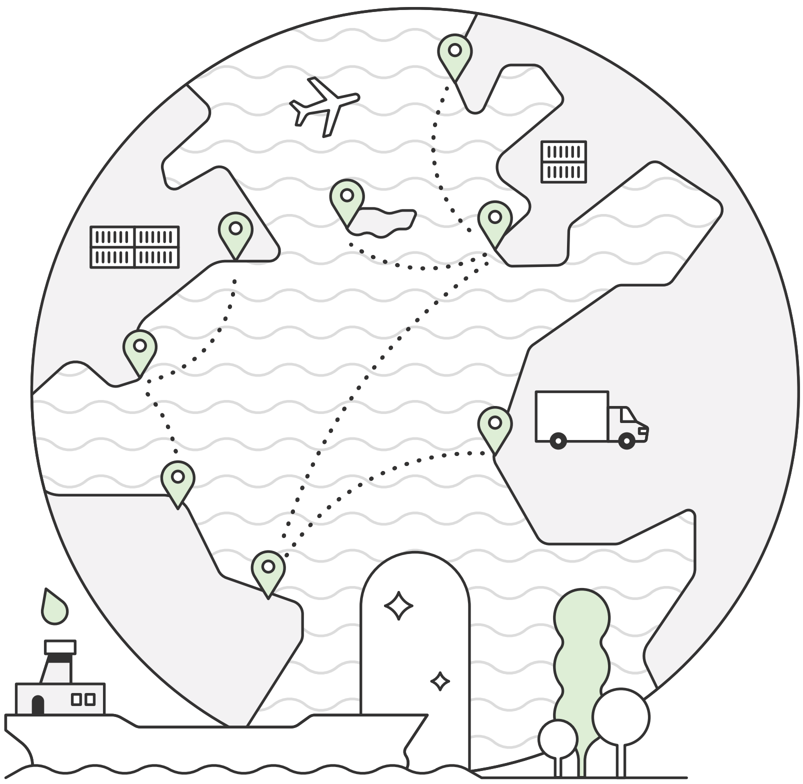
# Will renewable electricity availability limit e-fuels in the maritime industry?

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

# Contents





# Executive Summary

Decarbonizing the maritime industry will depend on alternative fuels. E-fuels are attractive because they offer the possibility to achieve substantial emission reductions. However, decarbonizing the maritime industry with low-emissions e-fuels will require a sufficient supply of renewable electricity, which is also increasingly in demand from other sectors that are also trying to decarbonize. If there is insufficient renewable electricity to meet demand from all industries, cross-sector competition and prices will increase. As the maritime sector has some of the highest abatement costs, it may not be willing or able to compete for high-cost renewable electricity, limiting e-fuel availability and hampering decarbonization efforts.

The long-term technical potential for global renewable electricity is more than enough to meet demand from all industries. Still, it is unclear whether we will be able to scale up renewable electricity capacity quickly enough to meet demand from every sector between now and 2050. To find out more about regulatory and supply chain constraints that may limit renewable electricity supply in the short term, we analyzed publicly available information, collected partner data, and conducted interviews with industry experts, including energy companies, technology providers, regulators, and finance companies.

We analyzed the political climate and regulatory factors in six countries with high technical potential for wind and solar installations and renewable electricity costs in the lowest 20% globally. National policies vary, and the situation is unique in each country. However, we found that most countries were increasingly in favor of renewables. Furthermore, we found that the timelines for permitting were adequate, with permitting, pre-construction, and construction taking 2-6 years in all countries. As a result, we concluded that regulation and policy are not major barriers to increasing renewable electricity capacity.

We also analyzed the supply of materials and resources across the wind and solar supply chains. We found four key constraints which may limit renewable electricity supply to the maritime industry in the 2030s and 2040s, and may result in a shortage of e-fuels:

1. The most concerning constraint is the availability of copper, a key material for solar and wind installations, which is typically slow to increase supply.

2. Nickel is also a concern, as it is already in high demand. Nickel is used in electrolyzers, which will be vital for producing hydrogen from renewable electricity for load balancing and e-fuels.

3. A shortage of rare earths may limit wind installations, but this may be overcome by using geared rotors that do not rely on rare earths.

4. Labor may be a constraint across the supply chain, from installing and maintaining solar and wind capacity, to increasing the manufacturing of transmission components. Workers could be transferred from oil and gas to combat this constraint. However, this will require retraining, which takes time.

We also identified limitations on transmission component manufacturing and installation vessels for offshore wind. We expect e-fuel production to be integrated at solar or wind farm sites, so these limitations are unlikely to impact the maritime industry directly. However, they could increase the pressure on global renewable electricity supplies and increase prices.

Our analysis suggests that renewable electricity will be limited in the 2030s and possibly into the 2040s due to material and labor constraints that will impact our ability to build capacity. As a result, we expect supplies of e-fuels for the maritime sector will be limited in the 2030s and possibly 2040s. Shipowners should be wary of relying on e-fuels alone for decarbonization.

To avoid a shortage of renewable electricity and e-fuels, the maritime industry could secure long-term renewable electricity supplies contractually before other sectors move. Otherwise, the maritime industry may need to expect to utilize other fuel pathways during the transition period; depending on availability, these could include blue fuels, fuels produced using nuclear power, batteries, or biofuels. Regulators can ensure a smooth transition by supporting the use of transition fuels on the path to decarbonization.

# 1. Introduction

There is growing pressure for the shipping industry to decarbonize. Decarbonization will necessitate a transition to alternative fuels with lower greenhouse gas (GHG) emissions than their fossil-based counterparts. However, since no single alternative fuel will be able to meet demand from the entire maritime industry, we expect shipping to utilize a range of fuels on the path to decarbonization, including blue fuels, biofuels, and e-fuels.[1]

E-fuels are synthesized from e-hydrogen made from green electricity and water electrolysis (see Figure 1). They are attractive alternative fuels in the shipping industry because they offer significant GHG emission reductions compared to fossil fuels. For example, from a well-to-wake perspective, e-ammonia and e-methanol emit just 3% of the emissions from low-sulfur fuel oil (LSFO). However, to achieve such low emissions, e-fuel production must use renewable electricity derived from naturally replenished sources such as solar, wind, hydroelectric, or geothermal energy.

Before shipowners rely on e-fuels for decarbonization, they need to consider whether there will be enough e-fuels to make them a viable pathway for the shipping industry. A sufficient supply of e-fuels depends on an adequate supply of renewable electricity. NavigaTE estimates that the maritime industry needs 1,100 GW of renewable electricity capacity installed by 2050 if 50% of the total energy demand comes from e-fuels. In 2020, the installed capacity of renewable electricity was just under 3,000 GW, with 735 GW of wind and 740 GW of solar capacity.[2]

However, the shipping industry is not the only industry relying on renewable electricity to decarbonize. Some industries expect to utilize direct electrification, others require e-hydrogen, and others e-fuels (see Figure 2).[3] Global forecasts suggest we will need 25,000 GW of renewable electricity capacity in 2050 to cover demand from all industries following a 1.5°C trajectory in line with the Paris Agreement.[4] Projections indicate that the majority of new renewable electricity installations between now and 2050 will be from wind and solar,[5] while hydroelectricity and geothermal power are not expected to increase as significantly. As a result, global decarbonization will require approximately 6,000-8,100 GW of wind capacity and 11,000-15,000 GW of solar capacity by 2050.[4]

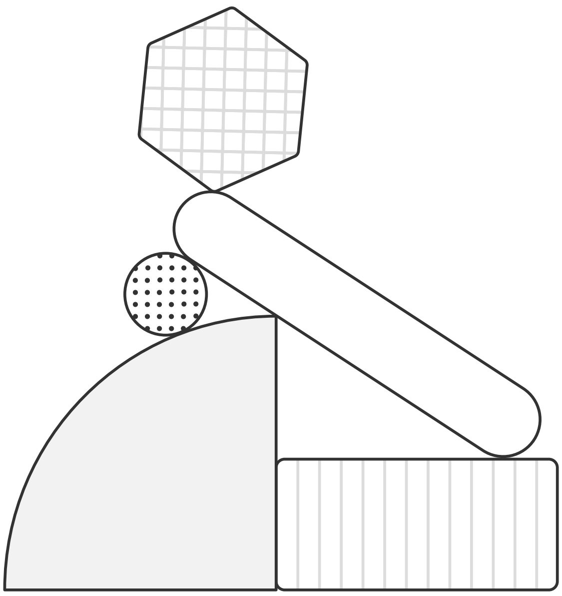
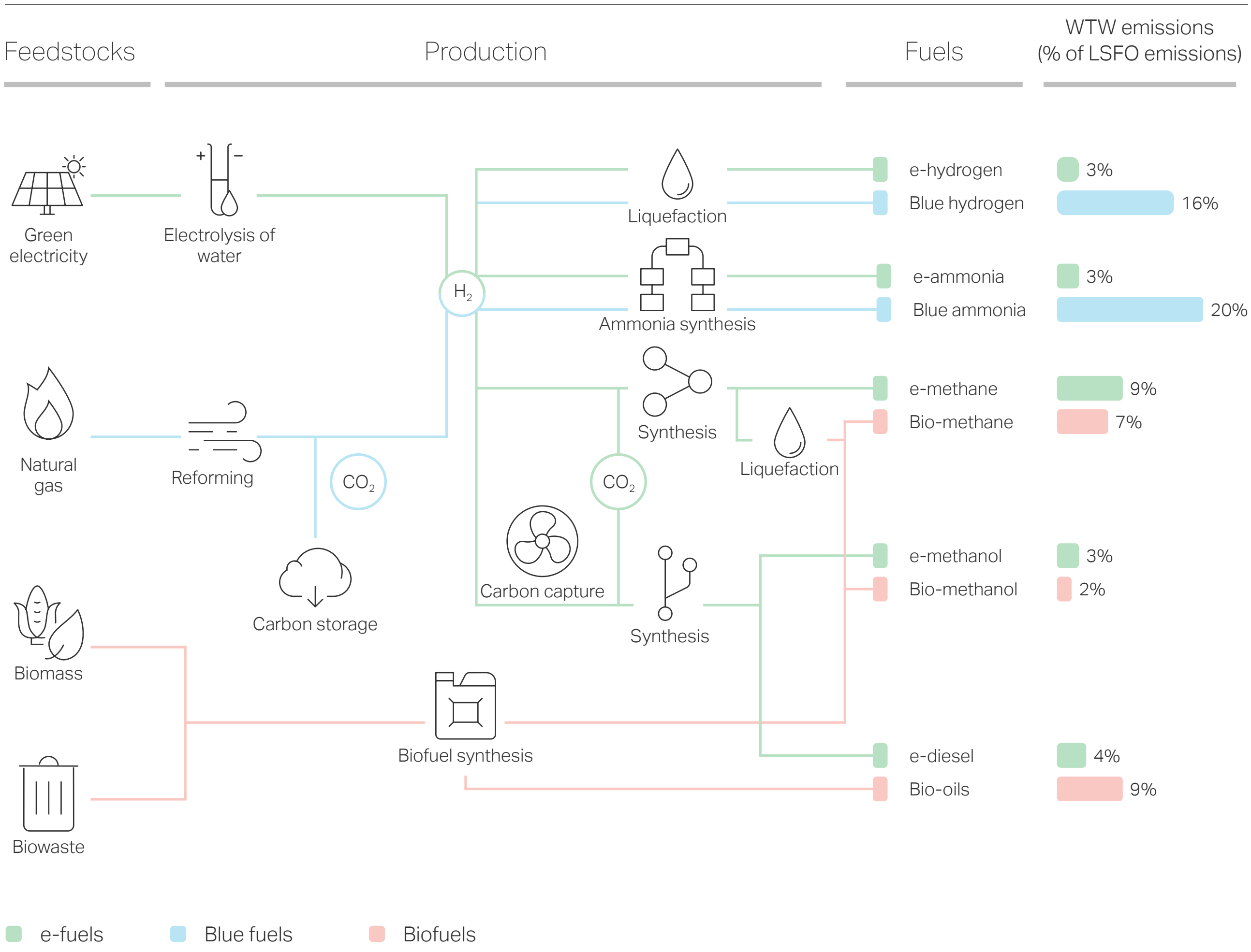


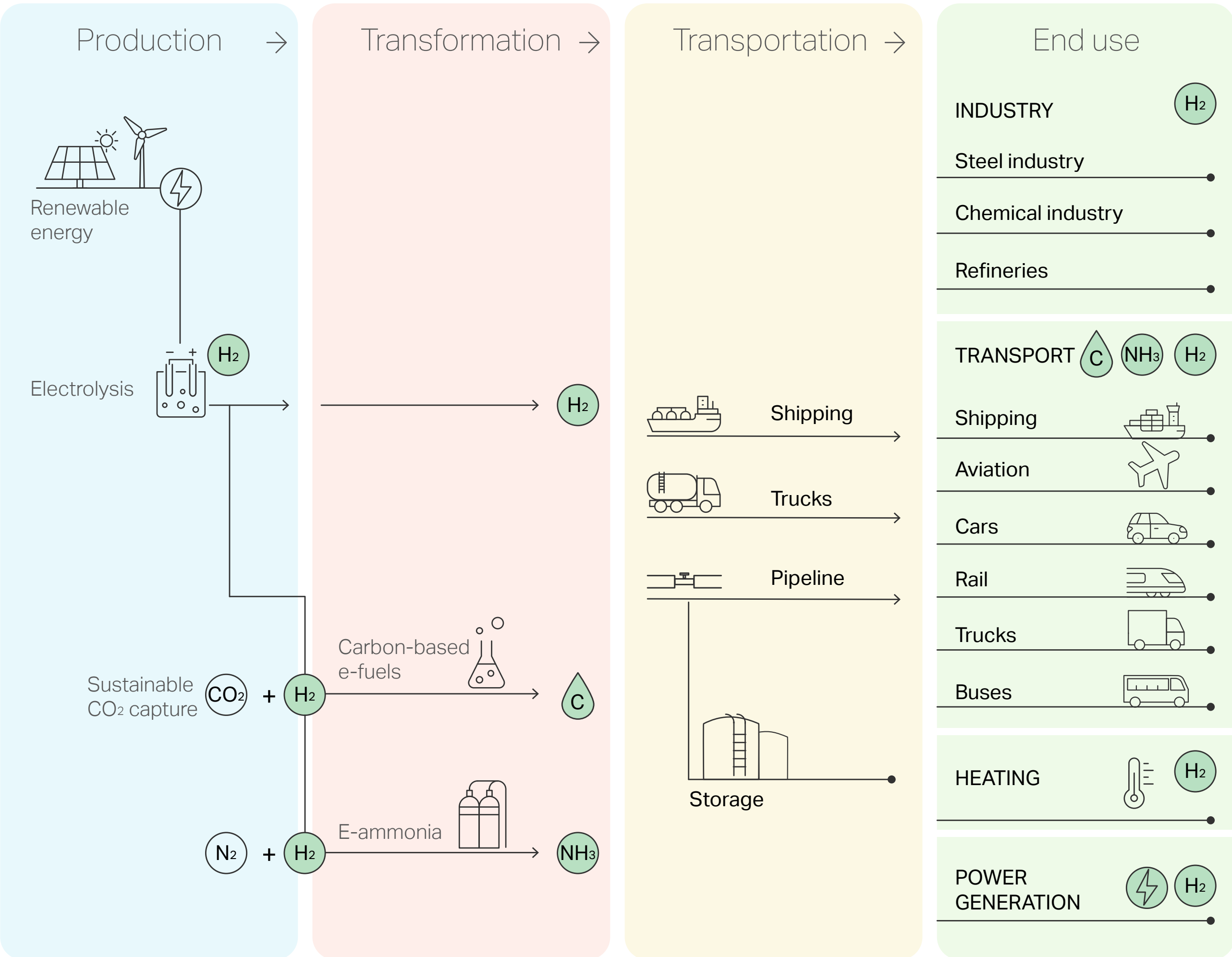
Figure 1: Alternative fuel production pathways in shipping.



In the future, the global upply of renewable electricity will be limited to the global technical potential to produce renewable electricity, i.e., the energy content of all wind and solar resources that can be effectively harvested through the installation of wind parks and photovoltaics. Key factors in the global technical potential include: the energy content of worldwide wind and solar radiation, the efficiency of converting this primary energy into electricity, and the availability of suitable land to harvest energy from wind and solar.

Further refined scopes could be assessed, beyond the technical potential; in particular, the economic potential and market potential would describe supplies that are cost competitive and that satisfy demand. These additional constraints were not evaluated in the present work. As part of an analysis of future hydrogen prices, the International Renewable Energy Agency (IRENA) mapped the technical potential wind and solar capacity around the globe. It found the resulting global technical potential of hydrogen to be more than ten times larger than the projected global total energy demand in 2050.[6]

Figure 2: Examples of industries likely to use e-hydrogen or e-fuels to decarbonize.[3]



Although there is enough technical potential for wind and solar to meet renewable electricity demand in the long term, it is still unclear whether industries will be able to scale up capacity quickly enough to meet global demands in the short and medium term. Meeting global demand in 2050 would require increasing annual wind installations by over three times, in scenarios with reasonable compounded annual growth, from about 100 GW/year today to over 340 GW/year between now and 2050. Similarly, new annual solar installations would need to increase by four times, from 150 GW/year today to over 600 GW/year between now and 2050.

Meeting the targets for renewable electricity between now and 2050 will require enormous action and a massive scale-up of capacity. Furthermore, it will depend on supportive policies and regulations, material availability, and sufficient labor across the supply chain. Currently, it is unclear whether the supply will be able to overcome certain constraints in the short term, which could make alternative decarbonization scenarios more probable.

If humanity cannot install enough renewable electricity to meet the demand globally, commercial electricity prices and, in turn, e-fuel costs, would likely rise. Abatement costs in the shipping sector are high,[7] so it will likely be among the last-to-pay for e-fuels. This may mean that if renewable electricity is scarce, e-fuels will become too expensive to rely on for decarbonizing the shipping industry. As a result, if the renewable electricity supply is limited, the maritime sector may need to utilize other alternative fuels which do not rely on renewable electricity, such as biofuels or blue fuels, in the early years of the transition.

To attempt to answer the question 'Will renewable electricity scale-up limit e-fuel availability to the maritime industry?', we analyzed publicly available information, partner data, and interviews with industry experts, including energy companies, technology providers, regulators, and finance companies. During the project, we investigated the availability of materials, components, labor, capacity, and regulatory factors relevant to increasing solar and wind capacity, which could limit scale-up and short-term supply, and compared them to demand based on an International Energy Agency (IEA) net zero by 2050 (NZE) 1.5°C scenario in 2030 and beyond.

The project was a collaboration between the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) and our strategic partners: Sumitomo Corporation, TotalEnergies, BP, Mitsubishi Heavy Industries (MHI), and Siemens Energy. MMMCZCS knowledge partner The Boston Consulting Group and IRENA also contributed to the project. This position paper summarizes the results of the project research. Based on the current outlook, we also provide recommendations for shipowners building strategies to decarbonize with e-fuels and regulators planning to accelerate maritime decarbonization.

Our project partners

bp

BCG BOSTON CONSULTING GROUP

TotalEnergies

IRENA International Renewable Energy Agency

MITSUBISHI HEAVY INDUSTRIES, LTD.

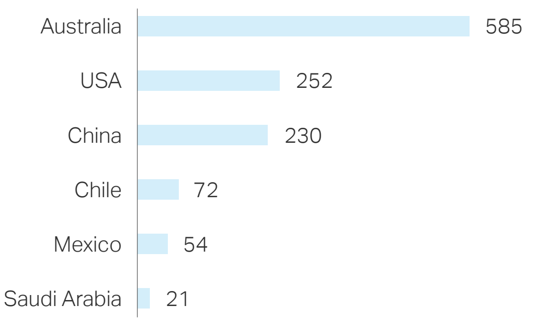
SIEMENS energy

Sumitomo Corporation

# 2. Will regulation and political barriers limit scale-up?

Ramping up renewable electricity supplies will demand political willingness and regulatory support. We analyzed the regulatory frameworks and challenges in six countries with high technical potentials for wind and solar installations[6] and renewable electricity costs in the lowest 20% globally:[8] Australia, the United States of America (USA), China, Chile, Mexico, and Saudi Arabia (Figure 3). Any of these countries alone could supply the renewable electricity needed for e-fuels by the maritime industry. For each country, we examined factors including: political backing for renewables, long-term climate targets, financial incentives, the availability of grid connection, permitting processes, and environmental activism issues that could affect renewable electricity installations.

Figure 3: Technical potential of (EJ/year) Australia, USA, China, Chile, Mexico, and Saudi Arabia in 2050.[6]




We found that most of the selected countries are increasingly supportive of renewable energy. One exception is Mexico, where the currently elected regime imposes ongoing resistance to the approval of renewable projects, instead continuing to prioritize fossil fuels. Several of the counties we analyzed are now aiming to increase their renewable electricity capacities, with some seeking to export additional electricity. For example, the USA has recently introduced incentives such as the Inflation Reduction Act, which provides an estimated $386 billion in financing for green initiatives, including renewable electricity, via tax credits.[9,10] In Australia, the new government is set to reverse previous anti-renewable policies, making building renewable electricity capacity more attractive in the coming years. As a result, some states are targeting more than 100% green power, and intending to export their surplus.[11] China and Chile are also investing heavily in renewable energy, with China aiming for full decarbonization by 2060[12] and Chile developing an ambitious green hydrogen strategy with the expectation of exporting surplus supplies.[13, 14, 15, 16]

However, each county we analyzed also has challenges in scaling up capacity. For example, in the USA, climate leadership in the country depends heavily on which political party is in power, which could change over the coming decades, thus impacting the continued availability of funding for renewable electricity between now and 2050. In Saudi Arabia, project approval depends on good relations with government sponsors, and land is typically tendered via the government. Furthermore, all six countries have issues with grid connectivity.

Historically, obtaining permits to build capacity has been time-consuming. If permitting processes continue to be slow and cumbersome, this could limit how fast a country can increase capacity. The results of our analysis of the current permitting and construction times for each country are summarized in Figure 4. Total times for permitting, pre-construction, and construction vary from 2.6 years in the USA to over five years for Australia, Mexico, and Saudi Arabia. We could not obtain complete comparative data for permitting and construction times for solar installations for all six countries. Data analysis from the Boston Consulting Group estimates similar timelines to wind installations, with 1-3 years for permitting, between 9 months and 2 years for pre-construction, and 6-12 months for construction in most countries, resulting in a total timeline of 2.3-6 years.

Overall, we do not expect political or regulatory factors to be major barriers to renewable electricity scale-up. Although the situation in each country is unique, governments are increasingly becoming more in favor of renewables. Furthermore, permitting times are generally adequate. However, e-fuel producers should carefully analyze their chosen country's political and regulatory situation before embarking on renewable electricity projects.

Figure 4: Permitting, pre-construction, and construction times for onshore and offshore wind in Australia, the USA, China, Chile, Mexico, and Saudi Arabia.

## Onshore wind

| | Permitting | Pre-construction | Construction | Total |
|---|---|---|---|---|
| Australia | 2 years | 1.2 years | 2.3 years | 5.5 years |
| USA | 7 months | 6 months | 1.5 years | 2.6 years |
| China | 2 years | 2.1 years | 1.5 years | 5.6 years |
| Chile | 5 months | 1.6 years | 1.7 years | 3.7 years |
| Mexico | 1.8 years | 1.2 years | 2.5 years | 5.5 years |
| Saudi Arabia | 1.5 years | 6 months | 3 years | 5 years |

## Offshore wind

| | Permitting | Pre-construction | Construction | Total |
|---|---|---|---|---|
| USA | 3.6 years | 1 year | 2 years | 6.6 years |
| China | 2 years | 2.9 years | 2 years | 6.9 years |

# 3. Will material availability constrain scale-up?

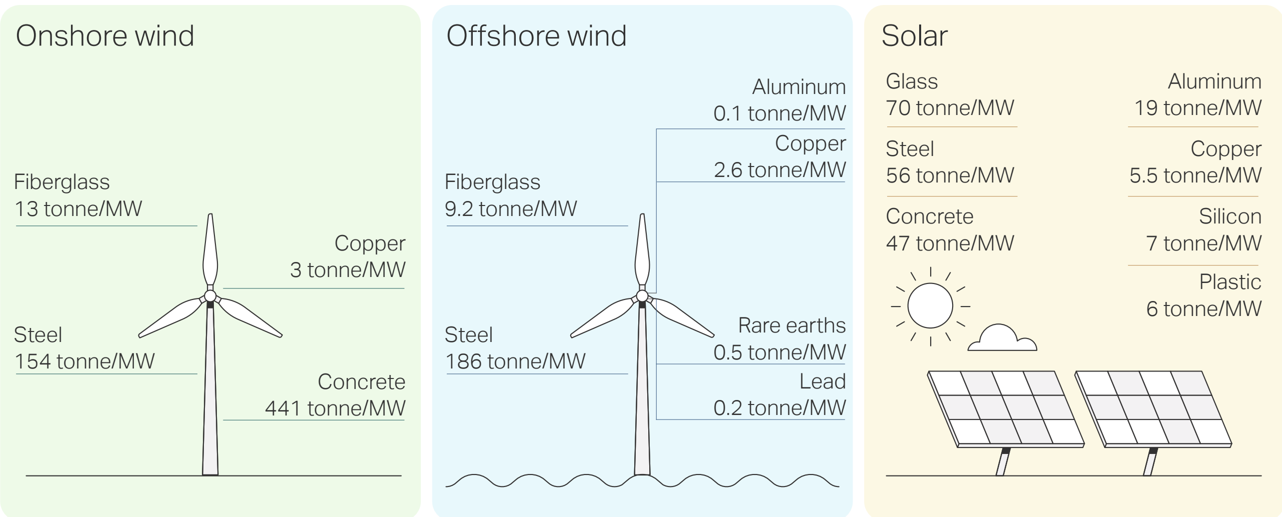
Wind and solar installations require a range of raw materials, as shown in Figure 5[17]. to determine whether raw material availability may limit renewable electricity scale-up, for each material we investigated: current production levels, future demand and supply forecasts, and estimated demand from the renewable electricity sector between now and 2050.

For cement, steel, aluminum, lead, fiberglass, plastics, and polycrystalline silicon, we expect current or future production levels to be able to meet the demand from the renewable electricity industry.[17,18,19] For example, in 2030, renewable electricity installations will require just 5% of the total steel production in 2019 of 1,900 million tonnes.[20] As a result, we concluded that the supply chains for wind and solar are unlikely to suffer fundamental long-term shortages of cement, steel, aluminum, lead, fiberglass, plastics, or polycrystalline silicon. However, some periods of high demand for key materials may result in near-term high prices and construction delays.

While many of the materials for solar and wind installations will be readily available, some key materials may be limited. Analysis from project partners suggests that there may be an insurmountable shortage of copper, a key component for solar and wind, in the 2030s (see Section 3.1 for more detail). Nickel is also a concern because of the demand from electric vehicles, which may limit the availability of electrolyzers needed for grid load balancing as well as e-fuels production (see Section 3.2 for more detail). Silver, used in contacting in solar photovoltaics, is also a supply concern.[19] Furthermore, we expect offshore wind installations will be limited by rare earth supply (see Section 4.1).

The impacts of materials shortages could be counteracted or overcome by using alternative materials or increasing recycling. For example, increasing the circularity of solar supply chains would have a long-term beneficial impact on the availability of raw materials. However, policies mandating increased use of recycled components (e.g., copper, silicon, silver) could lead to costlier materials in the near term before supply chains adapt.

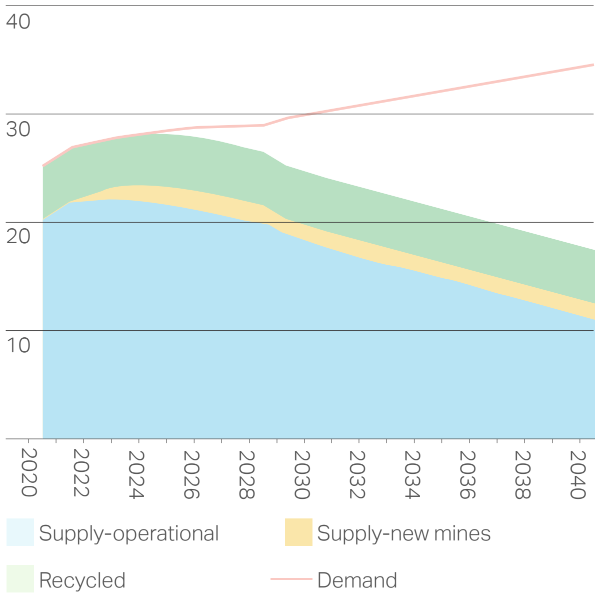
Figure 5: Raw materials used in onshore wind, offshore wind, and solar installations.[17]



## 3.1 Copper supply may limit capacity in the 2030s

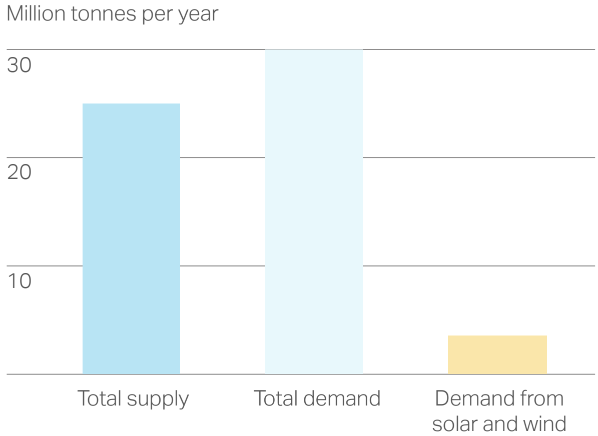
Copper is used extensively in technologies that are key to the energy transition, including energy generation, electric vehicles, electrolyzers, networks, and heat pumps. It is also a key material in wind and solar installations (see Figure 5). Currently, 20 million tonnes of copper are produced annually,[21] with around 5 million harvested from recycled copper. Clean energy technologies already use over 20% of the world's annual copper production, and demand is set to increase with electrification and decarbonization (Figure 6).[22]

Figure 6: Demand and supply of copper between 2020 and 2040.[17,22]




As shown in Figure 5, wind and solar installations require 2-5.5 tonnes of copper per installed megawatt capacity. In 2030, if we follow an IEA 1.5°C scenario, this translates to a demand for copper of around 1 million tonnes per year for wind installations and 2.5 million tonnes for solar (Figure 7).[17] While there are ample reserves to meet the long-term demand for copper from all industries,[23,24,25] the current mining capacity is not enough, and it may take up to a decade to build enough capacity. This will likely result in higher copper prices and some end users being forced to use different materials.

Figure 7: Expected supply of copper in 2030 following an IEA 1.5-degree scenario compared with total global demand and demand from solar and wind.[17]



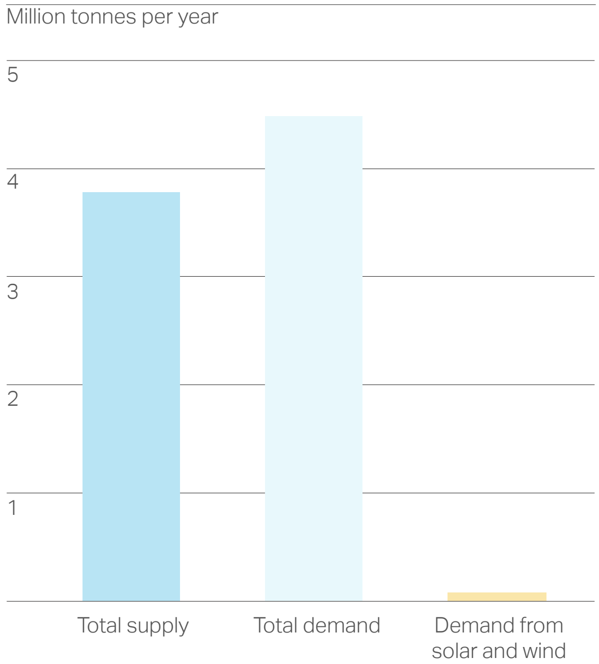

The effects of the copper shortage in the 2030s could be counteracted by mitigations such as replacing copper with other materials, for example using aluminum instead of copper for onshore underground cables, increasing recycling rates from the current rate of 40%,[22] or utilizing mine tailings or mines under maintenance to ramp up supply quickly.

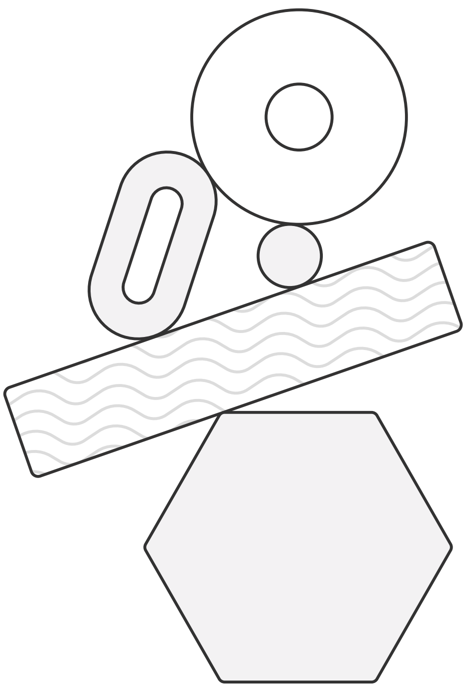
## 3.2 Supply of nickel for electrolyzers

While not directly supplying electricity, electrolyzers will be essential to load-balancing variable renewable energy generation via hydrogen storage. The current global electrolysis capacity stands at around 1.5 GW of installed capacity.[26] An IEA analysis suggests that this could reach 145 GW by 2030.[27] Although encouraging, this growth rate still falls far short of IEA 1.5°C scenario requirements of 850 GW of installed electrolysis capacity by 2030 and 3.600 GW by 2050. The potential shortage of electrolysis capacity has already been highlighted, and the EU has set a target to reach 40 GW of capacity by 2030.[28] It is currently unclear whether the global capacity for electrolyzer production can reach the required scale to support a 1.5°C scenario in 2030. We will examine the role of electrolyzer supply in decarbonization of the shipping industry in a follow-up study.

Nickel is used in all major electrolyzer technologies and is also in demand from the battery sector. Current nickel supply is around 2 million tonnes per year, with clean energy technologies accounting for about 10% of supplies.[22] Nickel demand is expected to grow to nearly 4.5 million tonnes in 2030, and an IEA analysis estimates nickel demand for hydrogen production to be 7,360 tonnes per year by 2030 (Figure 8).[22] However, an investigation by MHI based on announcements from manufacturers of alkaline electrolyzers suggests that nickel demand from electrolyzers could reach approximately 70 kilotonnes if nickel can't be substituted with other materials, intensifying the shortage of nickel and potentially impacting renewable electricity supplies.

Figure 8: Expected nickel supply in 2030 following an IEA 1.5-degree scenario compared with total global demand and demand from electrolyzers.[17]



# 4. Are there any other supply chain constraints?

To determine if there are any other constraints on renewable electricity scale-up, we looked across the wider supply chain. We identified offshore wind supply constraints (installation vessels and rare earths), transmission component supplies, and labor as potential limitations. The following sections outline these constraints in more detail.

## 4.1 Offshore wind supply constraints

Offshore wind capacity may ultimately represent only about 10% of future onshore wind power capacity; and it is not expected as a major source of renewable electricity for e-fuel production. However, constraints in offshore supply may put more pressure on the total global renewable electricity supply.

### 4.1.1 Installation vessels for offshore wind

Increasing offshore wind capacity relies on purpose-built installation vessels to carry and install wind turbines and their foundations offshore. There are currently 32 active turbine installation vessels and 14 foundation installation vessels. There are also a further five turbine installation vessels and five foundation installation vessels already on order. In recent years, there has been an oversupply of installation vessels. However, a recent analysis by Rystad Energy[29] suggests that increasing wind installations may mean demand will outstrip supply by 2025. By 2030, they expect demand to reach 79 vessel years.

Wind turbines are expected to increase in size in the coming years as the next generation of larger wind turbines, such as GE's Haliade-X, become commercially available. By 2030, Rystad Energy expects that most installations will be for turbines that are 9+ MW. Currently, there are only four installation vessels capable of handling such large turbines, so there may be a shortfall in installation vessels for large turbines. Although the maritime industry is not expected to utilize offshore wind for e-fuel production, this shortage of installation vessels may put more pressure on the global renewable electricity supply.

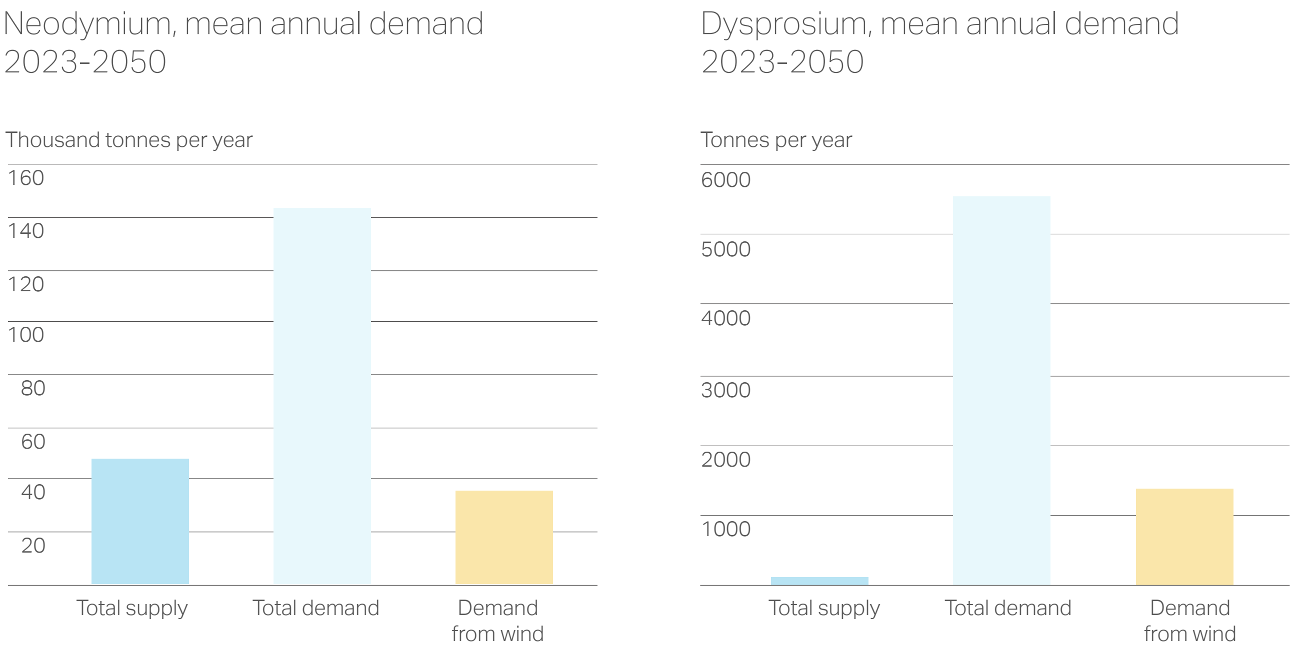
Figure 9: Offshore wind installation vessel. Image reproduced with permission from Van Oord.

### 4.1.2 Rare earth supply may limit offshore wind installations in the 2030s

Neodymium and dysprosium are integral to manufacturing permanent magnets used in direct-drive rotors for offshore wind. If renewables must eventually service 80% of global power needs, then more than 2,000 GW of offshore wind power capacity will need to be deployed by 2050; this, in turn, could require around 1 million tonnes of neodymium and 40,000 tonnes of dysprosium cumulatively by 2050 (Figure 10).[17] Global annual production rates are estimated to be 24,000-48,000 tonnes neodymium/year and just 100 tonnes dysprosium/year. Like copper, long-term resources can easily meet demand. However, the current production capacity is insufficient, and wind must compete with other sectors, including electric vehicles, to access the available resources. As a result, we expect rare earths to be limited in the 2030s. Furthermore, 70-80% of the world's rare earth mining and processing capacity is in China,[22] meaning that adverse relations between the West and China could exacerbate future supply constraints.

Rare earth constraints on wind installations could be overcome by switching to geared rotors, which do not require rare earths. However, this would increase operating and maintenance costs and, therefore, the levelized cost of energy.[22]

Figure 10: Present annual supply of neodymium (left) and dysprosium (right), compared to annualized demand for these minerals towards 2050, following an IEA 1.5-degree scenario.[17]

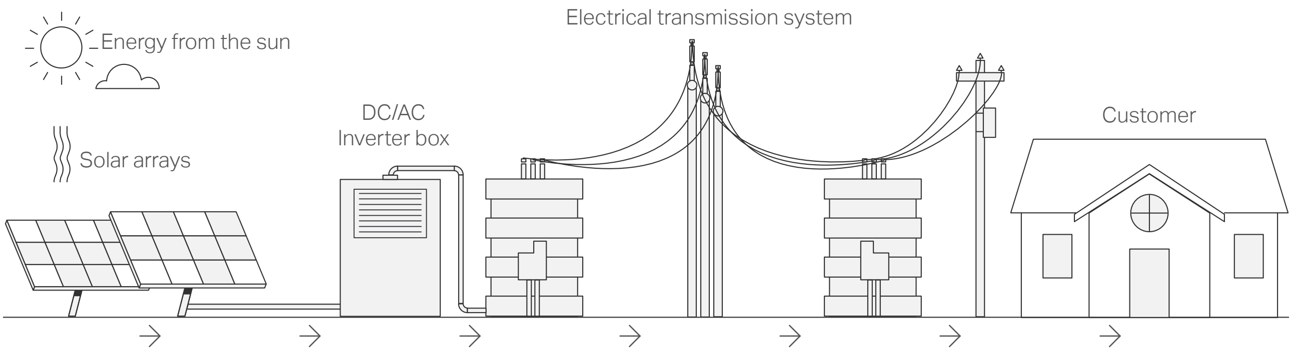


## 4.2 Supply of transmission components

Increasing wind and solar capacity also demands sufficient infrastructure for transmitting electricity to the grid and consumers (Figure 11). The IEA estimates that grid expansion must more than double, with a 50% increase in transmission lines and a 35% increase in distribution network lines to account for the increase in renewable electricity capacity in 2040.[22] This will demand significant investments in the production and installation of transmission components, including power lines and electrical transmission hardware. Current manufacturing capacity is lagging in factories worldwide as there is already a shortage of electrical components needed for transmission, including transformers, inverters, switchgears, and converters.[18]

Increasing manufacturing capacity for transmission components will be imperative to meeting demand. However, this is expected to take years as the sector relies on skilled workers. There are already jobs left unfilled across the sector, limiting the ability to increase manufacturing capacity. If manufacturing capacity cannot be increased, and there are not enough transmission components to meet demand over the coming decades, or the components are too expensive, this could slow the growth of renewable electricity. Although the maritime industry is not expected to rely as heavily on transmission components compared to the power generation sector – since we expect most e-fuel production will be integrated at solar or wind farm sites – this shortage may put more pressure on the global renewable electricity supply.

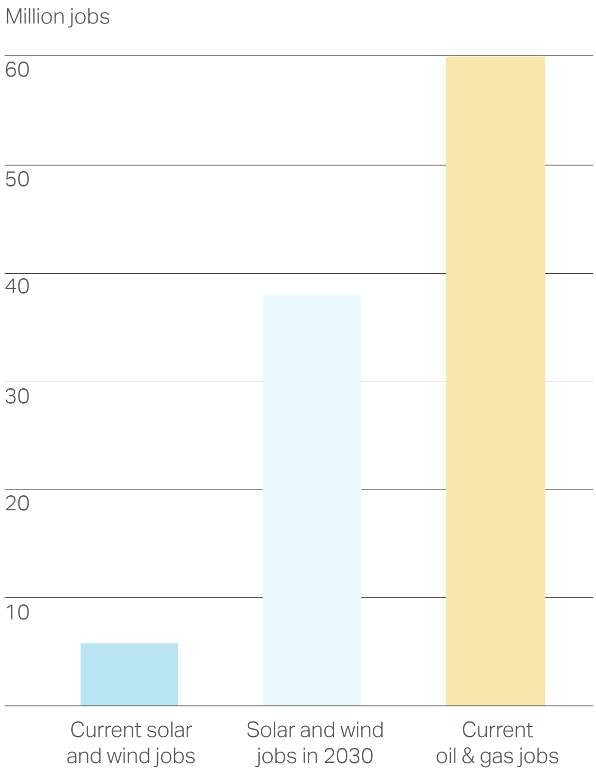
Figure 11: Role of transmission components in renewable electricity supplies.

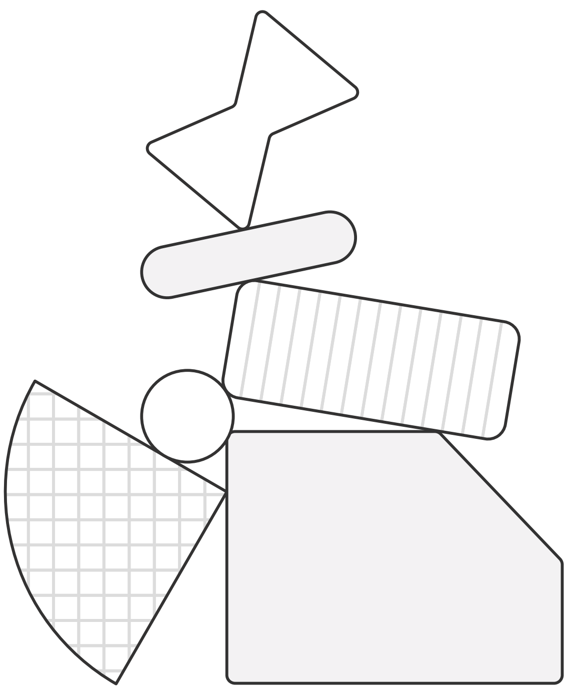


## 4.3 Labor constraints

Installing more solar and wind capacity doesn't only require sufficient technical potential and materials. It also demands labor across the entire supply chain, including jobs in building and maintaining wind turbines, solar panels, and transmission lines. IRENA has reported that there are currently 5.7 million jobs in solar and wind, which will increase to over 38 million in 2030 (Figure 12).[30] Currently, there is a shortage of workers with the required skills. It could be possible to meet some of the demand for labor by transferring workers from other sectors, such as oil and gas. Still, these workers will require retraining, creating a lag time that may disrupt renewable electricity supply in the coming decades.

Figure 12: Current jobs in solar and wind, expected jobs in 2030, and current jobs in oil & gas.



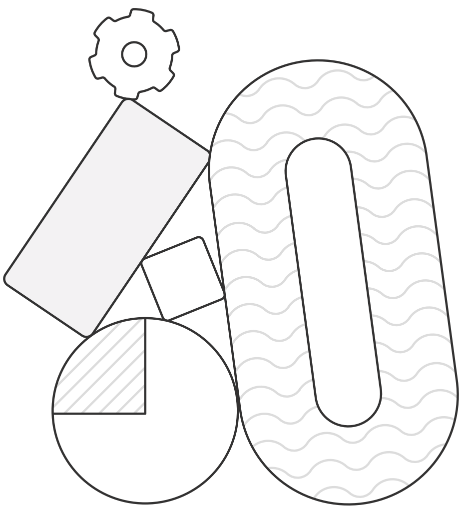
# 5. Overall Outlook and Recommendations

Although the long-term potential for renewable electricity is obviously sufficient, our analysis suggests that constraints in scaling up will limit wind and solar availability for producing e-fuels in the 2030s and possibly into the 2040s. The main likely constraints include the limited availability of key materials such as copper and nickel for electrolyzers. Furthermore, labor shortages may also limit scale-up. Although the maritime industry is unlikely to rely on transmission components or offshore wind to the extent that the power generation sector will, limitations on transmission component manufacturing and installation vessels for offshore wind may also increase the pressure on global renewable electricity supplies and thereby increase prices.

A shortage of renewable electricity in the 2030s and 2040s will leave many sectors competing for supplies, increasing renewable electricity prices. While we cannot predict how cross-sector demand will impact supplies of renewable electricity to the maritime industry, the cost-per-$CO_2$ abated is higher for maritime than other sectors, suggesting the maritime industry may be unable to compete for supplies.[7] As a result, renewable electricity supplies may be insufficient to meet the demand from the maritime industry.

There are several options for increasing renewable electricity availability to the maritime industry. Future legislation could promote decarbonization in the maritime industry, allowing decarbonization business models to evolve more quickly than other sectors. The maritime industry could also increase access to renewable electricity using first-mover contracts to secure supply ahead of other sectors. Finally, if cross-border transport of energy shifts to e-fuels instead of fossil-based, and if long-distance electric transmission is slowed by policy and equipment supply, this could increase e-fuel availability to the industry.

Due to the risks posed by limitations on renewable electricity, shipowners should be wary of relying solely on e-fuels for decarbonization. During the transition period, the maritime sector will likely need propulsion power from alternative low-emissions sources, such as blue fuels, nuclear power, or biofuels to bridge the time until renewable electricity availability increases. Batteries represent another supplementary option because, although they are currently expensive and also reliant on renewable electricity, they retain and utilize more of the primary energy, thus minimizing the amount of renewable electricity required. Shipowners should consider these options in their decarbonization strategies. Regulatory bodies should also recognize the potential shortfalls of relying solely on renewable electricity and e-fuels, and ensure that policy and legislation supports a smooth transition by permitting transition fuels in the coming decades. Furthermore, potential producers of e-fuel should assess the full investment landscape, including supply chain risks, as demand for renewable electricity increases.



# 6. Project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners.

Project lead and corresponding author:
Brandon McKenna (MMMCZCS)

Contributing authors and project participants:
Torben Nørgaard (MMMCZCS), Christian Føhrby (MMMCZCS), Joe Bettles (MMMCZCS), Valerick Cassagne (TotalEnergies), David Bowers (BP), Oliver Hirschfelder (Siemens Energy), Alexander Rentschler (Siemens Energy), Kei Kato (Sumitomo), Philp Joerg (Sumitomo), Shimada Motoo (Sumitomo), Florian Moellenbruck (MHI), Jannis Deitert (MHI), Lars Holm (Boston Consulting Group), Rajat Walia (Boston Consulting Group), Peter Jameson (Boston Consulting Group), Carlos Ruiz (IRENA), and Herib Blanco (IRENA).

Report preparation:
Emily Nordvang (MMMCZCS)

Design:
Karoline Anderson (MMMCZCS)

# 7. References


1 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Maritime Decarbonization Strategy 2022. (2022).

2 IEA. World Energy Outlook 2021 – Dataset. Preprint at (2021).

3 IRENA. Geopolitics of the Energy Transformation: The Hydrogen Factor. (2022).

4 IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. (2022).

5 IHS. IHS Markit Global Energy Scenarios data set – Energy outlook to 2050. (2021).

6 IRENA. Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Trade Outlook for 2050 and Way Forward. (2022).

7 Goldman Sachs. Carbonomics: Affordability, Security and Innovation. (2022).

8 Internal intelligence from IRENA.

9 Committee for a Responsible Federal Budget. What's In the Inflation Reduction Act? https://www.crfb.org/blogs/whats-inflation-reduction-act.

10 U.S. Government Publishing Office. 117th Congress Public Law 169. Preprint at https://www.govinfo.gov/content/pkg/PLAW-117publ169/html/PLAW-117publ169.htm (2022).

11 Govlaunch. Australian cities make the shift to 100% green energy. https://govlaunch.com/stories/australian-cities-make-the-shift-to-100-green-energy (2022).

12 UN News. China headed towards carbon neutrality by 2060; President Xi Jinping vows to halt new coal plants abroad. https://news.un.org/en/story/2021/09/1100642 (2021).

13 Port of Rotterdam. Ministry of Energy in Chile and Port of Rotterdam Authority sign MOU on green hydrogen. https://www.portofrotterdam.com/en/news-and-press-releases/ministry-energy-chile-and-port-rotterdam-authority-sign-mou-green-hydrogen (2021).

14 The Korea Herald. S. Korea, Chile sign MOU on hydrogen energy cooperation. https://www.koreaherald.com/view.php?ud=20211109000136 (2021).

15 Port of Antwerp. Port of Antwerp, Port of Zeebrugge and Chile join forces to foster hydrogen production. https://newsroom.portofantwerpbruges.com/port-of-antwerp-port-of-zeebrugge-and-chile-join-forces-to-foster-hydrogen-production (2021).

16 Ministry of Foreign Affairs, C. G. Chile signs agreement with Germany's largest port for green hydrogen exports. https://www.minrel.gob.cl/news/chile-signs-agreement-with-germany-s-largest-port-for-green-hydrogen (2022).

17 Internal intelligence from BP.

18 Internal intelligence from Siemens Energy.

19 Internal intelligence from TotalEnergies.

20 World Steel Association. World Steel in Figures 2022. (2022).

21 IEA. Committed mine production and primary demand for copper, 2020-2030. https://www.iea.org/data-and-statistics/charts/committed-mine-production-and-primary-demand-for-copper-2020-2030.

22 IEA. World Energy Outlook Special Report: The Role of Critical Minerals in Clean Energy Transitions. https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf (2021).

23 USGS. Estimate of Undiscovered Copper Resources of the World. https://pubs.usgs.gov/fs/2014/3004/pdf/fs2014-3004.pdf (2013).

24 International Copper Study Group. Long Term Availability of Copper. https://icsg.org/long-term-availability-of-copper/ (2022).

25 U.S. Geological Survey, Mineral Commodity Summaries. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-copper.pdf (2022)

26 IEA. Technology Deep Dive: Electrolysers. (2022).

27 IEA. Global Hydrogen Review 2021. (2021).

28 European Commission. Powering a climate-neutral economy: Commission sets out plans for the energy system of the zuture and clean hydrogen. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1259 (2020).

29 North American Wind Power. Rystad Energy: Fleet of Offshore Installation Vessels Will Be Outpaced by Demand. https://nawindpower.com/rystad-energy-global-fleet-of-offshore-installation-vessels-outpaced-by-demand (2020).

30 IRENA. Renewable Energy and Jobs – Annual Review 2022. https://www.irena.org/publications/2022/Sep/Renewable-Energy-and-Jobs-Annual-Review-2022 (2022).

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