Shipping sun and wind to Belgium is key in climate neutral economy

Hydrogen Import Coalition
Final report

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Executive summary

The Hydrogen Import Coalition

This coalition brought together its industrial expertise in order to conduct research into the importing of renewable energy by means of hydrogen carriers. The analysis covers all steps of the value chain from renewable energy production, electrolysis and synthesis into a hydrogen carrier molecule, to shipping, terminalling and end use in Belgium.

In the course of 2020, the year in which this study was conducted, the coalition has witnessed an increasing focus on the role of hydrogen within the energy transition. European, national and regional strategies were deployed by several countries and a growing interest from companies in green hydrogen was observed. Also Flanders published its hydrogen strategy[1] and a hydrogen strategy is being prepared at the federal level. This study provides necessary insights into the technological and economical aspects of the hydrogen import value chain in order to fully acknowledge this renewed focus on hydrogen and provides a basis for its further roll-out.

Renewable imported molecules will become a vital part of the EU energy mix

Renewable energy import originating from wind and sun will become a necessary and vital part of our energy supply if we want to achieve a carbon neutral society by 2050. These circular and sustainable imports of energy will be complementary to local renewable electricity production in terms of security of supply, stability and flexibility. Market dynamics will decide on the optimal balance between domestic production and imports.

Imported molecules will also play a fundamental role in the transition towards carbon neutrality of many end-users such as shipping and aviation, and - combined with circular carbon - as a feedstock for our national industrial clusters. Hydrogen is already being extensively used as feedstock in Belgium for many industrial processes and needs to be decarbonised. Our country is ideally placed to become a frontrunner in the green hydrogen economy development, with its well-developed pipeline network connecting neighbouring states, seaport and terminal infrastructures, industrial clusters and a strong customer base.

[1] https://beslissingenvlaamseregering.vlaanderen.be/document-view/5FAD539C20B6670008000274

Importing hydrogen carriers is feasible and cost-effective

This study demonstrates that this type of large scale green hydrogen imports is both technically feasible and cost-effective, even under a conservative off-grid / independent design that reserves potential energy synergy upsides for project realisation. When delivered to Belgium, the cost range of imported renewable energyn from low-cost locations lies in the range of 65-90 €/MWh by 2030-2035 with a further potential cost reduction to 55-75 €/MWh or less by 2050. As several hydrogen based carriers are feasible and many sourcing regions are capable of providing cost competitive energy, sound and sufficiently diversified geopolitical and market dynamics are confirmed.

The most promising hydrogen-based energy carriers - ammonia, methanol and synthetic methane - are not hindered by technological scale up hurdles today and could already be deployed in existing transport lines and off-take markets. A diversified portfolio of initial projects and demonstrators for all these carriers and technologies will serve to gain experience and further reduce the cost gaps. A fast realisation of such projects under a more detailed roadmap and national industrial hydrogen strategy is strongly recommended.

Scaling up with public-private funding

Scale is essential in order to bring costs down to competitive levels. In order to scale up these renewable energy imports, any competitive disadvantage with fossil alternatives will need to be mitigated. Environmental externalities need to be better incorporated in energy markets by applying cost-reflective carbon pricing. By means of Carbon Contracts for Differences or other forms of temporary incentives, the cost gap can be bridged and a level playing field ensured. Some early-movers may require investment support in the early stages of development to close the remaining funding gap and boost the maturity of the technologies employed, similar to the way in which wind and solar were developed until they reached the verge of market maturity.

Scaling up will also require a stable and robust roadmap and an energy policy and regulatory context that is open to importing renewable energy and feedstock, alongside domestic production. In this sense, it will be essential to guarantee international cross border recognition for green molecule guarantees of origin (both with countries outside and within Europe), maximalising compatibility with the existing systems for green gas certification (within Europe). Carrier conversions need to be facilitated by the appropriate certification system. The coalition is committed to supporting policy makers in the development of these roadmaps and measures, which will also have to address missing port and transport infrastructural links.

This study is also an open call for action to public and private stakeholders to forge partnerships for the purpose of implementing specific pilot projects designed to support national and regional competitiveness and strengthen the Belgian presence in this European fast-developing market.

About the hydrogen coalition

The climate target to reduce CO_2 emissions in Belgium by 80% by 2050 compared to 2005 levels is a major challenge. Hydrogen has an important role to play in the mix of solutions to achieve results. That is why Deme, Engie, Exmar, Fluxys, Port of Antwerp, Port of Zeebrugge and WaterstofNet have joined forces. This report is the first tangible result of this collaboration and serves as a basis to coordinate delivery of specific projects that will shape the production, transport and storage of hydrogen.

The partners in the coalition have pooled their experience and industrial know-how, built up over many years active in the sector, together covering each step of a hydrogen import value chain. This unique blend of industrial competence sets this study apart from many other, more theoretical approaches.

Introduction: setting the scene

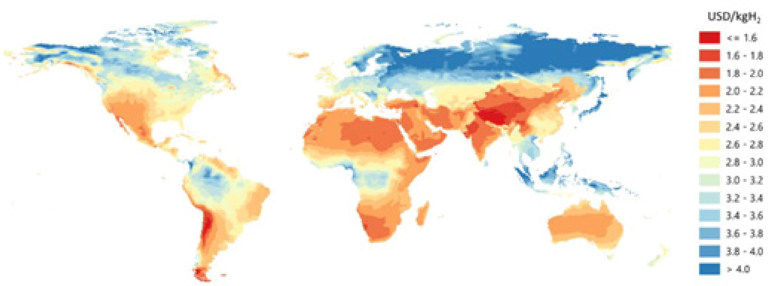
Fossil energy has created an enormous economic and social added value during the past century. But the combustion of this fossil energy has thoroughly disrupted the natural CO_2 balance in the atmosphere. The resulting greenhouse gases form the cause of a climate change with major consequences for people and planet. The Paris climate goals (COP21) will need to be achieved by 2050 to reduce this over-exploitation of our planet. We must make a transition to a carbon-neutral society that is based on renewable energy and circularity. 2050 is clearly a hard deadline by which to achieve a climate neutral economy.

Looking at the biggest climate change issue - our energy supply - it is clear by now that sun and wind will become two of the primary sources of sustainable energy. The question we must ask ourselves is how this solar and wind energy can be efficiently delivered to all of us. An energy system predominantly based on local renewable energy and the transmission of electricity via high-voltage lines encounters several challenges. In order to ensure a future-proof, robust and cost-efficient energy system, also other means of energy transport will have to be considered, taking into account the following concerns.

Solar and wind energy is not always available **where** we need it

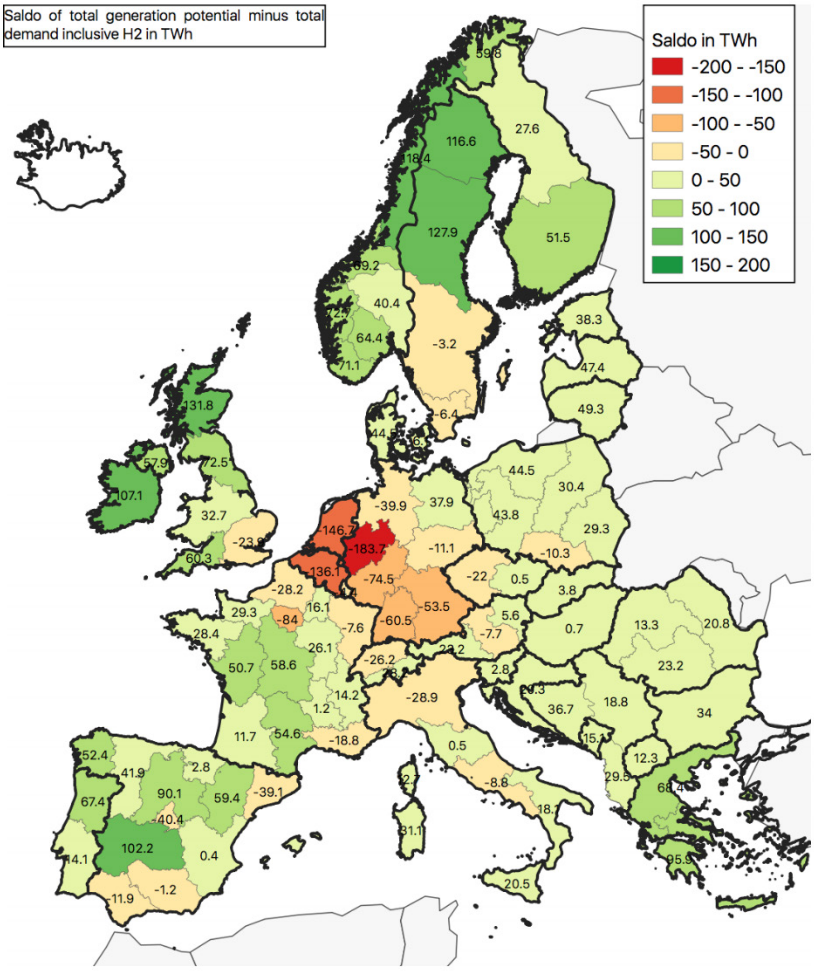
The sun shines less in North-Western Europe than in Southern Europe, the Sahel or the Middle East. This means that the same solar panel elsewhere can produce up to 3 times more than in North-Western Europe. The same panel is therefore much more cost-effective and also requires less space to generate the same energy. Wind "sweet spots" do exist all over the earth, but the space required to install turbines is a major constraint in some regions. It may therefore be more economical and easier to produce part of our renewable energy in regions where the combination of sun, wind and space is abundant, shown as red shaded areas in the picture below.

Hydrogen costs from hybrid solar PV and onshore wind systems in the long term



Source: IEA hydrogen report 2019

Aside from the economics, Western Europe needs more energy than it can produce locally. In specific terms, the highly industrialised region of Belgium-Netherlands-North-Rhine Westphalia consumes much more energy than what can be provided locally or even regionally, as shown in the map below. Europe, in general, is also expected to keep its negative energy balance in the future.



Source: Wuppertal Institute

The question is how to get this energy to users located in Western Europe. The last two decades have clearly shown that support for and public acceptance of new high-voltage lines in Western Europe is limited, while the transmission capacity would have to multiply and become more efficient (reducing the current major disparities between physical and commercial flows in real time) to bring all solar and wind energy to the energy consumers. In this case, molecules acting as a transport vector provide a potential solution, since molecules can be transported efficiently by (underground) pipeline or ship. Molecules are also an alternative for the large-scale transportation of energy across ultra-long distances.

Renewable electricity can be converted into hydrogen by means of electrolysis closely integrated with remote solar and wind production sites. Energy can be transported as pure hydrogen (in gaseous or liquid form depending on the distance) or, after synthesis with carbon or nitrogen, as a “hydrogen carrier” such as methanol, methane or ammonia. Such hydrogen carriers can be more efficient to transport and use, depending on the case.

Solar and wind energy is not always available **when** we need it

Solar panels only produce energy when the sun is shining, wind turbines produce whenever the - preferably strong - wind is blowing. Electricity systems have to be balanced at all times, which means that the electricity injected in the system must exactly match the electricity being consumed in real time, otherwise the system will need to be rebalanced through remedial actions which, in general, cost money. In the past, this balance was achieved by instantaneously matching production with demand via flexible thermal generation assets. Due to the high proportion of non-dispatchable production, wind and solar and the difficulties associated with the prediction of their profiles, energy storage is becoming paramount as a means of maintaining the balance, though it comes at a significant cost too. Despite the declining costs, battery storage remains expensive and other solutions are needed for longer term storage. Moreover, batteries require significant amounts of scarce raw materials in their production. Molecules can be a much more efficient storage medium for storing large volumes of energy for a longer period of time (seasonal regulation capabilities), thereby helping to maintain system stability.

Electricity is not always the most **appropriate** energy vector

Not all energy consumers can use electricity as an energy source as easily, or they require heat at high temperatures which electricity cannot provide as efficiently. Besides, many industrial processes require molecules for intermediate and end products. The current molecules used in these processes need to be decarbonised. Renewable hydrogen and hydrogen-based platform-molecules provide a feasible decarbonisation path for the latter. There are also other applications in transport and in the B2C sector. Consider ships or airplanes that require a high degree of autonomy and power, and in which the energy density of a liquid fuel cannot be matched by stored electrical energy. Or the heating of existing buildings in urban areas, where switching to electrically powered heat pumps could be unfeasible from an economic point of view and where cheaper molecule-based solutions could provide a cheaper option for decarbonisation. Replacing today's fossil fuels with hydrogen or hydrogen-based clean synthetic fuels is capable of contributing towards the transition in a large number of sectors.

Don't forget the **feedstock**

Where renewable energy will be the standard for our energy supply, circularity will be the new standard for our products and materials. Organic chemistry, a sector that is well represented in Flanders, is entirely dependent on the supply of hydrogen and carbon molecules as its raw material. It is evident that these products can no longer be sustainably produced from natural gas or petroleum. In part, these hydrocarbons might originate from sustainable biomass, to the extent that these are available in sufficient quantities. Circular processes (recycling) will also deliver part of the molecules required for high value chemicals[2]. The remainder can be supplied by the same hydrogen carriers that facilitate the transport and storage of energy. Hydrogen carriers are therefore the molecules that can be used to fulfil our energy and feedstock needs.

[2] e.g. see recent VLAIO study of Deloitte/VUB-IES/AMS/Climact; https://www.vlaio.be/nl/publicaties/naar-een-koolstofcirculaire-en-co2-arme-vlaamse-industrie

All things considered, the partners in this hydrogen import coalition have dedicated themselves to thoroughly investigating the concept of importing renewable carrier molecules produced from wind and solar energy in regions with abundant supply of sun and wind combined with large available space for such farms. Existing or future harbour facilities for terminalling and for the long-distance transportation of the renewable carrier molecules on board large ships is also of the utmost importance. The partners have pooled their know-how and market knowledge in order to map the entire value chain - from production abroad to delivery via ships and pipelines to Belgium - in a detailed and substantiated manner. Based on this study, the coalition has identified the cost structure of the hydrogen import value chain and has been able to detect technological and regulatory barriers that would impede a roll-out of the import concept. The coalition has also defined meaningful stepping stones, essential innovation and pilot projects to scale up the hydrogen economy in a manner that would provide added value for our local industry.

The coalition methodology

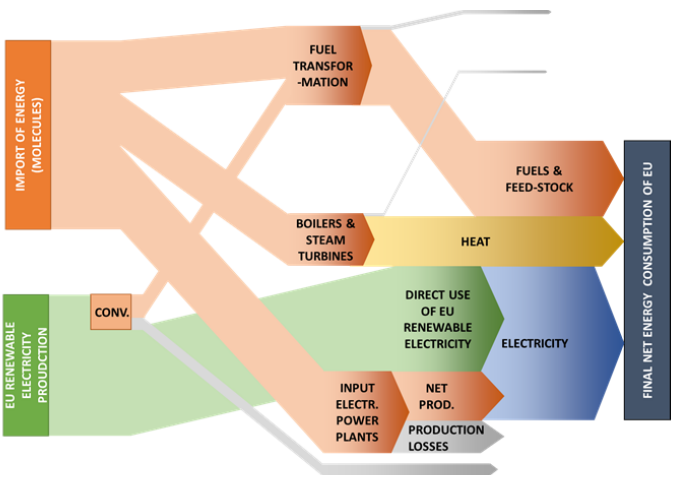
Key Assumptions

System dimensioning

In order to make the renewable import hypothesis tangible, an assumption was made with regard to system dimensioning. By 2050, a renewable energy import system supporting the Western European energy and feedstock transition would have to be of an order of magnitude of thousands of TWh of energy per year, which is of the same order as ambitious local renewable energy targets. Even in the medium term, renewable energy imports will be on a scale that surpasses the current limits of what exists today. On the other hand, this sheer size comes with significant economies of scale, which is crucial if a cost effective roll out of the supply chain is to be achieved.

In order to identify some grounds on which to base its assumption, however, the coalition focused on the throughput of the current LNG hub in Zeebrugge for first commercial scale purposes (medium term scenario, '2030-2035').

annual +/- 30%	EU	Belgium
2050	**7.000 TWh**	350 TWh local *+ 400 TWh transit*
2035	1.050 TWh	**110 TWh import**



Source: hydrogen import coalition

Knowing that the corresponding energy fluxes (at around 110 TWh per year) would only be sufficient to cover part of the national energy demand and given the function of the Belgian Seaports region as an energy hub for hinterland energy supply, a second, long-term ('2050') full-scale scenario has been created. In this scenario, Belgium would import around 750 TWh per year, with a larger part being designated for transit towards the hinterland. These dimensioning assumptions focus on Belgium. Taking into account the parallel focus on imports in most adjoining EU member states and that of the Commission itself[3], it may be assumed that shipping of renewable energy using hydrogen as an energy carrier will soon become a commodity economy with a calling that will surpass local demand-based dimensioning.

System security of supply

Secondly, the coalition focused on designing a supply chain that is absolutely secure in its supply and capable of matching demand at all times. Given the intermittent nature of the primary energy sources - solar and wind - the coalition has integrated adequate buffering, so as to allow a single-source baseload supply. Every single sourcing area therefore incorporates a certain factor of renewables over-dimensioning, battery power storage to optimise electrolyser operation and synthesis operation (e.g. Haber-Bosch synthesis in the case of ammonia) plus hydrogen storage to allow carrier synthesis optimisation. These elements, combined with the inherent storage in ships, terminals and pipelines, ensure a baseload hydrogen carrier output out of each individual export location. This solid but conservative approach (in which no grid synergies are considered and all costs are addressed in the own business model as an off-grid independent baseload-capable design) creates confidence and ensures a conservative cost estimation in the case of the baseload energy supply (leaving upsides as upsides, rather than already incorporating them in the model on the basis of external systems configurations and opportunities that are, as yet, uncertain).

The baseload design assumption assures that the imported renewable energy of molecules can unmistakably be considered as fully additional to existing renewable energy sources.

Carbon source

For large scale methanol and methane carrier production, carbon is needed in large quantities. It is clear that in a carbon neutral energy and feedstock system, the carbon source should also be fully circular. The coalition therefore based its cost assumptions on the atmospheric capture of CO_2 (Direct Air Capture or DAC) as the main future source of carbon, which is also a conservative assumption. This approach does not prohibit the use of any local CCU opportunities, but neither does it restrict the production potential of carbon carriers to the availability of point sources in the production region. In terms of pricing, it is assumed that DAC will reach parity with the current pricing of point-source capture, i.e. 80€/ton CO_2.[4] For modelling sensitivity purposes, a scenario in which the cost of DAC would stay at a level of 160€/ton CO_2 has also been taken into account.

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0301&from=EN
[4] Techno-economic assessment of CO_2 direct air capture plants, Mahdi Fasihi*, Olga Efimova, Christian Breyer - ENTSO-E/ENTSO-G CO_2 price projections

Analysis framework
The carriers

The selection of carriers is based on following principles:

- The spectrum of carriers has to be broad enough in terms of different production processes, transport technologies as well potential use in applications. One should not start by prejudging which carriers will be selected, based on one element in the supply chain. This full techno-economic supply chain analysis will determine the ideal carrier.
- The carriers have to be relevant in terms of close to market readiness and benchmark studies.
- The carriers together should cover the full spectrum of possible hydrogen carrier technologies, such that the final methodology is complete and one is able to add new carriers easily in the future.
- Carrier technology should be scalable.

This results in the final choice for five carriers divided in three subgroups:

1. Pure Hydrogen

- **Liquid hydrogen:** This is the 'purest' method of transporting renewable energy and possesses the major advantage of not needing chemical transformation steps throughout the supply chain. However, the low volumetric energy density and the very low boiling point (-253 °C) present major technical challenges.

2. E-fuels – Hydrogen derivatives

The three simplest molecules from three different chemical groups are chosen, namely: methane (alkane), methanol (alcohol) and ammonia (nitrogen hydride)

- **Synthetic methane:** This molecule has the advantage of being already a widespread energy carrier, with existing infrastructure for terminalling and transport. However, the low boiling temperature (-162°C), the potential climate impact (e.g. methane slip)[5] are disadvantages. The carrier is not carbon free, as CO_2 is still required in the production process.
- **Synthetic methanol:** This molecule has the advantage of already widespread infrastructure and being liquid in atmospheric conditions. The carrier is not carbon free, as CO_2 is still required in the production process.
- **Synthetic ammonia:** This molecule has the advantage of not needing CO_2 in the production process and having a moderate boiling temperature (-34 °C), however its high toxicity and the fact that it is difficult to use it directly in energy applications comes with big challenges. On the other hand, the reconversion of ammonia into hydrogen is a feasible although the technology is not yet fully mature and it adds costs.

3. LOHC – Liquid Organic Hydrogen Carriers

- **Dibenzyl toluene:** This molecule is chosen to represent the broader LOHC group of carriers. However, scalability, the hydrogenation and dehydrogenation steps and the costs are still uncertain and challenging.

[5]Although methane slip is less likely to happen with synthetic methane compared to the extraction of natural gas.

The sourcing regions

Remote locations

Based on the market intelligence of the coalition partners, the analysis was carried out for several regions throughout the globe with promising conditions for efficient hydrogen production. The first and foremost criterion is the potential to generate low-cost renewable electricity on large scale, which requires excellent wind and irradiation conditions throughout the year as well as sufficient space. This was complemented with criteria such as the availability of seaports and political stability. The selected sourcing regions together with the considered seaport facilities and shipping routes are represented on the map below. The regions selected provide a representative sample of possible regions, although other regions are also possible.

Source: hydrogen import coalition

Benchmarks

As a benchmark to these remote sourcing areas, some alternatives in Europe, such as Iberia and North Sea offshore wind, were also considered.
Windy areas in Spain were considered to represent Iberia and both transport via ship and transport (of compressed gaseous hydrogen) via pipelines were evaluated. Note however that the potential of Iberia is not sufficient to provide Europe with carbon-neutral energy and that other claims on these sites might exist, such as for the production of local renewable electricity.
With regard to offshore wind, both near-shore and far-shore North Sea sites were considered. For the near-shore scenario, a 1GW concession in the Belgian Economic Zone was considered, in which hydrogen production took place offshore and energy was transported to the mainland via hydrogen pipeline. The volume potential of such a site is of course limited, but the concept of hydrogen as the carrier could solve

the electricity grid congestion problems that currently hamper the development of such wind farms for Belgium and would be a promising technology pilot project.

As far as far-shore wind is concerned, two concepts were investigated. The first concept assumes an electrical high-voltage AC connection to a far-shore artificial island, with hydrogen production on the island and a pipeline connection to the mainland. The alternative concept assumes a high-voltage DC electrical connection to the mainland with hydrogen production on the mainland.

For all offshore scenarios, it must be noted that the design requirement of supplying full baseload energy was not imposed and the injection of an intermittent hydrogen flow into the mainland grid was accepted, which, of course, would give rise to additional system costs to buffer such intermittency when required.

It is also necessary to note that the economical volume potential of North Sea offshore wind is of the order of hundreds of TWh[6,7] per year and hence, contrary to what is sometimes assumed, most likely not sufficient by itself to satisfy the energy and feedstock demand that exists in Western Europe.

Technology

Electrolysis

Water electrolysis is a well-established technology which has been used for almost a century for miscellaneous applications in industry. The electrochemical generation of hydrogen on an industrial level began at the end of the 19th century.
It consists of the splitting of water molecules into gaseous Hydrogen (hydrogen) and Oxygen (O2) using electricity (direct current). This electrochemical reaction occurs when an external voltage is applied to a device called an electrolyser. Water electrolysis is the combination of two half reactions, which take place at the cathode and at the anode. The overall reaction is represented here as:

$$2\,H_2O + Electricity \rightarrow 2\,H_2 + O_2 + heat$$

This conversion is often referred to as Power-to-Gas and it is an increasingly important component of the future renewable energy system as it enables electrical energy to be converted into chemical energy. This conversion can either be used as a storage medium for renewable electricity in the form of green molecules. Indeed, as renewable energy generation peaks during sunny and windy periods, electrolysis can consume large quantities of electricity, thereby avoiding overloading the grid. Alternatively, the conversion can be used to convert electricity into another energy carrier that is more suitable for other applications. For example, when using electrolysis, the energy is converted into hydrogen which can be used as raw material in the chemical industry, as a combustible (a so-called e-fuel) or synthesised into a gaseous or liquid energy carrier which can be more easily stored and transported than hydrogen itself.

[6] Wind Europe, 11/2019, https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf

[7] European commission, 11/2020, EU strategy offshore renewable energy, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0741&from=EN

As water electrolysis has been known for a long time, several technologies have been and continue to be developed. Today, three main technologies are available on the market:

- Alkaline electrolyser (AEL)
- Proton Exchange Membrane Electrolyser (PEMEL)
- Solid Oxide electrolyser (SOE)

The first two technologies are well developed and already commercialised. The technology readiness level (TRL) is at 9 (Full commercial application). The third technology is the least mature of the three and has not been considered for the purpose of this project. The considerably higher efficiencies expected for SOE are considered as an upside to this study.

Alkaline is the most mature technology, having existed for well over 50 years. The electrolyte is a liquid solution of water with 30% (in weight) of Potassium Hydroxide (KOH) – called potash. Soda can also be used, but potash is preferred mainly for higher ionic conductivity reasons, which leads to a better efficiency in the stack.

Alkaline electrolysers can be atmospheric or pressurised. In the case of pressurised electrolysers, pressure typically reaches 30 barg or more, depending on the suppliers. Alkaline technology is widely tested, for high power and for atmospheric devices.

The main contaminants of hydrogen in this technology are water, oxygen and electrolyte.

PEM technology differs from alkaline electrolysis in that the electrolyte is a solid electrolyte with a proton-conducting polymer membrane. Only protons (H+) can migrate through the membrane. In contrast to the alkaline technology that allows ions OH- migration, the polymer membrane is hermetic to anions as well as oxygen and hydrogen.

PEM electrolysers are typically pressurised. This type of technology is mature and well known for small capacities because it has been used for several decades in space and submarine applications. It is also available for larger power levels but less feedback is available regarding the benefits of using it for that type of products.

The main contaminants of hydrogen in this technology are water and oxygen. Since it does not have a liquid electrolyte in contact with the gas, the PEM technology has the advantage of producing a slightly purer hydrogen.

Pressurised alkaline electrolysers have similar response times as PEM electrolysers.

Synthesis

Methanation

With the help of captured CO_2, hydrogen can be converted into methane (CH_4) according to the exothermic Sabatier reaction (also named methanation reaction):

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O \qquad -164\frac{kJ}{mol}\ at\ 25\ °C$$

The two most mature technologies for CO_2 methanation are

- Thermocatalytic methanation: CO_2 and hydrogen are fed to a reactor containing a catalyst (mostly nickel based)
- Biological methanation: the feed gases are dissolved in a reactor containing microorganisms that will use hydrogen as an energy source and CO_2 as a carbon source to power their metabolism, thereby producing methane and water.

Interest in CO_2 based methanation increased in the 1980's, focusing on off-gases from steel production, such as blast furnace gas and coke oven gas, but that interest stalled due to intensive gas cleaning requirements.

Today, a total of 14.5 MWe of methanation capacity is installed, mostly in the context of biogas or sewage gas from wastewater treatment. Some methanation units already demonstrate flexible operation. It is therefore assumed that by 2030-2035 and 2050 higher flexibility of between 50 and 100% of its capacity can be reached.

Haber-Bosch

Since its discovery in 1909, the Haber-Bosch process has progressively become the only way to produce ammonia. This process requires:

- Nitrogen, extracted from air
- Hydrogen, nowadays mainly produced from natural gas (using a steam methane reformer SMR), coal or other hydrocarbons
- Catalyst, usually iron and potassium hydroxide

$$N_2 + 3H_2 \rightleftharpoons 2NH_3 \qquad -92\frac{kJ}{mol}$$

The Haber-Bosch process is a mature industry, thanks to its use in fertilizer industry. In 2018, over 200 million metrics tons of ammonia have been produced.

Nowadays, smaller Haber-Bosch units are demonstrating their flexibility in production. The same flexibility assumptions as methanation have therefore been taken into account for 2030-2035 and 2050.

Methanol unit

Methanol is produced from carbon monoxide, carbon dioxide and hydrogen and is catalytically converted to methanol. Today, this hydrogen is most often derived from natural gas, produced using steam methane reforming (SMR).

$$\mathrm{CO + 2H_2 \leftrightharpoons CH_3OH} \qquad \Delta H_{298K} = -90.64\ \frac{\mathrm{kJ}}{\mathrm{mol}}$$

$$\mathrm{CO_2 + 3H_2 \leftrightharpoons CH_3OH + H_2O} \qquad \Delta H_{298K} = -49.67\ \frac{\mathrm{kJ}}{\mathrm{mol}}$$

$$\mathrm{CO + H_2O \rightarrow CO_2 + H_2} \qquad \Delta H_{298K} = -41.47\ \frac{\mathrm{kJ}}{\mathrm{mol}}$$

High-pressure methanol synthesis was developed in the 1920s. Thanks to advances in catalyst technology and the switch from coal to natural gas as the predominant feedstock, low-pressure methanol synthesis was developed during the 1960s and is still used today.

The methanol process is a mature industry and has a yearly production rate of over 100 million metric tons per year.

Nowadays, smaller methanol units are demonstrating their flexibility in their production. The same flexibility assumptions as methanation have therefore been taken into account for 2030-2035 and 2050.

Shipping

Shipping methane, methanol or ammonia is already carried out on a large scale today. Methane is shipped as LNG (Liquefied Natural Gas) in a large fleet of LNG ships with global shipping volumes of over 300 million tons per year. This is equivalent to the transport of 12,000 TWh of energy per year. Ammonia and methanol transport over sea takes place on a much smaller scale at the moment, but the existing shipping technology can easily and quickly be enlarged if the demand turns out to be there.

38.000 m³ ammonia transport vessel (courtesy of Exmar)

The transport over sea of LOHCs (such as DiBT) does not exist as yet, with the exception of small pilot projects in which the LOHC is transported by isotainers. Most LOHCs, however, are based on existing products such as toluene and can be transported easily as light oil products. This is transported today in product tankers and can be transported easily on a very large scale as well.

The most difficult to transport is hydrogen itself, both in pressurised form and in liquefied form. Plans are being made for very large liquefied-hydrogen carriers, but it is expected that the cost of those vessels will remain high in the decades to come. Vacuum-insulated tanks are required on a large scale to prevent the liquid from vaporising. At the temperatures at which liquefied hydrogen is transported, both air and nitrogen become liquid as well, which makes the handling of the product complex. On top of these technical challenges, the volumetric energy density of hydrogen is very low, which means the cost per energy unit transported is high.

Terminals

Large-scale terminals already exist for molecules such as methane (LNG), methanol and ammonia and this existing infrastructure could therefore be readily reused for the decarbonised alternatives proposed in this study. Due to the current techniques used in the manufacturing of double-walled, vacuum-insulated spheres, facilities for the storage of liquefied hydrogen are limited to a maximum size of about 20,000 m^3. Here, a scale-up of technology will be needed to meet the large energy requirements in the future. The most likely scenario will involve industry migrating to a concept of atmospheric storage tanks, which are also well known in the LNG business.

As mentioned above, the storage of ammonia in tanks is common practice in industry today, however in densely populated areas such as Western Europe and more specifically Belgium, the transportation of ammonia via pipeline is deemed more challenging due to safety reasons. For that reason, the catalytic cracking of ammonia into hydrogen could be considered as an alternative, the relevant technology is still at a low TRL.

Large-scale storage of LOHCs can be done in internal floating roof tanks, such as the ones used for hydrocarbon fuels. The challenge with LOHCs such as dibenzyl toluene, however, is the hydrogenation and dehydrogenation steps which are required and remain at low TRLs up to now.

Use cases

Infrastructure
As far as the carriers are concerned, an off-take market and parts of the infrastructure required are already in existence, though the volumes being considered in this study are not yet available for every carrier. The methane infrastructure from terminal to pipeline distribution is of course the most extensive and is ready for uptake of large volumes. The hydrogen pipeline network is nowadays extensive in Belgium but is not open-access and only present within the industrial fabric. Also, the capacity is not necessarily high enough for large scale energy transport. No liquid hydrogen terminal is in place at present. In the case of ammonia and methanol, terminals are already present on a smaller scale, as we are already importing flows of these compounds into Belgium today. No extensive pipeline distribution is available, however.

Environmental impact
The toxicity of ammonia remains an important point of concern, especially when transported on the Scheldt or deeper into the mainland. For applications, in which the hydrogen carriers are burned (internal combustion engines or gas turbines), the air quality is one aspect to be kept under control, but various measures, such as flue gas treatment, can mitigate the impact.

Applications: – technology readiness
As for specific use cases themselves, we see that most of the technology is already on a demonstration scale (TRL 5 and above), or even on a commercial scale in other regions (e.g. MTO). Some applications can off-take multiple carriers, but are at different TRL levels. Specifically shipping (combustion engine: TRL: 9 for e-CH_4 / TRL: 7 for methanol, hydrogen / Low TRL for ammonia) and power/heat generation (TRL: 5 for hydrogen & methanol & 9 for admixture 30% hydrogen / TRL: 3-4 for ammonia / TRL: 9 for e-methane). Here, technology maturation and cost of carrier are 2 parameters that will decide which carrier is used. In the case of power, multiple carriers could be used in the same turbine.

As the hydrogen-carriers already play a role today in our industrial clusters, of course there are, of course, no technological barriers for drop-in use cases.

Taking the above into account, the OpEx cost gap for the renewable fuel/feedstock can be regarded as more of a hurdle, besides of course the Capex cost for the possible adaptation or the investment in new processes/plants.

The design

It is important to note that the coalition embarked on an initial industrial design, by the consortium members' engineering experts, that would encompass all of the components of the value chain and would be based on industrial know-how of the partners. In addition, a first-order techno-economical chain optimisation was carried out among the different steps of the value chain. Although the exercise was complemented and substantiated on the basis of academic literature and results from other studies, this approach differentiates this study from many others published.

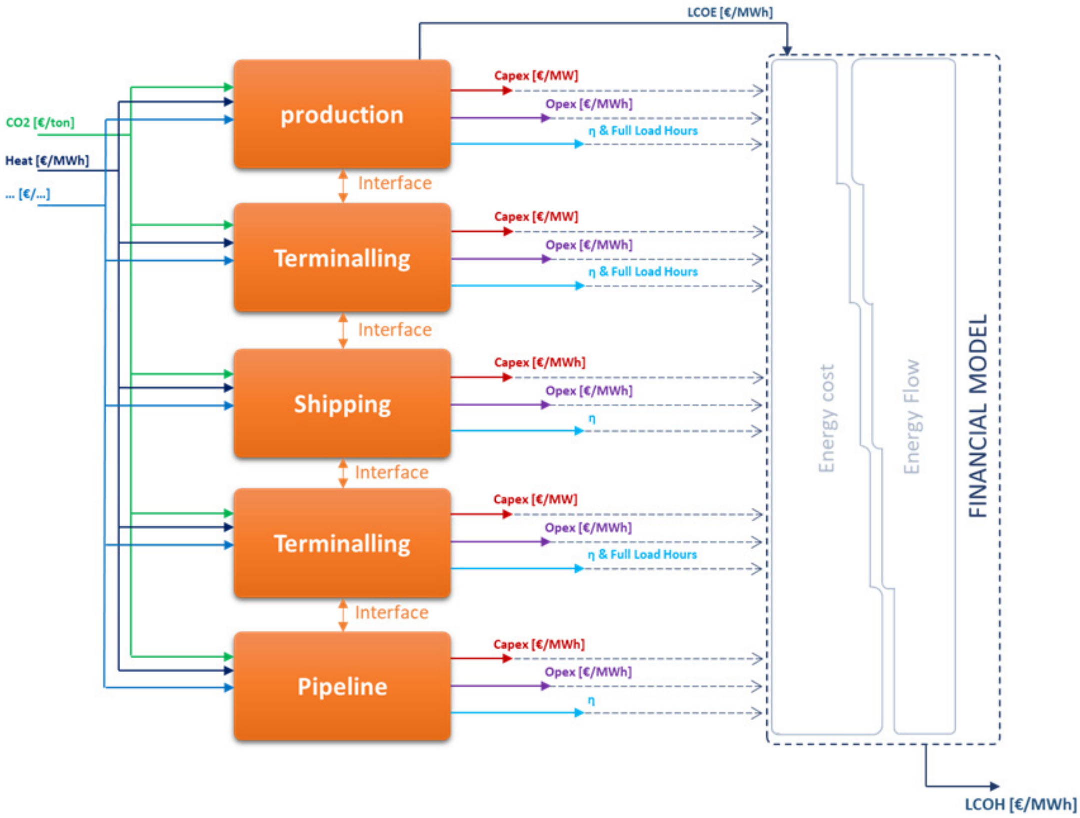
The coalition designed a large-scale, off-grid energy production system that is carbon neutral across the entire value chain and is capable of delivering baseload energy at the destination point. The large scale is capable of yielding significant economies of scale and is in the order of 20TWh per production site by 2030-2035 and tenfold by 2050. Such a scale also allows the largest scale of ship design, up to 1,7TWh per ship depending on the carrier. For the synthesis of methane and methanol, a carbon open loop is assumed, which implies local CO_2 sourcing at the production site. The same also applies in the case of nitrogen for the synthesis of ammonia. All molecules delivered to Europe are assumed to be carbon neutral at the end of the value chain, which implies that all fuels and energy consumed throughout the value chain are meant to be carbon neutral, for example, ships should sail on renewable fuel. Any onshore transport is assumed to be via pipeline and further downstream distribution is not considered.

The financial model and economic assumptions

All capital and development costs (CapEx), operations and maintenance costs (OpEx) and efficiency losses for every stage within the full value chain have been included in the financial analysis[8] and summarised by means of a “Levelized Cost of Hydrogen” (LCOH), expressed in euros per MWh[9], similar to the existing concept of Levelized Cost of Energy (LCOE) as shown in the equation below. The LCOH includes all the costs considered, up to the delivery of the energy at the flange of the industrial off-take centre, and hence represents the minimum average price level over the lifetime that is required in order to provide an acceptable return to the investors.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

- I_t = Investment expenditures in the year t
- M_t = Operations and maintenance expenditures in the year t
- F_t = Fuel expenditures in the year t
- E_t = Electricity generation in the year t
- r = Discount rate
- n = Life of the system



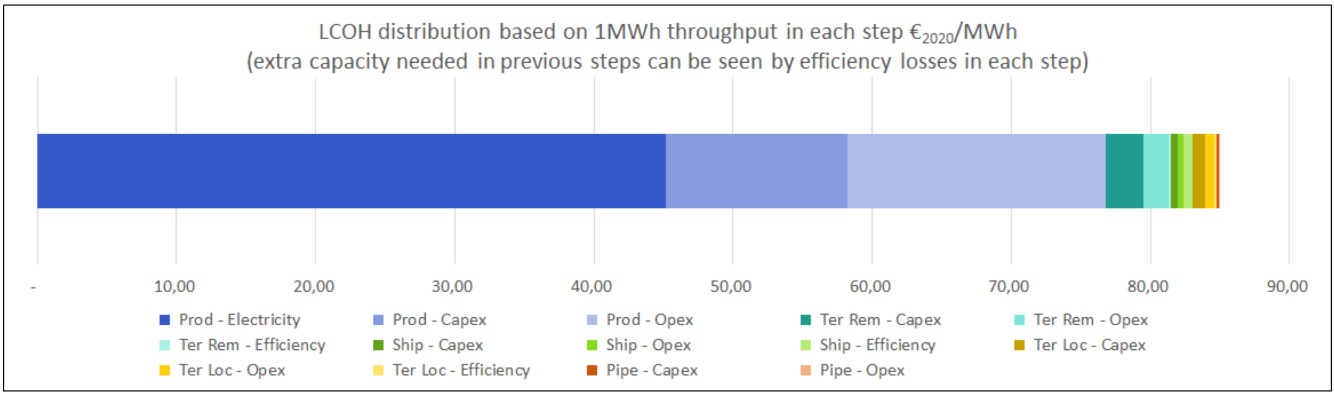
Levelized cost of energy - principle
Source: Hydrogen import coalition

[8] Excluding corporate tax and value added tax , excises, levies and import / export duties on commodities, including cargo and other insurances, other taxes, charges and duties (e.g. port and channel duties)

[9] Higher heating values are used throughout the report.

All financial parameters are expressed in 2020 euros and the discounting was carried out at one unique cost of capital of 4.3% per annum in real terms for the whole value chain[10], no further financial leverages included. The time horizon was set to 40 years of operation, in order to level out different lifetimes for each step in the value chain, hence regular reinvestments have been included as required.

The resulting LCOH can be broken down into different components as shown in the picture below:



Source: Hydrogen import coalition, LCOH for synthetic methane from Morocco by 2030-2035

The first and most important cost component corresponds to the cost of producing the renewable electricity which will power the electrolyser. However, this component does not merely reflect the LCOE (Levelized Cost of Energy), but also includes the cost of curtailment and storage. Indeed, as a key assumption is to provide baseload energy, it is not economical to convert all the peak power into hydrogen, as this would require a disproportional investment for the electrolyser. A significant amount of electric storage is not only required to smooth out the electric peak, but also to provide stable operating conditions to the electrolyser and synthesis reactor[11]. The amount of curtailment and storage to achieve the economic optimum depends on the production profile (wind and sun profile) that is typical in each region and hence explains some of the significant differences observed among some regions.

It is important to note that many studies do not take into account the assumption of off grid, base-load supply and corresponding techno-economical optimisation of curtailment and storage. Curtailment implies off-grid operation, as it is unlikely that the excess of electricity can be economically dispatched into the electricity network at this scale and with a large penetration of renewables as is expected by 2030-2035 / 2050. It is also the case that the production locations with optimal wind and sun conditions will often be located far from urban or industrial areas and hence will not always justify a grid connection.

[10] Except for the wind and solar farms which apply technology specific discount rates for mature technology.

[11] For example, in order to ensuring a minimum load at all times required for stable operation.

Results

The economics

Reading guide

The total cost of renewable imported energy delivered to Belgium for 2030-2035 is summarised in the chart on page 23, for the different regions. All of the carriers considered have been included and are expressed in 2020 euros and higher heating value. The hydrogen scenarios involving transportation by ship are always based on liquefied hydrogen, as the study quickly pointed out that the transportation of hydrogen in gaseous form by ship is not feasible for economic reasons associated with the limited energy density of gaseous hydrogen. When pipelines are an option (H2_P scenario for Morocco and Iberia and the North Sea offshore scenarios), hydrogen is assumed to be transported as a compressed gas, providing more or less inherent storage capabilities, depending on the design of the pipeline at variable or constant pressure.

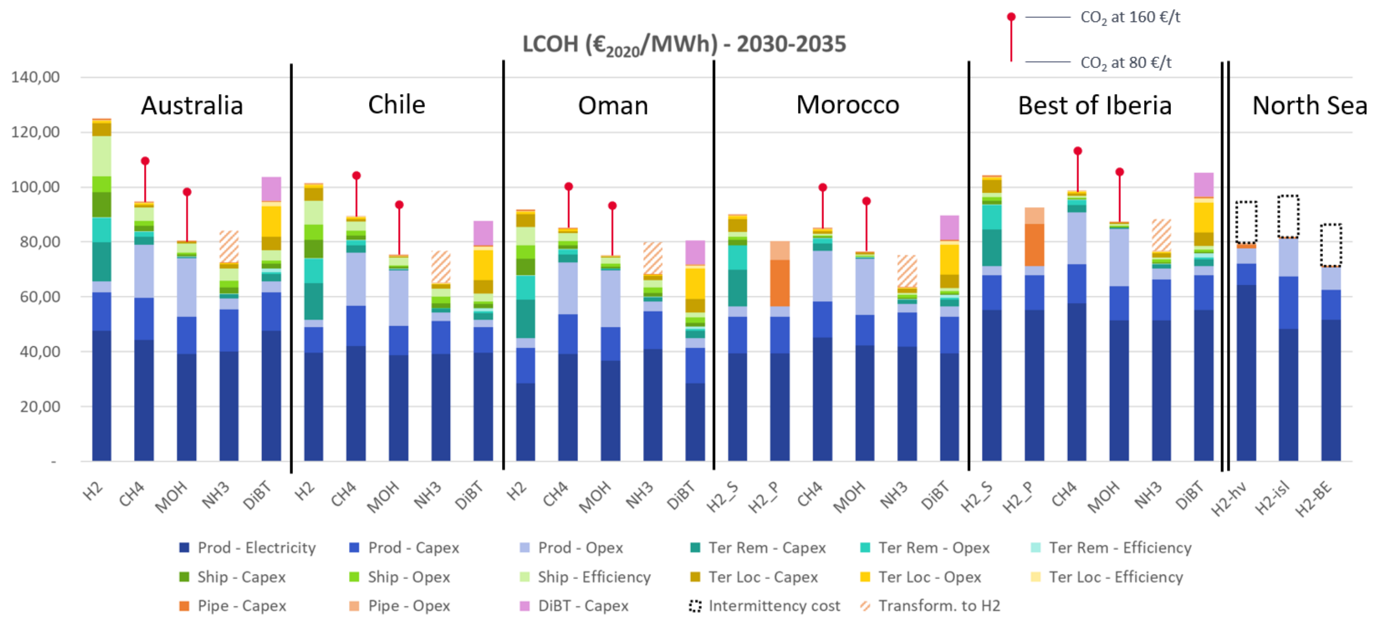
The pipeline scenarios also deviate from the strict baseload assumption, and in order to make all results comparable, the "storage" or "system" cost to cope with the intermittent nature of the energy supply has been added. For the Morocco and Iberia scenario, this cost was roughly estimated by calculating the cost of a direct pipeline to Belgium, assuming that the 2000-km pipeline will have sufficient buffer capacity to provide baseload at the end point. Note that this choice is somewhat arbitrary and only for illustration, as it is rather unlikely that a direct, variable pressure pipeline will be implemented and also considering that alternative solutions, such as salt cavern storage will be considered. For the offshore scenarios, a similar rationale was followed, represented by the dotted lines. In practice, the coalition assumes that the market will determine the optimal way in which to incorporate these intermittent energy streams into the energy mix, but the additional cost components at least indicate the system cost impact of baseload versus intermittency.

Given the toxic hazard posed by ammonia transport, it is questionable if ammonia will continue to be transported as an energy carrier further downstream. For that reason and with the exception of some direct industrial off-takers of ammonia, such as the fertilizer industry, an additional cost has been added to represent the additional cost for converting ammonia into hydrogen. This cost was based on a literature review and was not analysed in detail by the coalition, hence the reason why it is represented as a shaded area. In the case of DiBT, the carrier molecule itself also represents a significant (investment) cost shown as DiBT-Capex.

All scenarios (except some offshore scenarios) are based on large scale production as described above, however, not all regions are capable of providing Europe with energy on a stand-alone basis. The potential volume that can be realised in certain regions (such as Chile or Australia) is far greater than in others (Iberia, Offshore), but the coalition assumes a complementarity between the regions, that is also driven by market dynamics and geopolitical considerations and security of supply. Iberian scenarios are referred to as “best of Iberia”, as within a region, not all locations have the same economics, especially for rather constrained regions as Iberia.

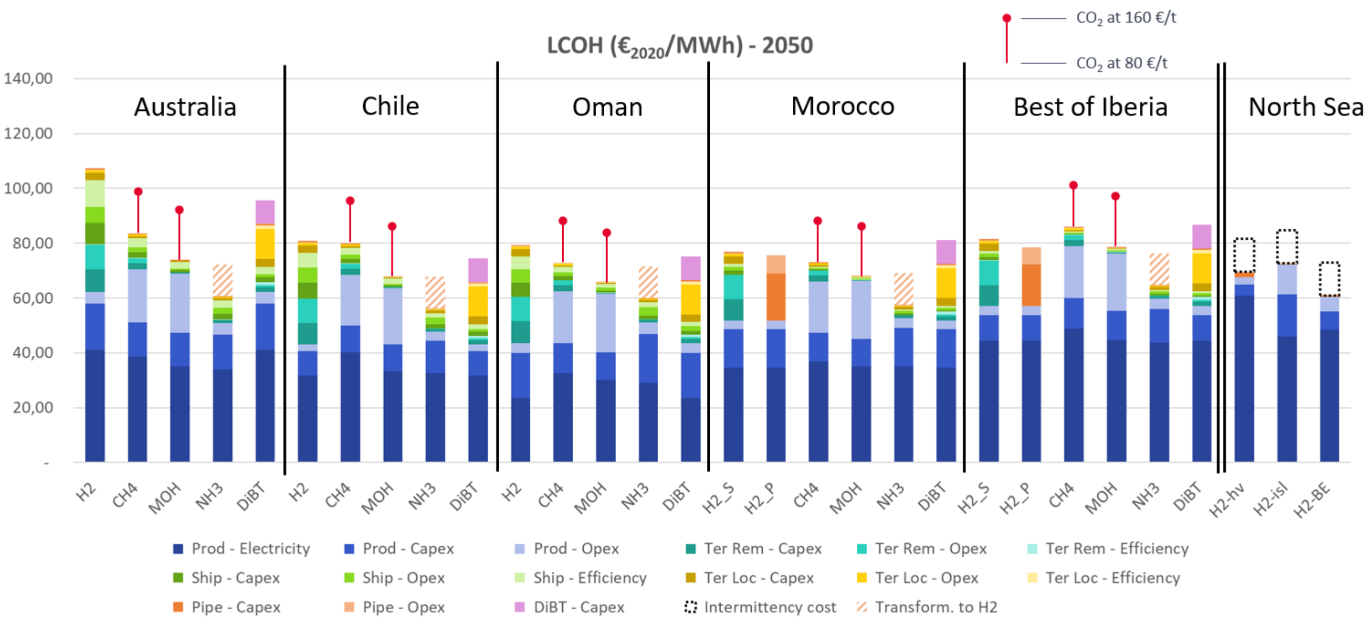
For the offshore scenario involving the use of an artificial island, the cost of the island is taken into account as a variable concession cost and forms an abstraction of the (enormous) investment of such a (multi-functional) island.

The CO_2 that is required for the synthesis of methane and methanol, represents a significant portion (70-80%) of the operational cost (Prod-OpEx). This cost is heavily dependent on the cost of sourcing the CO_2. In the charts, a cost of 80€/ton is assumed, but the impact of doubling this cost to 160€/ton is represented by the red line.



Source: hydrogen import coalition

The chart below shows the same results expected by 2050, based on further cost reductions due to additional scale and technology maturity.



Source: hydrogen import coalition

Main conclusions on the economics

As an overall conclusion[12], it can be determined that the cost of renewable imported energy lies in the range of 65-90€/MWh by 2030-2035 with a further cost reduction potential down to 55-75 €/MWh or lower by 2050, thereby providing a complementary solution that will enable the 2030-2050 targets to be reached in the EU.

Although importing from Australia seems to be on the more expensive side at first glance, some carriers remain very cost effective. The impact of the long shipping distance mainly affects the cost for hydrogen (and to a lesser extent methane), as the energy required to propel the ship (as a fraction of the energy transported) has a significant impact on the shipping cost (Ship-Efficiency). Compared to Australia, the similarly long shipping distance for Chile and more nearby Oman is partially compensated by the lower production costs of the energy due the better full load hours of wind and sun.

The higher production costs for Iberia and (to a lesser extent) Morocco are partially compensated for by the lower transport costs due to their proximity, which means that these are also competitive as sourcing regions.

It must also be noted that the coalition found the overall feasibility of liquefied hydrogen and DiBT to be significantly lower, compared to the more mature value chains of transporting liquefied methane, ammonia or methanol.

[12] Under the hypotheses of the study, including the conservative off-grid, baseload assumption. Relaxing the latter assumption will reduce overall LCOH.

The pipeline benchmark scenarios for Iberia and Morocco show that pipelines can provide cheaper molecules if the baseload requirement can be relaxed. However, a pipeline supply chain has its own issues (less flexible, higher fixed costs, less compatible with market dynamics) and both pipeline and shipping scenarios have their own rationale and merit to be considered further.

The North Sea offshore benchmark scenarios show that offshore wind is capable of providing competitive renewable molecules, however again, not necessarily always at baseload. The molecular route could make far-shore offshore wind feasible, including in the event that the electrical grid infrastructure were to become a bottleneck, but the electrical route will probably always be complementary to molecules as a means of bringing energy to the mainland.

The global picture remains unchanged by 2050, although hydrogen makes up for its cost gap, mainly due to greater potential in the predicted reduction in the cost of technology and further reductions in the production cost of renewable electricity.

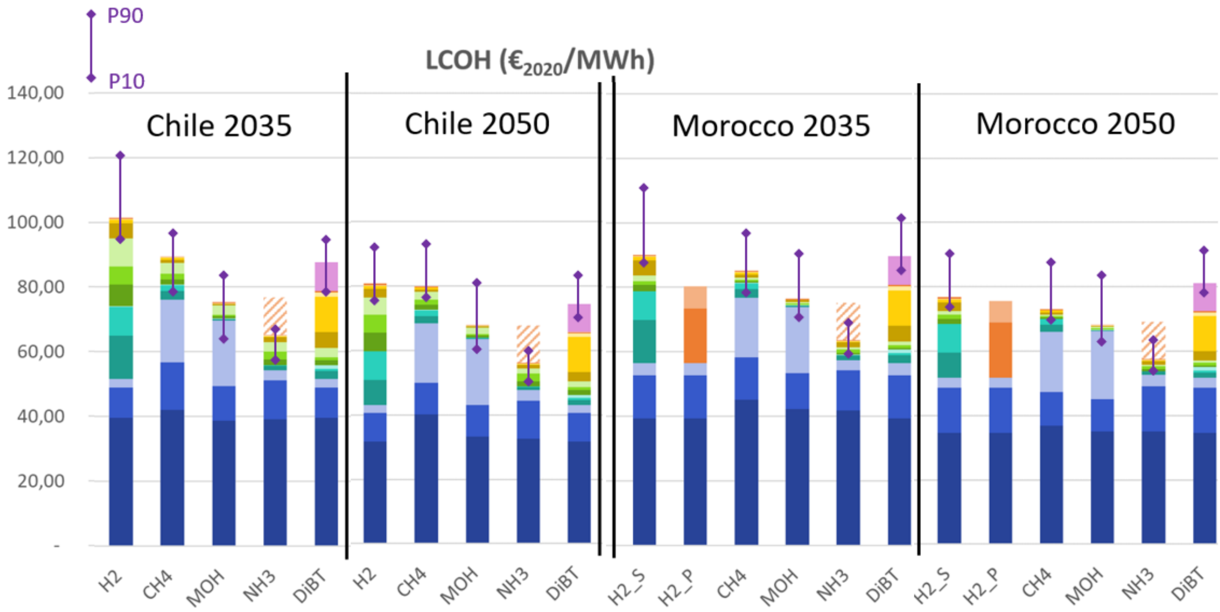
Overall, we can conclude that all routes look promising under conservative assumptions and there is no clear winner, region nor carrier, and that this should rather be considered as a good starting point. This implies that a level playing field potentially exists among the different options which will stimulate market dynamics. Moreover, the complementarities (technological and regional diversification) needed for system resilience and security of supply under an environment that will certainly encompass any new factors that are unknown to us today will be increased. In a situation in which multiple regions are capable of providing competitive renewable energy, the security of supply, including in a geopolitical context, would be greatly improved.

No silver bullet: no clear winner scenario. Market demand (Use case scenarios) will strongly influence the outcome.
➔ multiple carriers and locations remain feasible

Source: hydrogen import coalition

Sensitivity

For all cost assumptions, not only a predicted average was considered, but also a more optimistic and pessimistic assumption[13] which is reflected in the form of an uncertainty range (P10-P90 range) of the outcome, as represented in the chart below.



Source: Hydrogen import coalition

The main drivers of uncertainty[14], which explain the vast majority of the uncertainty range, differ from carrier to carrier. The table below shows the two most significant drivers per carrier.

uncertainty driver	H2	CH4	MOH	NH3	DIBT	offshore
1st	term.capex	CO2 cost	CO2 cost	LCOE	LCOE	prod. capex
2nd	LCOE	LCOE	LCOE		DiBT & term.capex	

Source: Hydrogen import coalition - 'LCOE' refers to the cost of renewable electricity in the country of origin, 'term. capex' refers to the terminal investment cost, 'prod. capex' refers to the electrolysis and synthesis investment cost, 'CO_2 cost' refers to the cost of CO_2 serving as feedstock to synthetize CH_4 (methane) or MOH (methanol). NH_3 refers to ammonia.

[13] The results are based on computing many parameters. For most of the parameters, not only an "expected average' value was defined, but a likely range. These probability ranges are consolidated by means of the Monte-Carlo technique, leading to a probability range of the outcome, which is represented by its P10 and P90 values in the chart.

[14] In the Monte Carlo technique, the relative contribution of each parameter compared to the overall uncertainty range can be traced back

It can be seen that hydrogen exhibits the largest uncertainty, which is reflective of the technological challenges. Methane and methanol exhibit a similar uncertainty profile despite more mature technology, as that uncertainty is based on uncertainty in the cost of CO_2. Ammonia benefits from the lowest uncertainty, however without considering uncertainty as to the predicted cost of immature reconversion technology and not accounting for potential safety considerations. DiBT suffers from uncertainty associated with the cost of the DiBT carrier molecule and the technological challenges regarding DiBT terminal design.

It is also important to note that timing is not neutral. The technology that is first adopted by the market will upscale faster and the maturity of technology could give the first mover a sustained competitive advantage. In the worst case, this could lead to a lock-in of a technology which does not necessarily provide the best long-term cost reduction potential.

Economics of the Use Cases

It is important to note that the quantitative analysis to determine the absolute cost of renewable imported energy ends at the delivery of the energy into Belgium. However, the coalition also analysed the cost impact that the imported molecules would have on the end products for which these energy vectors could serve as raw material (feedstock or energy). This analysis has proven complex, but overall conclusions are presented below.

A market for all carriers - no clear winner

The industrial end-users of the hydrogen-carriers are of course a vital part of the import value chain. The demand for the different carriers and the willingness-to-pay (WTP) will create the market. All of the hydrogen-carriers already play a role in our industry today, and all of them can potentially play a role in the transition to climate-neutrality for different applications. Although there is a growing market in the case of all of the imported hydrogen-carriers, for the majority of applications, the preferred transition pathway remains open (electrification, biomass, recycling and re-usage.) and the expected demand volumes therefore remain for a large part unclear.

As a carrier, ammonia is gaining momentum globally in announced projects, as it offers the lowest costs, existing infrastructure is available and no carbon is involved. It may be a promising market for the purpose of kick-starting the import chain, with large initial volumes, but the number of applications seems to be limited, as shipping and fertilizers are the main or only application areas in which it is applied directly. There is greater demand for pure hydrogen in most applications and it is possible that the technological solutions will develop along with the demand. The economics of the reconversion of ammonia to hydrogen are also unclear and there are environmental risks associated to the offshore mass-transportation of ammonia in the form of a generalised-energy vector.

The cost-gap with the fossil benchmark needs to be bridged

In general, the fuel or feedstock cost-gap between a hydrogen carrier and its fossil benchmark is substantial for different end-users. However, the cost-gap for feedstock is smaller than for energy use. Under the current market conditions, the WTP of the industrial end-users is still unclear today, but, in any case, is not large enough to close the cost gap.

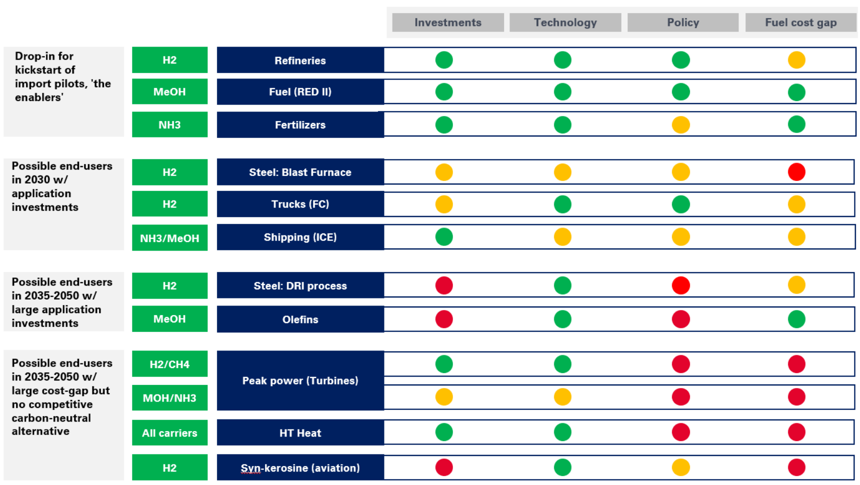
A growing ETS[15] cost will increase the WTP and hence reduce the cost gap. Some applications are already cost-competitive when considering the energy cost (e.g.: Methanol-to-Olefins versus naphtha cracking), while other applications are really far from being cost-competitive (e.g.: >€300/ton of CO_2 to produce electricity with gas turbine power plants). This gap could also be covered (at least initially) by carbon contracts for differences.

Some (new) applications yield a higher fuel efficiency with hydrogen compared to the existing fossil approach (e.g. fuel cells compared to internal combustion engine). Because of this higher efficiency, lower volumes of energy/feedstock are needed per output unit, mitigating the cost gap.

To achieve climate neutrality for some large CO_2 emitters, embedding carbon capture in the existing process sometimes proves to be more cost effective, as the required investments and/or higher running costs outweigh the cost of CCS, at least during its first technological stages.

Policy framework for carbon-neutrality

A clear policy framework needs to set the right conditions in order to bridge the cost-gap with the fossil benchmark. This can be achieved by setting clear targets for different end-users (e.g.: RED II), by creating a level playing field (Carbon Border Adjustment Mechanism, ETS CO_2 prices…) and by financial support. It is very clear that OpEx support through for instance 'Carbon Contracts for Differences' is vital for kick-off phase. Also new applications (DRI for steel, hydrogen turbines, etc.) will need Capex support to make the transition from existing assets possible, in markets where the margins are often very small in the current market. R&D support will also be needed. This reflects the way in which wind and solar were developed until they reached the verge of market maturity as they have today.



Source: hydrogen import coalition

15 EU Emissions Trading Scheme, European cap-and-trade mechanism to internalise the cost of emitting greenhouse gasses in industrial sectors, a cornerstone of the EU's policy to combat climate change.

Regulatory

Intra EU carbon imports

The coalition has investigated the potential regulatory hurdles with regard to synthetic carrier imports, specifically in relation to carbon. Although both carbon carriers are known in their present identical -fossil- form, the coalition looked into the potential regulatory importation hurdles for their synthetic counterparts. None were detected.

The coalition however took note of an indirect economic hurdle, arising from the IPCC carbon origin accounting rules: disregarding the nature of the carbon present in a hydrogen carrier, any non-biogenic carbon is deemed fossil. This means that, even though our analysis assumed all carbon as derived atmospherically through direct air capture with only renewable energy being used in the process, the IPCC provides no advantage in terms of reducing greenhouse gas emissions. In reality, a complete value chain LCA following general EU guidelines would show that the greenhouse gas contribution of such fully circular carbon carrier molecules is zero. With the European Union adapting these IPCC accounting rules up to the present day and imposing them onto the Member States for the purpose of their National Energy and Climate Plans, the effect on the economic potential of carbon carriers (whether being imported or produced domestically) is not sufficiently constructive to adequately promote circular non-emission technologies. Given the importance of carbon carrier molecules with zero emission as an enabler of the energy and feedstock transition, either as a transport vector or as a fuel or feedstock, this regulation may not be progressive enough for technology. The coalition will pledge adaptation.

Border Taxes for Hydrogen (Energy Taxation Directive)

There is no minimum excise duty level (border taxation) for hydrogen imports at EU level. Member States do not impose excise duties on hydrogen imports either. However, importers are expected to declare the energy imported to customs and the use of imported (as that of the locally produced gas) is subject to consumption related taxes (direct or indirect, excise duties, VAT, CO_2 price in case of and depending on country).

Technical Standards and Miscellaneous Regulations related to international transport of hydrogen

The international transportation of hydrogen for import purposes is a non-regulated activity, however there is a set of regulations and standard technical rules that apply on a European and national level.

Guaranties of Origin and CO_2 contents

EU level

At European Union level, RED-II applies, which includes following principles on guarantees of origin (GOs):

1. Member states shall refuse GOs from non-EU member states, unless the EU has concluded an agreement with that third country on mutual recognition and only where there is direct import or export of energy
    - This is a possible issue for import of renewable hydrogen or other renewable hydrogen-carriers
    - Direct import: probably linked to the possibility to 'physically' trace the renewable hydrogen. In case of ship transport and pipelines, the consequences may be different
    - Mutual recognition: no information yet on whether this is being developed already. This might become more realistic once the ongoing standardisation on GO in the EU has already been finalised
2. GO cannot be used as proof of climate objectives or subsidies associated with these.

Renewable hydrogen is a renewable gas and should be kept as compatible as possible with the official EU certification system for renewable gases. It is key that the central registry for GO be created in a timely manner and that certificates are recognised across borders.[16] The whole system should remain flexible enough to allow for multiple carrier conversions. European and international agreements are also needed with regard to the thresholds to be applied in order to determine whether hydrogen is to be considered as renewable or green.

The EU is preparing the application of a Carbon Border Adjustment Mechanism to prevent carbon leakage and a reform of the Emissions Trading Scheme, as integral part of the European Green Deal. Additionally, the European Hydrogen Strategy published in the summer of 2020 also mentions the possibility of applying Carbon Contracts for Differences, which could affect the business case for hydrogen imports (depending on how these are designed).

Member State (Belgian) Level

In Flanders, regional GO for renewable gasses (including renewable hydrogen) has been in place since May 2020. A local registry also exists. For the time being, the GO system in Flanders is for renewable gas (applied today to biomethane) but it does not enable cross-border recognition, which means it does not provide any support for hydrogen imports or for the conversion of foreign GO to the local system. This is a key barrier to be addressed in the case of renewable hydrogen imports, since the cross-border compatibility of certificates (not only within the EU but also with third countries from which the imports may be sourced) will be essential.

In Wallonia the current system of 'label de garantie' d'origine' is not compliant with the RED II art 19, and adaptation of the legal framework is in progress to include amongst others renewable hydrogen.

In Brussels there is no news of any progress on creating a compliant legal framework for GO's.

[16] EU member states have the obligation to have a GO system by 1st July 2021 (RED II art. 37)

With regard to these aspects, the Belgian Federal Government has competences for biofuels. It is important to note, however, that when RED-II addresses biofuels for this topic it refers to transportation, the regions can monitor objectives etc., and the Federal level defines the product standards and coordinates several other aspects.

Main conclusion on regulatory hurdles

No immediate showstoppers were detected, but actions in several regulatory domains will be required in order to create the level playing field that is needed in order for the renewable energy carrier import economy to grow and become mature. Actions range from taxonomy (border taxes, carbon border tax adjustment), adapting the way in which greenhouse gas reductions are calculated so that circular carbon carriers are taken into account, ensuring low threshold cross-border exchanges by ensuring an adequate framework for GO's and renewable transport fuels and energy carriers.

Note on EU collaboration

As most sourcing regions lay outside the EU, dedicated collaboration agreements will have to be set up between the country of origin and the receiving state. A certain level of coordination at EU level will probably yield better results than uncoordinated initiatives by the member states.

Technology

No showstoppers have been detected coming from technological hurdles. Almost every component in the supply chain is however subject to potential upsides, optimisation and risks. The elements that exert the greatest influence are as follows:

- Electrolysis clearly requires cost efficiency improvement, production scale ramp up is a concern
- Synthesis: requires cost efficiency improvement; the flexibility of the processes involved is subject to innovation and optimisation
- Shipping: liquefied hydrogen transport clearly requires innovation so as to render the option economically feasible
- Terminals: carrier splitting, especially for ammonia, is an important innovation target
- Use cases: almost all of the use cases envisaged are subject to innovation in coping with hydrogen and its carriers

All qualifying carrier elements, whether they are in favour or not in favour of certain carriers, have been summarised in the table below.

	Pro	Con
H2	• Less conversion losses • Premium for molecule compared to energy only use • Carbon free • Only option for CO2 reduction of steel production: large volumes at one off-taker and potential quick take-up • Drop-in for refineries and fertilizer production: early off-takers foreseen in EU H2 Strategy & both largest H2 users today • Heavy duty transport as off-takers • Power & heat production possible through admixture or full H2 in upcoming turbines from 2030 onwards, or blending in local networks • Reuse (retrofitting) of existing infrastructure in Belgium	• Challenging to store and ship (low density, very low temperature liquefaction) • Innovation needed for use in chemical industry as platform molecules • Overall more expensive for long distance import
CH4	• Existing mature supply chain, proven technology • Reuse of existing infrastructure in Belgium: not only pipeline, but the whole gas use; Huge addressable market (gas is #1 energy for Heat application), existing biogas market (and off-takers) • Re-use of existing LNG infrastructure in transport (road-sea)	• Large quantities of affordable CO2 required upstream • Ongoing debate about of methane slippage, although risk is limited for renewable methane (main methane slippage comes from well-heads, not applicable here)
MOH	• Premium for molecule compared to energy only use • Cost efficient shipping and storage • Drop-in for chemical production & new processes. • MOH demand could increase until 2050 due to demand for fuel additive, thermoset plastics, Methanol-to-Olefins, … • MOH is today also mostly imported • Safe fuel (shipping); mixes with water • Works with existing engine technology as drop-in or dual fuel	• Large quantities of affordable CO2 required upstream • Competition from bio-based feedstock for end products (eg.: olefins, …) and decreasing demand for fuel (additives).
NH3	• Potential to decarbonize fertilizer market on short term • Carbon-free, avoided CO2 instead of 'circular/neutral' CO2 • Good overall economics if no H2 splitting required downstream	• Toxicity might hinder public acceptance, especially downstream • Environmental impact also includes on the cycle of Water for fertilizer application • Downstream H2 splitting negatively impacts economics • Not suitable as feedstock for petrochemical industry • Only addressable market is ammonia, unless splitting, which is low TRL (therefore, limited market) • Fertilizer production might relocate to NH3 production locations • NOX emissions when combusting NH3 (in transport/power& heat applications)
DiBT	• Efficient way of H2 transport without need for CO2	• Low technology readiness • Big uncertainties, questionable scalability • Complex supply chain • Total value chain rather expensive due to complex dehydrogenation & high capex LOHC • Only viable if heat sink/source available at hydrogenation / dehydrogenation step

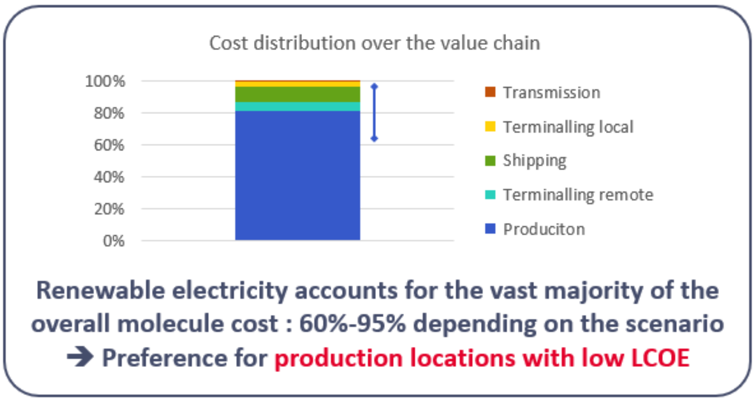
Source: hydrogen import coalition

General conclusions

The carrier proposition

The analysis proves that the import of renewable energy by means of carrier molecules is a feasible and economically sound solution for the long-distance transportation of renewable energy by ship (and pipelines). The overall cost of importing hydrogen by ship can be generally significantly reduced when deploying carrier molecules, mainly methane, methanol and ammonia. Moreover, these carriers face fewer technological hurdles for shipping, to a certain extent because the molecules involved are 'known' to our economy in the form of their identical fossil counterparts. The fact that to a large extent, these molecules can use existing assets, reduces the investment risk and lead time. Although less competitive for long-distance transportation per ship, hydrogen as such will not be ruled out, as potential technological breakthroughs might enable liquid hydrogen production and bulk transport[17].

By making long term transport of renewable energy technically and economically feasible, hydrogen and its carriers also make it economically attractive to import low-cost renewable energy from remote locations and as such can serve as a strong enabler for the energy transition in Europe. Indeed, renewable electricity accounts for the vast majority of the energy costs and this will enable Europe to source its renewable energy from locations where supply is abundant and less costly, even following transportation to Europe, as the benchmark scenarios clearly show.



Source: hydrogen import coalition

[17] Including retrofitted pipelines which allow cost effective continental transport.

An additional advantage is especially relevant with regard to feedstock supply: our European organic chemistry sector needs hydrogen and carbon. As carbon carriers, methane18 and methanol therefore combine the logistical advantage with the supply of circular carbon. An additional aspect lies in the fact that the transportation of molecules by ship is a feasible and proven method of importing energy (in this case, renewable energy) on a massive scale across ultra-long distances (for example Oceania-to-Europe or South-America-to-Europe) and in the fact that the transportation flows of molecules in grids (when we are speaking of pipes) is relatively easy to control and very efficient in terms of costs and investments.

Based on current knowledge, the Liquid Organic Hydrogen Carrier (LOHC) option on the other hand proves to be less attractive: the advantage of the lower operational costs for absorption-desorption processes (as opposed to molecular synthesis) does not compensate for the higher transportation costs and for the carrier molecule itself. Moreover, the supply chain is overly complex and technology readiness is rather low and lacks a clear pathway to a mature LOHC solution. However, a technology breakthrough might alter the situation.

Renewable imported molecules in the European Energy mix

The import of renewable energy by means of hydrogen carriers is assumed to be necessary and complementary to the pathways leading to a sustainable transition in domestic energy in the EU. It has the advantage over the bio-route by virtue of its almost unlimited volume potential and its clearer cost reduction path in the long term. It has the advantage over domestic renewables due to the fact that it is able to provide baseload, additional energy, while a domestic all-electric renewable scenario is still unclear with regard to total system costs, congestion management and system stability. It has the advantage over CCS (carbon capture and storage) pathways, including blue hydrogen, as it is fully circular and therefore sustainable in the long term.

Hydrogen carriers such as methanol and ammonia will, in part, be integrated in EU economy as they are, as they form the building blocks of sustainable chemistry, climate neutral shipping etc. It can however be expected that hydrogen will become an important energy transportation and storage vector and that an extensive pan European hydrogen grid will be deployed. The hydrogen vector will grow and provide solutions that service a need for renewable molecules and wherever electric transmission lines lack acceptance, cost efficiency or pace of deployment. Besides sharing technology with this domestic hydrogen economy development, hydrogen imports will partially share value chains. Alongside the direct use of imported hydrogen carriers, carrier splitting into hydrogen gas as well as potential future imports of (liquefied) hydrogen gas will also form an important aspect of the supply chain.

The coalition expects and pledges to consider imported renewable energy as an essential element of any energy transition pathway towards sustainability, in terms of pace, robustness, flexibility, sector integration and cost efficiency. Market forces will determine what the optimal equilibrium between the domestic -wind and solar based- production and carrier imports will be, taking into account costs, risks, spread etc.

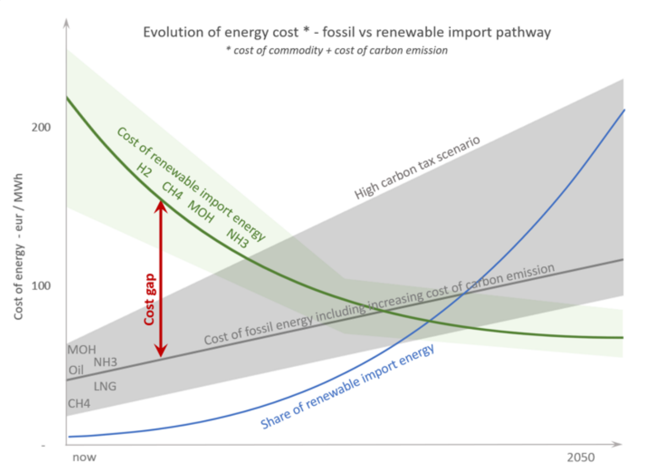
[18] Sometimes referred to as "synthetic methane"

How to scale up the import of renewable energy - the role of public-private funding

If the import of renewable energy proves to be a feasible and a cost-competitive pathway towards sustainable energy and feedstocks in Europe, it will need to be scaled up in order that fossil energy and feedstock can be replaced with carbon-neutral imported energy.

First and foremost, the competitive advantage of fossil energy due to the fact that it does not internalize the climate and environmental costs, will be eliminated. This process is partly ongoing by means of production-focused carbon taxation. Far more interesting, however, are the Carbon Border Taxation path, creating a level playing field for all products seeking entry into EU markets, and a considerable push towards a climate ambitious EU industry.

In order to quantify this effect, a relevant number of use cases have been analysed. It does not come as a surprise that none of the selected use cases were found to achieve cost-parity with its fossil benchmark at present. This is represented in general terms in the chart below. However, several use cases have been identified, in which the cost gap lies in the range of only several tenths of a percent. A temporary effort to close the funding gap for selected cases will provide the necessary stimulus to scale up the import pathway. The Carbon Contract for Differences tool, already known as an efficient tool for the deployment of local renewable power assets (wind, solar etc.) and already designated in some of our neighbouring EU Member States as the tool with which to bridge temporarily OPEX gaps, will be needed to allow early-mover offtakers to consume the first imported renewable volumes needed.



The renewable import pathway will become competitive on the longer term thanks to significant cost reduction potential. ➔ Financial incentives are required on the short term in order to support industrial scale up.

Source: hydrogen import coalition

Offtakers are an important piece within the import supply chain puzzle. However, simultaneous infrastructure development and adaptation will also be needed, with heavy and risk bearing investment cases being needed in order to obtain CAPEX funding.

Finally, applied innovation will enable new green carriers to be integrated within our industrial and societal fabric, allowing use cases to adapt to the new energy carriers and feedstock and vice versa to allow carriers to be transformed into usable forms.

Next steps

Policy and regulatory actions

In order to create the right dynamics to allow coalition partners and potential third parties to make the concept of importing renewable energy real, an adapted policy and regulation is needed.

First of all, in order to allow Belgium to host carrier importing terminals, a feasibility analysis is needed, involving the Seaports present in the coalition and the relevant departments and agencies of the Flemish and federal government. Spatial policy will be a key element, both for the portal planning process as well as grid infrastructure corridors linking the Belgian industrial clusters. The coalition will seek to develop a partnership in between the Seaport members of the coalition and the authorities and other industrial, regulated and research actors.

Besides spatial and infrastructure planning, the general policy and regulatory context has to be open to importing renewable energy and feedstock, alongside domestic production. This concerns both the local (i.e. National or regional) context, in addition to the EU context. Topics range from 1) a robust and futureproof National energy action plan that is open to all sustainable routes and takes into consideration as many integration costs, congestion management costs and logistics aspects as possible for all energy carriers, and 2) an EU-wide Guarantee of Origin that allows imported renewable carriers to be considered as such and enables them to be transported across borders within the EU, and 3) amendments and corrections to public funding systems and stimuli incentivising the use of renewable energies imported using hydrogen carriers.

The coalition will therefore seek cooperation with the relevant governmental bodies to ensure sufficient public-private momentum.

Spin off projects

The analysis has shown that hydrogen imports can contribute to the energy transition in the EU in many different ways. The partners in the coalition do not simply wish to analyse, but above all wish to act and therefore contribute to the national transition economy. To do so, specific pilots need to be deployed and will require broad public-industrial partnerships.

The coalition partners will focus on setting up specific first deployment importing pilots from a range of the regions mentioned in the analysis. They will do so from within the coalition as well as in good cooperation with parallel endeavours emanating from a broader ecosystem of technology providers, investors, industrial consumers and logistic operators and are contributing to the importing economy. The coalition will seek maximum synergy with local economy, without losing focus on transition goals.

Roadmap

Large-scale intra-EU renewable carrier imports through Belgian seaports present a complexity of their own, as many public and private interdependent actions will be required along the future way. Creating a roadmap will make it possible to create clarity with regard to goals, milestones and actions and the interdependencies that exist between them.

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