. G., Jordal, K., Kraemer, D., Mikunda, T., ... & Yearwood, J. (2019). High Level Report: CCUS in Europe.

[446] Koytsoumpa, E. I., Magiri–Skouloudi, D., Karellas, S., & Kakaras, E. (2021). Bioenergy with carbon capture and utilization: A review on the potential deployment towards a European circular bioeconomy. *Renewable and Sustainable Energy Reviews*, *152*, 111641.

developed processes include the production of dimethyl ether and methanol from CO_2,[447] and the use of CO_2 in the construction industry to make inorganic carbonates for building materials.[448]

CO_2 utilization in durable products, such as building materials and plastics, requires innovation in both production systems and applications for CO_2 to become a key feedstock. This may involve the development and standardisation of new materials or the optimisation of existing production methods to incorporate CO_2.[449] Innovation in the design and application can aim to maximise CO_2 utilization and widen the range of suitable product-applications.[450] For example, this may involve the development of new building materials that incorporate CO_2 in their structure, or the creation of plastic products that utilize CO_2 as a raw material. This will require collaboration between engineers, designers, and other experts to develop innovative solutions that effectively utilize CO_2 in these applications.[451]

In order to qualify as contributing to carbon dioxide removal, CO_2 storage through utilization in long-lived products should overall yield a net-negative carbon balance demonstrable through a full cradle-to-grave life cycle assessment.[452]

Overall, the use of CO_2 in durable products requires both technological innovation and creative problem-solving toward effective, sustainable, and economical solutions through collaboration of experts across a range of fields and sectors, including materials science, chemical engineering, and product design.[453] Products based on captured CO_2 often involve a cost-penalty compared to conventional products, which may require for them to be incentivised through carbon markets, policies or regulations.[454,455]

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[447] Nyári, J., Magdeldin, M., Larmi, M., Järvinen, M., & Santasalo-Aarnio, A. (2020). Techno-economic barriers of an industrial-scale methanol CCU-plant. *Journal of CO2 utilization*, *39*, 101166.

[448] Baena-Moreno, F. M., Rodríguez-Galán, M., Vega, F., Alonso-Fariñas, B., Vilches Arenas, L. F., & Navarrete, B. (2019). Carbon capture and utilization technologies: a literature review and recent advances. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *41*(12), 1403-1433.

[449] Naims, H., & Eppinger, E. (2022). Transformation strategies connected to carbon capture and utilization: A cross-sectoral configurational study. *Journal of cleaner production*, *351*, 131391.

[450] Mikulčić, H., Skov, I. R., Dominković, D. F., Alwi, S. R. W., Manan, Z. A., Tan, R., ... & Wang, X. (2019). Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO2. *Renewable and Sustainable Energy Reviews*, *114*, 109338.

[451] Naims, H. (2020). Economic aspirations connected to innovations in carbon capture and utilization value chains. *Journal of industrial ecology*, *24*(5), 1126-1139.

[452] da Cruz, T. T., Balestieri, J. A. P., de Toledo Silva, J. M., Vilanova, M. R., Oliveira, O. J., & Avila, I. (2021). Life cycle assessment of carbon capture and storage/utilization: From current state to future research directions and opportunities. *International Journal of Greenhouse Gas Control*, *108*, 103309.

[453] Gür, T. M. (2022). Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. *Progress in Energy and Combustion Science*, *89*, 100965.

[454] Koytsoumpa, E. I., Magiri–Skouloudi, D., Karellas, S., & Kakaras, E. (2021). Bioenergy with carbon capture and utilization: A review on the potential deployment towards a European circular bioeconomy. *Renewable and Sustainable Energy Reviews*, *152*, 111641.

[455] Tarufelli, B. L. (2020). Overlooked Opportunity: Incentivizing Carbon Capture through Carbon Tax Revenues.

c) Infrastructure for transport and storage development

Storage and utilization of captured CO_2 requires a functioning infrastructure ensemble, which are complex (especially the first time around) and costly to set up. These multi-decadal investment decisions must be approached with a systemic perspective including synergies with various CO_2-sources and storage/utilization hubs and clusters, transport routes (e.g. locations for pipelines [456], ship terminals[457]), compatibility of interfaces, gas compositions, concentrations and pressures, social acceptance and industry actor interests and likely more.[458]

R&I areas to tackle these issues may also include technologies to improve monitoring, e.g. via remote sensing, to meet some of the practical challenges related to MRV during transport[459] and storage. Artificial Intelligence can play a central role in estimating e.g. mass flows in CO_2 transport, trapping of CO_2 during injection, and material interactions in CO_2 utilization.[460]

Interdisciplinary research projects may aid identifying key success factors in the selection of storage sites as well as the design of policies that may foster development of transport and storage infrastructures.

Research and innovation of products suitable for permanent CO_2 storage needs to be promoted. Among promising groups of materials are building materials such as cement, timber, and others, as well as E-fuels and chemicals. Energy use and costs related to these alternatives to conventional materials need to be tackled, and policies incentivising their use must be designed to scale up their application.

A5.11.2 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

In short, R&D funding accompanying real-world roll-out of storage and utilization hubs and clusters can help navigate public perception by strengthening transparency through stronger monitoring, long-term observation means and monitoring of cost structures.

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[456] Onyebuchi, V. E., Kolios, A., Hanak, D. P., Biliyok, C., & Manovic, V. (2018). A systematic review of key challenges of CO2 transport via pipelines. *Renewable and Sustainable Energy Reviews*, *81*, 2563-2583.

[457] Kjärstad, J., Skagestad, R., Eldrup, N. H., & Johnsson, F. (2016). Ship transport—A low cost and low risk CO2 transport option in the Nordic countries. *International Journal of Greenhouse Gas Control*, *54*, 168-184.

[458] Nazeri, M., Haghighi, H., Mckay, C., Erickson, D., & Zhai, S. (2021, September). Impact of CO2 Specifications on Design and Operation Challenges of CO2 Transport and Storage Systems in CCUS. In *SPE Offshore Europe Conference & Exhibition*. OnePetro.

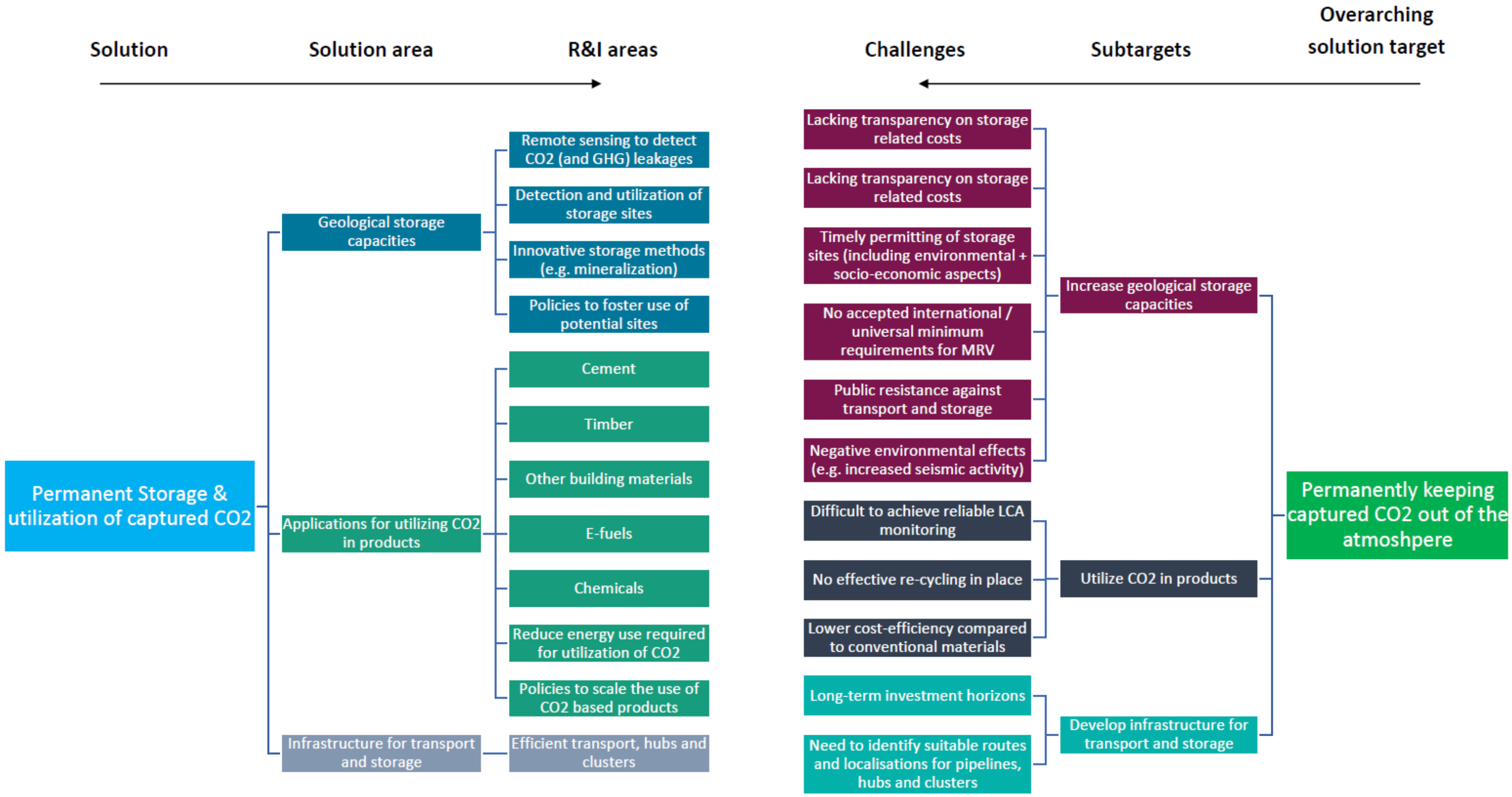
[459] Vitali, M., Zuliani, C., Corvaro, F., Marchetti, B., Terenzi, A., & Tallone, F. (2021). Risks and safety of CO2 transport via pipeline: A review of risk analysis and modeling approaches for accidental releases. *Energies*, *14*(15), 4601.

[460] Yan, Y., Borhani, T. N., Subraveti, S. G., Pai, K. N., Prasad, V., Rajendran, A., ... & Clough, P. T. (2021). Harnessing the power of machine learning for carbon capture, utilisation, and storage (CCUS)–a state-of-the-art review. Energy & Environmental Science, 14(12), 6122-6157.

R&D support can also enable innovation breakthroughs in CO_2 utilization both in their production and applications where consumption-side measures can help overcome cost-penalties.

Research can dramatically strengthen the systems planning for efficient transport and storage networks.

Figure 11 Solution Landscape Permanent Storage & utilization of captured CO2. Source: ICF & partners, 2023



A5.12 Terrestrial ecosystem-based removals

A5.12.1 Goals and challenges

Responsibly managing terrestrial ecosystems to realise the capture and storage of CO_2 can help achieve net-zero targets in agriculture and forestry.[461]

To achieve the full potential of terrestrial ecosystems towards removals, three objectives have to be met: (1) first, conflicts with other land uses must be avoided, since fertile land is limited and serves several ecosystem and human services, like food and materials provision, biofuels, biodiversity, and leisure[462]; (2) carbon uptake and storage of managed lands (agricultural and forestry) should be improved – often counter to a multi-generational decarbonisation trend; and, (3) all measures ought to contribute socio-economic and environmental co-benefits. Such synergies and co-benefits will be crucial to achieve scale up and long-term sustainability, especially in rural and under-developed areas.[463]

Specific challenges related to land-use conflicts include trade-offs on land, fertilizer and water, as well as unclear legislation and ownership regarding land and land use. Trade-offs can occur when modern agricultural systems are excessively optimised to serve one single purpose[464]. Consequently, land use often follows an either-or rather than a both-and approach toward fulfilling multiple objectives, including carbon uptake. Excessively pushing for biomass-based carbon removals through strong incentives can risk increasing conflicts and trade-offs with adverse effects[465] also on public acceptance and geopolitics[466], leading to a backlash to the long-term role of terrestrial ecosystem CDR.

Regulations and ownership are often unclear when it comes to land-use and agricultural systems. Potential large-scale application of terrestrial ecosystem-based removals holds the potential for land-grabbing, which needs to be avoided if socio-economic co-benefits are to be harvested. Unclear regulation and ownership hold the potential for geopolitical

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[461] Dooley, Kate; Nicholls, Zebedee; Meinshausen, Malte (2022): Carbon removals from nature restoration are no substitute for steep emission reductions. In: One Earth 5 (7): p. 812-824.

[462] Honegger, M., Baatz, C., Eberenz, S., Holland-Cunz, A., Michaelowa, A., Pokorny, B., Poralla, M. & Winkler, M. (2022). The ABC of Governance Principles for Carbon Dioxide Removal Policy. Frontiers in Climate, 4, 884163.

[463] Janssens, I. A., Roobroeck, D., Sardans, J., Obersteiner, M., Peñuelas, J., Richter, A., ... & Vicca, S. (2022). Negative erosion and negative emissions: Combining multiple land-based carbon dioxide removal techniques to rebuild fertile topsoils and enhance food production. *Frontiers in Climate*.

[464] Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., ... & Keesstra, S. (2019). Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. *Annual Review of Environment and Resources*, *44*, 255-286.

[465] Honegger, M., Michaelowa, A., & Roy, J. (2021). Potential implications of carbon dioxide removal for the sustainable development goals. *Climate policy*, *21*(5), 678-698.

[466] Kreuter, J., & Lederer, M. (2021). The geopolitics of negative emissions technologies: Learning lessons from REDD and renewable energy for afforestation, BECCS, and direct air capture. Global Sustainability, 4, E26. doi:10.1017/sus.2021.24

implications.[467] Further, accounting,[468] liability and obligations for MRV and reversals need to be clarified.[469]

To improve the carbon uptake of existing agricultural systems, the first challenge is to actually increase the application of related measures.[470] As outlined above, the aim should be to not to expand into hitherto unused areas, but rather to increasingly use already cultivated land for CDR purposes. This implies that cultivation practices need to be altered to meet the specific CDR requirements on top of the requirements posed by the original use. Landowners are often hesitant to change successful production patterns as needed for CDR and would need reliable incentives to do so.[471] Likewise, policy makers in most legislations so far have held back from implementing such incentives and have little motivation to change this pattern: public debate,[472] along with farmer´s reservation towards changing proven practices, makes it challenging to implement concrete incentive schemes.

The permanence of CO_2 stored in biomass and soils[473] depends on plants and soils remaining intact. A shift from using biomass in short-lived towards long-lived products play a central role in reducing the short-term re-emission and increases the net carbon stored in wood products[474]. There is significant variability across world-regions regarding both natural and human influence on durability. Natural disasters such as fires, droughts or floods strongly challenge this precondition, with the frequency of extreme events likely increasing due to climate change. Likewise, local and regional conflicts can lead to the re-emission of GHG from terrestrial ecosystems. This challenges the effectiveness of ecosystem-based CDR. Related to this challenge is the lack of institutional frameworks and reliable methods for MRV. Reversals and re-emissions need to be accurately, reliably and comparably measured over large areas and timeframes to assure correct calculation of activities´ contribution to climate goals.

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[467] Ibidem.

[468] Paschen, M., Meier, F., & Rickels, W. (2021). *Accounting for terrestrial and marine carbon sink enhancement* (No. 2204). Kiel Working Paper.

[469] Ruseva, T., Hedrick, J., Marland, G., Tovar, H., Sabou, C., & Besombes, E. (2020). Rethinking standards of permanence for terrestrial and coastal carbon: implications for governance and sustainability. *Current Opinion in Environmental Sustainability*, *45*, 69-77.

[470] Paustian, K., Cotrufo, M. F., Al-Kaisi, M., Birdsey, R., & Field, J. (2018, December). Carbon-dioxide removals through land management-challenges and constraints to multi-Gt scale-up. In *AGU Fall Meeting Abstracts* (Vol. 2018, pp. GC41A-08).

[471] Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., & Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *Wiley Interdisciplinary Reviews: Climate Change*, *11*(6), e671.

[472] Cox, E., Spence, E., & Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nature Climate Change*, *10*(8), 744-749.

[473] Lal, R., Monger, C., Nave, L., & Smith, P. (2021). The role of soil in regulation of climate. *Philosophical Transactions of the Royal Society B*, *376*(1834), 20210084.

[474] Grassi, G., Fiorese, G., Pilli, R., Jonsson, K., Blujdea, V., Korosuo, A. and Vizzarri, M., Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution, Sanchez Lopez, J., Jasinevičius, G. and Avraamides, M. editor(s), European Commission, 2021, JRC124374.

Challenges regarding the third sub target (realising environmental and socio-economic co-benefits) relate mainly to difficulties in quantifying and ensuring co-benefits. Some effective and efficient methods of terrestrial ecosystem-based removals threaten biodiversity and socio-economic systems.[475,476] Avoiding such measures despite their frequent advantages in short-term cost-efficiency might not be easy, and incentive schemes must therefore be robust regarding safeguarding socio-economic and environmental co-benefits.[477] However, even if such safeguards are implemented, they remain challenging to monitor and enforce. Furthermore, especially environmental co-benefits are difficult to quantify on different time scales, which further complicates their enforcement.[478]

A5.12.2 Solution and R&I areas

The solution areas to counter the challenges outlined above cover the whole range of removal methods based on terrestrial ecosystems. Most research and innovation areas we identified are relevant to more than one removal method. Transdisciplinary research to better understand the interplay of carbon uptake and storage, sustainability, and co-benefits is key to all methods to enable responsible and effective large-scale applications. Incentive systems for such applications must be developed to ensure clarity in legislation and ownership, as well as accountability and monitorable safeguards to socio-economic and environmental aspects. Sustainable land-management practices and their application to removal purposes need to be further researched from a political science perspective to ensure co-benefits are sufficiently considered.[479] Co-benefits associated with systems altered to increase carbon uptake and storage (e.g. enhanced draught resistance) need to be analysed, further evaluating the potential for multiple purposes of agricultural systems. Regarding storage in soil carbon, potentials of annual and perennial grains and crops with deeper roots is a promising field of research to increase effectiveness of terrestrial biosphere-based CDR methods. Genome sequencing (and other genetic approaches) can improve CO_2 uptake and storage of

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[475] Dooley, Kate; Nicholls, Zebedee; Meinshausen, Malte (2022): Carbon removals from nature restoration are no substitute for steep emission reductions. In: One Earth 5 (7): p. 812-824.

[476] Grassi, G., Fiorese, G., Pilli, R., Jonsson, K., Blujdea, V., Korosuo, A. and Vizzarri, M., Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution, Sanchez Lopez, J., Jasinevičius, G. and Avraamides, M. editor(s), European Commission, 2021, JRC124374.

[477] Dooley, K., Harrould-Kolieb, E., & Talberg, A. (2021). Carbon-dioxide Removal and Biodiversity: A Threat Identification Framework. *Global Policy*, *12*, 34-44.

[478] Guillén-Gosálbez, G., Werner, C., Sunny, N., Hamelin, L., Guillén-Gosálbez, G., & Jackson-Blake, L. Comprehensive sustainability assessment of terrestrial biodiversity NETPs.

[479] Buck, H. J. (2016). Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change*, *139*(2), 155-167.

plants.[480] To enable reliable MRV, remote sensing technologies for large areas and CO_2, as well as non-CO_2 GHG should be enhanced.

A5.12.3 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

In short, transdisciplinary research formats in which researchers and practitioners learn from one-another can help overcome obstacles for sustainable terrestrial ecosystem-based carbon removal. R&D should in particular address:

- effectiveness of afforestation and reforestation projects regarding long-term carbon flows and other sustainability dimensions;
- biomass harvesting systems energy crops (carbon flows and sustainability) including secondary land-use change effects;[481]
- enhancing high-carbon ecosystem resilience with limited management; and,
- effectiveness of soil carbon enhancements through enhanced mineralization[482], altered soil management, and biochar applications (carbon flows, sustainability and business case).[483]
- development of practical and reliable monitoring technologies including AI-enabled.

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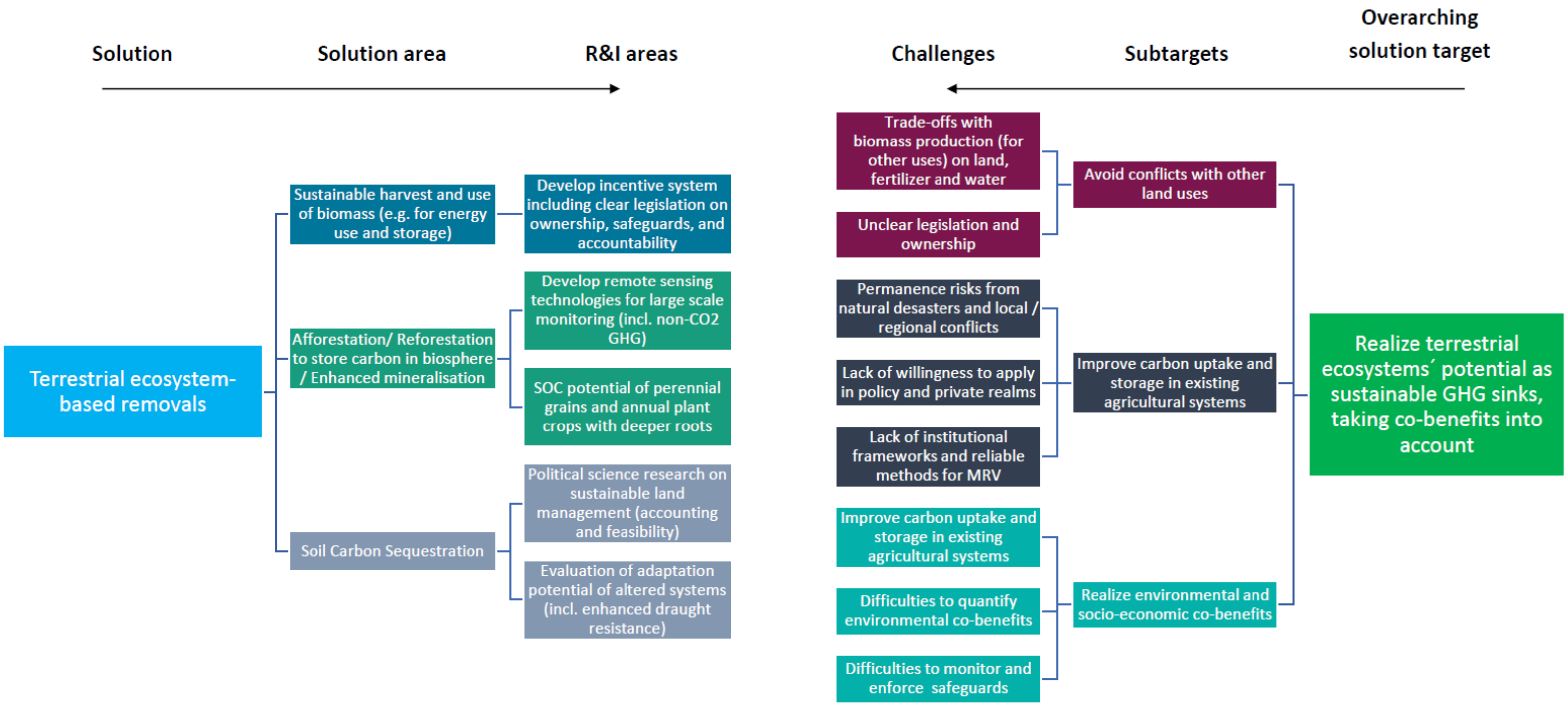
[480] Zahed, M. A., Movahed, E., Khodayari, A., Zanganeh, S., & Badamaki, M. (2021). Biotechnology for carbon capture and fixation: Critical review and future directions. Journal of Environmental Management, 293, 112830.

[481] Camia, A., Robert, N., Jonsson, K., Pilli, R., Garcia Condado, S., Lopez Lozano, R., van der Velde, M., Ronzon, T., Gurria Albusac, P., M´Barek, R., Tamosiunas, S., .Fiore, G., dos Santos Fernandes de Araujo, R., Hoepfner, N., Marelli, L. & Giuntoli, J. (2018). Biomass production, supply, uses and flows in the European Union: First results from an integrated assessment. EUR 28993 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-77236-8

[482] Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., ... & Banwart, S. A. (2020). Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242-248.

[483] Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., ... & Hansen, J. (2018). Farming with crops and rocks to address global climate, food and soil security. *Nature plants*, *4*(3), 138-147.

Figure 12 Solution Landscape Terrestrial ecosystem-based removals. Source: ICF & partners, 2023.



A5.13 Ocean-based ecosystem removals

Oceans currently take up vast amounts of the human-emitted CO_2 in the atmosphere. Some measures could potentially enhance the oceans' capacities for further CO_2-uptake, which otherwise is in gradual decline due to saturation. However, such measures are characterised by large scientific uncertainties regarding their efficacy as well as side effects, both of which warrant careful R&D efforts.

A5.13.1 Goals and challenges

The Solution Landscape for ocean ecosystem-based removals includes four sub-targets (see figure below), which contribute to the overarching target of developing and standardising effective and sustainable CO_2 removal techniques with reliably measurable outcomes.

Uncertainty regarding effectiveness and costs of ocean-based CDR solutions is large due to lack of technology maturity.[484,485] The absence of practical regulation, especially covering the high seas, is holding back innovation. Novel MRV frameworks will be needed for open-water CDR methods. Furthermore, there is no clarity as to which nation results would have to be accounted to, and national regulation of coastal areas is often also inadequate to reliably govern CDR applications.[486]

Large uncertainties regarding ecosystem effects of various marine CDR applications require further research: the high complexity of marine systems means that any intervention can lead to multiple, unanticipated alterations on different scales of time and distance.[487] Feedback loops regarding e.g. energy and nutrients are also poorly understood. Artificially induced algae blooms may lead to nutrient robbing (i.e., algae consume nutrients, which are then no longer available to other organisms). The connectivity and sheer size of marine systems, with full permeability in all dimensions in the water column puts a major challenge to understanding marine feedbacks, and to safely applying marine CDR.

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[484] Wan, X., Li, Q., Qiu, L., & Du, Y. (2021). How do carbon trading platform participation and government subsidy motivate blue carbon trading of marine ranching? A study based on evolutionary equilibrium strategy method. *Marine Policy*, *130*, 104567.

[485] Sarwer, A., Hamed, S. M., Osman, A. I., Jamil, F., Al-Muhtaseb, A. A. H., Alhajeri, N. S., & Rooney, D. W. (2022). Algal biomass valorization for biofuel production and carbon sequestration: a review. *Environmental Chemistry Letters*, 1-55.

[486] Webb, R., Silverman-Roati, K., & Gerrard, M. (2021). Removing Carbon Dioxide Through Ocean Alkalinity Enhancement and Seaweed Cultivation: Legal Challenges and Opportunities. *Sabin Center for Climate Change Law, Columbia Law School, Columbia Public Law Research Paper Forthcoming*.

[487] Boyd, P. W., Bach, L. T., Hurd, C. L., Paine, E., Raven, J. A., & Tamsitt, V. (2022). Potential negative effects of ocean afforestation on offshore ecosystems. *Nature Ecology & Evolution*, 1-9.

Reliable methods for monitoring are currently missing to track removals and any secondary emissions-effects in the ocean.[488]

A5.13.2 Solution and R&I areas

On the solution side, two solution areas can be distinguished: First, "long-shot" ocean removals, which may deliver massive removal potentials, but currently are underdeveloped and face serious obstacles. These include methods like artificial up-/down welling, ocean alkalinity enhancement (OAE),[489] and micro-nutrient fertilisation. Second, the more manageable approaches which are mostly removal methods in coastal areas (also known as "blue carbon"), including capture and storage of CO_2 in mangroves,[490] as well as seagrass[491] and kelp farming.[492]

Research and innovation support for both solution areas need to focus on enhancing the understanding of how the complexity of marine systems (tipping points; biological and biogeochemical responses under hypoxic and/or anoxic conditions; and, abundances and diversity of phytoplankton) intersects with realistic application scenarios.[493]

The development of reliable MRV systems has to build on the above, but also include advancing remote sensing options.[494] Developing remote sensing technology in such a way as to support the overall objectives requires doing so in an interdisciplinary setting and with a view to realistic application scenarios within an overall MRV system and regulatory context.

In addition, several regulatory and socio-economic aspects need to be researched in applied transdisciplinary settings: interpreting existing and developing options for future Governance of the high seas, as well as of domestic law regarding coastal ecosystems, will be key to achieve feasibility and transparency in ocean removals.[495] Potential co-

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[488] Gagern, A., Manley, J., & Kapsenberg, L. (2022). Ocean-Based Carbon Dioxide Removal: A New Frontier in the Blue Economy. *Marine Technology Society Journal*, *56*(1), 40-48.

[489] Fakhraee, M., Planavsky, N., & Reinhard, C. (2022). Ocean alkalinity enhancement through blue carbon ecosystem restoration.

[490] Atwood, T. B., Connolly, R. M., Almahasheer, H., Carnell, P. E., Duarte, C. M., Ewers Lewis, C. J., ... & Lovelock, C. E. (2017). Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change*, *7*(7), 523-528.

[491] Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation?. *Frontiers in Marine Science*, *4*, 100.

[492] Lezaun, J. (2021). Hugging the shore: tackling marine carbon dioxide removal as a local governance problem. *Frontiers in Climate*, *3*, 684063.

[493] Gagern, A., Manley, J., & Kapsenberg, L. (2022). Ocean-Based Carbon Dioxide Removal: A New Frontier in the Blue Economy. *Marine Technology Society Journal*, *56*(1), 40-48.

[494] Campbell, A. D., Fatoyinbo, T., Charles, S. P., Bourgeau-Chavez, L. L., Goes, J., Gomes, H., ... & Lagomasino, D. (2022). A review of carbon monitoring in wet carbon systems using remote sensing. *Environmental Research Letters*.

[495] Boettcher, M., Brent, K., Buck, H. J., Low, S., McLaren, D., & Mengis, N. (2021). Navigating potential hype and opportunity in governing marine carbon removal. *Frontiers in climate*, *3*, 664456.

benefits of ocean-based CDR applications and the respective methods´ economic feasibility, as well as effectiveness, requires further research.[496]

A5.13.3 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

R&D funding for ocean-based carbon removals ought to further develop, assess potentials and risks of currently immature methods (artificial up-/down welling, ocean alkalinity enhancement (OAE), and micro-nutrient fertilisation). R&D is also needed to ensure the feasibility of more mature approaches (mangroves, seagrass and kelp farming) through appropriate implementation and monitoring technologies and practices that track both the carbon flows and ecosystem effects under realistic application scenarios – including remote sensing. Transdisciplinary R&D can also enable resolving regulatory and public acceptance barriers including governance problems of the high seas and domestic law.

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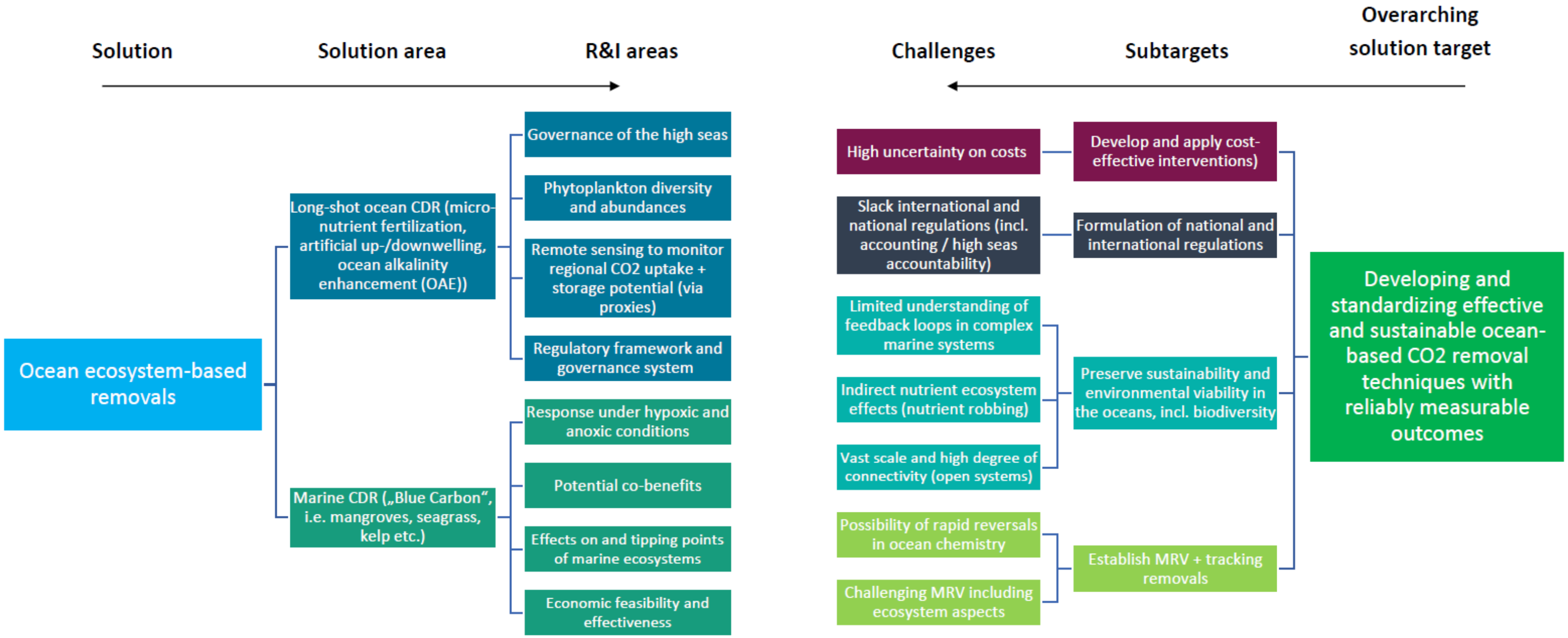
[496] Coleman, S., Dewhurst, T., Fredriksson, D. W., St Gelais, A., Cole, K., MacNicoll, M., ... & Brady, D. C. (2022). Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal. *Frontiers in Marine Science*, 1460.

Figure 13 Solution Landscape Ocean ecosystem-based removals. Source: ICF & partners, 2023.



A5.14 Solution landscapes driven by lifestyle/societal trends low-carbon scenarios

A5.14.1 Circular economy

A5.14.1.1 Goals and challenges

Circular economy is one essential building block of the European Green Deal and a prerequisite to achieve the EU's 2050 climate neutrality target. Therefore, the implementation is supported by the new Circular Economy Action Plan (CEAP).[497] Furthermore, it is a main pillar to address resource constraints and resource efficiency.[498]

Alongside the undoubted importance of the circular economy concept, it is also appropriate to keep the broader and more general limitations (e.g., system boundary limitations or path dependencies) of the concept in mind that cannot be readily solved or addressed, even by the more specific challenges on the path to a more circular economy that are described below.[499]

In terms of R&I, the circular economy is a highly cross-cutting issue. For the concept to work effectively[500], as well as regulatory and governance aspects to create the appropriate conditions for incorporating such technologies into a circular economy.[501] On the other hand, the concept is also supported by research from other broader areas, such as carbon storage and removal (see above), or material sciences (e.g., research for a circular plastics economy).,[502]

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[497] European Commission, Directorate-General for Communication, Circular economy action plan: for a cleaner and more competitive Europe, Publications Office of the European Union, 2020, https://data.europa.eu/doi/10.2779/05068

[498] IRP (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

[499] Korhonen, Jouni; Honkasalo, Antero; Seppälä, Jyri (2018): Circular Economy: The Concept and its Limitations. In: Ecological Economics 143, S. 37–46. DOI: 10.1016/j.ecolecon.2017.06.041. Lehmann, H., Hinske, C., de Margerie, V., & Slaveikova Nikolova, A. (Eds.). (2022). The Impossibilities of the Circular Economy: Separating Aspirations from Reality (1st ed.). Routledge. https://doi.org/10.4324/9781003244196

[500] European Commission, Directorate-General for Research and Innovation, Products and circular economy : policy recommendations derived from Research & Innovation projects, Publications Office, 2020, https://data.europa.eu/doi/10.2777/15587

[501] Stahel, Walter R. (2016): The circular economy. In: Nature 531 (7595), S. 435–438. DOI: 10.1038/531435a

[502] European Commission, Directorate-General for Research and Innovation, Research & innovation enables the transition to a circular economy, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/44587

However, in addition to the technology-specific aspects and challenges, the concept still faces some general challenges that can be grouped according to different sub-goals[503] on the way to a climate neutral circular economy:

a) Harmonised markets

The harmonised market refers to the challenge to create a sustainable product policy framework. This can be done by regulatory or by economic approaches (e.g. steering financing towards more sustainable products, restricting single use). However, this is also linked with some challenges such as the large product variety, standards and norms (both missing norms as well as existing ones) and the digitalisation of products (providing digital product information and enabling the tracking of relevant products and materials).[504]

b) Circularity in production process

In order to integrate not only the use of products and technologies, but also their production into a circular economy, the implementation and enabling of industrial symbiosis[505] is a key challenge, which is also mentioned in the CEAP.[506] Here, one essential goal is to recover the value of by-products and waste, hence increasing the resilience of the economy to external shocks brought about by raw material supply uncertainties.[507]

A relevant debate in this context is the discussion on the responsibility for the negative externalities of the end-of-life-processes of products, and whether the costs of enabling circularity should be borne by the producer or the consumer[508]. The European Commission has legislated in this regard for the producers to assume responsibilities (and hence internalising the externality costs) in several sectors such as packaging, electronics, and batteries[509].

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[503] Ibidem.

[504] European Commission, Directorate-General for Communication, Circular economy action plan: for a cleaner and more competitive Europe, Publications Office of the European Union, 2020, https://data.europa.eu/doi/10.2779/05068

[505] Industrial symbiosis - Circular Economy Guide (ceguide.org)

[506] European Commission, Directorate-General for Communication, Circular economy action plan: for a cleaner and more competitive Europe, Publications Office of the European Union, 2020, https://data.europa.eu/doi/10.2779/05068

[507] Yu, Yifei; Yazan, Devrim Murat; Bhochhibhoya, Silu; Volker, Leentje (2021): Towards Circular Economy through Industrial Symbiosis in the Dutch construction industry: A case of recycled concrete aggregates. In: Journal of Cleaner Production 293, S. 126083. DOI: 10.1016/j.jclepro.2021.126083.

[508] Lenzen, M., Murray, J., Sack, F., & Wiedmann, T. (2007). Shared producer and consumer responsibility—Theory and practice. *Ecological economics*, *61*(1), 27-42.

[509] Laubinger, F., Brown, A., Dubois, M., & Börkey, P. (2021). Modulated fees for Extended Producer Responsibility schemes (EPR), OECD Environment Working Paper 184, 2021.

c) Empowering consumers

The demand side plays an essential role in the implementation of the circular economy. Therefore, it is extremely important to empower consumers to participate in the circular economy and to steer the market towards sustainable products and materials. One challenge in achieving this sub-goal can be, for example, a lack of (product) information, which is of course also related to the goal of a harmonised market for the circular economy (see above). Other challenges may be related to difficult maintenance and disposal of products and equipment (e.g., lack of spare parts, dismantling capabilities, hazardous materials - see also below).

d) Less waste

The fourth major sub-target considered in the solution landscape is the reduction of waste in the context of the circular economy. This includes challenges that complicate the collection and appropriate categorisation of waste/end-of-life products, such as a lack of product information and tracking of materials used in different products and devices. Other challenges may include the use of hazardous materials (making recycling difficult) or a lack of disassembly capability (including reparability / remanufacturing), which also hinders a potential recycling process or even the reuse/repurposability of a product.

In addition to these sub targets, there are also several cross-cutting aspects, which are also mentioned in the CEAP. These include: circularity as a prerequisite for climate neutrality; getting the economics right; and, monitoring.[510]

A5.14.1.2 Solution and R&I areas

In general, many of the required R&I efforts to enable the circular economy are directly linked to specific technologies and the materials used in them, with the goal of making them "circular economy ready.[511] Therefore, such R&I areas should be directly addressed in the respective solution landscapes for different materials and technologies.

Another approach often used in the literature to look at circular economy is to take the perspective of specific industries or product groups to examine the requirements for successful circular economy implementation in them (e.g., circular economy in fashion,

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[510] European Commission, Directorate-General for Communication, Circular economy action plan: for a cleaner and more competitive Europe, Publications Office of the European Union, 2020, https://data.europa.eu/doi/10.2779/05068

[511] Ernesto (2022): Developing Insulating Polymeric Foams: Strategies and Research Needs from a Circular Economy Perspective. In: Materials 15 (18). DOI: 10.3390/ma15186212. Ahn, Namhyuck; Dodoo, Ambrose; Riggio, Mariapaola; Muszynski, Lech; Schimleck, Laurence; Puettmann, Maureen (2022): Circular economy in mass timber construction: State-of-the-art, gaps and pressing research needs. In: Journal of Building Engineering 53, S. 104562. DOI: 10.1016/j.jobe.2022.104562.

Munaro, Mayara Regina; Tavares, Sérgio Fernando; Bragança, Luís (2020): Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. In: Journal of Cleaner Production 260, S. 121134. DOI: 10.1016/j.jclepro.2020.121134.

electronical equipment or buildings).[512] However, both the technology-specific and the branch- or product-oriented perspective need to be complemented by a more general and systemic view. Therefore, the focus here will be on the more overarching and general frameworks and concepts, which should also always be kept in mind and included when defining the R&I topics for different solutions and technologies for a climate neutral Europe. This is because the circular economy is a key component for this goal.

The solution areas of circular economy can be structured around three main solution areas, in agreement with the 9 Rs framework (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover)[513] These areas and their respective Rs are: 1) smarter product use and manufacture including refuse, rethink, and reduce; 2) extended lifespan including reuse, repair, refurbish, remanufacture, and repurpose; and, 3) useful application of materials, including recycle and recover. An alternative approach to the solution areas can be made by clustering the 9 Rs according to those that are close to/addressable by the consumer (i.e., refuse, reduce, reuse, repair), those that are mainly addressed by business activities (i.e., refurbish, remanufacture, repurpose) and those that are the least desirable (i.e., recycle, recover).[514]

A review of more than a hundred circular economy R&I projects has shown that the social dimension of the circular economy, in particular, has been neglected in the past and that a more systemic approach with a strong combination of R&I and regulatory policies is needed.[515]

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[512] Zhang, Lisa; Hale, Jo (2022): Extending the Lifetime of Clothing through Repair and Repurpose: An Investigation of Barriers and Enablers in UK Citizens. In: Sustainability 14 (17). DOI: 10.3390/su141710821.

Rahla, Kamel M.; Mateus, Ricardo; Bragança, Luís (2021): Implementing Circular Economy Strategies in Buildings—From Theory to Practice. In: Applied System Innovation 4 (2). DOI: 10.3390/asi4020026.

Pan, Xu; Wong, Christina W.Y.; Li, Chunsheng (2022): Circular economy practices in the waste electrical and electronic equipment (WEEE) industry: A systematic review and future research agendas. In: Journal of Cleaner Production 365, S. 132671. DOI: 10.1016/j.jclepro.2022.132671.

[513] Kirchherr, Julian; Reike, Denise; Hekkert, Marko (2017): Conceptualizing the circular economy: An analysis of 114 definitions. In: Resources, Conservation and Recycling 127, S. 221–232. DOI: 10.1016/j.resconrec.2017.09.005.

[514] Reike, Denise; Vermeulen, Walter J.V.; Witjes, Sjors (2018): The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. In: Resources, Conservation and Recycling 135, S. 246–264. DOI: 10.1016/j.resconrec.2017.08.027.

[515] European Commission, Directorate-General for Research and Innovation, Products and circular economy : policy recommendations derived from Research & Innovation projects, Publications Office, 2020, https://data.europa.eu/doi/10.2777/15587

Other sources also stress the importance of the effect of value chain activities on circular economy, as well as the integration of the digitalisation in the circular economy (see also circular economy Solution Landscape).[516]

A comprehensive list of possible, systemic and cross-cutting R&I areas, which refer to all the below mentioned solution areas and could support the implementation of the circular economy, can be found in the following publication: *European Commission, Directorate-General for Research and Innovation, Products and circular economy: policy recommendations derived from Research & Innovation projects, Publications Office, 2020, https://data.europa.eu/doi/10.2777/15587*

Here, the key points for a systemic, joint approach of policy and R&I are:[517]

- Define, quantify and measure circularity.
- Strengthen policy coherence and comprehensiveness, avoid conflicts and create synergies.
- Create a level playing field for a circular economy.
- Support circular practices on the ground.
- Understand the mechanisms and impacts of markets and consumption.
- Create opportunities and markets for circularity.
- Make circular products and services a market reality.
- Help consumers take informed individual decisions.
- Probe the potential for circular products and processes in industry.
- Raise the circularity readiness level in industry.
- Stimulate resource-efficient and circular design, sourcing and manufacturing.
- Stimulate recycling and the use of secondary materials.

These key issues and related R&I can support all of the solution areas described below. The following description of the latter is therefore intended to summarise only some of the important aspects that must be considered when developing R&I areas for specific technologies and solutions if the circular economy is to be implemented at scale and successfully.

a) Smarter product use and manufacture

These solutions include, for example, improvements in the manufacturing of products, such as the use of more sustainable resources (e.g., bioresources), the reduction of material requirements (e.g., through lightweight construction), or the improvement of the durability of products.

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[516] Alhawari, Omar; Awan, Usama; Bhutta, M. Khurrum S.; Ülkü, M. A. (2021): Insights from Circular Economy Literature: A Review of Extant Definitions and Unravelling Paths to Future Research. In: Sustainability 13 (2). DOI: 10.3390/su13020859.

[517] European Commission, Directorate-General for Research and Innovation, Products and circular economy: policy recommendations derived from Research & Innovation projects, Publications Office, 2020, https://data.europa.eu/doi/10.2777/15587

Smarter use of products can be addressed by increasing product use intensity through sharing economy concepts or alternative solutions, which should be strongly encouraged through the introduction and exploration of new business models.[518]

To this, an increased responsibility of the producers or manufacturers towards the end-of-life stages of the product can be added as a policy measure to internalise the costs of the entire lifespan of the product.

b) Extend lifespan

An extended lifespan could increase the sustainability of product use (e.g., repairing and repurposing clothes).[519] Two main approaches can be mentioned here. One approach is to extend the life of the product itself by improving durability (selected materials, etc.) and promoting reparability. Another complementary approach is to enable a "second life" of products. This could be done by improving upgradeability (e.g., by bringing an older device up to current standards) or by remanufacturing, repurposing, and refurbishing old devices and products. It is important to recognise that specific R&I areas for this solution area are highly dependent on the product classes or technologies involved. However, these could be promoted through a strong combination with general regulatory measures (see above).

c) Useful application of materials

Finally, the last solution area refers to 'recycle' and 'recover', the last-preferred Rs, and presents solutions when none of the solution options described above are possible. Here, recycle refers to the *"processing of mixed streams of post-consumer products or post-producer waste streams using expensive technological equipment including shredding, melting and other processes to capture (nearly) pure materials"*.[520] In contrast, recovery in most cases means recovering the energy contained in the waste when recycling is not possible. As already mentioned above, the R&I areas here are very closely linked to specific materials and products. In general, consistent policy implementation is also needed to address challenges such as tracking and collection of relevant materials and waste, as well as regulatory challenges, such as creating a market that can regulate the flows of new (virgin) and secondary materials in a sustainable manner.

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[518] Ferasso, Marcos; Beliaeva, Tatiana; Kraus, Sascha; Clauss, Thomas; Ribeiro-Soriano, Domingo (2020): Circular economy business models: The state of research and avenues ahead. In: Bus Strat Env 29 (8), S. 3006–3024. DOI: 10.1002/bse.2554.

[519] Zhang, Lisa; Hale, Jo (2022): Extending the Lifetime of Clothing through Repair and Repurpose: An Investigation of Barriers and Enablers in UK Citizens. In: Sustainability 14 (17). DOI: 10.3390/su141710821.

[520] Reike, Denise; Vermeulen, Walter J.V.; Witjes, Sjors (2018): The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. In: Resources, Conservation and Recycling 135, S. 246–264. DOI: 10.1016/j.resconrec.2017.08.027.

A5.14.1.3 Role of disruptive General Purpose Technologies

There are signs in the literature that Artificial Intelligence may have an impact on the push towards a circular economy by optimising recycling processes as well as enabling sustainable project design, but the magnitude of the potential impact is not clear from the literature[521].

A5.14.1.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

As previously described, the topic of circular economy is cross cutting and relevant across all technologies to ensure the sustainability of future solutions and to respond to challenges in the area of material availability (and dependencies). Therefore, this topic should not only be considered as an isolated research topic, but should be an integral part of future research projects for new or improved technologies. This is also evident in the more technically oriented solutions landscapes described above, in which all these aspects are reflected.

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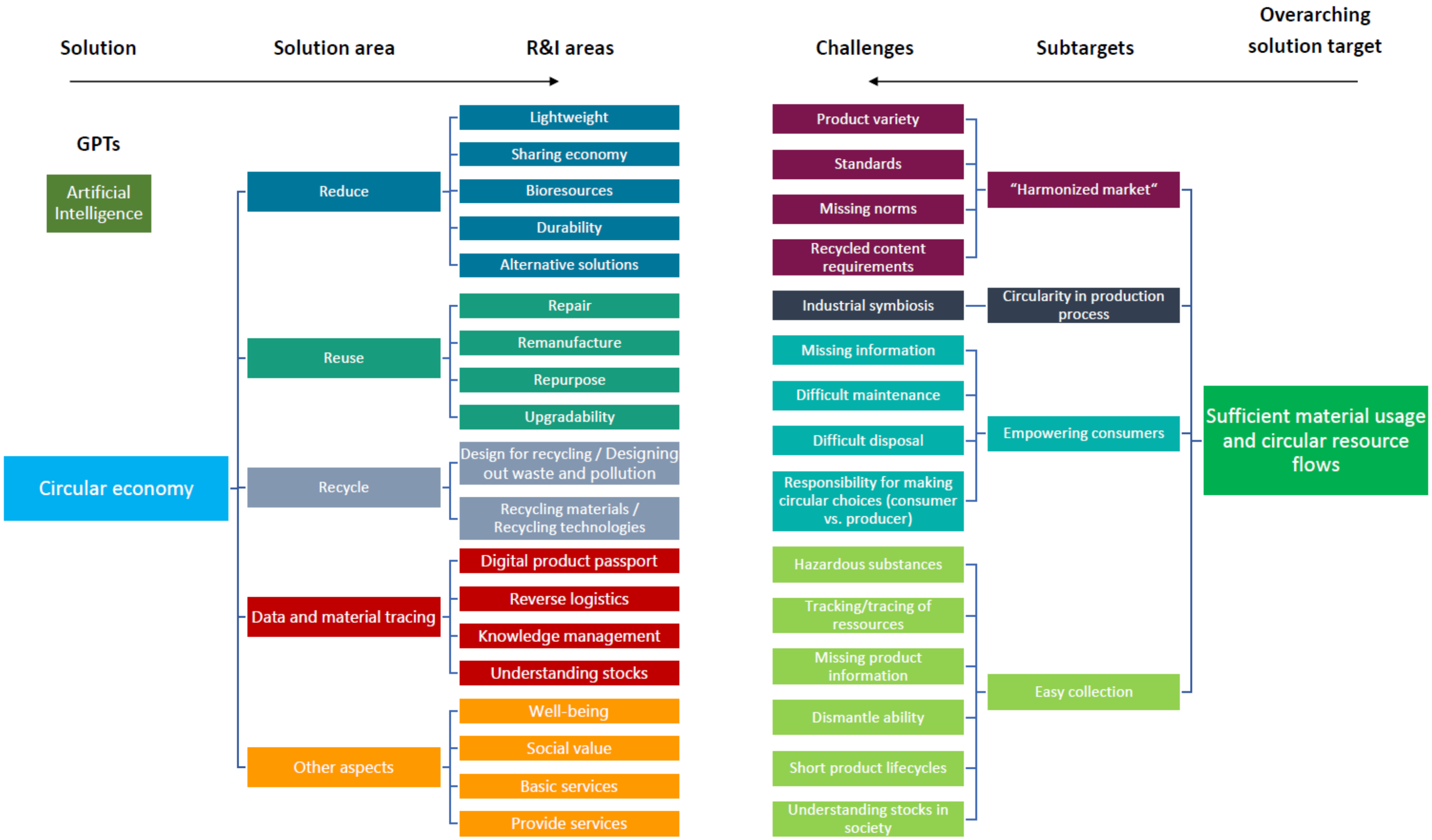
[521] Agrawal, R., Wankhede, V. A., Kumar, A., Luthra, S., Majumdar, A., & Kazancoglu, Y. (2021). An exploratory state-of the-art review of artificial intelligence applications in circular economy using structural topic modeling. Operations Management Research, 1-18.

Figure 14 Solution Landscape Circular economy. Source: ICF & partners, 2023.



A5.14.2 New food

A5.14.2.1 Goals and challenges

The agriculture sector faces multiple challenges in adapting to a changing world, notably in responding to the challenges posed by climate change. Climate change contributes detrimentally (and will continue to do so) to the yields of agriculture and fisheries, as well as pest patterns; it also increases the probability of extreme weather events, increasing the need for resilience in the food sector.

With world population predicted to keep rising and peak later this century, the needs of the population are both increasing and changing. Health concerns, especially in response to obesity, are a significant challenge to overcome in the food sector, all the while maintaining food safety and quality standards. These challenges tie in with food security concerns in the EU, notably associated with geopolitical dependencies of food supply chains.

The food industry, especially the meat industry, has also had to face the challenge of high emissions intensities and high water and resource consumption that menace resource availability (such as in the fisheries sector). Alternatives to meat and fish exist and continue to be developed, but their acceptance among the broader population is a challenge that needs to be overcome.[522]

A5.14.2.2 Solution and R&I areas

a) Food processing

The first area of research and innovation concerns improvements in food processing, namely in the transformation of raw products into consumable foods. Non-thermal food processing methods, such as electric field processing, ultrasound processing, or high-pressure food processing are an area of active research that will likely continue to be focus areas in the future. Enzyme technologies, in particular, have been demonstrated to have long-term effects that might contribute to increased efficiency in food processing. The rise of 3-D printing, a general-purpose technology, might further lead to increased acceptability of alternative foods by enabling the creation of “designer foods”.

b) Cultivation methods

Genetic editing technologies, amplified by the rise of CRISPR[523], have the potential to increase crop yields, and presents a significant improvement over traditional crop

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[522] Bryant, C., Barnett, J., 2020. Consumer acceptance of cultured meat: an updated review (2018–2020). Appl. Sci. 10 (15), 5201. https://doi.org/10.3390/app10155201.

[523] An acronym for Clustered Regularly Interspaced Short Palindromic Repeats which represents a segment of DNA containing short repetitions of base sequences.

improvement methods.[524] The cultivation of crops that are underutilised or thought of as unsuitable for consumption might help reduce the pressure on traditionally cultivated sources of nutrients. These crops are referred to as Neglected, Underutilised, and Wild Edible plants (NUWEPs). NUWEPs have been seen as being useful to introduce diversity in food systems that increase the capacity of crops to contribute to climate adaptation and mitigation, as well as to increase the resilience of food systems.[525] In addition, techniques such as regenerative agriculture and reliance on methods such as crop rotation with a focus on soil health and a self-sustainability of agriculture have the potential not only to contribute towards food security but also towards climate mitigation (through carbon capture by plants), preservation of biodiversity, as well as climate adaptation and resilience[526][527].

c) Animal husbandry and fisheries

The animal husbandry sector is often at the centre of discussions on the subject of GHG (methane) emissions from the food sector, particularly from ruminant animals such as cattle, from enteric fermentation, as well as from manure.[528] Several strategies to reduce methane emissions are still being researched, with further research being necessary. Changing livestock feed by introducing additives, or the vaccination of livestock to reduce their methane production, or selective breeding of low-methane producing cattle are among the research directions currently being studied.[529] In the fisheries sector, aquaculture (namely the cultivation of aquatic animals in closed and controlled environments) may aid in reducing pressure on natural environments, as well as form a part of climate adaptation and resilience strategies to combat sea-level rise and habitat destruction.

d) Meat alternatives

Alternatives to GHG-intensive meat have been discussed widely in the literature, the most prominent being ‘lab-grown meat’ or ‘cultured meat’. Cultured meat generally seems to promote many positive environmental externalities, since it bypasses many of the GHG-intensive and resource-intensive steps of traditional methods of harnessing

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[524] Scheben, A., Wolter, F., Batley, J., Puchta, H., Edwards, D., 2017. Towards CRISPR/Cas crops–bringing together genomics and genome editing. New Phytol. 216, 682–698.

[525] Baldermann, S., Blagojevic, L., Frede, K., Klopsch, R., Neugart, S., Neumann, A., Ngwene, B., Norkeweit, J., Schr€oter, D., Schr€oter, A., 2016. Are neglected plants the food for the future? Crit. Rev. Plant Sci. 35 (2), 106–119. https://doi.org/10.1080/07352689.2016.1201399.

[526] White, C. (2020). Why regenerative agriculture?. American Journal of Economics and Sociology, 79(3), 799-812.

[527] Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of soil and water conservation*, *75*(5), 123A-124A.

[528] Jairath, G., Mal, G., Gopinath, D., Singh, B., 2021. A holistic approach to access the viability of cultured meat: a review. Trends Food Sci. Technol. 110, 700–710. https://doi.org/10.1016/j.tifs.2021.02.024.

[529] Wattiaux, M.A., Uddin, M.E., Letelier, P., Jackson, R.D., Larson, R.A., 2019. Invited review: emission and mitigation of greenhouse gases from dairy farms: the cow, the manure, and the field. Appl. Anim. Sci. 35 (2), 238–254. https://doi.org/10.15232/aas.2018-01803.

meat.[530] However, uncertainties still exist in the technology required to produce cultured meat, as well as in increasing public acceptance of such meats.[531] Other alternatives are nature-based solutions that are widely discussed, and include protein sources such as seaweed or algae, which are seen as 'plant-based alternatives'[532], or insect consumption.

e) Digitalisation / Agriculture 4.0

Another important technological development to take into account is the integration of digital technologies in the food supply chain to enable better and more efficient tracking of food from the "farm to the fork". This could alleviate many consumer concerns about safety and quality, in addition to leading to improvements in reducing food waste.[533]

Other directions of research include space farming, in tandem with current and future space exploration missions.[534]

A5.14.2.3 Role of disruptive General Purpose Technologies

As mentioned in the previous section, progress in space technology and astrobiology has the potential to introduce innovations in food production on Earth. More promising, however, are the potential disruptive effects that are enabled by advances in Genome editing such as those brought about through the advent of CRISPR/Cas.[535]. In a similar vein, advances in synthetic biology might have a significant impact on the food production system for the future, for instance by amplifying advances in genetic engineering as well as by rendering crops more resistant to pests[536][537].

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[530] Jairath, G., Mal, G., Gopinath, D., Singh, B., 2021. A holistic approach to access the viability of cultured meat: a review. Trends Food Sci. Technol. 110, 700–710. https://doi.org/10.1016/j.tifs.2021.02.024.

[531] Tomiyama, A.J., Kawecki, N.S., Rosenfeld, D.L., Jay, J.A., Rajagopal, D., Rowat, A.C., 2020. Bridging the gap between the science of cultured meat and public perceptions. Trends Food Sci. Technol. 104 (August), 144–152. https://doi.org/10.1016/j.tifs.2020.07.019.

[532] Santo, R.E., Kim, B.F., Goldman, S.E., Dutkiewicz, J., Biehl, E.M.B., Bloem, M.W., Neff, R.A., Nachman, K.E., 2020. Considering plant-based meat substitutes and cell-based meats: a public health and food systems perspective. Front. Sustain. Food Syst. 4, 134. Frontiers media S.A https://doi.org/10.3389/fsufs.2020.00134.

[533] Holden, N.M., White, E.P., Lange, M.C., Oldfield, T.L., 2018. Review of the sustainability of food systems and transition using the internet of food. NPJ Sci. Food 2 (1), 1–7

[534] Haveman, N., Paul, A.-L. and Ferl, R. (2022). Plant Biology and a New Approach to Space Farming. In In-Space Manufacturing and Resources (eds V. Hessel, J. Stoudemire, H. Miyamoto and I.D. Fisk). https://doi.org/10.1002/9783527830909.ch4.

[535] Scheben, A., Wolter, F., Batley, J., Puchta, H., Edwards, D., 2017. Towards CRISPR/Cas crops–bringing together genomics and genome editing. New Phytol. 216, 682–698

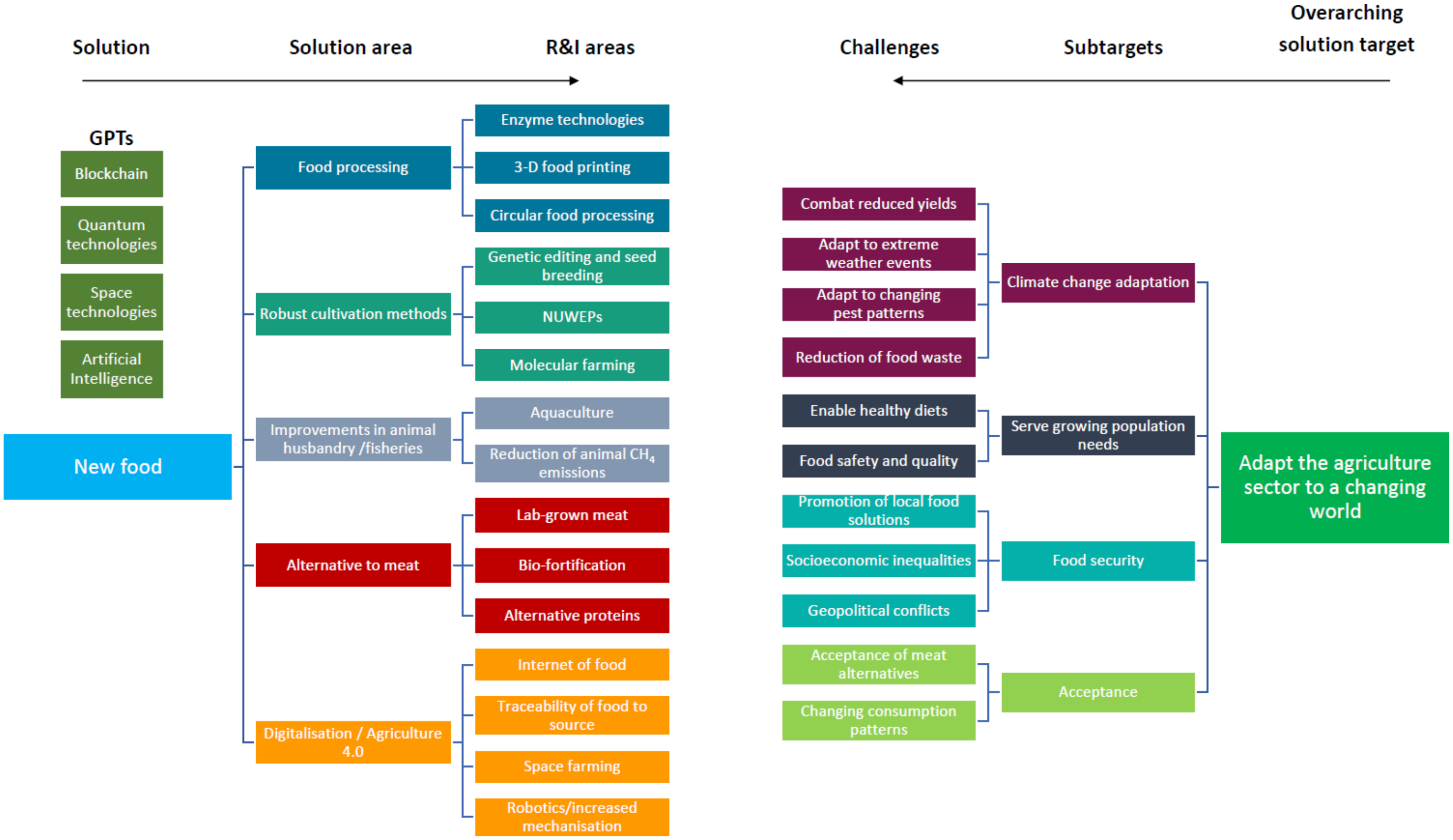
[536] Goold, H. D., Wright, P., & Hailstones, D. (2018). Emerging Opportunities for Synthetic Biology in Agriculture. *Genes*, *9*(7), 341. https://doi.org/10.3390/genes9070341.

[537] Wurtzel, E.T., Vickers, C.E., Hanson, A.D. *et al.* Revolutionizing agriculture with synthetic biology. *Nat. Plants* **5**, 1207–1210 (2019). https://doi.org/10.1038/s41477-019-0539-0.

A5.14.2.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

R&D funding in new food should concentrate on both climate mitigation and climate adaptation, since each of them have clear and distinct roles in the new food landscape. The development of alternatives to meat consumption has a large role to play in reducing emissions from the food production sector (whereas the social acceptance of these alternatives is still unclear). At the same time, when it comes to adaptation and building resilience to a changing climate, improvements in crop cultivation methods appear to be the most relevant factor arising out of this literature review.

Figure 15 Solution Landscape New food. Source: ICF & partners, 2023.



A5.14.3 Digitalisation

A5.14.3.1 Goals and challenges

Digitalisation in general - but also the digitalisation of our energy system[538] represents a cross-cutting solution landscape with the potential not only to improve monitoring and data-driven optimization of various parts of the system, but also to significantly support the transformation of production and consumption.[539] As a consequence, it involves and combines actors, topics and challenges from many different areas. Therefore, it includes various, very different sub targets with respect to the goal of a safe and sustainable digitalised energy system, namely: empowering of consumers, sustainability, safety, and digital energy system governance.

a) Empowering consumers

The sub target of empowering consumers refers to the (active) participation of consumers on the energy system of tomorrow. Therefore, it includes the change from consumers to prosumers (consumers who also produce energy)[540] and finally prosumagers (active participation of households in the energy system by renewables self-consumption, storage and management).[541] In addition to the technological requirements, this development is associated with three major challenges. The first challenge is to enable (active) participation - not only by providing technologies, but also by providing access to relevant skills and knowledge. The second challenge concerns the necessary acceptance for such a transformation of the energy system. It is therefore also closely linked to the security sub target (see below). Finally, the resulting decentralisation of the energy system is a major challenge that requires not only new technologies, but also new solutions in terms of governance and organisation (see below).

b) Sustainability

In achieving the overall objective, it is important to ensure the sustainability of the solutions and technologies achieved or developed and their application.[542] Therefore, care must be taken in the production of the required technologies and the selection of the materials used here (also to avoid possible material limitations). In addition, the resulting hardware should be as efficient as possible and enable a simple recycling loop

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[538] https://ec.europa.eu/commission/presscorner/detail/en/QANDA_22_6229

[539] https://www.misolutionframework.net/pdf/Net-Zero_Innovation_Module_3-The_1.5_%C2%B0C_Compability_Pathfinder_Framework_(CPF)-v1.pdf

[540] Surmann, Arne; Chantrel, Stefan P. M.; Utz, Manuel; Kohrs, Robert; Strüker, Jens (2022): Empowering Consumers within Energy Communities to Acquire PV Assets through Self-Consumption. In: Electricity 3 (1), S. 108–130. DOI: 10.3390/electricity3010007.

[541] https://newtrends2020.eu/wp-content/uploads/2022/03/Prosumagers_Lukas-Kranzl.pdf

[542] Gährs, Swantje; Aretz, Astrid; Rohde, Friederike; Zimmermann, Hendrik (2021) Digitalizing the Energy System in a Sustainable Way; Ökologisches Wirtschaften Online Issue 01/2021 (36).

for all materials (see also circular economy solution landscape). There are, however, potential synergies between the digital and green transitions that can be harnessed[543].

c) Security

One of the most urgent subtasks in the pursuit of a digitalised energy system is to ensure its security.[544] This becomes even more important and challenging in combination with the possible decentralisation of the energy system (see above). In addition, there are two main challenges regarding security. One is the international dimension of the energy system with different interdependencies. Possible solutions therefore also require an international component. The second challenge relates to "internal" (stability, resilience, etc.) and "external" (security against cyber-attacks, etc.) security, both of which are necessary to ensure a reliable energy system.

d) Digital energy system governance

The final sub target is to develop appropriate governance for the digital energy system. Due to the transformative nature of a digitalised energy system, new solutions and forms of governance are also required.[545] In addition, this area is also essential for achieving the other sub targets. At the same time, it is also dependent on the upcoming technologies and therefore strongly linked to the solution part of the solution landscape. Related important challenges concern data (e.g., security and privacy, availability, democratisation/ participation, standardisation, management), distributional effects (e.g., finance and capital, digital skills, asset ownership, connectivity), organisational culture (e.g., direction-setting and strategy, communication, skills and capacities), regulatory challenges (also including monopolies) and politics, as well as automation (e.g., responsibilities and accountabilities).[546]

A5.14.3.2 Solution and R&I areas

From a technological and solution-oriented perspective, the literature mentions several different and strongly interrelated technological solution areas that relate to the goal of a secure and sustainable digitalised energy system. Here, areas that relate to a specific and important technical requirement (blockchain, AI) can be distinguished from those that are broader and relate to a more general and systemic development (Industry 5.0, IoT, digital infrastructure). Nevertheless, these different areas are highly interdependent and often only represent different perspectives on a particular solution (e.g., application-

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[543] European Commission, "2022 Strategic Foresight Report "Twinning the green and digital transitions in the new geopolitical context", 2022.

[544] Fulli, G., Kotsakis, E. and Nai Fovino, I., Policy and regulatory challenges for the deployment of blockchains in the energy field, EUR 30781 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-40551-1, doi:10.2760/416731, JRC125216.

[545] https://geography.exeter.ac.uk/media/universityofexeter/schoolofgeography/images/researchgroups/epg/Digital_Energy_Governance_Challenges_-_Discussion_Paper_-_FINAL.pdf; https://es.catapult.org.uk/report/delivering-a-digitalised-energy-system/

[546] https://geography.exeter.ac.uk/media/universityofexeter/schoolofgeography/images/researchgroups/epg/Digital_Energy_Governance_Challenges_-_Discussion_Paper_-_FINAL.pdf

oriented vs. technology-oriented). Depending on the approach chosen and the level of analysis, different solution areas are also possible.[547]

At this point, it is also worth mentioning that some of the literature points out that the digital transformation should be associated with regulatory, rather than technological changes, especially in the renewable energy sector.[548]

a) Blockchain

The energy and blockchain domains are well suited for a beneficial coexistence.[549] Indeed, blockchain technology has a great, though disruptive, potential as an enabling technology for a digitalised energy system. Here, in the short-term, this technology can enable electric vehicle integration to the grid, while in the long-term blockchain could enable peer-to-peer microgrids.[550] Therefore, blockchain is important for the decentralisation of the energy system, energy trading and the integration of RES.[551] In addition, it can be an enabling condition for different other areas and applications, e.g., in the context of the Internet of Things (IoT, see below).[552] However, currently, the greatest challenges for this solution area are the inflexible legal framework conditions.[553]

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[547] Park, Chankook; Cho, Seunghyun; Heo, WanGyu (2021): Study on the future sign detection in areas of academic interest related to the digitalization of the energy industry. In: Journal of Cleaner Production 313, S. 127801. DOI: 10.1016/j.jclepro.2021.127801.

[548] Pakulska, Teresa; Poniatowska-Jaksch, Małgorzata (2022): Digitalization in the Renewable Energy Sector;New Market Players. In: Energies 15 (13). DOI: 10.3390/en15134714.

[549] Nai Fovino, I., Andreadou, N., Geneiatakis, D., Giuliani, R., Kounelis, I., Lucas, A., Marinopoulos, A., Martin, T., Poursanidis, I., Soupionis, I. and Steri, G., Blockchain in the Energy Sector, EUR 30782 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-40552-8, doi:10.2760/061600, JRC125221.

[550] Brilliantova, Vlada; Thurner, Thomas Wolfgang (2019): Blockchain and the future of energy. In: Technology in Society 57, S. 38–45. DOI: 10.1016/j.techsoc.2018.11.001.

[551] Hasankhani, Arezoo; Mehdi Hakimi, Seyed; Bisheh-Niasar, Mojtaba; Shafie-khah, Miadreza; Asadolahi, Hasan (2021): Blockchain technology in the future smart grids: A comprehensive review and frameworks. In: International Journal of Electrical Power & Energy Systems 129, S. 106811. DOI: 10.1016/j.ijepes.2021.106811.

[552] Ibidem.

[553] Brilliantova, Vlada; Thurner, Thomas Wolfgang (2019): Blockchain and the future of energy. In: Technology in Society 57, S. 38–45. DOI: 10.1016/j.techsoc.2018.11.001.

Fulli, G., Kotsakis, E. and Nai Fovino, I., Policy and regulatory challenges for the deployment of blockchains in the energy field, EUR 30781 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-40551-1, doi:10.2760/416731, JRC125216.

b) Artificial Intelligence (AI)

One major role of AI in the future energy system is the integration of energy supply, demand, and RES into the power grid (i.e., the smart grid).[554] This can be done by tasks such as demand side management (autonomous using smart software that optimises decision-making and operations), forecasting network stability and generation for the next day.[555] In addition, AI is also important for big data processing and analysis for energy analytics, cyberattack prevention, and as an enabler for smart factories (see also IoT and industry 5.0) and other smart applications in the context of IoT.[556]

As mentioned with blockchain technologies, regulatory approvals and governance for new services and products are also a key challenge here.[557]

c) Digital infrastructure

While digitalisation - and thus digital infrastructure - can be used to make our energy system more sustainable, it should not be forgotten to also consider the digital infrastructure itself. For this reason, "Greening of IT" is an important cross-cutting aspect if we want to achieve a sustainable energy system. “Greening of IT" in this context refers to the efficiency of the devices and applications (e.g., data transmission and processing, green IoT, cloud computing). It also embraces the materials used and the possibility of recycling them, so that the digital infrastructure can be part of a possible future circular economy.

d) Internet of Things (IoT)

The IoT is the core technology to connect physical things to the world.[558] Therefore, it enables broader and important concepts and research areas, such as smart grids (and the integration of RES), smart cities, smart buildings/homes and smart factories (for industry 5.0). In order to successfully realise these concepts (also sustainably) via the

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[554] Ahmad, Tanveer; Zhang, Dongdong; Huang, Chao; Zhang, Hongcai; Dai, Ningyi; Song, Yonghua; Chen, Huanxin (2021): Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities. In: Journal of Cleaner Production 289, S. 125834. DOI: 10.1016/j.jclepro.2021.125834.

[555] Neeraj; Twala, Bhekisipho (2022): Energy System 4.0: Digitalization of the Energy Sector with Inclination towards Sustainability. In: Sensors 22 (17). DOI: 10.3390/s22176619.

[556] Neeraj; Twala, Bhekisipho (2022): Energy System 4.0: Digitalization of the Energy Sector with Inclination towards Sustainability. In: Sensors 22 (17). DOI: 10.3390/s22176619. Ahmad, Tanveer; Zhang, Dongdong; Huang, Chao; Zhang, Hongcai; Dai, Ningyi; Song, Yonghua; Chen, Huanxin (2021): Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities. In: Journal of Cleaner Production 289, S. 125834. DOI: 10.1016/j.jclepro.2021.125834.

[557] Ahmad, Tanveer; Zhang, Dongdong; Huang, Chao; Zhang, Hongcai; Dai, Ningyi; Song, Yonghua; Chen, Huanxin (2021): Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities. In: Journal of Cleaner Production 289, S. 125834. DOI: 10.1016/j.jclepro.2021.125834.

[558] Neeraj; Twala, Bhekisipho (2022): Energy System 4.0: Digitalization of the Energy Sector with Inclination towards Sustainability. In: Sensors 22 (17). DOI: 10.3390/s22176619.

IoT, many research areas in the context of the IoT and the corresponding smart solutions are still open for further research. These areas include:[559]

- IoT Architecture.
- Technologies for IoT.
- Cloud IoT.
- Fog IoT.
- IoT Applications.

An overarching important challenge also remains the lack in security, decentralisation, transparency, and trust-less approaches. However, this could be addressed by combining IoT with blockchain technologies.[560]

e) Industry 5.0

The principles of industry 5.0 according to the Directorate-General for Research and Innovation can be summarised as:[561]

- Design out waste and pollution;
- Keep products and materials in productive use and circulation; and,
- Regenerate natural systems and enhance carbon sink.

Therefore, this represents an update of industry 4.0, a paradigm that is essentially technological, by providing a stronger connection with sustainability and circular economy.[562] Nevertheless, digital technologies will still have a major role in enabling this transformation. Important aspects are, for example, new forms of business model,[563] new approaches to manufacturing, smart contracts, automation and robotisation, nanotech and network computing.[564] For this reason, the other solution areas of the

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[561] European Commission; Directorate-General for Research and Innovation; Renda, A.; Schwaag Serger, S.; Tataj, D.; Morlet, A. et al. (2022): Industry 5.0, a transformative vision for Europe : governing systemic transformations towards a sustainable industry: Publications Office of the European Union.

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[564] European Commission; Directorate-General for Research and Innovation; Renda, A.; Schwaag Serger, S.; Tataj, D.; Morlet, A. et al. (2022): Industry 5.0, a transformative vision for Europe : governing systemic transformations towards a sustainable industry: Publications Office of the European Union.

digital transformation (especially IoT and AI) also have to contribute to this area to be successful and achieve smart and sustainable factories.[565]

A5.14.3.3 Role of disruptive General Purpose Technologies

As Digitalisation is an umbrella term for a broader trend towards a higher integration of digital technologies in the economy as well as in everyday life for citizens, Artificial Intelligence and Blockchain technologies are, as GPTs, also widely applicable in this Solution Landscape, as detailed in the previous section.

A5.14.3.4 What does it mean in terms of R&D funding to support new solutions that should reach the market by 2040?

As a cross-cutting and rapidly evolving area with a potentially very broad impact on the energy system, digitalization especially faces challenges in the areas of governance and security. Accordingly, the focus here should be on how the rapidly developing new technologies in the field of digitalization can be integrated into the (energy) system as quickly, securely and sustainably as possible in order to make the greatest possible contribution to achieving the goal (climate neutrality 2050).

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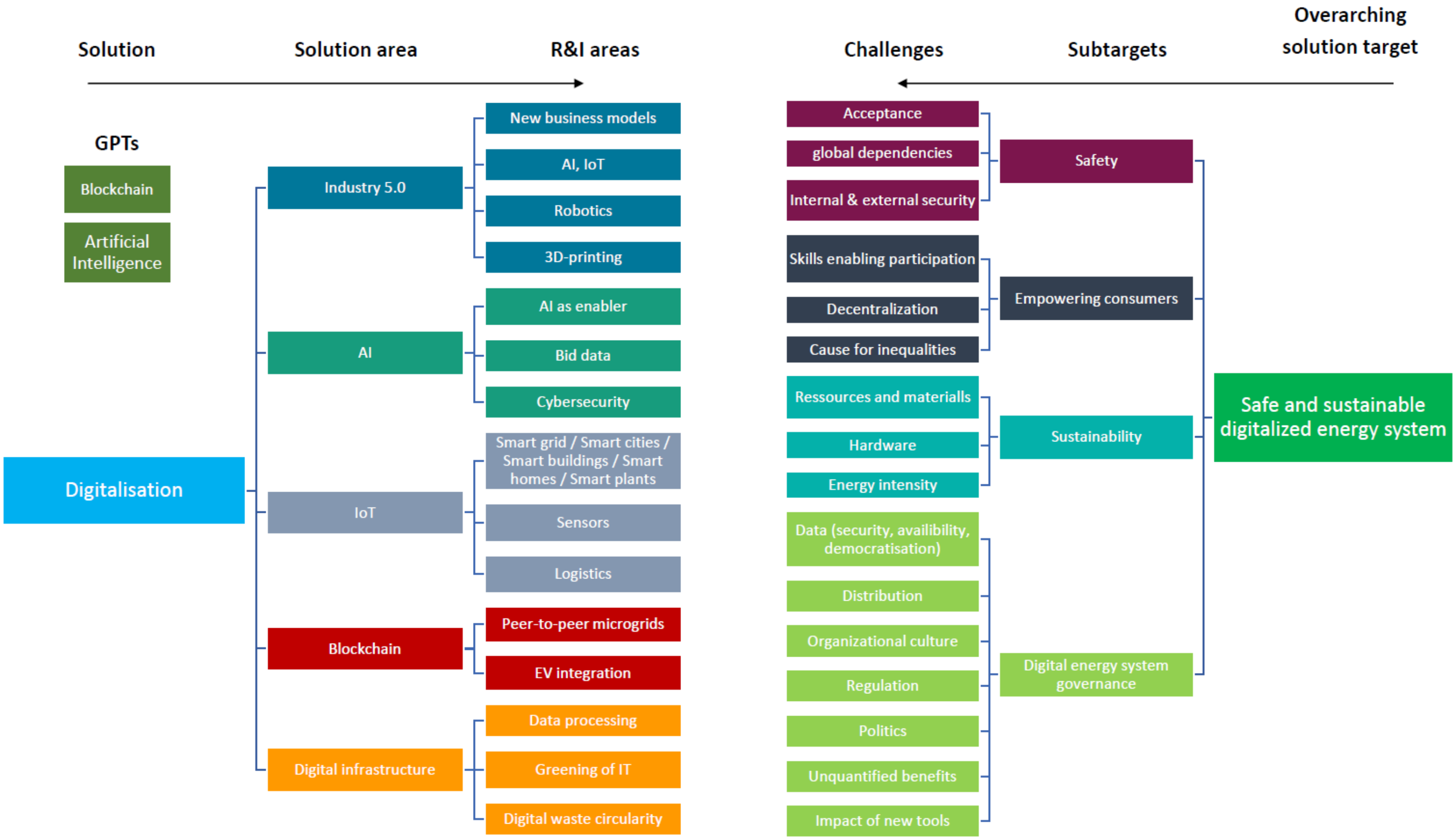
Figure 16 Solution Landscape Digitalisation. Source: ICF & partners, 2023.



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Transforming Europe into a climate neutral economy and society by 2050 requires extraordinary efforts and the mobilisation of all sectors and economic actors, coupled with all the creative and brain power one can imagine. Each sector has to fundamentally rethink the way it operates to ensure it can be transformed towards this new net-zero paradigm, without jeopardising other environmental and societal objectives, both within the EU and globally. Given the scale of the transformation ahead, our ability to meet climate neutrality targets directly depends on our ability to innovate. In this context Research & Innovation programmes have a key role to play and it is crucial to ensure they are fit for purpose and well equipped to support the next wave of breakthrough innovations that will be required to achieve climate neutrality in the EU and globally by 2050. The objective of this study is to contribute to these strategic planning discussions by not only identifying high-risk and high-impact climate mitigation solutions, but most importantly look beyond individual solutions and consider how systemic interactions of climate change mitigation approaches can be integrated in the development of R&I agendas.

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