Shipping's Role in the Global Energy Transition

A report commissioned by the International Chamber of Shipping, written by researchers at the Tyndall Centre for Climate Change Research at the University of Manchester

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Email: info@ics-shipping.org

Web: www.ics-shipping.org

EXECUTIVE SUMMARY

This executive summary sets out the scale of the global energy transition needed to meet the Paris Climate Agreement goals, the implications for the shipping sector, and actions which could be taken by national energy ministries and by the shipping sector to help deliver this transition.

Scale of the global energy transition

It is imperative that nations keep global heating below 1.5˚C – in line with the Paris Climate Agreement. Even at 1˚C of warming, climate impacts on humanity and nature are already extensive and growing. The risk of passing multiple climate tipping points increases rapidly between 1.5˚ and 2˚C.

To meet the Paris goals, major and unprecedented levels of carbon dioxide emissions reductions are needed this decade, on a pathway to zero emissions around 2050. The timescales are extremely urgent. Delay is not an option.

Meeting this challenge has profound implications for global energy use, and the systems that provide that energy. A suite of energy scenarios that limit temperature rises to 1.5˚C are assessed in this report. Five changes to the energy system by 2050 are consistent across these scenarios:

- Reductions in overall global energy consumption, mainly due to greater energy efficiency;
- Rapid electrification of many sectors of the global economy;
- Rapid decarbonisation of the electricity sector, with large increases in wind and solar replacing coal and gas;
- Rapid reductions in coal, oil and gas use;
- Growth in the use of lower-carbon fuels such as hydrogen and bioenergy.

However, **delivery of these changes is currently way off-track. Far more assertive Government action is urgently required.**

Implications for the shipping sector of meeting the Paris goals

If realised, these energy system changes will have profound implications for shipping, as 36% of the shipping sector's current trade is transporting energy products, primarily oil, coal and gas. In future, shipping will transport different fuels, in different quantities, between different countries, and if the 1.5˚C scenarios become a reality, this transition will start in earnest in a **timeframe as short as months and years.** This presents challenges and opportunities.

Overall, the mix of energy products transport by ship changes, while total **shipping of energy products falls**: growth of transport of new fuels is outweighed by greater falls in shipments of oil and coal. Figure A shows potential shipments of fuels in the 1.5˚C scenarios reviewed here, compared with today.

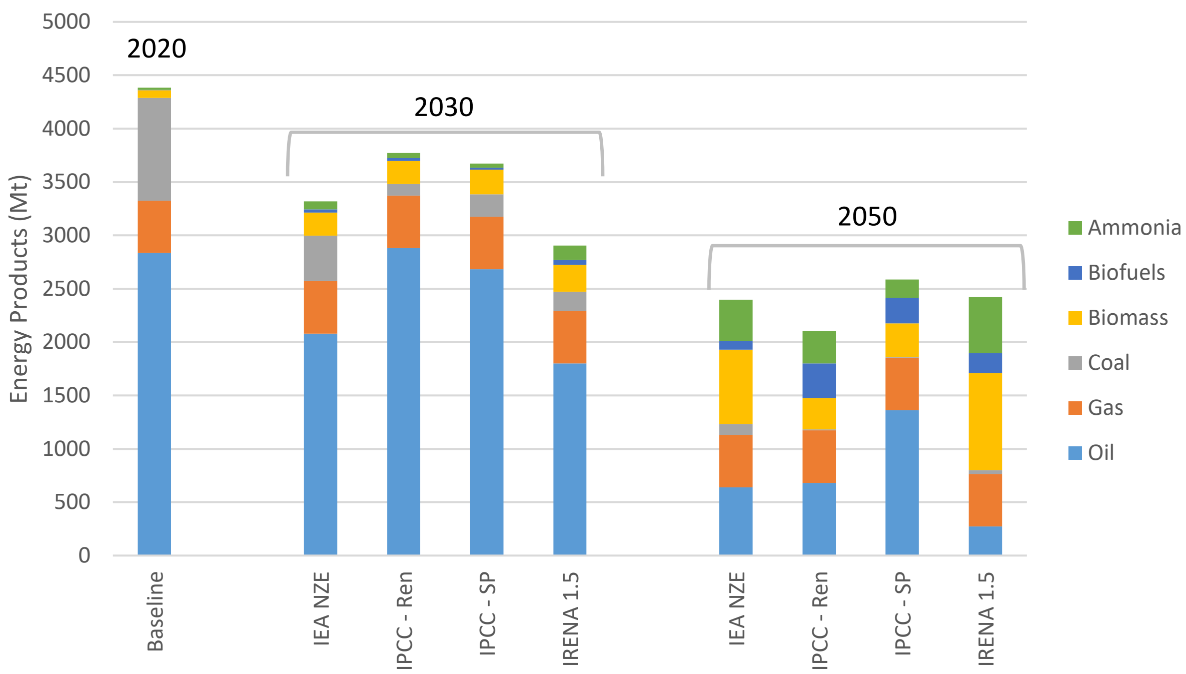

Figure A: Potential seaborne trade outcomes for the 1.5˚C scenarios, assuming higher levels of trade of emergent low-carbon fuels and deployment at scale of carbon capture and storage technologies.

The scenarios show that a 1.5˚C transition reduces the global quantities of coal, oil and gas produced, transported and consumed, and increases the quantities of hydrogen and biomass, with hydrogen transported by ship in the form of ammonia.

To realise these scenarios, the shipping sector needs to prepare for a rapid transition away from transporting coal and oil for energy consumption**. Reductions start this decade**. By 2050 coal shipments fall 90-100%, oil 50-90%. Although natural gas consumption decreases too, a greater proportion of this gas is transported by ship, so the shipping sector would expect a continuing role for shipping natural gas products in the medium-term.

An opportunity is that future bioenergy and ammonia shipments have the potential to be as high as coal and gas shipments today. These increased shipments will not be technically difficult for the sector to deliver, given existing infrastructure and familiarity with cargoes. Nevertheless, such increases still do not offset an overall decline in energy products transported by sea.

Gap between plans and real progress on delivering 1.5 ˚C

Hydrogen-based fuels present a major opportunity for the shipping sector. However, there is a big gap between the planned production of low-carbon hydrogen, and what is required to deliver these 1.5˚C scenarios. The International Energy Agency estimates low-carbon hydrogen production of 24 Mt by 2030 but **1.5˚C scenarios need at least double that figure, see Figure B**. Moreover, the majority of the projects comprising this 24 Mt are still at concept or feasibility stage. Although project announcements are growing very rapidly, projects with final investments decisions are scarce; with project developers unsure of potential markets, and potential consumers unsure of suppliers. Stronger policies are needed now to translate the recent surge of interest in hydrogen into actual projects, and to connect consumers and producers.

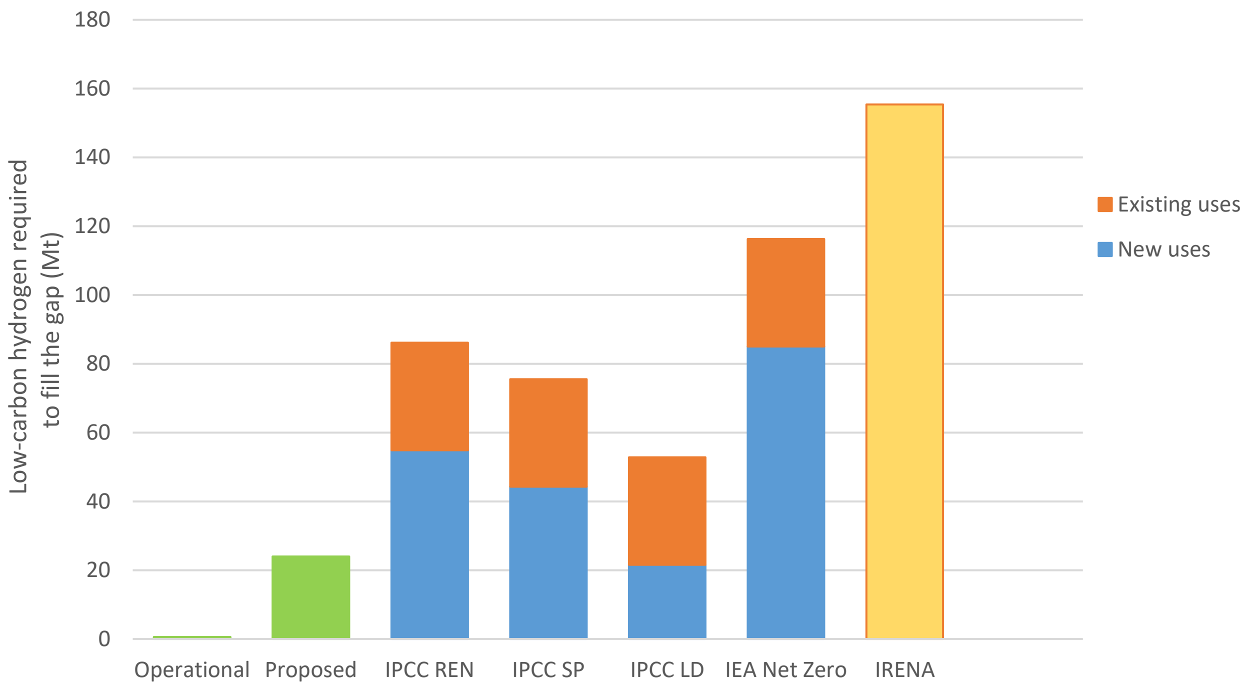

Figure B: the gap between proposed 2030 low-carbon hydrogen (green), and what is needed in 1.5˚C scenarios (blue/red). IRENA values as expressed here merge low-carbon hydrogen for existing and current uses (yellow).

There are two sources of demand for low-carbon hydrogen. First, replacing the highly carbon-intensive current method of "grey" hydrogen production. Second, 1.5˚C scenarios assume a growing need for hydrogen in new uses – for example in industry, shipping, aviation and power generation. This must also be low carbon. Current grey hydrogen tends to be produced very close to where it is used, with low transport needs. However, given that for green hydrogen in particular, producer countries are likely to be distant from consumer markets, transport of green hydrogen will be necessary, either by pipeline or ship. As distances increase, shipping will be preferable.

It is economically more efficient to ship hydrogen as ammonia. There is however a cost penalty at the destination in converting ammonia back to hydrogen. Therefore, the best export markets for green hydrogen producers are likely to be those with direct uses of ammonia, such as in fertiliser manufacture – avoiding the need for reconversion. Five insights that arise from increasing production and shipping of green ammonia are:

- Existing **fertiliser manufacture is the largest potential market** for low-carbon hydrogen to 2030, while new energy uses scale up.

- It is imperative that **existing hydrogen production is decarbonised quickly**, as part of the wider global energy transition; grey hydrogen production is highly carbon-intensive, with CO_2 emissions equivalent to the entire shipping sector.

- Imported green ammonia can **reduce reliance on natural gas**, increasingly important for many countries' strategic goals around energy security.

- Green ammonia is becoming **economically viable -** the recent price hikes for natural gas, and falls in electrolyser, wind and solar costs, mean that in the EU, imported green ammonia can be cheaper than domestic grey ammonia production, around a decade earlier than thought likely just two years ago.

- The shipping sector will need to **increase the number of ammonia-carriers**, accelerating to construction of around 20 large vessels a year in the latter half of the decade. This represents a scale-up of the recent rate of five vessels a year.

Bioenergy use grows in the 1.5˚C scenarios, but needs to be subject to strict requirements on sustainability impacts. It is likely there will be growth in shipments of both biomass and biofuels, although there is great uncertainty about sustainable levels of bioenergy production, and the countries that would see greatest growth.

For bioenergy too there is a gap between planned projects and required ambition. The growth rate for biofuels has been 5% a year in the last decade, however **the growth rate in sustainable biofuels needs to increase to between 7% and 18% per year** to deliver these 1.5˚C scenarios by 2030.

Production scale-up appears stalled by a lack of confidence in sustainable markets for low-carbon hydrogen and second generation bioenergy products. Action from governments and investors is needed if these fuels are to reach the levels required.

Priorities for policy makers

There is a coordination issue potentially holding development of hydrogen in limbo, with hydrogen projects requiring buyers before final investment decisions are made, and sectors planning a move into hydrogen being unsure of supply. These are compounded by major further infrastructure investments often being needed to deliver hydrogen products from producers to consumers. **The priority is therefore to convert the current explosion of interest in hydrogen into actual projects in the coming few years.**

National hydrogen strategies for consumer countries need to have a greater focus on imports if the gap between what's needed in the 1.5˚C scenarios and what is materialising in practice is to close in time. The EU's recent RepowerEU target to import 10Mt green H_2 by 2030 is a positive example, but needs to be backed up with enabling policies. Four examples are:

- The German H_2Global contract-for-difference double-auction proposal is a positive development, providing **guaranteed markets and prices for producers and consumers.**

- **Bilateral contracts between countries could be deployed to a greater extent** – mirroring the accelerated growth of the Australian LNG sector in the 2010s after long-term high-volume contracts were signed with China.
- **Mandates for increasing percentages of green hydrogen should be introduced**, as is being explored by India for its fertiliser and refinery sectors.
- Stronger policy is also necessary in more producer countries - the recent $3/kg H_2 production credit in the Inflation Reduction Act is a positive example **which could deliver exponential growth** in the USA's green hydrogen production.

The short-medium term gap between likely production and 1.5˚C requirements makes it even more imperative that countries **treat low-carbon hydrogen as a valuable resource that is deployed carefully and not used in sectors with cheaper and more efficient alternatives**, for example in surface transport and domestic heating. **Hydrogen strategies should prioritise decarbonising existing hydrogen consumption, and sectors where there are fewer alternatives – such as shipping.**

Because of shipping's international nature, there is a danger that shipping will slip through the net of national strategies, both in terms of investment in infrastructure for importing or exporting hydrogen, and for the shipping sector's own future use of hydrogen. The different pace of growth of new hydrogen demand across sectors has two main implications for shipping.

First, in the short term it is unlikely that the shipping sector provides the much needed demand-side impetus for green hydrogen projects. That role will fall to decarbonising existing hydrogen processes. If this occurs, **there will be a major role for the shipping sector as an enabler of the wider energy transition, in connecting producers and consumers.** There is extensive infrastructure already in place globally for ammonia shipments, and experience in using it. Annual build rates for new ammonia carriers to meet a rising demand for ammonia in 1.5˚C scenarios are high – at around 20 large carriers per year - but this is within the range of what has been achieved in previous years.

Second, because the sector has a slow turn-over of assets, **it will only be in the 2030s and 2040s that the shipping sector becomes a major user of hydrogen products**, including ammonia, to decarbonise its own operations. But steps need to be taken now to ensure infrastructure is developed in time for the rapid scale-up in the 2030s. **New ammonia carriers need to be designed to run on ammonia** to gain synergies in development and deployment of bunkering infrastructure. Overall, at least 5% of the fuel used by the shipping sector needs be low-carbon by 2030, as a platform for more rapid deployment in the 2030s. **In addition, deployment of green hydrogen hubs and corridor initiatives, as well as other measures to connect producers and suppliers** will be required. The work of the ICS' Clean Energy Marine Hubs, the Getting to Zero Coalition's green corridors work, and bunkering initiatives in Singapore and Rotterdam, among others, are recent examples of what will be needed.

Crucially, the success of low-carbon hydrogen and sustainable biofuels is **critically dependent upon robust and enforced mechanisms** to ensure full-lifecycle emissions and other sustainability impacts are fully accounted for, and that genuine sustainability and greenhouse gas (GHG) benefits are realised. This means ensuring bioenergy production does not cause deforestation or conflict with essential uses of land for food, and that for both bioenergy and hydrogen, upstream as well as downstream GHG emissions are measured. Clear accounting methodologies need to be strengthened, integrated and consistent across the whole energy sector.

The shipping sector will be pivotal in facilitating the global energy transition needed to protect humanity and nature from the worsening impacts of climate change. Although it can expect to transport far lower quantities of energy products in a 1.5˚C future, the sector has a crucial role in enabling trade in new low-carbon energy products. **If the shipping sector can energise faster growth in sustainable fuels, it will be playing a pioneering role in closing the gap between grand theoretical plans and a real world fit for future generations.**

1. Introduction

This report provides insights on the implications for the shipping sector of different global energy scenarios for pursuing efforts to limit global temperature rise to 1.5˚C, and the opportunities for shipping to support the global low-carbon transition. Shipping is integral to global trade, transporting ~80% of goods by volume (UNCTAD, 2021). Energy products were ~36% of global seaborne trade in 2021, with around 15% of coal, 17% of natural gas and 64% of oil produced globally moved by ship (Clarksons, 2022a). Interactions between the energy system and the shipping industry are a key determinant of the success of new supply chains for an energy transition compatible with limiting global warming to 1.5˚C.

The report presents an analysis of 1.5˚C energy scenarios alongside a review of existing hydrogen and biomass energy projects and plans, to explore the extent of the gap between what's needed to deliver a 1.5˚C future, and what's happening on the ground. It follows a period of high interest in low-carbon fuels – particularly hydrogen. At least 16 reports on future hydrogen production, demand and transport have been released between January and November 2022. Analysis of the global low-carbon hydrogen project pipeline indicates it is currently insufficient to meet required hydrogen usage scenarios, but announced projects are increasing exponentially. Growing biomass to remove CO_2 from the atmosphere and using biomass products for energy supply both have a prominent role in discussions about the future energy system. The rate at which various forms of bioenergy products can be scaled up and coupled with carbon capture and storage technologies to deliver net CO_2 reductions within the constraints of other sustainable development goals is uncertain and contested (Rose, 2022). Across the 1.5˚C scenarios reviewed in this report, modern bioenergy production ranges from between 45 EJ/yr and 99 EJ/yr by 2030 and from 54 EJ/yr to 153 EJ/yr by 2050, from a baseline of 38 EJ/yr. To keep within sustainability constraints, high bioenergy scenarios by IEA and IRENA also assume a transition to second generation biofuels largely based on wastes, residues and energy crops on marginal land. For both hydrogen and biomass-based fuels, there is a significant gap to close between stated ambition or plans, and in-development projects.

Limiting Global Warming to 1.5˚C

This study is framed by the ongoing energy system transition needed to limit climate change to a 1.5˚C temperature increase above the pre-industrial average. It also once again highlights that progress towards this goal is far too slow. While the analysis of fuels in Section 2 indicates that current trends make limiting warming to 1.5˚C unlikely, it remains the case that delivering the energy transition to minimise the risk of breaching this threshold is a global imperative. Climate change is impacting all sectors of the economy, both in terms of the energy transition to avoid it, and global warming driven impacts such as disruption from extreme weather (IPCC, 2022b).

When considering the barriers to the global energy transition, and the likelihood of its success, it is important at the same to keep in mind the significant threat to society, the environment and the economy if goals to limit climate change are not met. Even today (at ~1.1˚C global warming), the impacts of climate change are endangering life and damaging economies, and these impacts will continue to increase even if temperature rise is limited to 1.5˚C (IPCC, 2022a). If global temperatures are allowed to rise beyond this, climate change pressures will further grow through an increased frequency and intensity of droughts, floods and heatwaves, and even greater damage caused by storms as sea levels continue to rise (IPCC, 2022a). In addition, the risk of passing six climate tipping points, including the collapse of the Greenland and West Antarctic ice sheets, becomes likely in the range of 1.5˚C to 2˚C of global heating (Armstrong McKay et al., 2022).

Estimates of future economic damages are uncertain as scenario models do not fully include climate impact and adaptation costs, but studies do suggest that costs will increase *non-linearly* with global warming levels. For example, under a scenario with high warming (>4˚C) and limited adaptation, anticipated economic losses are expected to exceed those during the 2008-2009 recession and the COVID-19 pandemic in 2020 (Pörtner, 2022). Meanwhile, the Swiss Re Institute estimates global economic value reducing by 18% by 2050 under its 3.2˚C temperature increase scenario (Swiss Re Institute, 2021). Living with climate change is more costly than the transition to avoid it.

The economic impacts of a higher than 1.5˚C temperature rise have important implications for global trade and shipping. As food scarcity is expected in some regions as a result of climate change impacts on agriculture, there could be a potential role for shipping as an element of climate change adaptation through facilitating a shift in trading partners (Zimmermann, 2018). Adams (2021) however highlights that the risks to agricultural production in a warming world far outweigh the benefits. Furthermore, the specific infrastructure for shipping that supports food security is itself vulnerable to climate change impacts. Storm damage to a port is one such example, another is a flooding event or storm that blocks or disrupts a major sea channel – also known as a 'chokepoint'. Chokepoints, such as the Suez Canal, are known to create widespread supply chain disruption if subject to a blockage (King, 2022) – something expected to be more likely to occur as global temperatures rise (Masters, 2021). Moreover climate-related impacts on food security can have additional multiplier effects impacting on security and conflict, which in turn becomes an indirect cost to society and the economy associated with climate change (King, 2022). And while shipping's interconnected nature provides a degree of resilience, it also means that disruption to a port not only causes local impacts, but has global ripple effects across trade-dependent industries including food, energy and assembled products (Becker, 2018).

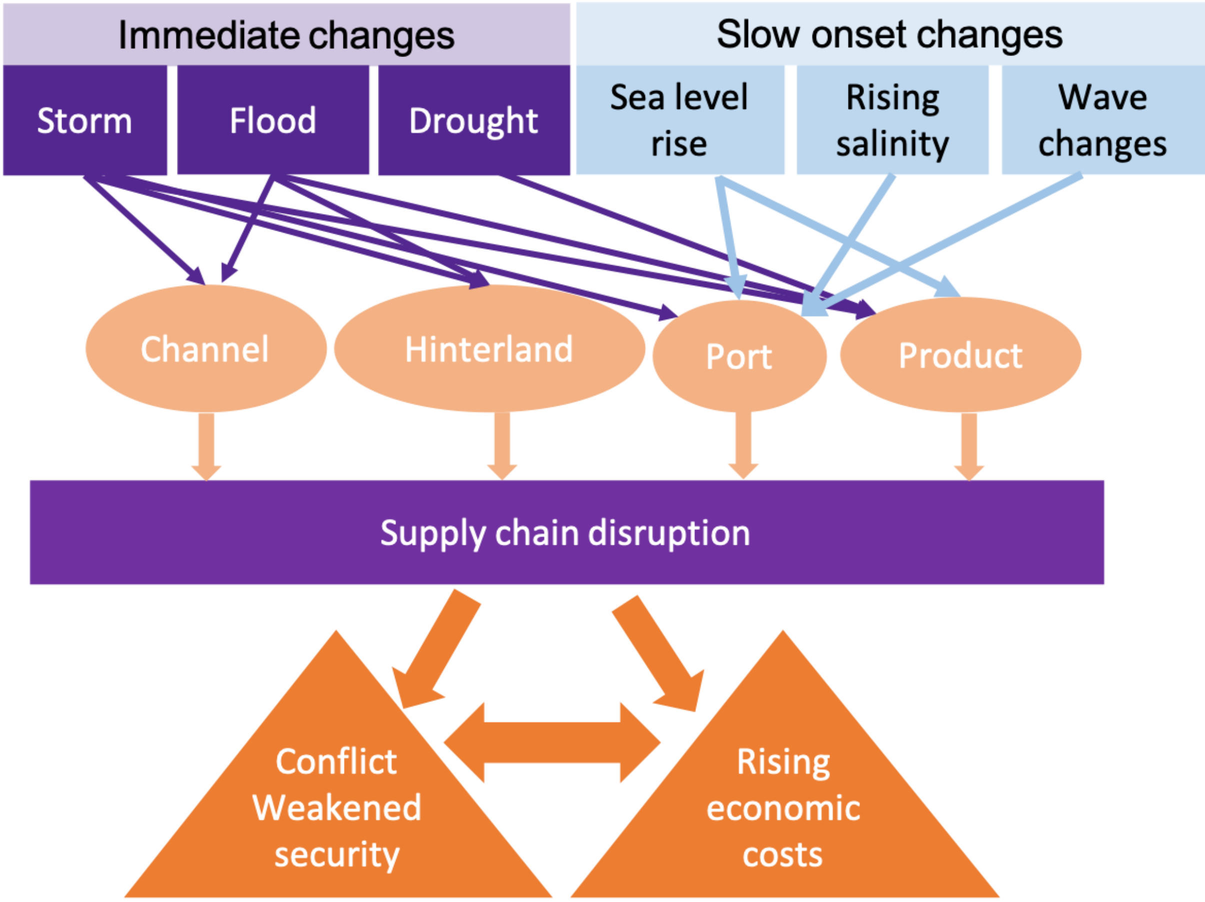

Figure 1: Schematic illustrating the various ways in which climate change will impact on shipping and ports, with anticipated rising costs and damage.

To support the energy transition to meet the 1.5 scenarios, shipping needs to reduce its overall energy fuel demand and transition rapidly to alternative fuels. Furthermore, the 1.5˚C scenarios imply a reduction in energy trade by ship, as in all cases overall global energy demand is lower through significant energy efficiency gains, and coal, gas and oil consumption is reduced. Scenarios exceeding 1.5˚C will also see impacts on trade, and this is aside from the direct climate impacts on the sector itself, which include slow-onset impacts to infrastructure maintenance costs from rising salinity and sea levels. Figure 1 highlights some of the ways in which climate change impacts on shipping and trade, impacts that are set to increase if an energy transition to 1.5˚C is not successful.

Table 1 summarises the implications of different global temperature outcomes for shipping and the wider economy based on IPCC climate impact projections (IPCC, 2022a) and IMO (IMO, 2020) assessments on shipping specific impacts. The key insight is that transition costs (changing demand and fuels) are linked to climate change costs. Pursuing a 1.5˚C limit entails a rapid shift in the energy sector with potentially higher costs than a slower transition, but the costs of climate change impacts are much reduced (Warren, 2022). Conversely avoided transition costs in a >2˚C temperature outcome also correspond to increasingly elevated climate induced risks, with associated adaptation and impact costs.

Table 1: Summary of the implications of different levels of global warming for shipping.

	Shipping's transport of fuels	Shipping sector's use of fuel	Impacts of climate change on shipping sector	Impacts of climate change on global society/economy
1.5°C	Very rapid transition away from transporting coal, coke, oil; slower transition for gas	Overall energy demand reduction plus very rapid transition to ammonia and other fuels	Some increased disruption and damage to coastal infrastructure	Far higher impacts than today, increased risk of passing tipping points
2°C	Rapid transition away from transporting coal and oil, very slow for gas	Demand constant, fast transition to NH_3 and other fuels	Damage and disruption increases, major events more likely	Catastrophic impacts and high risk of passing tipping points
3°C+	Rapid transition away from coal, slow transition away from oil, very slow on gas	Slow transition to other fuels, demand constant or increasing	Major, frequent damage and disruption to infrastructure	High risk to human life in several regions, major ecosystem collapse

An energy scenario focus

Given the imperative of limiting the global temperature rise to 1.5˚C, this study begins with a high-level assessment of future energy systems and changing fuel use within them for widely used scenarios premised on this temperature limit. Scenarios are selected on the basis that they include no or limited 'overshoot' of 1.5˚C, provide a range of future outcomes and supporting data is readily available. They comprise: 1.5˚C scenarios produced by the International Energy Agency (IEA), International Renewable Energy Agency (IRENA) and three distinct 1.5˚C limited overshoot scenarios from the Intergovernmental Panel on Climate Change (IPCC).

The gap between the required outcomes in the 1.5˚C scenarios and the current pipeline of low-carbon fuel technology development and deployment is explored. The potential to close this gap is then examined, with the implications for seaborne trade discussed.

2. Energy Use in Scenarios for Limiting Global Warming to 1.5˚C

This report considers three sets of future energy scenarios framed around meeting climate change and sustainable development goals. The scenarios are chosen for their compatibility with the aim of limiting global warming to 1.5˚C with only a small overshoot (not exceeding a 1.6˚C temperature increase this century) and data availability. Scenarios with significant overshoot of 1.5˚C (i.e. reaching 1.7˚C or above during the century) – for example Shell 'Sky' scenario and IPCC Illustrative

Pathway Negative Emissions focus scenario - are not included. Two scenarios produced in-house by international bodies – the International Energy Agency (IEA) 'Net Zero' scenarios (IEA, 2021c) and the International Renewable Energy Agency (IRENA) '1.5˚C' scenario (IRENA, 2022e) - are used. Three scenarios from a wide range of system modelling communities that have been harmonised and validated for use by the Intergovernmental Panel on Climate Change (IPCC) are also used, with varying assumptions for how the 1.5˚C goal is reached; aggressive energy reduction (as in IPCC Low Demand) (Grubler, 2018); high electrification with renewables (as in IPCC Renewables and IPCC Sustainable Development) (Soergel, 2021, Luderer, 2021).

Comparing across the different scenarios gives a broad understanding of how different mitigation pathways would impact the global energy system. The scenarios however cannot be compared as entirely consistent elements. All of the scenarios across the three sets are differentiated in how they are produced, the underlying assumptions on issues such as technology costs and demand, and what parameters they are working to. Key factors that shape scenarios include:

- The climate change outcome (measured as change in global average temperature above pre-industrial era) and whether the outcome is based on the end of the century value (i.e. potential to 'overshoot' a temperature threshold temporarily) or limiting to a maximum across the whole period.
- Underlying macro trends such as population and GDP.
- Meeting different Sustainable Development Goals (SDGs).
- Changes that ultimately lead to differing final energy consumption – energy efficiency, economic growth and energy access.
- Assumptions on technology costs, learning curves, access and cost of capital, future energy and commodity prices.
- Resource constraints such as land and water availability.
- Preferences for emergent technologies and expectations on how/if they are deployed – hydrogen fuels, carbon capture and storage (CCS).[1]
- The role of carbon dioxide removal (CDR) technologies in the future.

[1] Carbon Capture, Utilisation and Storage (CCUS) has a slightly different role in energy scenarios if featured

*Table 2: Key Features of Scenarios. *Temperature increase above pre-industrial average is the median value based on MAGICCv7.5.3 for IEA and IPCC scenarios, unclear what is used for IRENA emissions to temperature determination. Highlighted rows show 1.5˚C based targets. ** IRENA 1.5 based on emissions pathway 2020 to 2050.*

	PEAK TEMP (˚C)*	2100 TEMP (˚C)*	CUMULATIVE NET CO_2 (2020-2100, $GtCO_2$)	FINAL ENERGY CONSUMED 2050 (EJ)
IPCC - NDC MOD. ACT	2.7	2.7	2,963	552
IEA NET ZERO	1.5	1.4	500	344
IPCC - RENEWABLES	1.6	1.4	440	369
IPCC - SUS. DEVELOPMENT	1.6	1.2	564	355
IPCC - LOW DEMAND	1.6	1.3	227	243
IRENA 1.5	1.5	1.5	**496	348

Table 2 summarises key features of all the scenarios considered in this review. The IPCC scenario projecting forward CO_2 emissions based on national policies as of 2021 - Nationally Determined Contributions (NDCs) - is used for reference: note that this is not a 1.5˚C scenario. As can be seen, some have a limited overshoot in temperature at some point but temperatures in all scenarios reduce by the end of the century. Overshooting 1.5˚C for even a decade can still trigger greater climate impacts with potentially long lasting or even irreversible effects (notably species extinction) compared to scenarios that do not exceed 1.5˚C, or have limited overshoot (IPCC, 2022a). It is also a high risk that CDR cannot be deployed at the projected scale (IPCC, 2021, Larkin et al., 2018). All five 1.5˚C scenarios rely heavily on CDR at scale during 2050-2100, with CO_2 removals of up to 5 Gt/yr. A more precautionary approach would see steeper CO_2 reductions to 2050, to reduce risks around relying on CDR.

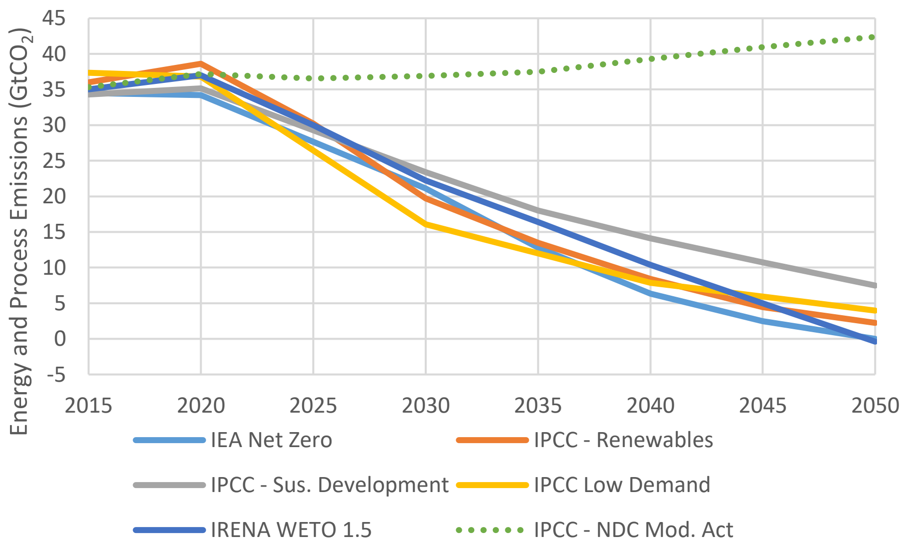

Figure 2: Emissions pathways in the IEA, IRENA and IPCC 1.5C scenarios and the IPCC projection of current national policies

In the 1.5˚C scenarios, the period 2020 to 2025 is an inflection point wherein CO_2 emissions must start a sustained decline (Figure 2). If emissions do not begin to decline before 2025, limiting temperature rise to 1.5˚C will almost certainly not be possible (IPCC, 2021). The IPCC scenario for current (though pre-2022) Nationally Determined Contributions (NDCs) and moderate action implies a global emissions pathway consistent with 2.5-3˚C of warming this century.

There are two main trends common to all the 1.5˚C scenarios. First, the scenarios all have a reduction in global final energy demand, with four scenarios having similar demand reductions from 2020 to 2050, in the range of 11-17%, and the IPCC low-demand scenario having reductions of 42% (Figure 3). This reflects the challenge of transforming energy system infrastructure in such a short space of time – the lower the demand, the quicker the transformation can take place.

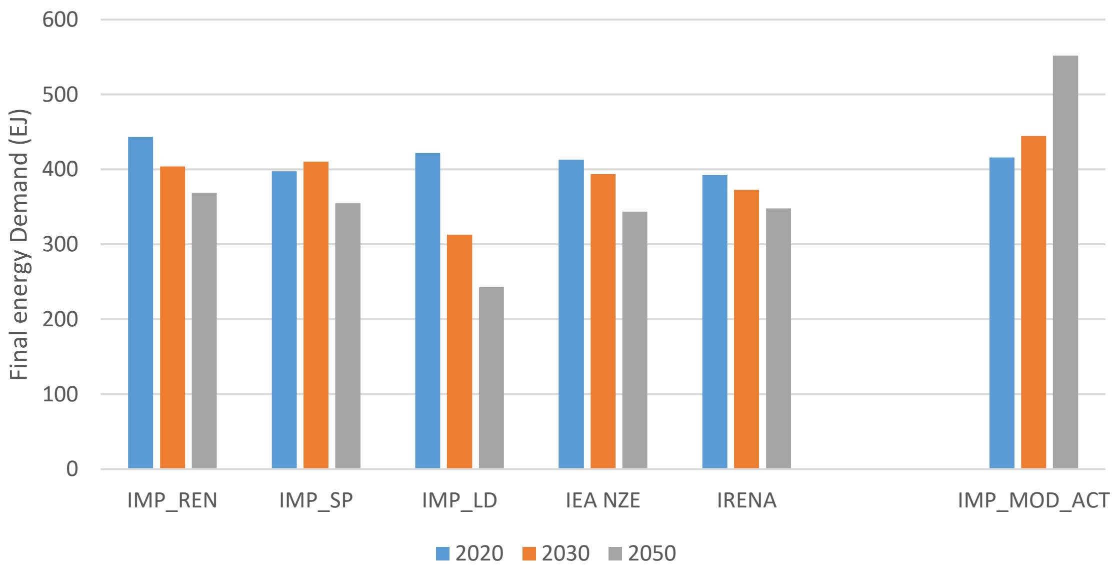

Figure 3: Global final energy demand by scenario, 2020 to 2050

Second, electricity provides a far higher proportion of final energy demand, increasing from 20% to 49-66%. This reflects a greater use of electricity for end-uses such as cars that currently use other fuels (Figure 4). Electricity is decarbonised also, with solar and wind becoming the predominant means of generation, compared with coal and gas today.

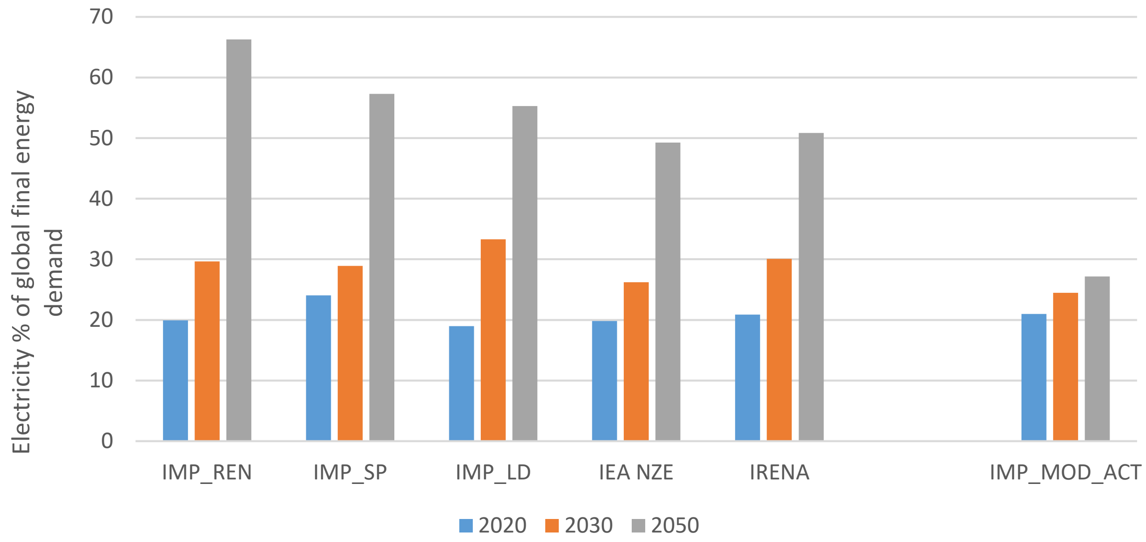

Figure 4: the increasing role of electricity in global energy consumption

These trends lead to a major decline in the use of coal, oil and gas to supply the global energy system (Figure 5).

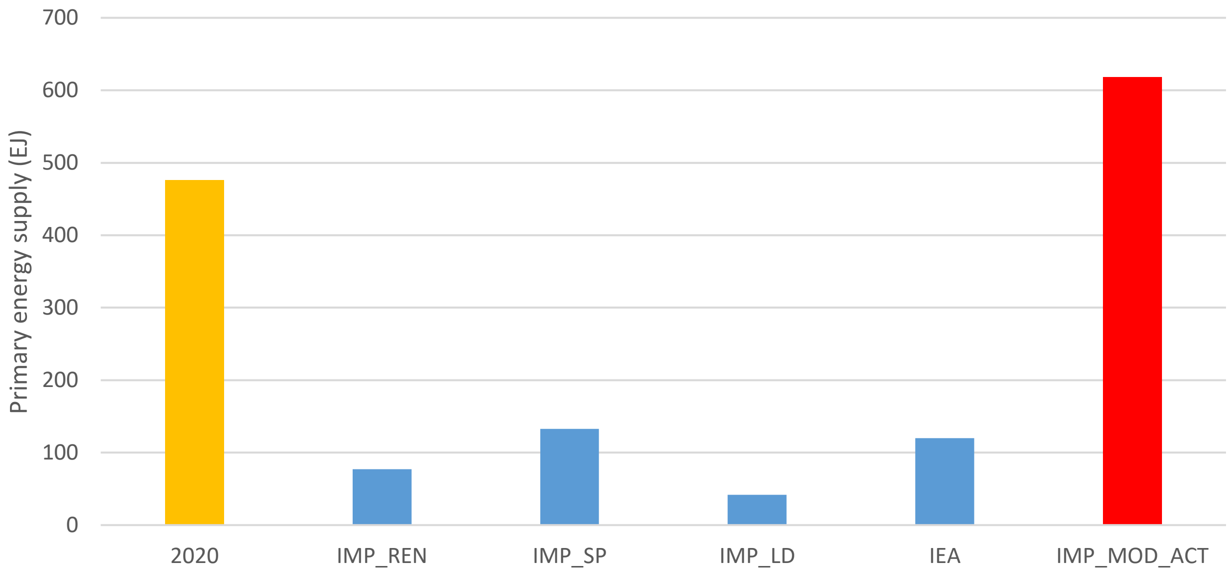

Figure 5: the decreasing contribution of fossil fuels to global energy supply. Blue and red bars = 2050 values, orange bar on left = 2020 value. Fossil fuels – coal, oil and gas.

Aside from these falls in overall energy demand, and in coal, oil and gas supply, the 1.5˚C scenarios see increases in bioenergy, set out alongside the changes to other primary energy sources in Figure 6.

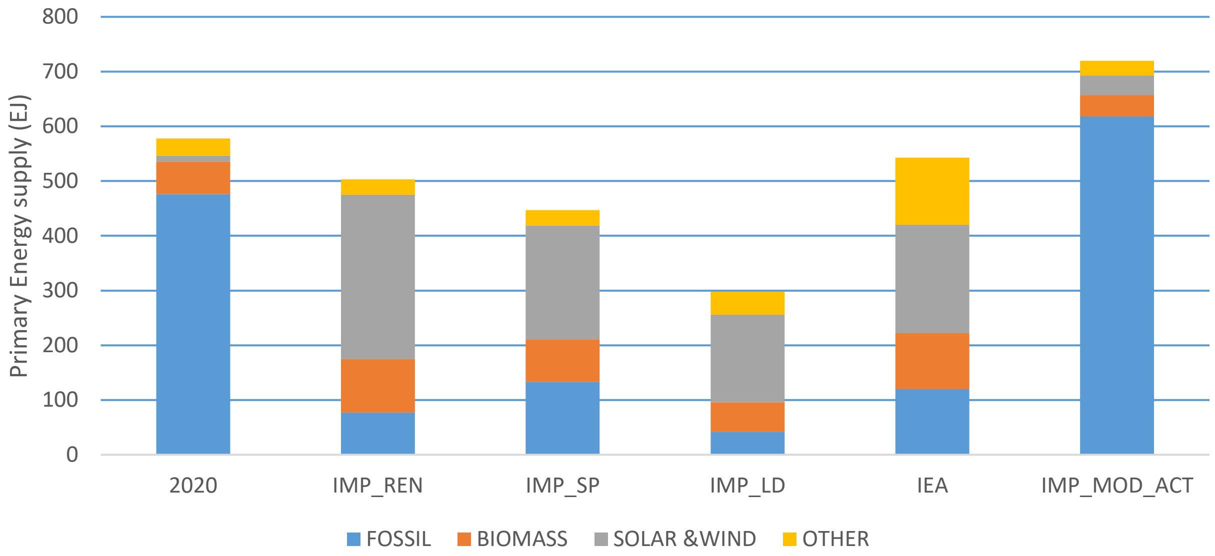

Figure 6: 2050 primary energy by type and scenario. NB: other comprises sources such as hydro, nuclear etc. and hydrogen as a secondary fuel will be captured within 'fossil' or 'solar & wind' depending on whether it is grey, blue or green.

The scenarios also have a major increase in "secondary" energy production of hydrogen, produced either from fossil fuel use with carbon capture and storage ("blue" hydrogen), or electrolysis using solar and wind electricity ("green" hydrogen). The growth in hydrogen varies considerably by scenario however, and this is discussed in detail in section 2.1.

The tonnage of fuel used in the 1.5˚C scenarios also declines, despite the lower energy content of some of the alternative fuels. Biomass and liquid biofuels have a lower calorific value (~16 to 27 EJ/Gt) in comparison with coal, oil and natural gas (~26 to 48 EJ/Gt), so when they substitute for fossil fuels, a greater tonnage of fuel is required for the equivalent energy provision. These issues are complex – for example in the case of hydrogen-based products, the energy per unit volume and the energy per tonne vary greatly depending on whether the fuel is in the form of either liquid hydrogen, gaseous hydrogen or ammonia. The volumetric energy density also depends on the temperature and pressure conditions required to transport the fuel. Overall, it is expected that per unit of energy, hydrogen-based products will require more volume to be transported (Mestemaker et al., 2019).

These changes are important to understand, but it is the large increases in electricity from renewable sources to meet energy needs that has a greater influence on fuel volumes. This means that overall there will be a significant reduction in the tonnage of fuels required in the 1.5˚C scenarios (Figure 6).

The scenarios show that a 1.5˚C transition reduces the global quantities of coal, oil and gas produced, transported and consumed, and increases the quantities of hydrogen and biomass. The next sections look in detail at hydrogen and biomass. For hydrogen, section 2.1 assesses the quantities required in 1.5˚C scenarios, particularly in the near term to 2030 and compares this with an assessment of likely production from hydrogen projects. The gap between current projections and required production is assessed in relation to developments in hydrogen deployment and policy in leading nations. Trends and requirements in biomass and fossil fuels are discussed in sections 2.2 and 2.3.

Section 3 assesses the implications of these changes for shipping. Changes to fuel production locations and changes to the types and quantities of energy required by different national economies affect the future need for transportation of coal, oil, gas, biofuels and hydrogen from producer to consumer. Geography and economics are two critical factors determining whether this transport would be by truck, pipeline, rail, plane or ship.

2.1 Hydrogen in 1.5˚C Scenarios

Hydrogen as a fuel is an emergent energy vector that is currently not established within the global energy system, but is expected to have a significant role in future low-carbon energy systems. Today hydrogen is primarily used for producing fertiliser, oil refining and steelmaking, and not, for example, as a transport fuel. It is produced almost entirely through the use of unabated fossil fuels – either directly through processes such as steam methane reformation (SMR) and coal gasification or as the by-product of another industrial process (often petrochemical). Scenarios for 1.5˚C envisage new roles for hydrogen as a transport fuel, heating buildings, in high temperature industrial processes and for power generation through combustion and fuel cells. As well as new uses, scenarios for 1.5˚C also entail a wholesale change in the production of hydrogen from current methods (referred to as 'grey' hydrogen) to one of the following:

- Electrolysis whereby electricity is used to separate hydrogen from water with a polymer electrolyte membrane (PEM), alkaline or solid oxide electrolysers. Electrolysis supplied by renewable energy is typically referred to as 'green hydrogen'.
- SMR, autothermal reformation (ATR) and natural gas decomposition with carbon capture and storage (CCS). This is typically referred to as 'blue hydrogen'.
- Biomass conversion routes through thermochemical and fermentation processes.

Low-carbon hydrogen is still at a very early stage of commercialisation, and so in any future scenario for limiting global warming to 1.5˚C with a role for hydrogen as a fuel, there needs to be a rapid scale-up of new hydrogen production capacity. Figure 7 shows the 2030 production of low-carbon hydrogen[2], predominantly for new uses, across the scenarios.

[2] Although other "colours" of hydrogen are possible, this report assumes that the overwhelming majority of low-carbon hydrogen will be green (electrolysis using renewable electricity) or blue (fossil fuel + CCS).

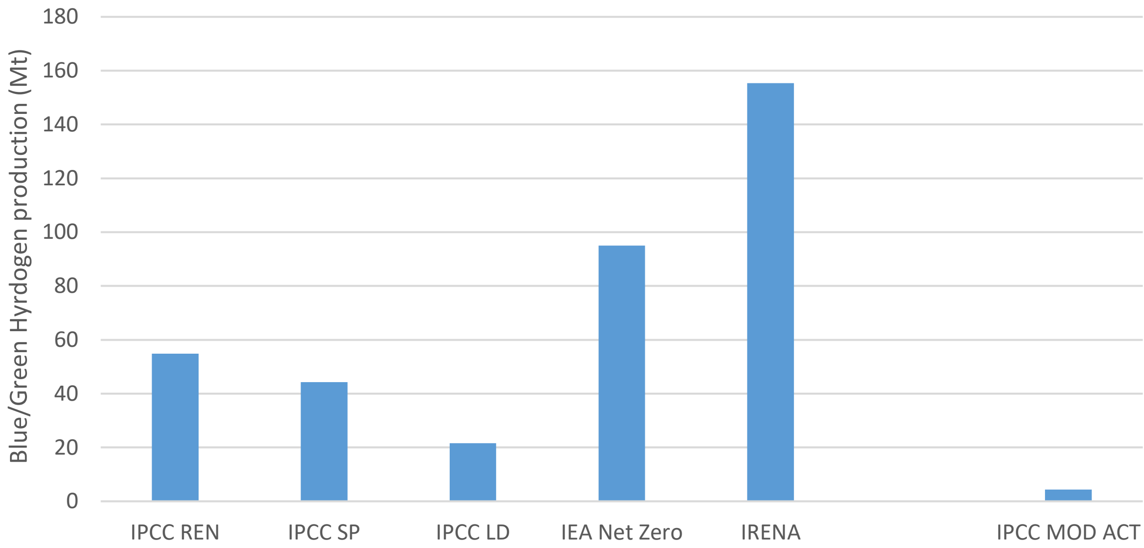

Figure 7: Low-carbon Hydrogen supplied for the energy system in 1.5˚C energy scenarios in 2030 (EJ)

There is a wide variation in low-carbon hydrogen production by 2030 across scenarios. This range continues out to 2050, with production in the range of 150-600 Mt per year in 2050 – reflecting the uncertainties around the extent to which hydrogen will penetrate into different economic sectors.

In the IRENA 1.5˚C low-carbon scenario, hydrogen supply for energy use (including to produce hydrogen derived fuels such as ammonia) increases very rapidly – from negligible in 2020, to ~20 EJ/year in 2030, before reaching ~70 EJ/year by 2050[3]. The IPCC 1.5˚C scenarios used in this report project lower levels of hydrogen supply to meet their emissions pathways.

Within these global hydrogen demand figures there are sectoral breakdowns for 2030 indicating where the scenarios envisage hydrogen demand happening and how hydrogen is used. The IPCC Renewables, Low Demand and Sustainable Development scenarios provide a longer-term breakdown of hydrogen energy use by sector. They show a model preference for hydrogen use in industry and transport over the residential and commercial building sector. This likely reflects the relative costs and competition with alternative low-carbon options for which there are fewer in heavy freight transport and industrial processes. The focus of hydrogen-based fuels in scenarios tends to be where the direct use of electricity is less feasible, consequently there is lower increased demand for hydrogen products in light road transport and heating buildings. There is also the potential for some transitional use of ammonia as a fuel in power stations, co-firing with coal or gas to lower these power stations' emissions, as being developed in Japan, India, South Korea and China (Atchison, 2022d, IHI Corporation, 2022, Xie, 2022).

2.1.1 The hydrogen production gap

There are two essential requirements for hydrogen for compatibility with a 1.5˚C pathway. First, existing grey hydrogen for non-energy uses needs to be replaced

[3] EJ to Mt conversion = multiply by 8.1

with low-carbon production methods. Second, accelerated production of low-carbon hydrogen is needed for new energy sector uses, for example as shipping and aviation fuel, for power, and in industrial processes such as steel and cement production. This section compares planned production with these scenario requirements.

There is a growing pipeline of new hydrogen projects, with many more being announced every year. However there is great uncertainty as to what percentage of these projects will become operational and if they will be on time.

The IEA maintains a database of planned blue and green hydrogen projects. Their September 2022 Global Hydrogen Review states that if all the announced projects are realised, then low-emission hydrogen production could be 24 Mt/yr by 2030, split between 14 Mt green hydrogen, 10 Mt blue (IEA, 2022d).

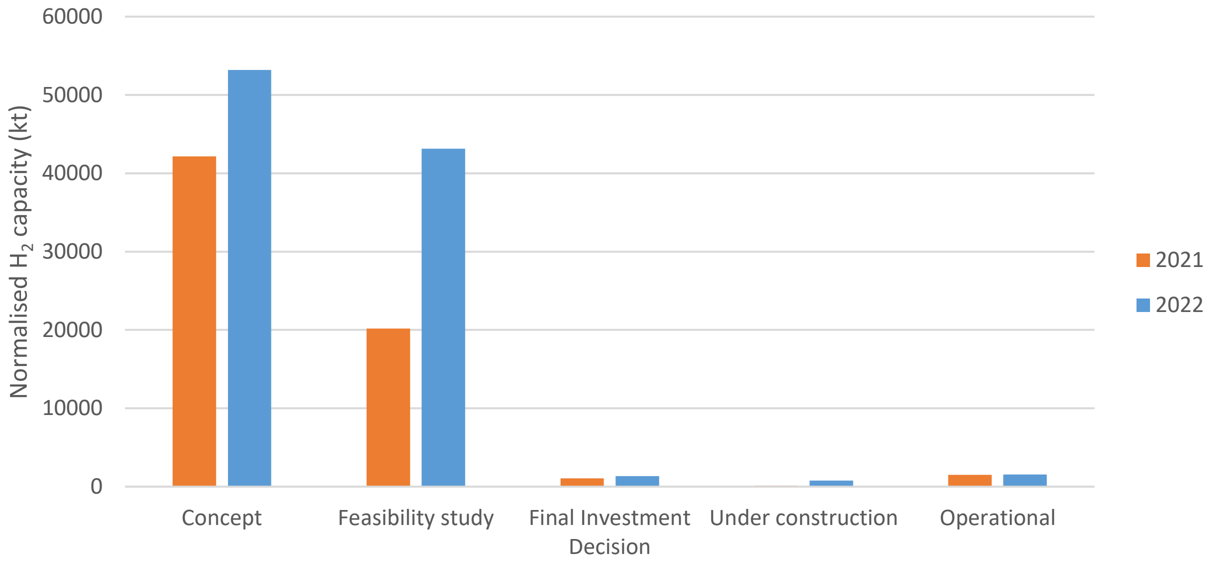

Figure 8: Status of Hydrogen projects in 2021 and 2022

These figures come with major uncertainties. On one hand it could be seen as an upper-bound, because **the overwhelming majority of these projects are only at feasibility or concept stage, with under 4% being in operation, under construction or with a final investment decision** (FID) (Figure 8). On the other hand, the projected pipeline is growing very rapidly – in the October 2022 update of the IEA's database (IEA, 2022e), the total normalised hydrogen capacity of all projects had increased by 50% compared with October 2021, from 66 Mt/yr to 100 Mt/yr of normalised production capacity[4]. Beyond the overall increase in projects, some additional stand-out changes in the twelve months from October 2021 to October 2022 are:

- 85% of the capacity in new announcements is for electrolyser projects;

[4] These figures are so much higher than the projected actual production of 24 Mt/yr because i) they are normalised capacity figures, ie for green hydrogen projects they don't take into account the load factor of the electrolyser, and ii) because the overall database contains many projects whose completion date is either post 2030 or currently unknown.

- Although operational/final investment decision projects have stayed broadly constant, projects are moving rapidly from "concept" to "feasibility study" – with the capacity of projects in the feasibility study category more than doubling in the last year;

- There is a major increase in the number of projects with a completion date of 2025-2027, and also 2030;

- 2022 has seen some new countries emerge as major players – notably the USA, Argentina, South Africa and Egypt – as well as some existing countries announcing new large-scale projects (Australia, Chile, UK). The biggest increases during 2022 are shown in Figure 9 and the countries with the largest portfolios of projects are shown in Figure 10.

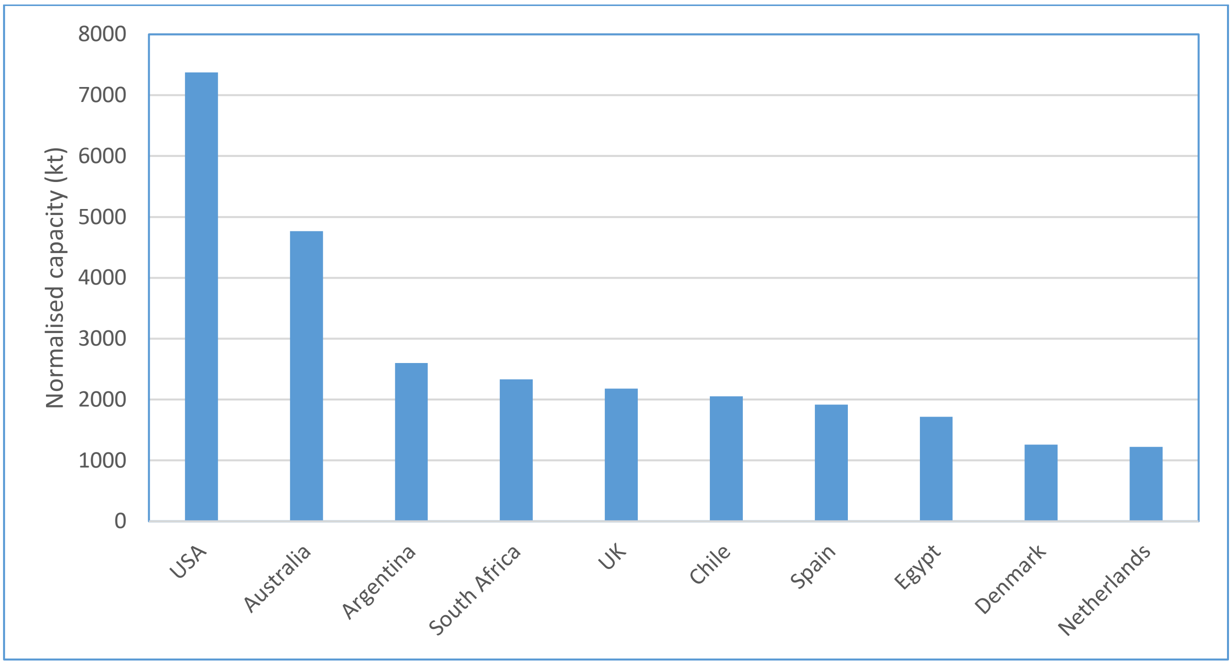

Figure 9: Countries with the biggest increases in new proposed low-carbon H_2 projects between October 2021 to October 2022

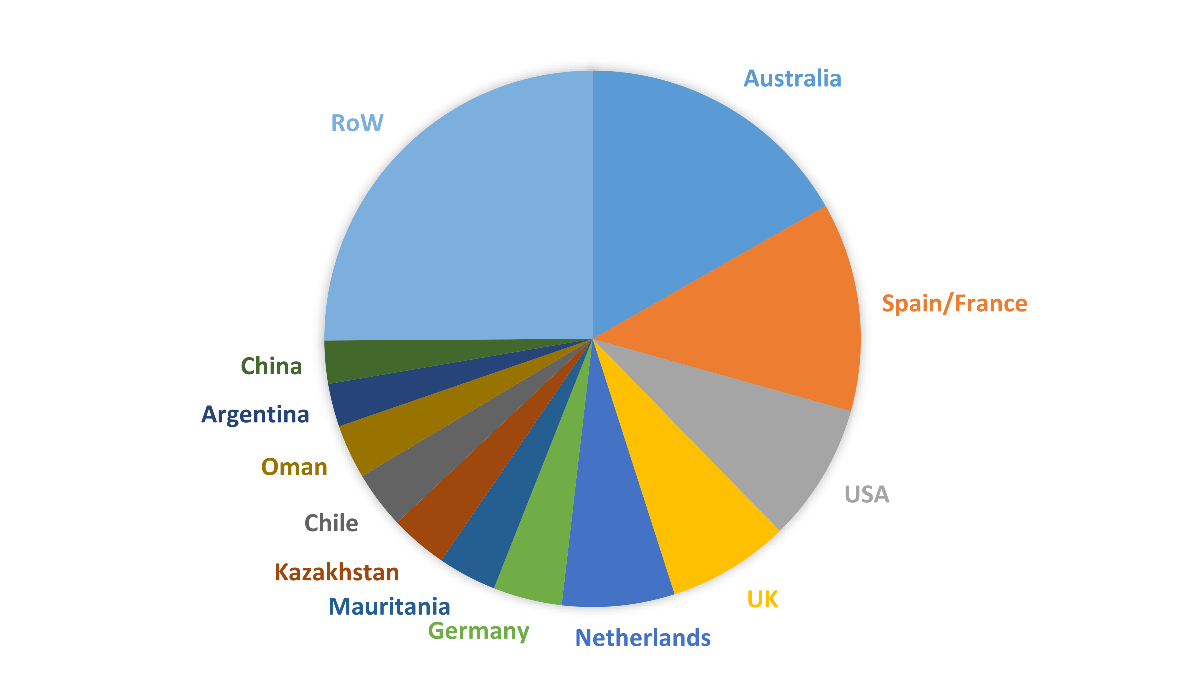

Fig 10: Countries with the greatest quantity of proposed low-carbon hydrogen production

Overall, the IEA's value of 24 Mt/yr low-carbon hydrogen production by 2030 can be seen as a best-estimate, but in practice the actual value achieved could easily be much lower or higher.

Figure 11 compares this 2030 production estimate with the quantities of low-carbon hydrogen required by that date in the 1.5˚C scenarios. It assumes first that major progress would be needed in decarbonising the existing hydrogen production: the IPCC assumes that as an average across all sectors, around 43% global emissions reductions are required by 2030 for 1.5˚C pathways (IPCC, 2022b). As a first-order estimate, this figure is applied to the hydrogen sector – meaning that around 31 Mt of low-carbon hydrogen is needed[5]. Moreover, the five scenarios estimate additional hydrogen that would be needed for new uses – these values vary greatly between scenarios, with considerably less hydrogen required in both 2030 and 2050 in the IPCC scenarios compared with the IEA/IRENA scenarios. However, even in the lowest demand scenario, the gap is over double that of estimated 2030 production. So, despite the rapid increase in new projects in just the last 12 months, greater capacity and on a much accelerated timeline is needed to bring this in line with the 1.5˚C scenarios.

[5] 2020 production was 90Mt, 72.7 Mt from fossil fuels (16 Mt as by-product from chemical processes); this estimate then assumes that 31 Mt (43%) of this would need to be replaced with low-carbon hydrogen.

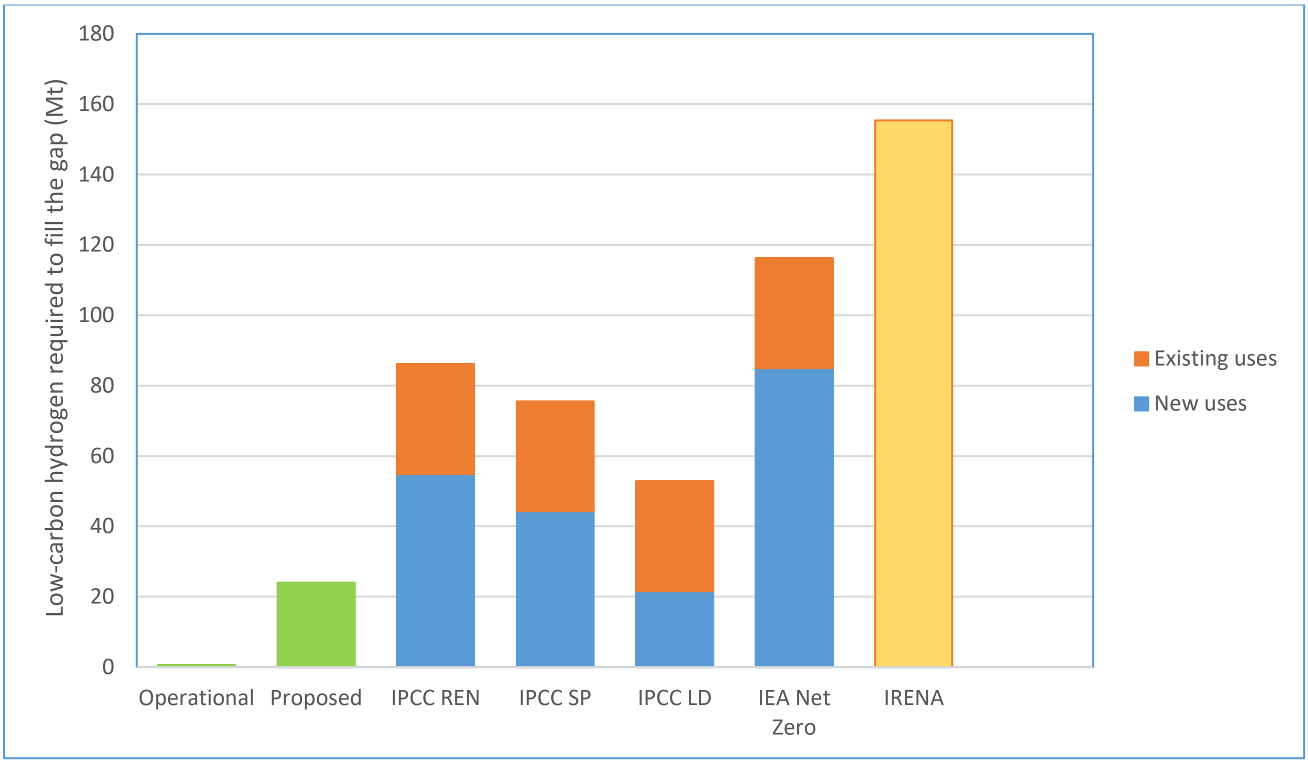

Figure 11: The gap between proposed 2030 low-carbon hydrogen (green), and what is needed in 1.5˚C scenarios (blue/red). IRENA values as expressed here merge low-carbon hydrogen for existing and current uses (yellow).

2.1.2 Closing the hydrogen gap

There are drivers and barriers affecting whether this gap could be closed, summarised for green hydrogen in Table 3. For blue hydrogen similar barriers exist in terms of supplier-producer agreements. Additionally, this pathway requires interactions with carbon capture and storage infrastructure, which is slow to develop. The Northern Lights sequestration project in Norway working with ammonia producer Yara is one of the most advanced blue hydrogen projects (capturing CO_2 from ammonia production) with a timetable to begin operation in 2025 (Yara, 2022a). Projects such as this and the UK blue hydrogen projects such as HyNet, must run on, or ahead, of schedule and scale up rapidly to align with quantities in the 1.5˚C scenario pathways. They also need to demonstrate consistent capture rates of >90% are possible in commercial operation. This would entail speeding up of government decision making on financial support – particularly when natural gas prices are high – and regulatory and liability issues around carbon storage being resolved.

Table 3: Drivers and barriers for green hydrogen projects:

Drivers	Barriers
Increasing number of announced projects – new Giga-scale projects every month	Lack of supportive domestic policies for hydrogen projects in many countries
Many bilateral hydrogen agreements forming	Higher relative costs for green hydrogen/ammonia versus grey will return if gas prices fall
Falling electrolyser costs	Very few projects are as yet progressing to final investment decisions
Falling solar and wind costs	Few concrete agreements between producer and consumer
Current high gas prices in Europe/Asia dramatically improves economics of green vs grey/blue hydrogen and ammonia	In shipping, ammonia twice as expensive as MGO; no carbon price which would make a material difference is likely in short or medium term

There is a coordination issue potentially holding development of hydrogen in limbo, with hydrogen projects requiring buyers before final investment decisions are made, and sectors planning a move into hydrogen being unsure of supply. These are compounded by major further infrastructure investments often being needed to deliver hydrogen products from producers to consumers. **The priority is therefore to convert the current explosion of interest in hydrogen into actual projects in the coming few years**. Increasingly there may be collaborations which seek to overcome coordination problems by linking many or all of the stages in the green ammonia/hydrogen supply chain, for example the recent initiative by Amon Maritime (Stott, 2022a).

Government policies that can bridge supply and demand – providing investors on both sides with greater confidence in the transition to low carbon hydrogen – will be an important factor in whether the gap between low-carbon hydrogen use in 1.5˚C scenarios and the current situation can be closed. This applies both to regions expected to be net importers of low-carbon hydrogen providing incentives and regulatory certainty around future demand, and potential exporter countries supporting investments in production capacity and supply infrastructure.

There are a number of major reports which have assessed the types of policy needed to accelerate low-carbon hydrogen deployment (IEA, 2019, IEA, 2022d, IRENA, 2022b). These policies have been categorised into five types:

- measures to reassure investors of a future market-place, such as national targets and hydrogen strategies;
- standards and certification policies to ensure robust sustainability benefits;
- policies to stimulate demand for low-carbon hydrogen;

- supply-side support, to accelerate investment in low-carbon hydrogen production, storage and transportation infrastructure;

- RD&D support for demonstration projects for elements of the hydrogen supply chain not yet fully market-ready (IEA, 2022d).

Recent reports cite literally hundreds of policies and give examples of planned or recently introduced measures across dozens of countries, right across the hydrogen supply chain. To a degree, the issue at hand is not so much that policies are needed, but which are the highest priority.

Assessing the most appropriate suite of policies is beyond the scope of this report, however certain measures introduced in the last year appear to be strong candidates for wider uptake. We highlight four here:

Using quotas and mandates: up until 2030, the biggest potential source of demand for new low-carbon hydrogen projects will be through replacing grey hydrogen in existing industrial processes, with green hydrogen. India has included within its evolving hydrogen strategy the potential to mandate rising percentages of green hydrogen within both fertiliser and refinery sectors (Staines, 2022). Similarly, in May 2022 the European Commission launched its RepowerEU package (European Commission, 2022a) to make Europe independent of Russian fossil fuels. This includes a major expansion of hydrogen, including an import target of 10Mt renewable H_2 by 2030. However the majority of this import target does not yet have clear markets. Use of increasing quotas, as being suggested in India, would accelerate the decarbonisation of EU refineries and fertiliser sectors, and increase demand for hydrogen projects in other countries.

Contracts for difference: two problems for low-carbon hydrogen are uncertainty for suppliers that they will have long-term buyers, and demand-side concerns regarding price. Contract for difference-style policy mechanisms can overcome both. One initiative by the German Government (H2 global, 2022) creates a double auction: first, producers bid for 10-year Hydrogen Purchase Agreements; second, consumers bid for Hydrogen Supply Agreements. The price difference is paid by an intermediary company, funded via the German Government. The details are being finalised (Freshfields Bruckhaus Deringer, 2022), with first delivery periods anticipated being for 2024 to 2033.

Hydrogen production credits: on the production side, in August 2022 a mammoth US Inflation Reduction Act was passed – including a package of measures aimed at boosting the hydrogen economy. The major element of this package is the Clean Hydrogen Production Credit, which introduces a 10-year sliding-scale of credits for hydrogen production, depending on carbon reductions – reaching $3/kg for green hydrogen projects, which is widely seen as large enough to allow green hydrogen to compete with grey hydrogen today (Webster, 2022), even with the USA's far lower than global average gas prices.

Prioritising end-uses: given the short- and medium-term gap between low-carbon hydrogen requirements for 1.5˚C, and likely production volumes, government clarity on the priority end-uses for hydrogen is particularly important. Hydrogen's production and storage is too energy-intensive for it to be wasted on sectors where there are alternatives. Beyond its essential uses in non-energy sectors such as fertiliser production, hydrogen's energy uses are best targeted at sectors where electrification is more difficult – such as shipping, aviation and steel manufacture. Governments should not be prioritising hydrogen use in buildings, most forms of road transport or power generation. A typology for a hierarchy of hydrogen use is set out in Figure 12.

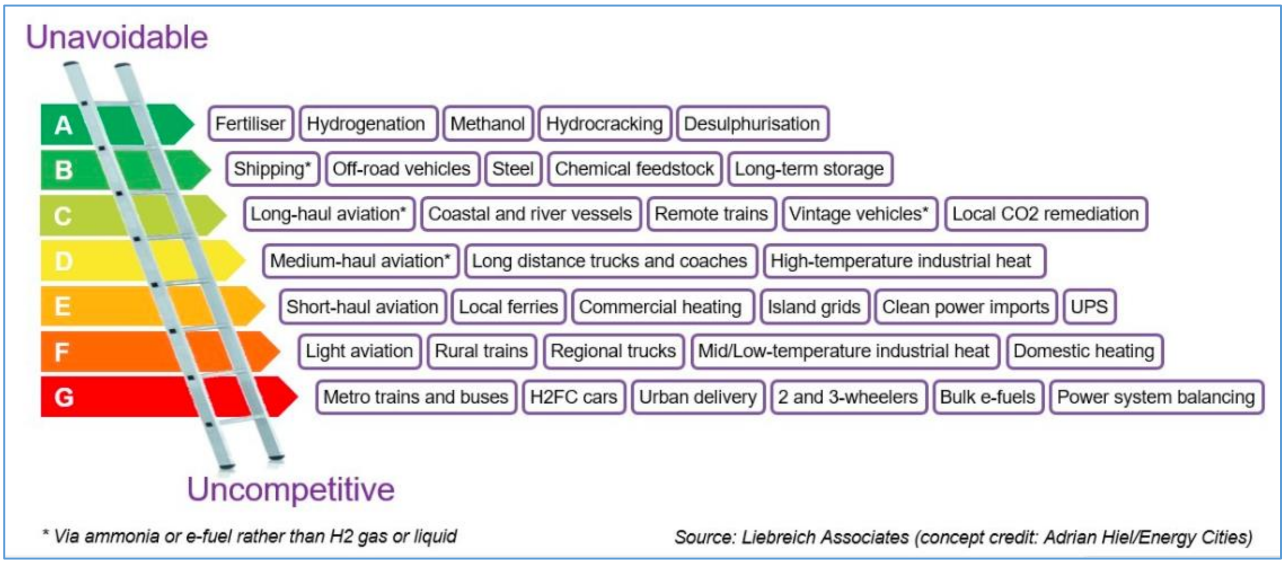

Figure 12: Hydrogen Ladder (Leibrich, 2021)

Finally, increasingly there are collaborations seeking to overcome coordination problems by linking many or all of the stages in the green ammonia/hydrogen supply chain, for example the recent initiative by Amon Maritime (Stott, 2022a), Clean Energy Maritime Hubs (Clean Energy Ministerial, 2022) and the Silk Alliance Green Corridor/hubs project for container shipping in Asia (Lloyd's Register, 2022). The actions of Maersk in agreeing contracts for supply of fuel for its new methanol vessels are a further example of forging stronger links between producers and consumer (Maersk, 2022)[6].

[6] Methanol emits CO_2 when burned, so to be carbon-neutral would either need to be produced from sustainable biomass (biomethanol), or from captured carbon dioxide and hydrogen produced from renewable electricity (e-methanol).

2.1.3 National hydrogen strategies

Figures 13 and 14 summarise progress on national low-carbon hydrogen strategies for countries expected to be leading consumers or producers in the emerging low-carbon hydrogen transition. The figure also highlights where there is interest in acting as international trading hubs for hydrogen – e.g. Singapore and the Netherlands.

Import orientated countries	Japan	South Korea	Germany	Singapore	EU
H2 strategy published	Yes	Yes	Yes	Yes	Yes
Is current import/export status aligned with strategy goals	Yes	Yes	Yes	Yes	N/A- depends on member states
H2 strategy discusses transport of fuels	Yes	Yes	Yes	Yes	Yes
Signed bilateral agreements on trade					
Signed bilateral agreements on tech/other					
In development* project capacity	0.003 Mt H2/yr	0.6 Mt H2/yr	4.6 Mt H2/yr	0.01 Mt H2/yr	34.4 Mt H2/yr
In development* project capacity as % of total global demand in 2021	0%	0.64%	4.9%	0.1%	36.6%
Existing operational blue/green H2 plants	0.002Mt/H2/yr 2 operational projects	None	0.01MtH2/yr 50 operational projects	0.0002MtH2/yr 4 operational projects	1.06MtH2/yr 98 operational projects
Sources of announced Investment and incentives	Government and private sector	Private sector only	Government and private sector	Private sector only	European Commission and private sector

*Figure 13: Progress on Implementing national hydrogen strategies of import focused countries. *In development refers to low-carbon hydrogen projects currently in construction, final investment decision, planning or concept stage. Import orientated status determined by stated aims in national strategies or scenarios/hydrogen literature as future blue/green hydrogen importers.*

Export orientated countries	Australia	UK	Spain	Chile	Saudi Arabia	Namibia	Netherlands	EU
H2 strategy published	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Is current import/export status aligned with strategy goals	Yes	No	No	No	Yes	No	Yes	N/A- depends on member states
H2 strategy discusses transport of fuels	Yes	No	No	No	No	No	Yes	Yes
Signed bilateral agreements on trade								
Signed bilateral agreements on tech/other								
In development* project capacity	16.8 Mt H2/yr	7.4 Mt H2/yr	14.9 Mt H2/yr	3.3 Mt H2/yr	0.4 Mt H2/yr	7.1 Mt H2/yr	6.8 Mt H2/yr	34.4 Mt H2/yr
In development* project capacity as % of total global demand in 2020	17.9%	7.9%	15.9%	3.5%	0.4%	0.6%	7.6%	36.6%
Existing operational blue/green H2 plants	0.0004MtH2/yr 5 operational projects	0.0003MtH2/yr 10 operational projects	0.00002MtH2/yr 2 operational projects	0.00001MtH2/yr 2 operational projects	none	none	1MtH2/yr 3 operational projects	1.06MtH2/yr 98 operational projects
Production projects close to coast/ports?	Majority- shipping likely	Yes- some shipping likely	No - Likely majority pipelines not ships	Yes- some shipping likely	Majority- shipping likely	Yes- some shipping likely	Yes- pipeline and ship likely	No - Likely majority pipelines not ships
Sources of announced investment and incentives	Government and private sector	Government and private sector	Government and private sector	Private sector only	Private sector only	Private sector only	Government and private sector	European Commission and private sector

*Figure 14: Progress on implementing national hydrogen strategies of export focused countries. *In development refers to low-carbon hydrogen projects currently in construction, final investment decision, planning or concept stage. Export orientated status determined by stated aims in national strategies or scenarios/hydrogen literature as future blue/green hydrogen exporters.*

National hydrogen strategies have become more widespread and detailed in recent years, however countries are at different stages of development. The front runners in this regard are Japan, South Korea and Germany. These nations have plans to stimulate industrial demand for hydrogen and ammonia fuels, trade deals with prospective exporter countries such as Australia, Saudi Arabia and Chile, and have also explored transportation options. These front runners also highlight the issues currently facing hydrogen and its derived fuels for energy usage. There is not yet a significant supply of low-carbon hydrogen production to meet the targets set in these hydrogen strategies even between the leading nations. Getting volumes of blue and green hydrogen to flow between producers and users is the emergent challenge for national hydrogen strategies – and for going further to meet the goals of 1.5˚C scenarios. Ultimately more low-carbon hydrogen production must come online in the next few years to meet even the slower growth rate of hydrogen reported in the IPCC 1.5˚C scenarios.

Table 4: Examples of key investments announced for hydrogen projects - all values normalised to US$

Country	**Government announced investment**	**Private sector/expected investment**
Japan	Government R&D funding of $344 million announced(Nakano, 2021)	$3.4 billion private sector funding expected.
South Korea	N/A	10 year fund from private sector coalition worth $383million (Hydrogen Central, 2022).
Germany	$8.1billion investment announced for speeding up market rollout of technology, and £2.3 billion for fostering international partnerships. Further $9.7 billion related to EU scheme (Huber, 2021).	Plans to trigger $38.3billion of private investment.
Singapore	$49million announced by government as a research and development fund (Ning, 2021).	N/A
EU	$5.4 billion announced for important projects of common European interest (IPCEI) in the hydrogen technology value chain (European Commission, 2022b).	Dependent on member states.
Australia	Government funding round of $47million announced and received by successful applicants (Australian Government, 2020). $2 billion investment into green hydrogen also approved by New South Wales Government (Carroll, 2021).	Private investment to sector valued at $88-123billion (Singh, 2022).
UK	£240million net zero hydrogen fund, and £60million for low-carbon hydrogen supply, as well as further funding for other projects involving hydrogen such as net zero transport (£183million), low-carbon fuels(£315million), and energy storage(£68million) (UK Government, 2021).	Unlocking of $4.5 billion private sector funding expected.
Spain	Allocation of $1.5billion to green hydrogen development as part of its 2 year energy plan (LSE, 2022).	Expected attraction of $9.3billion in private funding expected for renewables, green hydrogen and energy storage (Reuters, 2021).
Chile	N/A	Private investment of over $1billion sanctioned by government (Walne, 2022).
Saudi Arabia	N/A	£36 billion in private sector investment expected (FuelCellsWorks, 2022).
Namibia	N/A	$9.4 billion of private funding announced (FuelCellsWorks, 2021)
Netherlands	$740million announced as available from government for green hydrogen transport network (Biogradlija, 2022).	Private investment plan of $8.9billion announced (Gasunie, 2020).

(NB: all values cited converted from original currencies into US$, based on exchange rate at time of writing: 1USD= 1.01euro=0.88GBP=1.51 AU$)

The following two case studies look in more detail at two of the most developed regions for low-carbon hydrogen production – Australia and Europe.

Case Study: Australia

Australia is relatively advanced in moving forward as a potential low-carbon hydrogen exporter. It has the largest quantity and capacity of potential new hydrogen projects, existing port infrastructure for ammonia export, and very high renewable energy resources, planned projects near ports, and low costs of capital (IRENA, 2022b).

For a number of years, Australia has been developing a potential ammonia trading relationship with Japan, South Korea and Singapore. These are the most long-standing and advanced bilateral agreements on low-carbon hydrogen production and consumption. Further large consumer-supplier relationships between Australia and Germany (e.g. Fortescue and E.ON) have increased the importance of developments in Australia for the global low-carbon hydrogen trade.

Proposed hydrogen projects are spread across Australia – ten of the largest are set out in Figure 15.

Figure 15: Spatial Distribution of low-carbon hydrogen projects announced as of October 2022 (Source; IEA Hydrogen Project Database, 2022).

Table 5 highlights key attributes of the proposed projects in terms of their suitability for seaborne export. Projects in the North East are located near to major port infrastructure at Gladstone but are currently at relatively small scale. Larger projects on the West coast are located in the vicinity of port infrastructure for iron ore export, however the largest announced project – the Western green Energy Hub is further from large port infrastructure. Overall Australia has significant proposed capacity located near to suitable port infrastructure.

Table 5: Summary of proposed hydrogen projects in Australia

Project	Type	Normalised capacity (kt H_2)	Notes
WGEH	Green NH_3	3601	Longer distances to Asian markets. FID expected after 2028
AREH	Green H_2 and NH_3	2426	Very close to the Pilbara iron ore ports
HyEnergy	Green H_2	1386	Export focus
Desert Bloom	Green H_2	1386	Inland project
Murchison	Green H_2 and NH_3	750	Asia export focus
Stanwell	Green H_2	520	Local industry and export
H2Perth	Green & Blue H_2 & NH_3	520	Domestic uses and export
Gladstone	Green NH_3	494	Major port infrastructure at Gladstone
Tiwi islands	Green H_2	485	Very close to Port Melville
Sun Brilliance	Green NH_3	454	Export to Korea and Japan

Beyond production, other aspects in the hydrogen/ammonia chain show progress, such as:

- Bilateral hydrogen agreements with Japan (Japan and Australia, 2020), Singapore on Maritime fuels, June 2021(Six, 2021), and South Korea (Morrison, 2021, Paul, 2022) including specific 200kt export deal (Vorrath, 2021).
- Producer to producer agreements:
    - Pipeline proposal green hydrogen to domestic ammonia production plant (Atchison, 2022b);
    - Offtake agreement for domestic use of green ammonia production (Atchison, 2022a);
    - Fortescue (Australia) and Covestro (Germany), 100ktH_2/yr (Petrova, 2022);
    - Fortescue and E.On (Germany) memorandum of understanding re 5Mt H_2/yr (E.On, 2022).
- Other elements of supply chains:
    - Electrolyser manufacturing plant construction starts at Gladstone (Fortescue Future Industries, 2022);

- April 2022, letter of intent re iron ore Green Corridor between Australia and East Asia, from BHP, Rio Tinto, Oldendorff Carriers, Star Bulk Carriers (BHP, 2022);
- Rio Tinto & Anglo Eastern plan ammonia-powered bulk carriers for Port of Newcastle (Atchison, 2022e).

Despite the large number of potential projects and agreements in Australia, the industry is nascent. It appears that projects have remained in limbo awaiting investors to commit capital to production facilities. The absence of clear consistent signals and support from the government in the transition from fossil fuels is a contributing factor (Fernyhough, 2022) – with the introduction of tax breaks (such as the USA's recent tax credit in the Inflation Reduction Act), carbon pricing and a clear renewables strategy cited as necessary. In addition, having guaranteed markets is seen as a prerequisite for project success, for example through the negotiation of long-term bilateral contracts for green hydrogen. Such contracts have been pivotal in the development of Australian LNG exports in the 2010s, with multiple 20-25 year high-volume LNG contracts signed between Australia and Chinese companies CNOOC, Petrochina and Sinopec (Yin and Lam, 2022).

The change in Australian Government following the May 2022 general election is likely to lead to stronger climate policy in general, potentially leading to a more supportive policy environment for green hydrogen projects. This may be helped by the delivery of a planned National Hydrogen Infrastructure Assessment, due in 2022. As these projects get nearer to construction there may be further barriers associated with bringing large infrastructure projects through to planning consent. The large Western Australia AREH project (1.6 Mt Hydrogen per year) has faced challenges over its environmental impact on wetlands, and the Western Green Energy Hub (WGEH) has been successful only through working with Aboriginal groups to allay concerns (Greenhalgh, 2022). At present analysis appears to show that the lack of supportive national policy is a key reason for difficulties in project delivery (Parkinson, 2022, Thornton, 2022). If this were resolved there could potentially be a step change in global low-carbon hydrogen production via the realisation of the project pipeline in Australia.

Case Study: European Union

The EU's ambition on hydrogen has increased significantly in the last three years, with an industry-led roadmap in 2019 (FCH, 2019) leading to the publication of a Hydrogen Strategy in 2020 (European Commission, 2020), then the "Fit for 55" package in 2021 (European Commission, 2021), and further strengthening of ambition and policy in the May 2022 RepowerEU proposals (European Commission, 2022a).

The EU's focus has been specifically on developing renewable hydrogen – the initial 2020 strategy set the strategic objective of 10Mt of renewable hydrogen production in the EU by 2020. The 2022 RepowerEU set an additional target of 10Mt of renewable hydrogen imports by 2030. To date the import focus has been on hydrogen corridors with nearby nations – highlighting the North Sea, Ukraine and the Mediterranean. So far, wider bilateral relationships at EU level are limited - the 2019 joint statement by Japan, the European Commission, and the USA (USA DoE, 2019) to strengthen trilateral cooperation is limited to technology cooperation, data sharing and joint research. However individual EU states have pursued a range of bilateral hydrogen agreements with more distant nations, for example France with India in October 2022 (Economic Times, 2022)(and see next section).

Member states have their own more developed plans for hydrogen. Most notably;

Spain: Spain may have a key role in EU hydrogen trade, via pipelines. Projects in development would make up almost 50% the EU's production capacity pipeline. However, slow progress is seen in achieving this. Despite export goals, Spain has not signed any bilateral agreements on hydrogen trade. Currently operating production of green/blue hydrogen is negligible, especially compared with the targets set by projects in development. There are limited developments in the shipping of hydrogen and its derivatives from Spain. The majority of transport projects are focused on pipelines, including proposed plans for hydrogen pipelines to Portugal, France and Italy. A further identified potential pipeline route would be between Spain and Morocco, therefore, opening up pipeline trade between Africa and the EU. Therefore, despite Spain's large potential for production, its interactions with the international shipping trade may be minimal.

Germany: National policy of Germany on hydrogen includes expectations that Germany will need to import hydrogen products from abroad, as well as producing it (German Federal Government, 2020). The hydrogen strategy therefore discusses preparing infrastructure for future hydrogen supply, including production, transport, storage and use, and building trust in a hydrogen economy. It also includes proposals to develop transport and distribution infrastructure is key to import hydrogen. Reducing reliance on Russian gas in the medium to longer term is one driver in potentially accelerating a move to hydrogen.

There is investment in production facilities, however current capacity is very small at 0.01 MtH_2/yr (IEA, 2021a), compared with projects in development expecting capacity of 3 MtH_2/yr, showing that there is significant work to be done to achieve this. Germany's high potential energy demand and geographical location may mean that importing from the Netherlands, Norway, Spain, and other closer European countries is necessary in the future. Recent bilateral trade agreements on hydrogen have been developed with Chile, Saudi Arabia and Australia. All these countries would require hydrogen or ammonia shipping to import hydrogen into Germany.

The new H2Global double auction policy (see Section 2.1.2) will reimburse sellers for the transport, logistics, and import duty costs of importing green hydrogen derived products. This means that the import of ammonia, methanol, and kerosene from green hydrogen will be promoted, and notably the initiative aim is to work with non-EU suppliers. This opens up the potential of the establishment of a hydrogen derivative shipping trade, between Germany and other nations.

Overall it looks like there is commitment to expanding the market for hydrogen energy products. Export of hydrogen production technology is also discussed in the strategy, mentions green hydrogen production as a stimulus for developing countries to rapidly expand renewable capacity, and benefit local markets. Technology or other bilateral agreements are with Singapore, UEA, New Zealand, Norway, Canada, Tunisia, Netherlands, Ukraine, Nigeria, China, Namibia and Japan.

Netherlands: The Netherlands' ambition to become an export nation is set out in its hydrogen strategy (Government of the Netherlands, 2020). Developments in Germany (such as increased hydrogen refuelling stations) are significant to the Netherlands, as some of this demand will have to be met through imports that enter Europe through the Netherlands. Therefore, the port of Rotterdam is set to be key in future hydrogen use in Europe, giving hydrogen and ammonia exporters access to the European market. The port was named as the "most active" organisation concerning international cooperation on hydrogen by the IEA.

Notably, the Netherlands has expressed interest in expanding existing infrastructure to increase ammonia imports. The port of Rotterdam is planned to expand its capacity for ammonia from 4000ktpa, to 1.2Mtpa by 2023, and invest in a port side ammonia-to-hydrogen cracking facility that will be operational by 2026. Investing in these new facilities could strengthen the Netherlands' position as a hydrogen supplier for the rest of Europe.

The strategy states that intercontinental transport is expected to take place by sea, likely in the form of ammonia, but transport across Europe will be cheapest via pipeline. The green octopus project aims to connect pipelines with seaports, therefore, opening up trade between further EU nations and non-EU hydrogen and ammonia suppliers. This could be advantageous for EU nations that have significant energy demands, but have less developed port infrastructure than the Netherlands.

The Netherlands is additionally exploring the possibility of intra-EU hydrogen shipping from Portugal. This is the only current example of a hydrogen shipping project planned within the EU, and would involve the shipping of 1Mtpa of hydrogen annually.

According to the IEA database the largest operational green/blue hydrogen production site in both Europe and worldwide, (1MtH_2/yr) is the Shell heavy residue gasification CCU - Pernis refinery. This site will utilise carbon capture in 2024, after the Porthos carbon storage project is realised in Rotterdam (Porthos Project, 2022). Capacity of projects in development stage is 5.6MtH_2/yr, meaning the ambition is to increase current production capacity by over five times

Overall the Netherlands' focus is on trade and market development. The strategy is well developed relative to other national hydrogen strategies, as it discusses next stages related to introducing regulation and laws related to hydrogen, as well as mentions of specific projects and future relationships. Even if the Netherlands does not become a major producer, its position in Europe related to sea trade means that it is still a key part of future hydrogen trade. Netherlands had bilateral trade agreements with Chile, Namibia, Canada, Portugal and Uruguay, all countries with export ambitions. This suggests that the Netherlands' position as an exporter may be related to re-selling and re-exporting hydrogen to the rest of Europe via Rotterdam.

2.2 Bioenergy in 1.5˚C Scenarios

Bioenergy has a more established supply chain when compared with hydrogen. In 2020 solid biomass and biofuels met 9% and 1% of global final energy demand respectively (IEA, 2021c). Biofuel increases to-date have been largely driven by government policies on tax and minimum content obligations in road transport and aviation fuels, while demand for solid biomass for heat and power generation has grown quickly in Europe due to subsidies and given its strong potential for use as a drop in fuel using existing infrastructure (IEA Bioenergy, 2018).

Bioenergy is expected to increase to some extent in all of the 1.5˚C scenarios examined, with the exception of IPCC Low Demand where primary bioenergy decreases slowly by 2050. Figure 16 shows modern bioenergy primary energy (biofuel gases, biofuel liquid and modern solid biomass) increasing from 38 EJ/yr to between 45 EJ/yr and 99 EJ/yr by 2030, and between 54 EJ/yr and 153 EJ/yr by 2050, while traditional biomass reduces to 0-5 EJ by 2050.

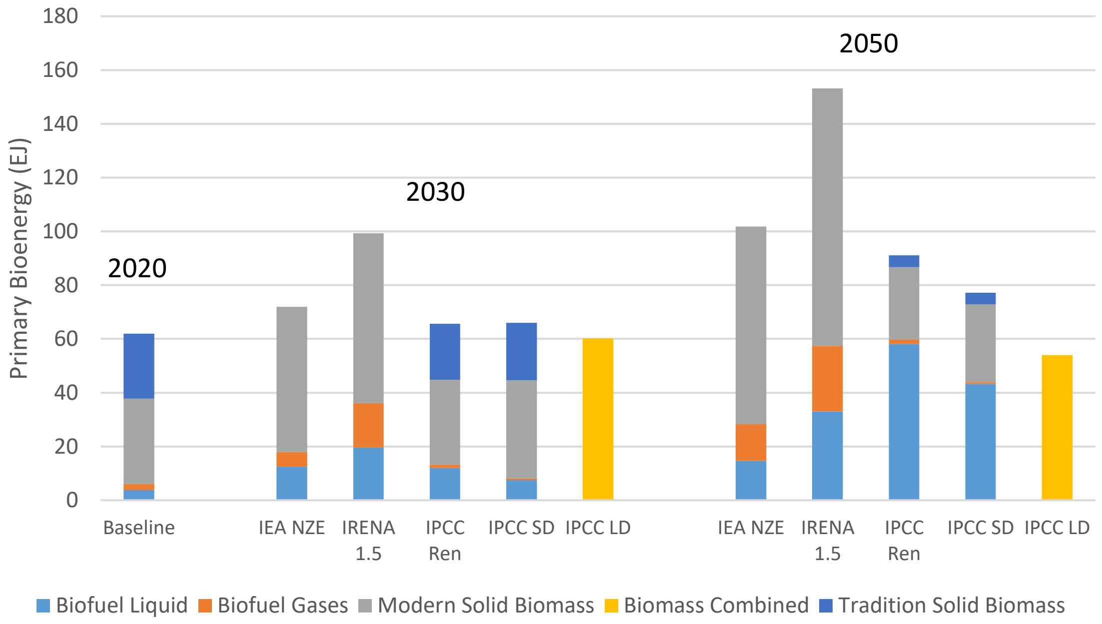

Figure 16: Primary Bioenergy Supply in Energy Scenarios (EJ). The IPCC Low Demand scenario does not break down biomass by type Modern bioenergy = biofuel liquid +biofuel gases +modern biomass.

As well as changing trends in bioenergy demand, the characteristics of bioenergy is expected to transform in three ways across the scenarios:

1: Changes in feedstock – from traditional biomass use (e.g. wood fires, charcoal) to modern biomass (pelletised fuels, liquid and gas bio products), and from first generation biofuels reliant on food crops (such as corn and soy) to second generation 'advanced biofuels' using forestry residues, energy crops grown on marginal land and wastes.

2: Changes in application – trending away from uses in power and road transport, towards the hard-to electrify sectors such as aviation, shipping and to generate heat for industry.

3: Interaction with carbon removal – with the exception of the IPCC Low Demand scenario, all of the 1.5˚C scenarios in this study (and more widely (IEA Bioenergy, 2022)) feature bioenergy carbon capture and storage (BECCS) to balance out excess GHG emissions in their carbon budgets.

Traditional biomass is currently ~40% of primary biomass energy (IEA, 2021c). This form of bioenergy is typically unsustainable in the methods used to source biomass and inefficient in the methods used to convert it to energy, therefore phasing out this form of bioenergy will be vital to achieving emission targets (Welfle et al., 2020). In the IEA NZE and IRENA 1.5˚C scenarios, traditional biomass is completely phased out by 2030, while in the IPCC Renewables and Sustainable Development scenarios this phase out is more gradual, and largely happens between 2030 and 2050. Therefore a very rapid and sustained growth of modern bioenergy will be required to balance biomass energy demands in the 1.5˚C scenario. The international trade of biomass and biofuels is expected to increase as overall demand for modern solid biomass and biofuels grows, as not every nation has adequate domestic feedstock supply to meet domestic demand (IEA Bioenergy, 2022). This will require new cooperative practices between agriculture, forestry, waste and the energy sectors and effective policy mechanisms to monitor, regulate and ensure sustainability, technical and carbon performances (IEA Bioenergy, 2022).

Another key feature is the transition away from 'conventional' (1st generation) biofuels that rely on agricultural land to be produced (such as sugar cane and corn ethanol) to 'advanced' (2nd generation) biofuels that do not directly compete with food production (such as agricultural residues, waste and woody crops). The IPCC Renewable scenario specifies second generation bioenergy crops (grassy and woody varieties) in its scenarios description (Luderer, 2021). IPCC Low Demand avoids competition between biofuels and food security by limiting biofuel use, predominantly through reduced transport energy demand (Grubler, 2018). Across the IPCC illustrative pathways there is a transition to advanced biofuels in the medium to longer term (IPCC, 2022b). In IEA NZE scenario most of the increase in liquid biofuels by 2030 – from 3.8 EJ/yr to 12.5 EJ/yr – is from new advanced (second generation and beyond) biofuel production methods, and between 2030 and 2050 there is a wholesale shift away from 1st generation biofuels (IEA, 2021c).

As well as changing the type of biomass used in bioenergy applications, the 1.5˚C scenarios imply a change in use in the energy sector. By 2050, the IEA NZE scenarios project that 74% of biomass feedstock supply will be solid biomass, 15% liquid biofuels and 14% biogases. The projected end-users of the solid biomass derived bioenergy will be directed for fuel switching in industries that require high-temperature heat, such as cement (30%) and paper/pulp production (60%), and for emerging economies, it will be used in the building sector (10%). 80% of biogases are projected to be used in fuel blending in industry and the remaining 20% is projected to be used by the building and transport sectors. Liquid biofuels are projected to be directed to the transport sector, particularly for the decarbonisation of road freight and aviation, although there is uncertainty in the breakdown of the liquid biofuel end-users due to the decarbonisation of the transport sector via electrification and hydrogen fuel switching (IEA Bioenergy, 2022). There is though a common feature that bioenergy (outside of carbon removal) is predominantly used in future for hard to electrify applications – such as some transport and industrial processes (IEA, 2021c, IPCC, 2022b, IRENA, 2022e).

In the interim to 2030, all scenarios see a rapid growth for liquid biofuels and modern solid biomass. The growth in liquid biofuels is in road transport while awaiting the uptake of electric vehicles and end of life of petrol and diesel engines. The IRENA 1.5˚C scenario has a greater role for bioenergy in heating throughout the pathways and very strong growth in liquid biofuel for transport to 2030, but as in the IEA NZE, this growth slows as the decarbonisation of road transport moves away from liquid fuels out to 2050 (IEA, 2021c, IRENA, 2022e). High demand for modern solid biomass in the IRENA 1.5˚C scenarios corresponds to the greater role of bioenergy with carbon capture and storage (BECCS) in keeping the scenario within a 1.5˚C consistent global carbon budget when compared with other scenarios. This also requires the co-development of CCS infrastructure to enable biomass use in this way, and the co-location of bioenergy facilities with carbon storage or transportation infrastructure – not an insignificant requirement. Depending on the nation, BECCS projects are expected to be deployed in industrial clusters, often formed around estuaries with strong access to shipping ports, providing the low-carbon opportunity to source biomass both domestically and internationally (IPCC, 2021).

There is also expected to be increased competition for all categories of sustainable biomass over the timeline to 2050, both from different users within the bioenergy sector and with wider sectors. For example, biomass (sustainable sources of carbon) is increasingly targeted by the chemical sector to produce low carbon bio-chemicals, bio-plastics etc. There may be opportunities for optimising the utilisation of available biomass through circular economy approaches and with development of bioenergy with carbon capture and utilisation (BECCU) initiatives.

2.2.1 The bioenergy production gap

The 1.5˚C scenarios call for an annual increase in liquid biofuel supply of between 7% and 18% across the pathways from 2020 to 2030, from ~4 EJ to between 8 EJ and 20 EJ per year primary energy. The IEA projected growth in production as potentially only averaging 3% per annum between 2020 and 2025 (IEA, 2020), this however is before impacts on transport demand in 2020 and 2021 due to the Covid-19 pandemic are factored in. As such even faster rates of production increase will be needed to get back on track even for the IPCC Sustainable Development scenario with relatively slow biofuel growth (7%/annum).

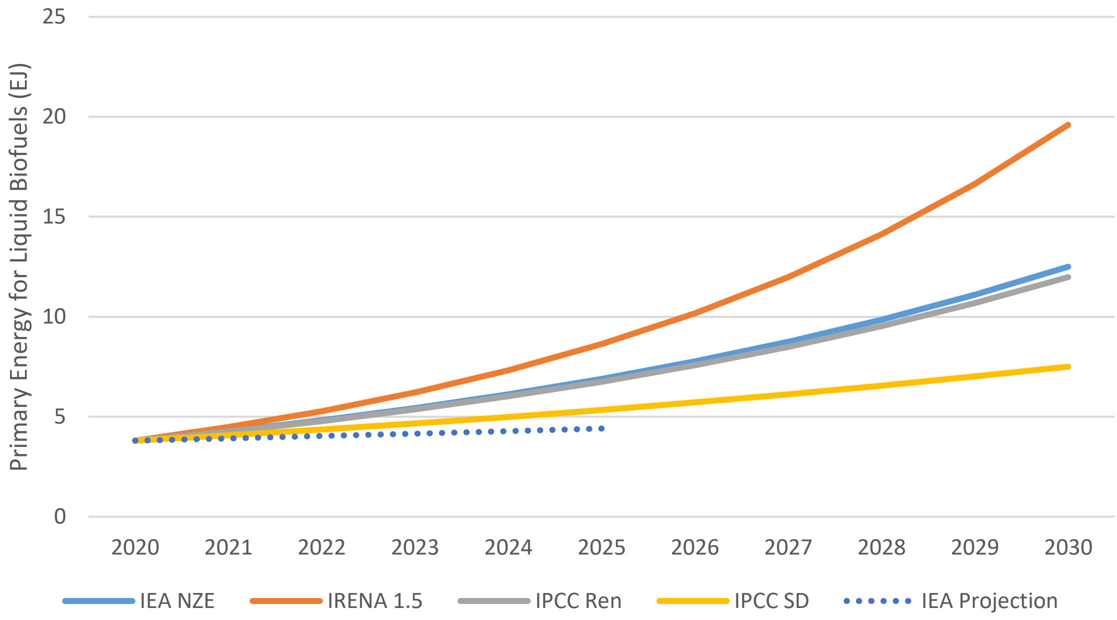

Figure 17: Implied liquid biofuel growth between 2020 and 2030 in the 1.5˚C Scenarios. Projected 5 year outlook for production capacity from IEA (2020).

Growth in biofuels has been 5%/yr in the last decade (IEA, 2021b). Biofuels are growing from a more established base than low-carbon hydrogen – accounting for 3% of transport fuel demand already (IEA, 2021b). In absolute terms, the gap between current production and the scenarios to 2030 is not as great as with hydrogen (see Figure 11). However, biofuel growth in the scenarios is largely expected to be from second generation biofuels in the longer term, yet currently only 7% of liquid biofuel production are second-generation. Second generation biofuels have so far not been able to compete with first generation fuels at scale due to higher costs (IRENA, 2019, IEA, 2021b). Closing the gap between biofuel and biomass uptake in the 1.5˚C Scenarios and current production would require additional government policies to grow/ produce / mobilise more feedstock supply to balance future increases in demand.

Improving vehicle efficiency and impacts on travel demand such as the Covid-19 pandemic have the potential to slow demand for biofuels. However, increased mandates and production policies appear popular in countries where first-generation food crop based biofuels (such as palm oil in biodiesel and corn ethanol) are dominant. This is because these countries have favourable geographic conditions for large scale crop growth, and have the required agricultural systems in place. This could however cause conflict related to food scarcity, as accelerated growth of first generation biofuels would naturally decrease the available land for food production. For example, the disruption to food production during the Russian invasion of Ukraine in 2022 has reportedly led to proposed waivers for existing biofuel blends and limiting the production of first-generation biofuels to ease food scarcity concerns (McFarlane, 2022). Specific mandates and direct support for advanced biofuels to replace cheaper first-generation fuels are lacking (IRENA, 2019). While first-generation biofuels dominate, the risk of actual and perceived conflicts with food production is likely to make accelerated growth unsustainable.

Bioenergy deployment faces similar challenges to hydrogen in terms of supply chain interactions, as raw biomass producers are not confident that demand will be met (particularly for energy crops and forestry) and land could have been better utilised for other production. Although, the majority of challenges facing bioenergy deployment are related to tensions between food and crop production, land-use change and biodiversity. Greater coordination, communication and transparency between sectors (agriculture, forestry and energy end-users) will be critical in ensuring that bioenergy supply chains are sustainably sourced and that the supply and demand between raw biomass-producing and bioenergy-consuming countries are sustainably and cost-effectively matched. Governance around procurement practices is a priority for bioenergy as bioenergy production interacts with eliminating hunger, increasing access to clean water, protecting biodiversity and economic development goals. Although there are both regulatory schemes (such as the EU Renewable Energy Directive) and voluntary schemes (such as the Roundtable on Sustainable Palm Oil (RSPO)), there is still no comprehensive governance framework for the wider 'bioeconomy' (IEA Bioenergy, 2022, Rose, 2022), and this is potentially a barrier to a rapid scale-up (Welfle and Roder, 2022).

In concert these factor lead to uncertainty about the quantities of biomass available to meet potential demand across all emerging sectors of demand. It is also unclear to what extent competing demand for biomass products as substitutes in bio-chemicals and bio-plastics will mean for availability in bioenergy applications. Competing demands for biomass from industrial processes are not integrated into future energy scenarios. The IRENA 1.5˚C scenario considers biomass as a feedstock to industrial products but it is not clear on the proportions expected for this use or the basis for these expectations. However although demand for non-energy bio-products may triple to 16 Mt by 2030, this is from a low base of 5.5Mt (E4 Technology, 2021). The literature on projected bio-plastic and bio-chemical demand out to 2050 is not sufficient to quantify how it might affect overall assumed biomass resources in energy scenarios. In the near term (to 2030), it is the capacity of biomass conversion and processing infrastructure and of end-user demand drivers, not resource availability, that are the limiting factors on bioenergy reaching the levels required in the scenarios. There is potential for intra-competition for biomass resources from liquid biofuel bioenergy projects and electricity BECCS projects. In some cases, such as the UK, the available biomass may be directed for BECCS-power projects (to meet carbon removal as well as energy needs) which may not leave enough available biomass for liquid biofuel production for transport and aviation, although currently the vast majority of BECCS projects (BECCS-Biofuels) in the US are producing liquid biofuels, such as bioethanol, which are being directed towards decarbonising road and shipping transportation (Consoli, 2019, Bello et al., 2020). The aviation sector has identified second generation biofuels as a key component of the sustainable aviation fuel agenda. Although still in an early stage, mandates for biofuels in aviation fuel are emerging – for example in California.

2.3 Fossil Fuels in 1.5˚C Scenarios

The phase out of unabated fossil fuel is a major component of the 1.5˚C scenarios. However international actors at the UNFCCC COP26 in Glasgow in 2021 only went as far as a promised 'phase down' of coal rather than a phase out of oil, natural gas and coal. Financial support from governments for fossil fuel production and consumption is increasing (IEA, 2022g) despite climate pledges meaning that the likely near term trend is to follow an emissions pathway to >3˚C rather than to limit to 1.5˚C.

Figure 18 highlights the potential gap between how current government policies could affect coal use and the pathways required for a 1.5˚C global warming outcome. For the 1.5˚C scenarios there is a sustained and rapid decrease in coal demand between 2020 and 2030.

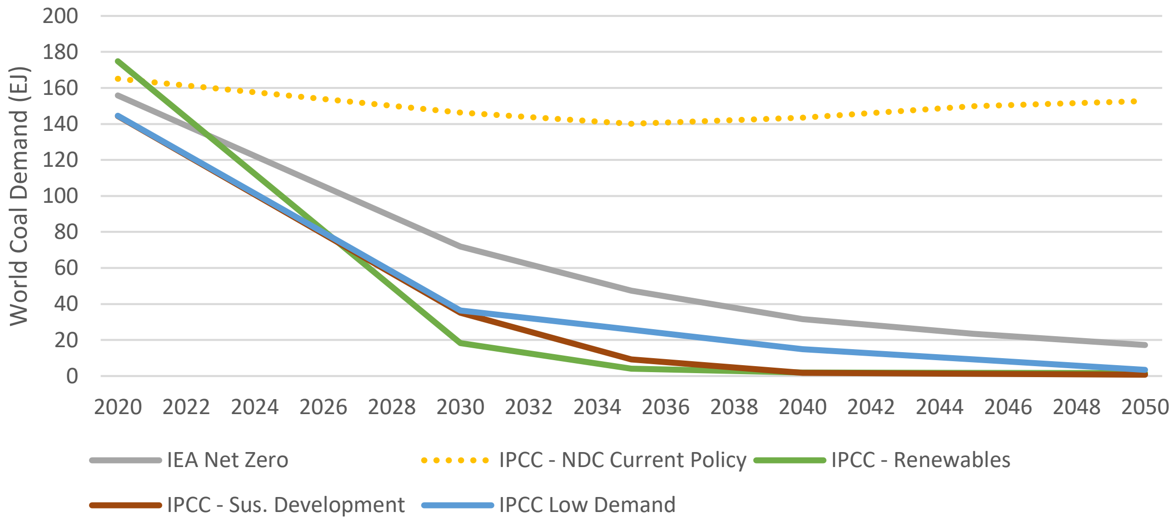

Figure 18: Projected coal demand in scenario pathways.

The current trajectory of coal use may exceed even the scenario based on current NDC pledges. Coal demand rebounded strongly from the Covid-19 economic downturn and may slightly increase out to 2023, or at least remain flat (IEA, 2022a). Disruption to world energy markets in 2022 due to the Russian invasion of Ukraine is one reason for this, however coal demand was increasing in 2021 also, highlighting that stronger policies and international cooperation is needed to close the gap on required declining coal use.

The 1.5˚C scenarios and the IPCC NDC based scenario assume that oil demand at least plateaus in the near term (to 2030), before declining steadily in the 1.5˚C scenarios (Figure 19). Regional breakdowns in the scenario datasets indicate growth in developing Asian economies partially or wholly offsetting declines in oil demand in Europe and North America to 2030 before declining in all regions post – 2030.

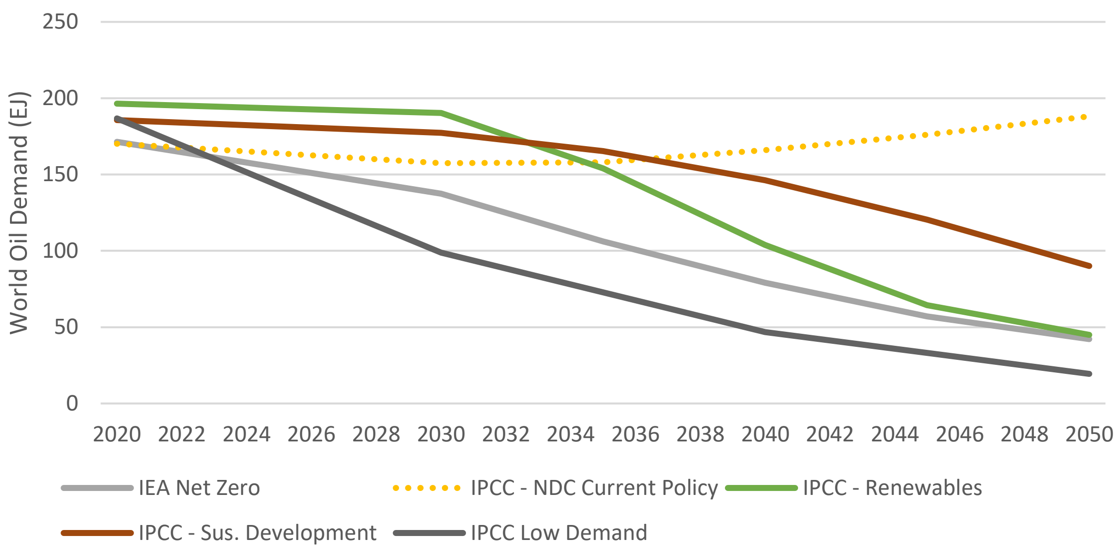

Figure 19: Oil demand pathways in scenarios.

As with coal, oil demand is not on track to peak and reduce in the near term. Even with a potential economic slowdown forecast for the 2022 to 2025 and higher prices, oil demand is not expected to plateau or decline in the existing market and policy context. Away from macroeconomic influences on oil demand (i.e. fuel price and GDP) there are also indications that policies to reduce demand are lacking. In Europe average CO_2 emissions (consequently fuel consumption) from new cars registered have been increasing again between 2016 and 2020, potentially due to the prevalence of heavier sports utility vehicles (SUVs) (European Environment Agency, 2022). Interim EU targets in 2024 for average new passenger vehicle fuel consumption, where scenarios anticipate oil decline happening earliest, look likely to be missed. Strong growth in the EV market and improvements to public and active transport are be needed to adjust underlying structural demand for oil aligned with 1.5˚C pathways.

Natural gas consumption is projected to have sustained growth through to 2050 in the current NDC policy scenarios, indicating that in the absence of further climate change policy it would increase to be a mainstay for global energy use (Figure 20). In the 1.5˚C scenarios the decrease in natural gas use declines to varying degrees between 2020 and 2030 before a more consistent rate of decline across all scenarios.

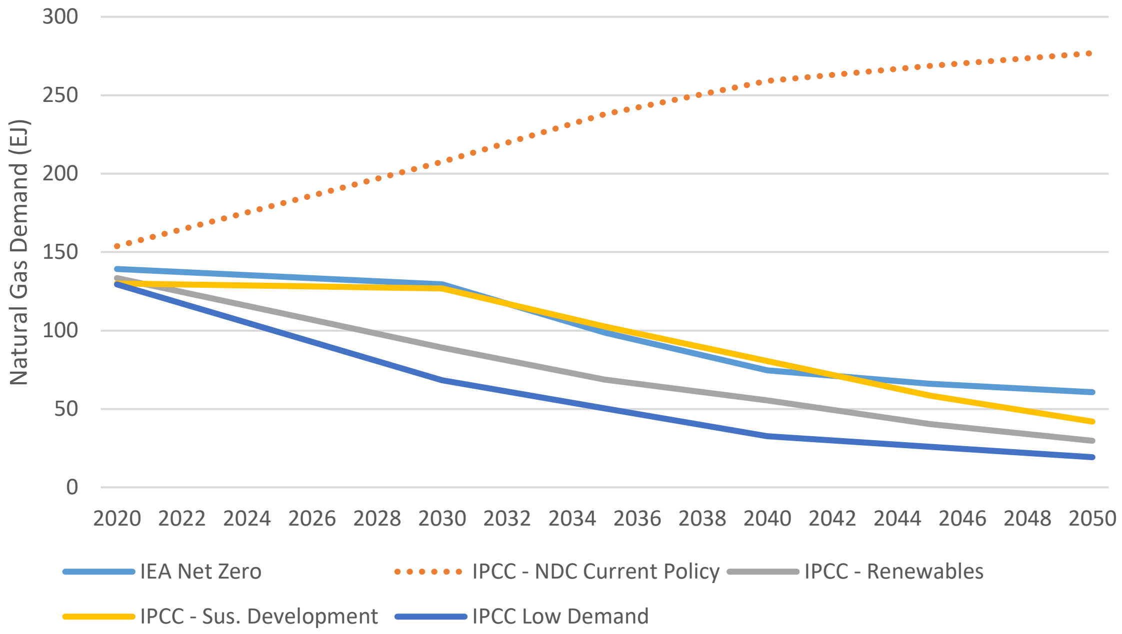

Figure 20: Natural gas demand pathways in scenarios

Higher gas prices and other impacts due to the Russian invasion of Ukraine suggest no or low growth in natural gas demand in the 2022 to 2025 period (IEA, 2022b). This effect is larger than any climate policy driven impact – prior to the Russian invasion, natural gas demand was expected to have robust growth (McKinsey, 2021). A return to growing unabated natural gas use is likely unless the response to supply disruption considers climate change co-benefits. However, sustained high prices could drive accelerated investments in supply alternatives and energy efficiency measures that could embed the longer-term transitional changes in energy systems required in 1.5˚C scenarios.

Comparing the required energy system changes to achieve the 1.5˚C scenario pathways highlights the need for a rapid phase out of coal and the peaking and phase down of oil and natural gas over the coming decades. The rates at which electrification, hydrogen and biomass fuels replace conventional fuels and energy demand reduces varies across the pathways. Current trends however point to a growing gap between the energy pathways for 1.5˚C and actual energy system characteristics. Energy demand globally increased in 2021 to higher than pre-Covid levels, fossil fuel use has not stopped growing and production of low-carbon fuels is nowhere near the pace required for the scenarios. Assertive government action is needed to drive investment and preference for low-carbon fuels and change the current direction of travel in order to limit global temperature rise to 1.5˚C. The next section of the report considers what the changes in the energy system if this were achieved could mean for the shipping industry.

3. Implications for Shipping

Across all of the 1.5˚C scenarios there is a rapid transition from fossil fuels to low-carbon fuels and renewable electricity. This reconfiguration of the energy system will have important implications for the global fuel trade as soon as 2030 if these low emissions pathways are achieved. Shipping is an important component of the global fuel trade, with these changes affecting not only the quantity and type of fuels shipped, but potentially the fuel use of ships themselves. This section considers the implications of the 1.5˚C scenarios for the seaborne fuel trade. Changes in global fuel demand implied by the scenarios are presented, key factors in determining to what extent low-carbon fuels are traded are discussed, before the potential implications for seaborne energy products trade are quantified.

In 2021 energy products accounted for ~36% of global seaborne trade by tonnage (Clarksons, 2022a). The relative significance of energy products to shipping has decreased overtime – from ~45% of seaborne trade in 2000 – while the shipping industry has grown (Clarksons, 2022a). Crude oil and oil products is the majority (~66%) of seaborne energy transported. At present, ~64% of oil, and ~15% of both natural gas and coal is transported by sea (see Figure 21).

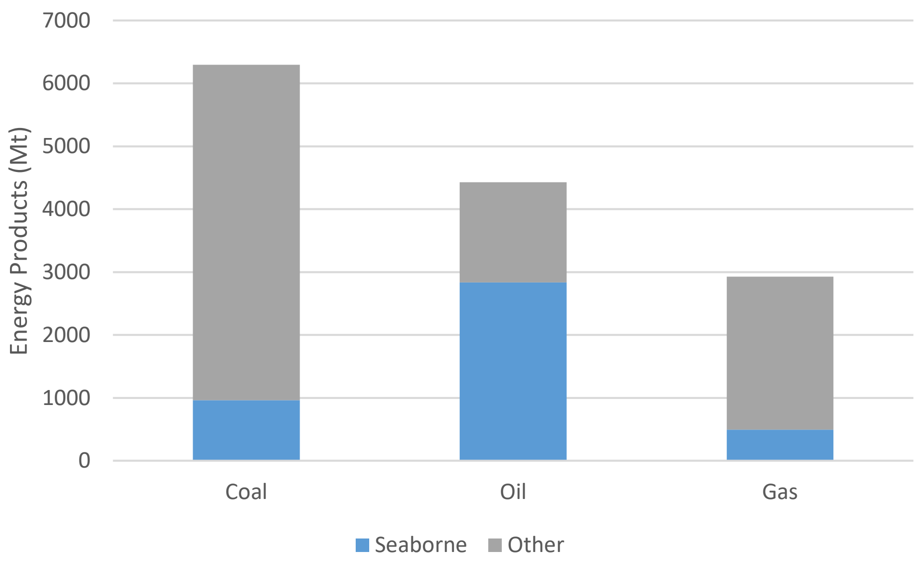

Figure 21: Fossil Fuel Energy Products - Total production in 2021 and the proportion transported by ship (seaborne) and either pipeline, road or rail freight (Other). Source (Clarksons, 2022a)

The implications for the shipping sector of changes in the global fuel mix depend on a range of factors. Features of a fuel and its production and consumption determine how it is transported. This includes the spatial relationship between where it is produced and consumed and the relative cost effectiveness and technical feasibility of alternative transport: by pipeline, road and rail (Figure 22). As fossil fuel use declines, the extent to which reduced capacity is replaced by low-carbon fuels depends largely on the features of low-carbon fuels in the same regard. The factors influencing the extent to which fuels might be transported by ship in the 1.5˚C scenarios is discussed in turn and the potential outcomes for quantities of seaborne energy products traded is considered across a range of possible outcomes.

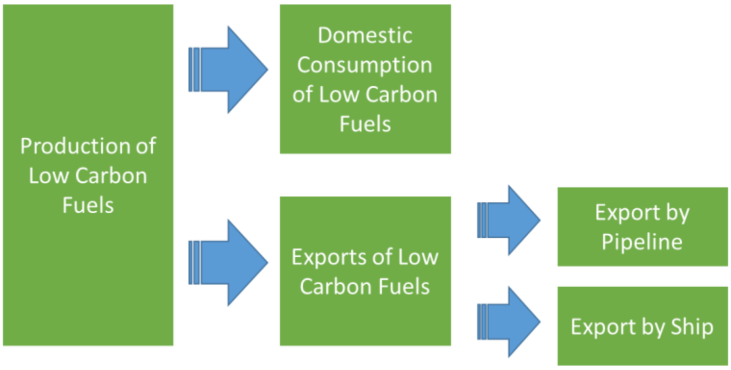

Figure 22: Flow chart of proportion of low-carbon fuels potentially transported by ship.

3.1 Seaborne Hydrogen Trade

The increase in hydrogen consumption for energy across the scenarios may be expected to lead to more hydrogen being traded between nations, but this will depend on how the global hydrogen economy develops. The type of hydrogen production (whether green or blue) and relative costs of production, transport and conversion to liquid hydrogen or ammonia all determine the extent to which hydrogen for energy use becomes a globally traded commodity.

Current grey hydrogen production is frequently co-located near to demand centres and methane supplies (in part due its use in oil refining processes). Although green hydrogen could be produced in a wider variety of locations and co-located with demand, differences in production costs, existing infrastructure and government policy means some trade between nations is likely. While there are plans for blue and green hydrogen production in consumer regions such as the EU and China, the lowest cost green and blue hydrogen may be produced in countries and regions such as Australia, the Middle East, Africa (e.g. Morocco and Namibia) and South America (Chile) (IRENA, 2022b). Countries with strategies to increase hydrogen demand in the near term – Japan, South Korea, Singapore and Germany – have bilateral trade agreements with these producer countries (Figure 6).

These exports would either be by pipeline or by ship. IRENA estimate that due to relative costs, pipelines are more likely for transmission distances up to 5,000km before shipping becomes more cost effective (IRENA, 2022b). Cost is not however the only issue: for mid-ranges the greater flexibility of ships over pipelines make shipping a potentially more attractive option to take advantage of changing prices for hydrogen, natural gas prices and power generation in different countries (ICS, 2022).

Hydrogen has a low volumetric density, and consequently to reduce the space required for its transport would require it to be liquefied or converted into ammonia. Trials of liquid hydrogen tanker ships are underway (Sonali P, 2022) however ammonia is already routinely shipped and there is currently an expectation that hydrogen will be predominantly shipped as ammonia in the future (IRENA, 2022b).

Transporting hydrogen as ammonia by ship may follow a supply chain as set out in the example in Figure 23 showing potential interactions between export and import countries and ammonia and hydrogen in the non-energy sector as well as for energy services.

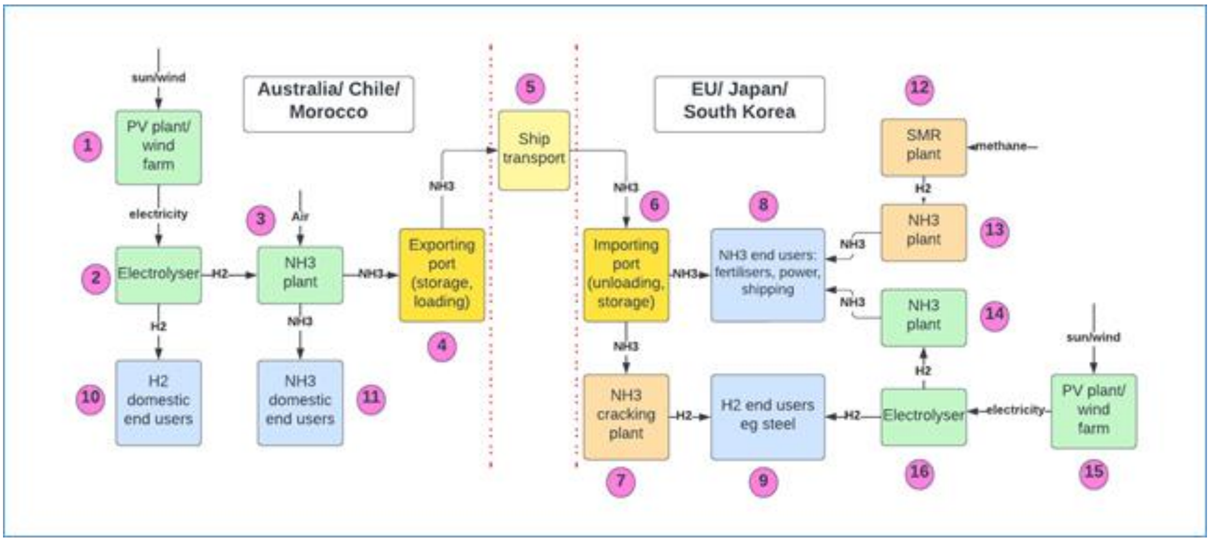

Figure 23: Stages in green ammonia production, transport and use

From an assessment of existing planned hydrogen projects, Australia, Mauritania, Oman, Chile, Saudi Arabia, Brazil, Morocco, Democratic Republic of Congo and Egypt are example potential exporters of hydrogen energy products. A number of issues affect the extent to which hydrogen in these countries might be exported by ship:

- Competing demand for hydrogen/ammonia within the producer country (points 10&11 in Fig. 23)
- The feasibility of a pipeline connection to a consumer country
- The relative cost of transport by ship versus pipeline
- The relative cost of imported green hydrogen/ammonia (points 1-3) versus grey/green/blue hydrogen/ammonia produced in the potentially importing country (points 12-16, Fig. 23)

The cost of transporting hydrogen by ship is cited as an issue (IRENA, 2022b), particularly when comparing hydrogen produced domestically with imports. This is because although it is most efficient to ship hydrogen as ammonia, because of hydrogen's low density, doing so incurs an energy and cost penalty, both in converting hydrogen to ammonia in the producing country, and then cracking this ammonia back to hydrogen in the consuming country.

This issue does not necessarily apply if the imported ammonia is used directly as ammonia in the consuming country, for example to use for power generation. In this case, cracking is not required. Overall, the actual transport cost of importing ammonia is low, adding around \$100/t NH_3 (IRENA, 2022a) and consequently imported green ammonia is already potentially competitive with green ammonia produced in the EU (ICS, 2022), given the cheaper costs of renewable electricity in exporting countries (points 6&7 in Figure 23).

In addition, the case for green ammonia imports in 2022 compared with using blue/grey ammonia is better than previously assumed due to increased natural gas prices. For example, one comparison of green vs grey/blue ammonia costs estimated green ammonia production costs of $1,055/t NH_3, compared with $375-475 for grey/blue (Yara, 2022b). This however assumes a gas price of $4.5/MMBtu from 2022 to 2050. Gas prices constitute around one third (Yara, 2022b) of grey/blue NH_3 production costs and have been over $10/MMBtu in Europe and Asia since May 2021, and have averaged over $30/MMBtu between October 2021 and June 2022 in Europe(YCharts, 2022, IEA, 2022f). While there is great uncertainty about future gas prices, and prices in 2021/22 have been impacted by the Covid-19 pandemic and the Russian invasion of Ukraine, gas future prices to 2025 are $24/MMBtu as of Sept 2022 (CME Group, 2022) . More recent reports (Janzow, 2022, Green Hydrogen Task Force, 2022, ICS, 2022), have brought forward the point at which green hydrogen/ammonia can be cheaper than grey/blue hydrogen/ammonia far faster than previous analyses have anticipated. This point does not apply everywhere however – although natural gas prices in the USA are higher in 2022 than in 2020, they are still very low (~$8/MMBtu) compared with 2021/22 prices in Europe and Asia.

Shipping green ammonia from countries such as Australia/Chile to Japan/Europe also has to compete with this ammonia (or hydrogen) being used domestically. Australia in particular has large industries and other sectors capable of soaking up a lot of hydrogen demand. However, the sheer scale of hydrogen resource potential in these countries is such that most analyses believe that many countries, including Australia, would be major net exporters of hydrogen (IRENA, 2022b, Janzow, 2022). The potential to diversify trading partners and the lower operating costs relative to capital costs for green hydrogen and ammonia could make this technology pathway appealing on energy security grounds as well (Janzow, 2022).

Overall, the possibility space for a global hydrogen trade remains broad. It is uncertain which countries will see the greatest growth in production of and demand for low carbon hydrogen. These dynamics will determine future trade patterns. IRENA estimates that potentially a quarter of hydrogen produced for energy will be traded internationally, of which 45% would be by ship. In other words, 11% of hydrogen produced for energy use could be transported by ship (IRENA, 2022b) representing a practical indication of how the hydrogen trade might develop if proposed projects and bilateral agreements are realised.

3.2 Seaborne Bioenergy Trade

There is high certainty that demand for biomass and biofuels from the international trade markets will continue to grow (Welfle, 2017). The uncertainties lie around how future bioenergy supplies will develop globally, as well as the regional distribution of production and demand.

Global bioenergy trade activity will vary by type. Europe has been the leading market for solid modern biomass products (Commission and Joint Research Centre, 2019). A large intra-European trade, as well as the development of trans-national biomass supply chains from North America to Europe, characterises most of modern solid biomass trade at present (5.8 Mt of wood pellets from North America to Europe, 6.7 Mt transported within Europe) (Junginger, 2019). This is because until recently, countries with growing demand and policy incentives for biomass have had relatively low biomass availability (Welfle and Slade, 2018). The UK and Italy for example import 95% and 81% of their wood pellet fuel respectively from other countries (Commission and Joint Research Centre, 2019). In the case of the UK, 7.8 Mt of wood pellets were imported, predominantly (82%) from North America. A significant proportion of global solid biomass trade is by ship – however most biomass is used domestically or regionally (IEA Bioenergy, 2018, Junginger, 2019).

There is debate about whether decentralised biomass production, using local resources to mitigate concerns about GHG emissions, biodiversity and food production impacts (Welfle and Slade, 2018, Forster et al., 2020), is more optimal than more centralised facilities that maximise economies of scale (Sanchez and Callaway, 2016). Port to port transport of biomass is not significant in determining the overall sustainability of a biomass product, however emissions can be reduced by minimising distances bulk biomass products are transported by road if shifted onto low-carbon transportation methods like shipping and rail (Sanchez and Callaway, 2016). The travel distance by road of solid biomass would therefore be a key consideration on its suitability for export if regulations were in place to minimise supply chain emissions of biomass resources. This is before interactions between biomass and carbon capture and storage infrastructure for carbon removals is considered. To what extent bulk biomass will be shipped to locations for carbon capture and storage is unclear given the slow development of carbon capture – however notably CO_2 is starting to be shipped from emissions sources to integrate into carbon storage infrastructure, as in the case of the Norwegian Northern Lights project and carbon capture projects in South Wales, London and Southampton in the UK (Yara, 2022a).

The trade in bioethanol has historically been predominantly regional within North America and Europe (0.1 Mt of bioethanol), with global trade mostly from Brazil to North America (0.5 Mt of bioethanol) and Japan (0.4 Mt of bioethanol) (Junginger, 2019). For biodiesel the significant flows are from Argentina (0.6Mt of biodiesel), Indonesia and Malaysia (0.2Mt of biodiesel) to North America, but leading biodiesel markets in Europe like Germany are currently self-sufficient. Demand is driven by mandates on the content of biofuels in transport fuels. In the near term, the largest growth in production capacity is in large bioethanol and biodiesel producer countries that are also increasing their fuel blend mandates – Indonesia, Brazil, USA and Malaysia (IEA, 2022c). Near term growth through expanded global trade in biofuels in not therefore expected. In the IEA NZE and IRENA 1.5˚C scenarios, biofuel demand growth slows after 2030 as liquid fuel use for transport declines from 2030 onwards. This is due to the electrification of surface transport while biofuels become more applicable to aviation, shipping and road haulage. Liquid fuels have a greater role in road transport in the IPCC Renewables and Sustainable Development scenarios and biofuel demand is greater suggesting fuel blend mandates increase and the move to electric vehicles is assumed to be slower. In recent years, major car markets across Europe, Japan, North America and China have stated that there will be prohibitions on new petrol and diesel cars in the 2030s. If implemented, there would be significant decline in the fuel systems that use biofuels for passenger vehicles by 2050 as indicated in the IEA and IRENA scenarios.

In 2019 it was estimated that ~2% of global bioenergy production was sourced from biomass feedstock that was transported via ship (Junginger, 2019). However there remains a diversity of views on what biomass resources will be dominant and where they will be produced (Rose, 2022). The costs of resources, carbon pricing and environmental and social constraints used in models lead to varying results (Rose, 2022). The key implication is that the type of biomass used – e.g. residues, energy crops and forestry – and whether countries self-consume, export or import, depends on how these features of the bioenergy sector develop. There is some evidence to suggest that bioenergy products could be largely consumed domestically or regionally where producer countries have policies to drive consumption (Welfle and Slade, 2018, Junginger, 2019, Welfle, 2017). However, this does not rule out the potential for a global biomass trade. The development of the bioenergy sector shows that regions with advanced incentives for bioenergy consumption can end up needing to import from countries with high resource and low utilisation (such as UK imports of biomass form North America). In the end, the extent to which biomass and biofuels will be shipped will significantly depend on the shift away from utilisation for road transportation and what feed-stocks come to dominate supply – which also hinges on the extent to which legislation, regulations and other protections focussed on biomass sustainability are put in place.

Changes in Fossil Fuel Seaborne Trade

Phasing out fossil fuel use globally will reduce traded volumes of energy products by ship. Although the relative share of energy products as a proportion of tonnage has been declining (Clarksons, 2022a), energy is an important part of shipping trade. Changes in oil and coal demand would be expected to translate into significantly reduced quantities of energy products shipped in the next decade. However, the outlook for natural gas shipments is distinct in that within the 1.5˚C scenarios, although overall demand reduces, it is projected to increase in developing countries (see Figure 24).

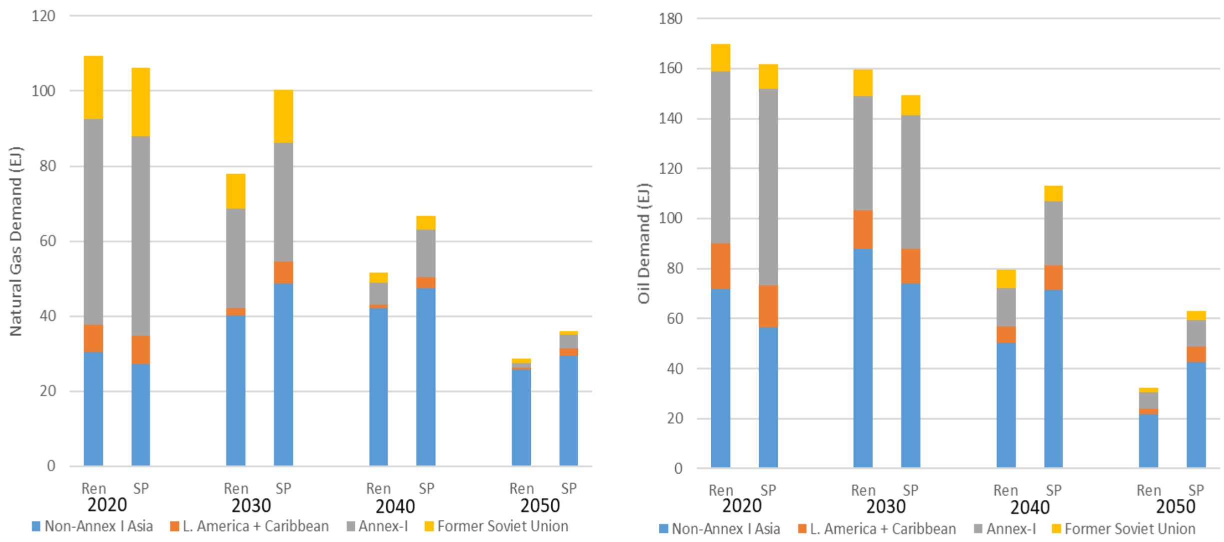

Figure 24: Regional distribution of natural gas demand in IPCC Renewables and Sustainable Development scenarios

In these IPCC scenarios, natural gas demand is between 452 Mt and 780 Mt greater in non-OECD Asian countries in 2040 compared to the 2020 baseline. In keeping with the common but differentiated responsibility and respective capabilities framing of much of the international climate change discourse, natural gas and oil use reduces at a much faster rate in developed OECD (Annex-I) countries while there is still growth in developing economies. This might be predominantly expected to be transported by ship, given current supply and the distances between key producers and consumers.

The IMO's assessment of future traded fuels in IPCC emissions pathways shows a similar expected outcome. Tonne mileages for coal and oil fall steeply, whereas gas tonne mileages rise (Table 6) – this is because although gas demand falls, the distance each unit gas is shipped almost doubles (IMO, 2020).

Table 6: Projected Transport Work (billion tonne miles) in IPCC 1.5C emissions pathways - SSP1_RCP1.9 and SSP2+RCP1.9, table 19, p372 in (IMO, 2020).

Billion tonne miles/yr	2020	2050	% change
Coal	5,563	1,089-1,553	-72 to -80
Oil	13,561	2,256-2,989	-78 to -83
Gas	1,781	2,075-2,245	+16 to +26

Therefore while coal and oil trade by ship is expected to reduce in line with declining global demand, natural gas shipments can be expected to at least remain at current levels and potentially increase to 2040 before reducing in 1.5˚C scenarios. A strong caveat to this assumption is that the full lifecycle GHG emissions of LNG shipments must be accounted for in any assessment of the relative merits of pipeline versus shipment of gas products, as overall gas use declines.

Projections of future seaborne transport of fuels

Based on the assessment above, two 'what-if' extrapolations for seaborne fuel trades in the 1.5˚C scenarios are shown in Figures 25 and 26. Traded volumes of coal and oil by are assumed to decrease proportionally with overall global demand changes in the scenarios. Natural gas transported by ship is assumed to stay constant in absolute terms out to 2050[7], though the proportional share of produced natural gas that is shipped increases from 15% (2020) to between 38% and 80% depending on the scenario by 2050.

High export and low export variations of low-carbon fuel seaborne trade are assumed. It is assumed that hydrogen is shipped as ammonia, and that the proportion shipped ranges from 7-15% in 2050, with a mid-value of 11% (IRENA, 2022b). For bioenergy, in the high export version it is assumed that the percentage of bioenergy shipped increases from 2% now to 15% by 2050, in line with the percentage of coal shipped. A low export version assumes an increase to half that amount (7.5%) by 2050. This variation highlights the potential for significant domestic and intra-regional utilisation of these fuels. This is still a considerable increase from the current 2% of biomass supply that is shipped. This increase would require policy to discourage the use of short-distance carbon-intensive HGV biomass transportation and encourage the recalibration of biomass supply chains to use low-carbon transportation alternatives such as shipping and rail.

[7] As a sensitivity, different assumptions of 40-60% of gas transported by ship in 2050 would give a range of 248-775 Mt, instead of the 492 Mt value in Table 7.

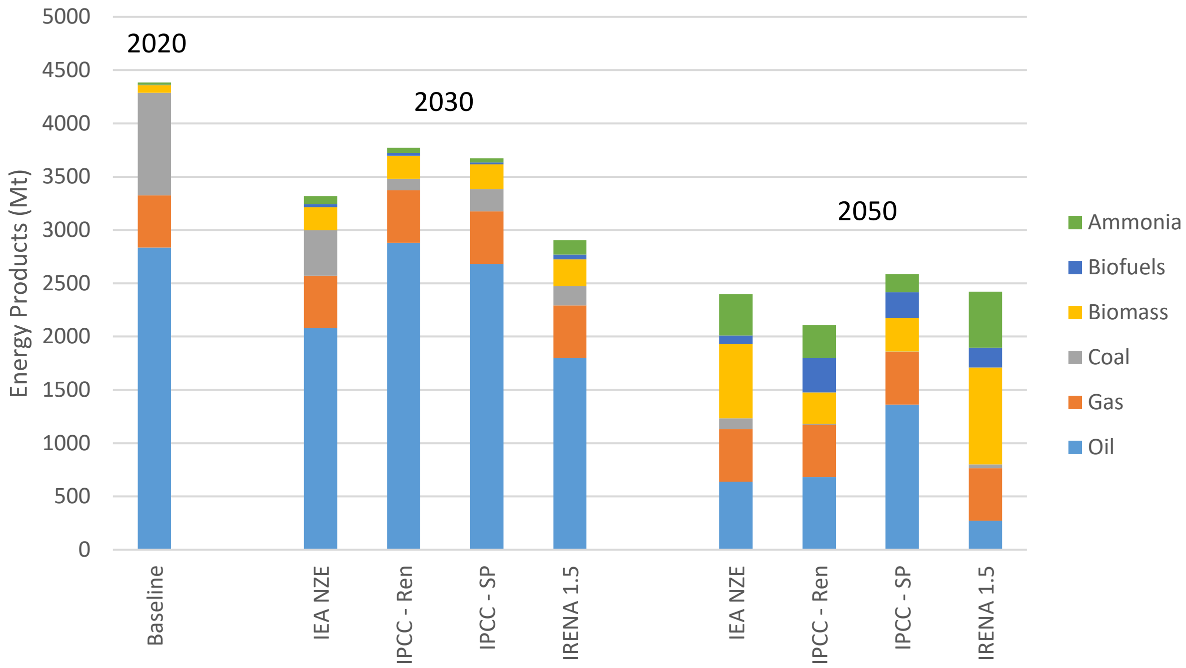

Figure 25: Potential seaborne trade outcomes for the 1.5˚C scenarios, assuming higher levels of trade of emergent low-carbon fuels and deployment at scale of carbon capture and storage technologies.

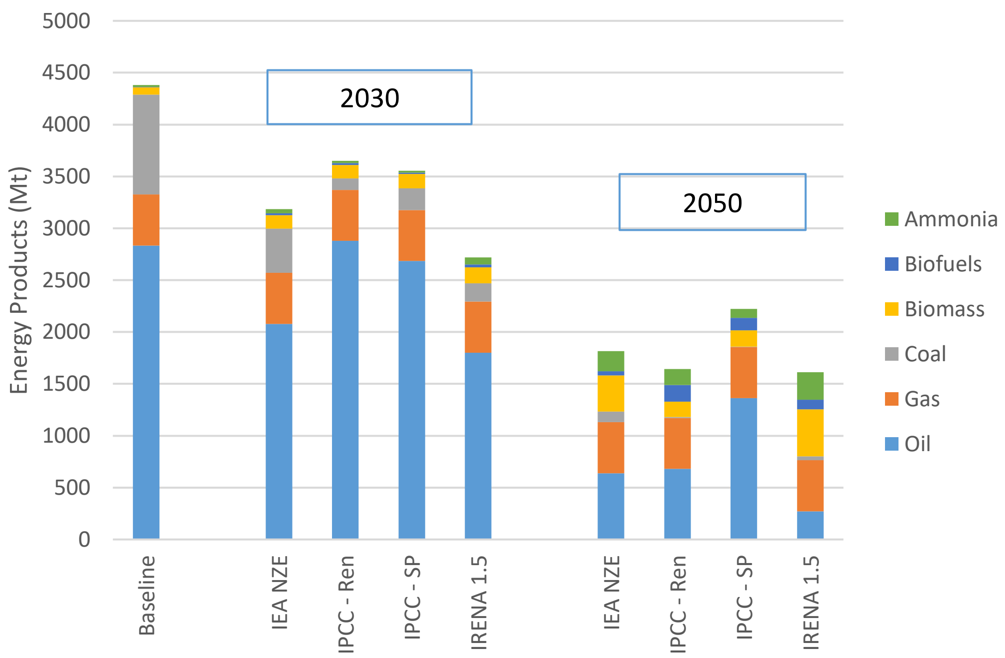

Figure 26: Potential seaborne trade outcomes for the 1.5˚C scenarios, assuming lower levels of trade of emergent low-carbon fuels and deployment at scale of carbon capture and storage technologies.

Table 7: Seaborne trade of fuels under high and low-carbon fuel trade assumptions across the 1.5˚C scenarios.

Mt/Year	2020	2030	2050
Oil	2834	1,801-2,879	272-1,363
Gas	492	492	492
Coal	963	108 - 426	4 -102
Biomass (High Export)	71	216-252	294 - 911
Biofuels (High Export)	3	18-47	81 - 322
Ammonia (High Export)	20	39 - 135	171 - 527
Biomass (Low Export)	71	130-153	147-156
Biofuels (Low Export)	3	11-28	41-161
Ammonia (Low Export)	20	19 - 68	86 - 264

Figures 25 & 26 and Table 7 show how overall tonnage of shipped energy products may evolve in the 1.5˚C scenarios. Even with the higher seaborne trade assumption for low-carbon fuels, natural gas shipments remaining constant and lower density ammonia assumed for hydrogen shipments, overall tonnage of energy products reduces by 41% to 52% across the scenarios. This is primarily because low-carbon fuels are not expected to fill the role that oil has today – an energy product traded predominantly by ship. It also highlights the implications in the scenarios of reduced energy demand and greater electrification of both surface transport and building energy use provided not by fossil fuels, but by renewables. Nonetheless, despite these overall falls, the shipping sector could be expected to become a major transporter of bioenergy products and ammonia, with overall tonnage of shipments for each comparable with current global shipments of coal and gas.

4. Shipping Enabling the 1.5˚C Scenarios

For low-carbon fuel shipments to be ready to support the deployment rates assumed in the 1.5˚C scenarios, global shipped trade of low-carbon fuels requires much more than production facilities and willing consumers. Infrastructure investments will be needed to get products to exporting ports, for storage, loading into appropriate vessels, for transport to market and then for unloading, storage and distribution at importing ports. **This section of the report considers the preparedness of the shipping industry to support the transport of low-carbon fuels**. Hydrogen and hydrogen-derived fuels are used as an example.

Countries and regions expecting to import hydrogen are already well equipped to deal with ammonia imports. 10% of global ammonia production (17 Mt/yr) is already traded (IRENA, 2022d), and there is a large global ammonia infrastructure in place. Furthermore, there is ammonia bunkering infrastructure at over 150 ports (DNV, 2022), with a total capacity of 5Mt (Table 8).

Table 8: Ammonia terminal capacity (source: analysis of AFI.dnvgl.com data)

Region	Number Ammonia terminals	Total tonnage
Europe & Russia	49	1,075,029
Asia	51	1,025,376
South & Central America	23	865,200
USA	19	715,200
Middle East	11	623,000
Africa	12	555,000
Australia	5	173,000
Total	170	5,031,805

Some ports are also actively planning additional ammonia infrastructure, for example Rotterdam. Other ports that do not have ammonia infrastructure (such as Singapore) are actively planning how to enable ammonia bunkering, for use by international shipping.

- Singapore
    - Consortium feasibility study on green ammonia supply chain and bunkering, March 2021 (Maersk, 2021), phase 1 report in April 2022 (SABRE, 2022, Stott, 2022b);
    - Sumitomo Corp and Keppel sign m.o.u for Singapore ammonia bunkering, Dec 2021(Pekic, 2021)
    - Ammonia bunker vessel gets Approval-in-Principle backing from classification society ABS (Ship Technology, 2022), June 2022
    - Sembcorp, Chiyoda and Mitsubishi sign green hydrogen into Singapore supply chain m.o.u (Sembcorp, 2022).

- Rotterdam
    - June 2022, final investment decision for OCI to triple ammonia capacity at Rotterdam to 1.2 Mt/y (OCI, 2022);
    - May 2022, 69 player consortium announces plans of import of 4Mt green H_2/yr into Rotterdam (Port of Rotterdam, 2022);
    - May 2022 Rotterdam signs hydrogen supply chain memorandum of understanding with Queensland, Australia (PACE, 2022)
    - June 2022, Air Products and Gunvor sign joint development agreement for green hydrogen import terminal (Air Products, 2022);
    - April 2022, Gasunie, HES international and Vopak announce plans for new ammonia import terminal (Vopak, 2022);

- 2021 Safety study for bunkering at Amsterdam (DNV, 2021b);

- 2021 Risk assessment for bunkering at Oslo (DNV, 2021a);

- Mitsubishi and Mitsui complete ammonia bunkering study, Feb 2022 (Mitsubishi, 2021);
- Yokohama, Japan, April 2022 alliance agreement signed on ammonia receiving terminals (JGC, 2022);
- Brunsbüttel, Germany, March 2022. 300kt ammonia import terminal announced (RWE, 2022).

While for importing ports, ammonia infrastructure is well developed, the outlook for new potential exporting ports is less so. For exporting ports, it is possible that new ammonia infrastructure will be required, as new production facilities are not guaranteed to be near ports that already have ammonia infrastructure. This is not a uniform picture – for example the planned Australian Renewable Energy Hub in Western Australia is close to the Pilbara ports, with 80,000 tonnes of ammonia storage, and Saudi Arabia has major plans for green hydrogen and ammonia production, and is already the world's largest grey ammonia exporter (4Mt/yr) with major ammonia infrastructure at multiple ports. Abu Dhabi has also announced a new planned ammonia export terminal (TAQA, 2021).

The outlook for vessels to support traded hydrogen and derived fuels also appears well positioned to support product flows as they develop. Currently there are 1,545 LPG vessels globally, 443 of these are classed by Clarksons as ammonia carriers. Other estimates are that only 40-170 or so vessels are responsible for the majority of global ammonia shipments (17 Mt/year)(IRENA, 2022d, IRENA, 2022c, Topsoe et al, 2020)[8]. LPG carriers can be adapted to carry ammonia, and there appears to be capacity in the current ammonia carrier fleet to absorb short-term increases in ammonia transport. However, over time additional ammonia carriers will be needed. Table 9 sets out some potential green ammonia demand figures for different sectors.

Table 9: Potential Green Ammonia Demands

Demand type	Ammonia requirement/yr	Assumptions
Japan co-firing in power stations	0.5 Mt	Tender issued by power utility JERA (Atchison, 2022c)
Australia-Japan iron ore	1 Mt	All the current iron ore trade on the route is replaced by 41 dedicated zero-emission vessels(Getting to Zero Coalition, 2021)
Asia-Europe shipping containers	3.5 Mt	17% of ships are zero emission by 2030 (Getting to Zero Coalition, 2021)
All Germany/ UK/ France/ Netherlands ammonia consumption	9Mt	Assumes all replaced with imports[9]

[8] With IRENA 2022d saying there are 170 vessels which can transport ammonia, and 40 doing so continually, and IRENA 2022c saying this trade is by 70 LPG tankers, citing Topsoe et al, 2020.

[9] Sources: Wits.worldbank.org for import/export data; production data from https://www.nationmaster.com/nmx/ranking/ammonia-production

The number of ships required to transport ammonia depends on:

- Ship size
- Ship speed
- Distance travelled
- Time between trips

Ammonia carriers vary greatly in size, from under 5000 Gt to over 50,000 Gt. The average size is 17,000 Gt. It could be expected that carriers supplying new ammonia transport from, say, Australia to Asia would be larger carriers. Carrying capacities for different vessel sizes are set out in Table 10.

Table 10: Ammonia carrier sizes and capacity

Example vessel name	Vessel size (gross tonnage)	Vessel ammonia capacity (m^3)	Vessel ammonia capacity[10] (tonnes)
Trammo Paris	17,242	23,237	15,848
Yara Aesa	25,118	38,000	25,916
Clipper Orion	36,459	60,000	40,920
JS Ineos Dolphin	59,299	81,898	55,854

Distances vary greatly. The average distance for an ammonia cargo in 2020 was 2,700 miles, which would be a round trip of 5,400 nautical miles. Assuming a speed of 11 knots, this is 21 days, a maximum of 17 round trips per vessel per year. A round-trip from Oman to South Korea would be 13,500 nautical miles, 51 days, with a maximum of only 7 round-trips a year possible. Australia to Singapore would be 4,400-8,300 nautical miles, depending on which Australian port was used.

Table 11 sets out the number of ammonia ships needed, depending on vessel size and route. This assumes an average speed of 11 knots, and 5 days between trips.

Table 11: ship requirements versus routes and size

	Number of ships needed to transport 1 million tonnes NH_3 per year		
Vessel size (gross tonnage)	Current average route	Port Hedland, Australia to Fukuyama, Japan	Duqm, Oman to Ulsan, South Korea
17,242	4.4	5.9	9.7
25,118	2.7	3.6	5.9
36,459	1.7	2.3	3.8
59,299	1.2	1.7	2.8

[10] Calculated assuming ammonia has a volumetric energy density of $0.682t/m^3$, reference Seo and Han, 2021.

As an example, assuming from Table 7 a mid-range value of an additional 60Mt of ammonia sea-trade in 2030 for a 1.5°C compatible pathway, this would be the equivalent of 101 large vessels on Australia-Japan length routes.

The historic build rate for ammonia carriers is set out in Figure 27. There are a further 16 on order books for delivery over the next three years – well below the historical build rate. If 101 vessels are needed by 2030, this would then require a further 85 vessels from 2026-2030, 21 a year, a rate that has been attained in six years in the last 20.

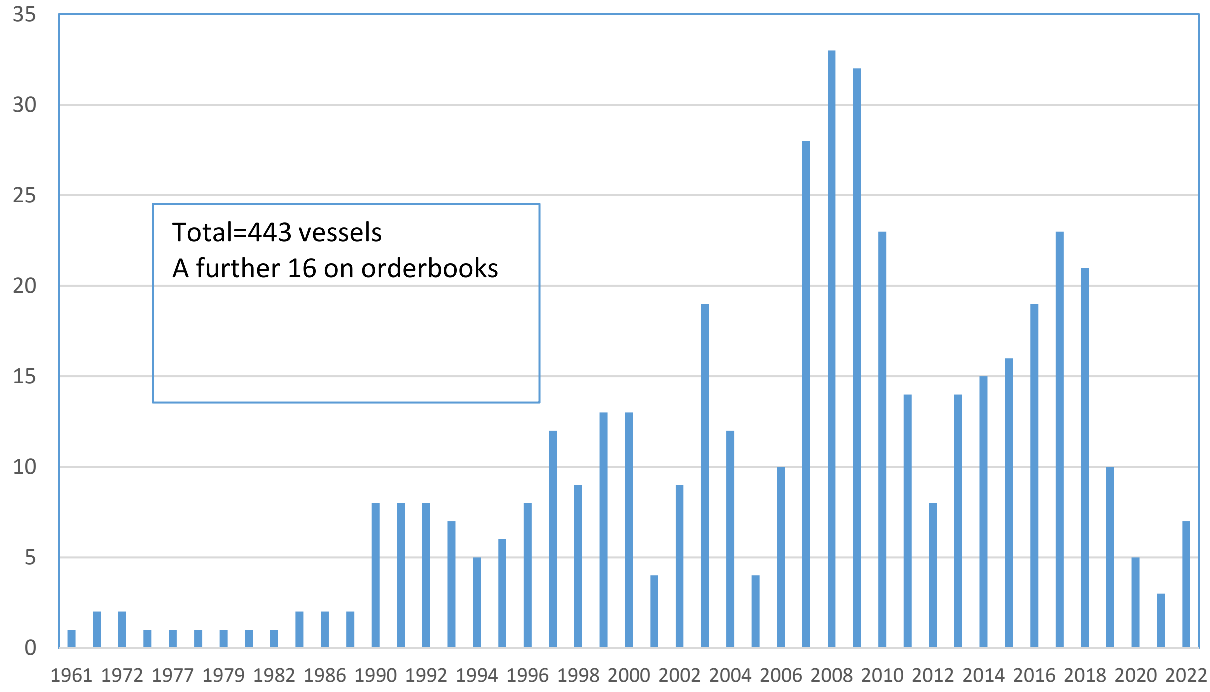

Figure 27: Ammonia carriers by year built. Source; Clarksons

Shipping as an Adopter of Low-carbon Fuels

The shipping industry itself can be an important market for emerging low-carbon fuels. In the IEA NZE 1.5˚C scenario for example, hydrogen based fuels account for 45% of shipping fuel in 2050(IEA, 2021c). Biofuels could also be an important drop-in and full fuel substitute for marine diesel in the nearer-term future. Due to wider sustainability concerns and engine compatibility, second generation biodiesels are the most likely drop-in fuel candidate. However, second generation feed-stocks for biodiesel (e.g. waste cooking oils) are relatively limited (compared to bioethanol) which may lead to competition with the aviation sector (IEA Bioenergy, 2017).

It is imperative that the 2020s sees scaling of the adoption of low carbon fuels to reach 5% of the international shipping fuel mix by 2030, to enable more rapid deployment through the 2030s and 2040s (Osterkamp, 2021). This 2020s focus on fuels would need to be complemented with a package of other measures, on energy efficiency, wind-assist technologies, shore power and other options, to deliver a

Paris-compatible trajectory for the international shipping sector of 34% cuts in carbon dioxide emissions on 2008 levels by 2030 (Bullock et al., 2022).

In terms of low-carbon vessels available in the near-term, there is growth in some segments (methanol, hydrogen) but this is from a very low base. Although many trials are underway, ammonia powered vessels are not expected in service until 2024. The status of alternative fuel vessels is set out in Figure 28. Although sea transport of ammonia is a well-established practice with strong safety protocols, it will be imperative that safety concerns are fully addressed, both for the expansion of port-side ammonia bunkering infrastructure, and the new safety requirements on vessels for the use of ammonia in engines (rather than solely their storage).

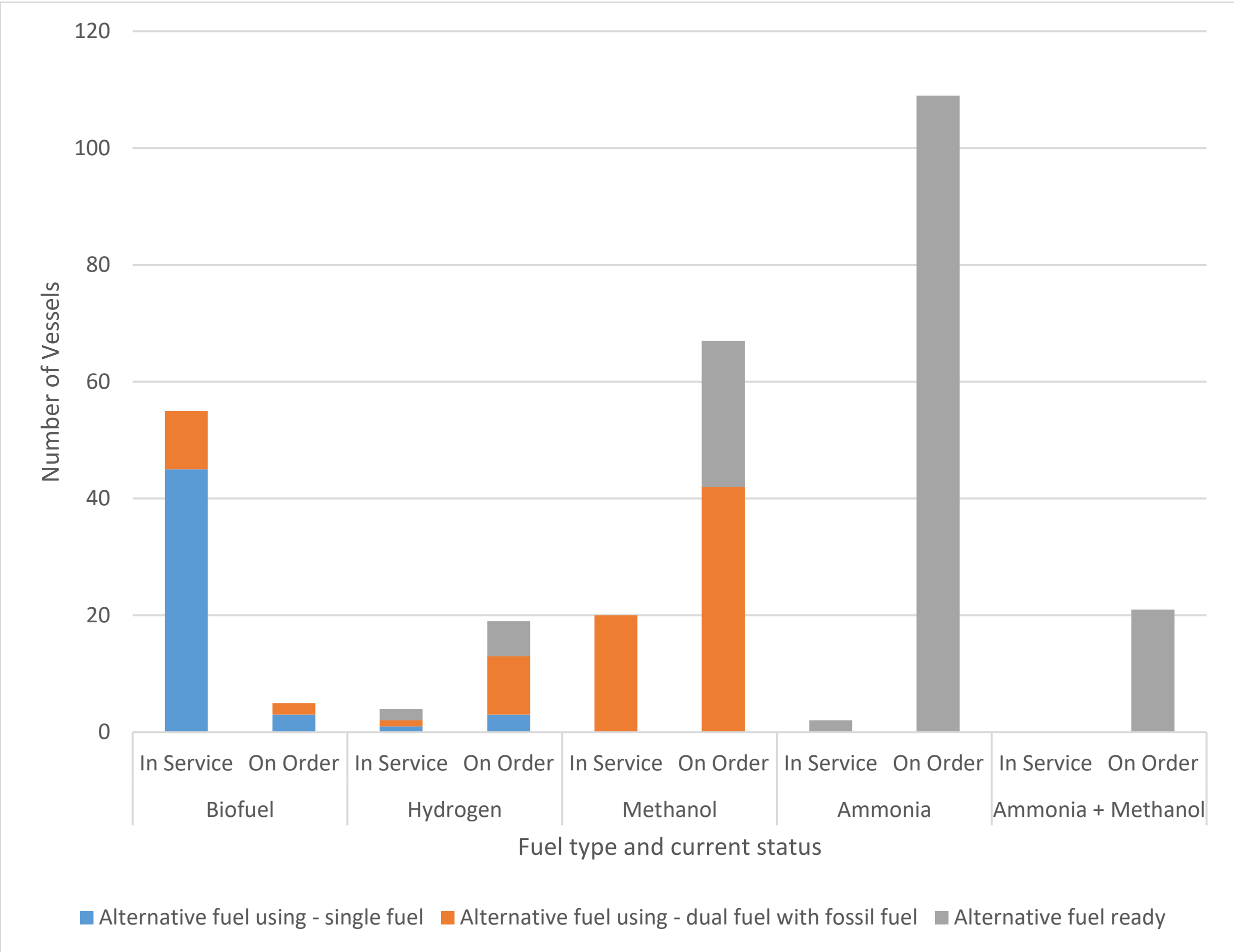

Figure 28: Numbers of vessels using different fuels, and ready to use different fuels, either already in service or on order (Clarksons, 2022b)

5. Conclusions

The climate and energy challenge

Unprecedented levels of greenhouse gas emissions reductions are needed this decade, on a pathway to zero emissions around 2050. The timescales are extremely urgent. Further delay is not an option. Meeting this challenge has profound implications for the global use of energy, and the systems that provide that energy.

Five changes to the energy system by 2050 are consistent across the 1.5˚C scenarios reviewed:

- Reductions in overall global energy consumption, mainly due to greater energy efficiency;
- Rapid electrification of many sectors of the global economy;
- Rapid decarbonisation of the electricity sector, with large increases in wind and solar replacing coal and gas;
- Rapid reductions in coal, oil and gas use;
- Growth in the use of lower-carbon fuels such as hydrogen and bioenergy.

These changes will have profound implications for shipping. In future, shipping will transport different fuels, in different quantities, between different countries, and if 1.5˚C of warming is to be avoided, this transition will start in earnest in a timeframe as short as months and years.

Implications for shipping

The shipping sector needs to prepare for a rapid transition away from coal and oil. Reductions start this decade. By 2050 coal shipments fall 90-100%, oil 50-90%. Although natural gas demand also decreases significantly, a greater proportion of gas is traded by ship, so the shipping sector can expect a continuing role for shipping natural gas products in the medium-term.

Bioenergy use grows in 1.5˚C scenarios, subject to strict requirements on sustainability impacts. It is likely there will be growth in shipments of both biomass and biofuels, although there is great uncertainty about sustainable levels of bioenergy production, and the countries that would see greatest growth.

Hydrogen presents a major opportunity fuel for the shipping sector. Replacing the highly carbon-intensive current method of "grey" hydrogen production which is produced close to where it is used currently, with green / blue hydrogen is an opportunity for more hydrogen trade.

Hydrogen is also expected to have new uses – for example in industry, shipping, aviation and power generation and the transport of green hydrogen will be necessary, either by pipeline or ship. As distances increase, shipping will be preferable, but it is economically more efficient to ship hydrogen as ammonia. There is also a cost penalty at the destination in converting ammonia back to hydrogen, so the best export markets for green hydrogen producers are likely to be those with direct uses of ammonia, such as in fertiliser manufacture.

In short, existing uses of hydrogen (fertiliser manufacture) are the largest potential market for low-carbon hydrogen to 2030. Moreover, imported green ammonia can reduce reliance on natural gas, increasingly important for many countries' strategic goals around energy security and despite its more energy intensive production needs, green ammonia is becoming economically viable.

Bioenergy and ammonia shipments have the potential to be as high as coal and gas shipments today, and these increased shipments will not be technically difficult for the sector to deliver, given existing infrastructure and familiarity with cargoes. However, overall the shipping of energy products will fall, as the growth of transport of new fuels is outweighed by greater falls in shipments of oil and coal.

Closing the gap between plans and hopes of delivering 1.5˚C scenarios

There is a major gap between the planned production of low-carbon hydrogen, and what is required to deliver the 1.5˚C scenarios.

Government policies that can bridge supply and demand – providing investors on both sides with greater confidence in the transition to low carbon hydrogen – will be an important factor in whether the gap between low-carbon hydrogen use in 1.5˚C scenarios and the current situation can be closed.

It is unlikely that the shipping sector provides the much needed demand-side impetus for green hydrogen projects but **there will be a major role for the shipping sector in connecting hydrogen producers and consumers.**

For bioenergy too there is a gap between planned projects and required ambition. **The growth rate in sustainable biofuels needs to between 7% and 18% per year to deliver the 1.5˚C scenarios.** Action from governments and investors is needed urgently if these fuels are to reach the levels required in time.

The role for the shipping sector

There is extensive infrastructure already in place globally for ammonia shipments, and experience in using it. Annual build rates for new ammonia carriers to meet a rising demand for ammonia in 1.5˚C scenarios are high, but within the range of what has been achieved in recent decades.

Because the sector has a slow turn-over of assets, it will be post 2030 before the sector uses hydrogen for more than 5% of its fuel, but in the 2030s and 2040s, the shipping sector is likely to become a major user of hydrogen products, including ammonia, to decarbonise its own operations.

In addition to measures focused on cutting the sector's CO_2 emissions during this decade (Bullock et al., 2020), steps need to be taken now to ensure infrastructures for new fuels are developed in time. There are two clear priorities. First, **ensuring new ammonia carriers are designed to run on ammonia**, to gain synergies in development and deployment of bunkering infrastructure. Second, **the scaling up in deployment of green hydrogen hubs and corridor initiatives, and other measures to connect producers and consumers**, such as in the work of the ICS' Clean Energy Marine Hubs, the Getting to Zero Coalition's green corridors work, and bunkering initiatives in Singapore and Rotterdam, among others.

Crucially, the success of low-carbon hydrogen and sustainable biofuels **is critically dependent upon robust and enforced mechanisms to ensure full-lifecycle emissions and other sustainability impacts are fully accounted for**, and that genuine sustainability and greenhouse gas (GHG) benefits are realised. This means ensuring bioenergy production does not cause deforestation or conflict with essential uses of land for food, and that for both bioenergy and hydrogen that upstream as well as downstream GHG emissions are measured.

The shipping sector will be pivotal in facilitating the global energy transition needed to protect humanity and nature from the worsening impacts of climate change. Although it can expect to transport far lower quantities of energy products in a 1.5˚C future, the sector has a crucial role in enabling trade in new low-carbon energy products. Now is a critical time for the sector to get on the front foot as a potential catalyst for change – but it will require many more hands on deck. It must build on its unique global reach to prioritise developing the networks and infrastructure to connect new fuel producers with the emerging consumers. **If the shipping sector can energise faster growth in sustainable fuels, it will be playing a pioneering role in closing the gap between grand theoretical plans and a real world fit for future generations.**

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