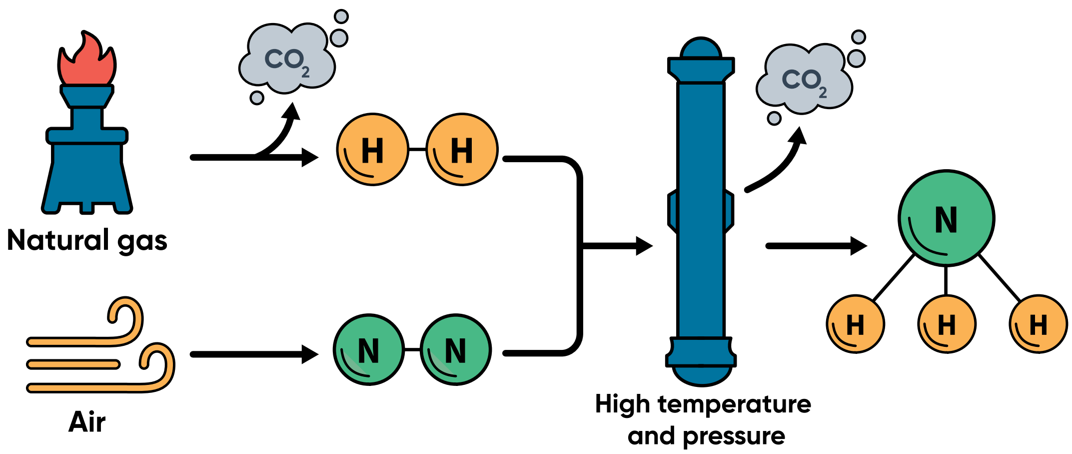
AMMONIA AS SHIPPING FUEL

Moving towards a climate-neutral ammonia-powered shipping industry

Finding ways to decarbonise famously hard-to-abate sectors like heavy industry, heating or mobility is both difficult and – given the current geopolitical situation and climate crisis – more important than ever. The most common solution mooted for this purpose is hydrogen, but pure hydrogen gas is famously difficult to store and transport. Ammonia has long been proposed as a solution to this issue, as it is much more stable and has a higher energy density in situations closer to normal atmospheric and temperature conditions. It is now increasingly being taken seriously as a future game changer.

A lifesaver

There was serious risk of a global food crisis in the beginning of the 20th century: the world was running out of nitrogen. A shortage of this essential source of fertiliser could threaten the very survival of the human species.[1] Natural nitrogen resources were being depleted at an alarming rate, even leading to international conflict.[2] A worldwide search for new nitrogen sources came to an end when the German chemist Fritz Haber developed a process that could synthesise nitrogen in the form of ammonia, a chemical which would come to form the basis of fertilisers used all over the globe. A few years later the process, which allowed the production of ammonia on an industrial scale, was commercialised by Carl Bosch.[3] Today it is known as the Haber-Bosch process. The extensive availability of ammonia satisfied the global demand for fertilisers and allowed for the world population to grow exponentially during the next hundred years – an expansion that is expected to continue well into this century.[4]



Ammonia production using fossil fuels. Including natural gas steam reforming for hydrogen, air separation for nitrogen and Haber-Bosch process for ammonia. Visual by IKEM, 2022.

1 Stranges, 'Fritz Haber: Chemist, Nobel Laureate, German, Jew'.

2 Cordle, 'The Guano Voyages'.

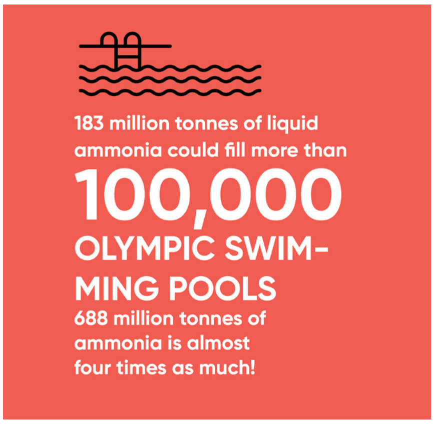
3 Kissel, 'The Historical Development and Significance of the Haber Bosch Process'.

4 Carreon, 'Plasma Catalytic Ammonia Synthesis: State of the Art and Future Directions'.

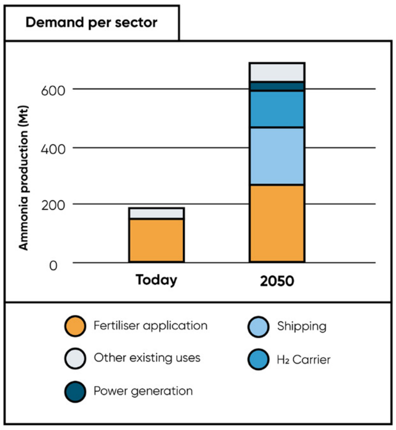
Ammonia is a simple molecule built up from one atom of nitrogen and three atoms of hydrogen. Since a molecule of ammonia (NH3) contains one more hydrogen atom than a molecule of hydrogen gas (H2) liquid ammonia contains 50% more hydrogen per volume than pure hydrogen gas, making it an efficient hydrogen carrier.[5] However, forming the bonds that hold the atoms in ammonia together requires a very large amount of energy – and thus the Haber-Bosch process requires a great deal of temperature and pressure.[6] Some 183 million tonnes of ammonia are produced globally every year, and 88% of it is used to produce fertiliser to support global food demand.[7] The energy-intensive production process means that ammonia production causes 1% of global greenhouse gas (GHG) emissions by itself.[8]

From polluter to sustainable solution

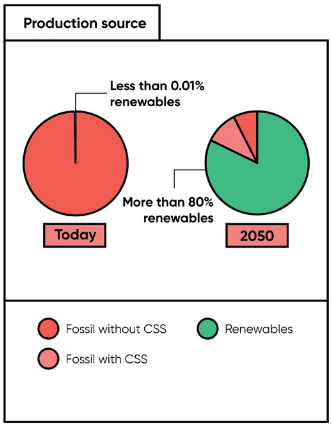
The world population is expected to grow by three billion by the end of this century and ammonia production needs to increase accordingly to help feed the additional humans.[9] In a business-as-usual scenario, this development would lead to a substantial increase in greenhouse gas emissions. To meet the climate goals the world has set itself, however, the energy consuming process of ammonia production will have to reduce its emissions. And if this were not challenging enough already, there is a new application for renewably produced ammonia that is likely to hugely increase demand: the energy sector, in which ammonia could serve as a new sustainable energy carrier and green fuel.[10] The need for clean energy is higher than ever, especially for hard-to-decarbonise industries like heavy transport – notably aviation and shipping. For the latter, green ammonia appears as a very promising sustainable alternative to fossil-based fuels. To ensure enough ammonia for both current and future uses, production is expected to quadruple to 688 million tonnes per year in 2050. Moreover, 80% of this amount should be produced using renewable energy sources.[11] Currently, there is just one renewable ammonia production plant in the world (in Cusco, Peru), which accounts for less than 0.01% of the global ammonia production capacity.[12] If these goals are realised, ammonia will no longer be a major source of greenhouse gas emissions but will serve as an essential component of the climate-neutral economy of tomorrow.



Visual by IKEM, 2022



Ammonia demand. Visual by IKEM, 2022.



Ammonia production. Visual by IKEM, 2022.

5 Seo and Han, 'Economic Evaluation of an Ammonia-Fueled Ammonia Carrier Depending on Methods of Ammonia Fuel Storage'.

6 Aziz, Wijayanta, and Nandiyanto, 'Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization'.

7 Rouwenhorst and Castellanos, 'Innovation Outlook: Renewable Ammonia'.

8 Seo and Han, 'Economic Evaluation of an Ammonia-Fueled Ammonia Carrier Depending on Methods of Ammonia Fuel Storage'.

9 Pfromm, 'Towards Sustainable Agriculture: Fossil-Free Ammonia'.

10 Rouwenhorst and Castellanos, 'Innovation Outlook: Renewable Ammonia'.

11 Pfromm, 'Towards Sustainable Agriculture: Fossil-Free Ammonia'.

12 Rouwenhorst, Travis, and Lefferts, '1921–2021: A Century of Renewable Ammonia Synthesis'.

Comparing marine fuels

The shipping sector is in desperate need of a sustainable fuel to decarbonise the industry. Most container vessels today are powered by heavy fuel oil (HFO) – the cheapest and most polluting fossil fuel.[13] Due to the use of HFO and the enormous dimensions of container vessels, which sometimes exceed 400 metres in length, the shipping industry accounting for over three percent of the global GHG emissions.[14,15]

Moving away from fossil fuels is not easy, since there are no climate neutral alternatives with the same advantages of high energy density and easy handling. The main contenders for replacing fossil energy carriers are e-fuels, that is, fuels produced using electricity – liquid ammonia and liquid hydrogen are the two most commonly proposed alternatives in this category. They are compared to heavy fuel oil in the table below.[16,17,18,19,20,21,22,23,24,25]

	HEAVY FUEL OIL	HYDROGEN	AMMONIA
(pros)	• Very high energy density • Easy to handle and transport (liquid at room temperature and atmospheric pressure) • Excellent combustion properties	• Produced and used without direct greenhouse gas emissions or air pollution • Very little toxicity in case of leaks • Excellent combustion properties	• Produced without direct greenhouse gas emissions or air pollution • Reasonable energy density (50% higher than liquid hydrogen) • Liquifies below -33 °C.
(cons)	• High GHG emissions • High air pollution • Serious toxicity to humans and ecosystems in case of leakage • Major contributor to current climate crisis	• Very low energy density (20% of heavy fuel oil) • Costly and energy-intensive to store and transport: H_2 liquifies below -253 °C and it makes steel tanks brittle. • Risk of explosion due to high flammability	• Low energy density (30% of heavy fuel oil) • Low flammability • Risks linked to leaks: toxic to humans and marine ecosystems • Harmful greenhouse gas emissions (nitrous oxide)

13 McKee et al., 'The Toxicological Effects of Heavy Fuel Oil Category Substances'.

14 Kim and Park, 'A Study on the Green Ship Design for Ultra Large Container Ship'.

15 Faber et al., 'Fourth IMO GHG Study 2020'.

16 Comer, 'Transitioning Away from Heavy Fuel Oil in Arctic Shipping'.

17 Cames, Wissner, and Sutter, 'Ammonia as a Marine Fuel'.

18 DeCola et al., 'Phasing out the Use and Carriage for Use of Heavy Fuel Oil in the Canadian Arctic: Impacts to Northern Communities'.

19 Dincer, 'Green Methods for Hydrogen Production'.

20 Ciniviz and Köse, 'Hydrogen Use in Internal Combustion Engine: A Review'.

21 Aziz, Wijayanta, and Nandiyanto, 'Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization'.

22 Lindstad et al., 'Reduction of Maritime GHG Emissions and the Potential Role of E-Fuels'.

23 McKee et al., 'The Toxicological Effects of Heavy Fuel Oil Category Substances'.

24 Faber et al., 'Fourth IMO GHG Study 2020'.

25 Valera-Medina et al., 'Review on Ammonia as a Potential Fuel: From Synthesis to Economics'.

Dual fuel: the best of both worlds

To summarise the difference between the fuels, ammonia is more energy dense and easier to store than hydrogen, and cleaner than heavy fuel oils (HFOs). However, replacing fossil fuels in marine engines is not straightforward, since there are major benefits and disadvantages to each fuel type. Ideally, one would be able to refit existing internal combustion engines (ICEs), the industry standard for large ships, for use with sustainable fuels instead of HFOs. An ICE releases the chemical energy stored in a fuel by combustion, which enables motion of the mechanical engine parts. This process does not have a very high energy efficiency – this is typically 15 to 30% – but, with the right fuel, it can deliver power at the quickly changing rates and over the long periods of time required for long-distance shipping. This makes it perfect for mobility applications that use a fuel with good combustion properties like HFO. Using pure ammonia, however, complicates things.

There is no extra conversion step needed to use pure ammonia from a fuel tank, so burning ammonia in an ICE leads to high energy efficiency. At the same time, while ammonia burns hot, it has a low flammability and flame velocity, which makes it unsuitable to powering a combustion engine on its own. Pure ammonia doesn't ignite easily and can be affected by incomplete combustion, which leads to harmful emissions. Compared to HFO, green ammonia as a fuel reduces greenhouse gas emissions by 94% – a major improvement – but the benefits can be diminished without careful combustion monitoring and emission aftertreatment.[26] Since the ultimate goal is for shipping to be more or less completely climate neutral in the future, a way must be found to further mitigate these remaining emissions.

Using pure green hydrogen improves the quality of combustion and cuts potential greenhouse gas emissions down to zero. However, liquid hydrogen stores a lot less energy per litre, and maintaining the high pressure and/or low temperature needed to keep it liquid can also consume a great deal of energy. Liquid hydrogen storage typically costs 29 times more than liquid ammonia over a period of six months.[27] To avoid this longterm storage issue, liquid hydrogen can be made on site from liquid ammonia, but this conversion (known as 'cracking') results in a lower energy efficiency.

Pure ammonia and pure hydrogen thus each have their own flaws when used as a fuel. These can be mitigated, however, by creating a dual fuel which consists of ammonia with a small proportion of hydrogen. To achieve this, the fuel tank can be filled with pure liquid ammonia, a small part of which is cracked into pure hydrogen to run the engine. Even at small concentrations in the resulting dual fuel, hydrogen acts as an effective combustion promotor, resulting in more complete combustion than pure ammonia can achieve, this causing less harmful emissions and unburned fuel to escape the engine.[28] The combustion process also requires lower ignition temperatures and flame speed is higher, thus leading to faster motion by the engine when the highly flammable hydrogen is in the fuel mix.[29]

Using hydrogen as the combustion promotor is ideal also from an environmental perspective, since it can be produced on site from green ammonia. If the cracking process is powered by renewable energy, the resulting hydrogen that is fed into the fuel mix is green as well. Another advantage is that current internal combustion engines can be retrofitted to suit this sustainable dual fuel, thus making optimal use of existing technologies and infrastructure. One downside, however, is that mixing fuels comes at the cost of additional energy loss for the conversion step – but since combustion is improved significantly at just five per cent in the volume concentration of hydrogen, only a small fraction of the ammonia needs to be converted.[30]

26 Lindstad et al., 'Reduction of Maritime GHG Emissions and the Potential Role of E-Fuels'.

27 Bartels, A Feasibility Study of Implementing an Ammonia Economy.

28 Lhuillier et al., 'Performance and Emissions of an Ammonia-Fueled SI Engine with Hydrogen Enrichment'.

29 Li et al., 'A Review on Combustion Characteristics of Ammonia as a Carbon-Free Fuel'.

30 Lhuillier et al., 'Performance and Emissions of an Ammonia-Fueled SI Engine with Hydrogen Enrichment'.

Emission mitigation

The reduction of harmful emissions is therefore substantial but not complete – mitigation measures are still required to minimise the remaining emissions. Both ammonia and hydrogen may be carbon free, but using them as dual fuel in an internal combustion engine can still lead to greenhouse gas emissions and fuel leakages with environmentally harmful effects.

The most potent greenhouse gas that can be emitted is nitrous oxide (N2O – also known as laughing gas), which has 300 times the atmospheric global warming effect of CO2 and remains stable in the atmosphere for over 114 years.[31] It is therefore crucial to minimise these emissions. This can be achieved by finetuning the combustion process by optimising the combustion temperature and the air-to-fuel ratio.[32]

The emission of nitrogen oxides (NOX) leads to air pollution in all layers of the atmosphere. In the lower tropospheric regions, NOX leads to ozone and fine particle formation that can cause smog pollution, causing health effects that typically bring about over a million deaths per year globally.[33 34 35 36] Higher up in the stratosphere, NOX destroys the protective ozone layer, leading to increased health risks such as skin diseases.[37 38] Using a dual fuel is already an effective mitigation pathway, since a hydrogen concentration of only 10% by volume achieves a reduction of nitrogen oxide emissions of over 40% compared to using pure ammonia.[39] Most of the remaining emissions can be neutralised at the exhaust through selective catalytic reduction which uses ammonia and a catalyst to turn nitrogen oxides into harmless substances.[40]

Although it is not a greenhouse gas in itself, pure hydrogen is highly reactive and can affect the environment in an indirect manner. An increased concentration of hydrogen in the atmosphere allows it to react with molecules that would otherwise react with methane, a strong greenhouse gas, leading to the methane remaining in the atmosphere. This extends the effective lifetime of methane in the atmosphere and thus boosts its global warming effect.[41] These effects are small but non-negligible, and the emission of pure hydrogen should best be avoided.[42]

Finally, when not combusted completely, ammonia fuel may slip through the engine and leak into the environment.[43] The chemical is lethal to humans at concentrations as low as 0.5% in the air and it also forms an acute risk to the marine environment. Another consequence of an ammonia leak in a water body is eutrophication, explosive growth of algae and microorganisms that disrupt the marine life cycle and can cause decline in biodiversity in a body of water.[44] The use of a double-walled engine system and installation of a suitable recirculation system at the exhaust can prevent ammonia from slipping out and enable it to be reintroduced into the engine.[45]

31 United States Environmental Protection Agency, 'Inventory of US Greenhouse Gas Emissions and Sinks'.

32 Mashruk et al., 'Nitrogen Oxide Emissions Analyses in Ammonia/Hydrogen/Air Premixed Swirling Flames'.

33 Zhang et al., 'Substantial Nitrogen Oxides Emission Reduction from China Due to COVID-19 and Its Impact on Surface Ozone and Aerosol Pollution'.

34 Sillman, 'Overview: Tropospheric Ozone, Smog and Ozone-NOx-VOC Sensitivity.'

35 Ebi and McGregor, 'Climate Change, Tropospheric Ozone and Particulate Matter, and Health Impacts'.

36 Ainsworth et al., 'The Effects of Tropospheric Ozone on Net Primary Productivity and Implications for Climate Change *'.

37 Ravishankara, Daniel, and Portmann, 'Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century'.

38 Norval et al., 'The Human Health Effects of Ozone Depletion and Interactions with Climate Change'.

39 Zhang et al., 'Characteristics of Ammonia/Hydrogen Premixed Combustion in a Novel Linear Engine Generator'.

40 Janssens et al., 'A Consistent Reaction Scheme for the Selective Catalytic Reduction of Nitrogen Oxides with Ammonia'.

41 Ocko and Hamburg, 'Climate Consequences of Hydrogen Emissions'.

42 Derwent et al., 'Global Environmental Impacts of the Hydrogen Economy'.

43 Cames, Wissner, and Sutter, 'Ammonia as a Marine Fuel'.

44 Smith, Tilman, and Nekola, 'Eutrophication: Impacts of Excess Nutrient Inputs on Freshwater, Marine, and Terrestrial Ecosystems'.

45 Gallucci, 'The Ammonia Solution: Ammonia Engines and Fuel Cells in Cargo Ships Could Slash Their Carbon Emissions'.

The alternatives: from fuel cells to batteries

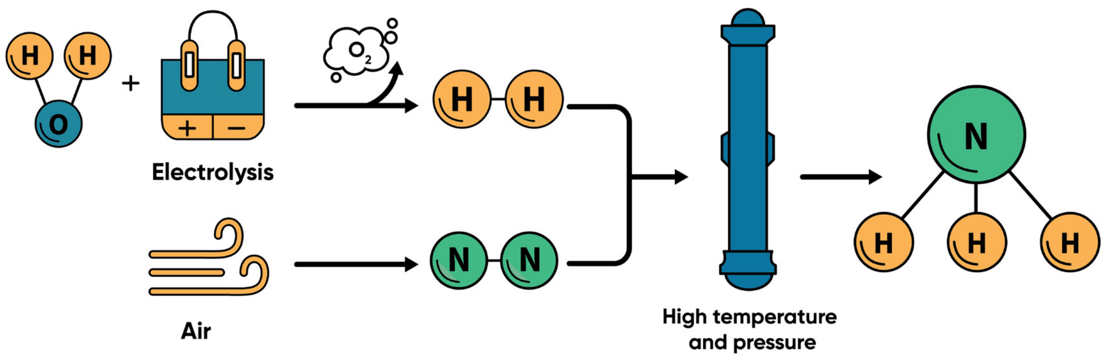
So far, the focus in the search for a sustainable new shipping fuel has often been on internal combustion engines with ammonia fuel. This is generally considered easier thanks to the existing infrastructure in place that would allow for a relatively quick transition towards sustainable fuels. In the long run, however, fuel cells may come to play a larger role in powering a climate-neutral transport sector.

A fuel cell converts the chemical energy stored in a fuel directly into electricity while only producing harmless emissions. This process generally has around twice the energy efficiency of a combustion engine, which can make an enormous impact on the production demand and storage capacity of sustainable fuels.[46] However, it requires a pure fuel (either ammonia or hydrogen, not a mixture); in the case of hydrogen fuel cells, this means that ammonia has to be converted into pure hydrogen. This additional step naturally reduces overall energy efficiency. Current fuel cells that use ammonia operate at temperatures of up to 1000 °C, thus requiring a long warm-up period. Moreover, they do best at a constant power output, which makes them more suitable for power generation than transport applications.[47]

There are other alternatives to ammonia that may also be suitable for internal combustion engines. In terms of liquid fuel alternatives, this includes other energy-dense sustainable e-fuels such as synthetic diesel, kerosene and methanol. However, the energy efficiency of the production process of these fuels is far lower than for green hydrogen and ammonia, making it a costly process.[48] Additionally, these fuels are carbon based, so using them leads to CO2 emissions, which – ideally – would have to be captured and stored.[49]

Another technology is battery storage, which is already very common – after all, when it comes to storing and using renewable energy, batteries are the most efficient technology.[50] However, for heavy transport applications such as shipping and aviation, batteries simply have too low gravimetric energy density. It would require too much weight to have batteries power long-distance shipping and the size of the required batteries would create great pressure on the already scarce resources needed for their production.[51]

The need for renewables



Renewable ammonia production. Including water electrolysis for hydrogen, air separation for nitrogen and Haber-Bosch process for ammonia, all powered by renewable energy.
Visual by IKEM, 2022

46 Rouwenhorst and Castellanos, 'Innovation Outlook: Renewable Ammonia'.

47 Valera-Medina et al., 'Review on Ammonia as a Potential Fuel: From Synthesis to Economics'.

48 Lindstad et al., 'Reduction of Maritime GHG Emissions and the Potential Role of E-Fuels'.

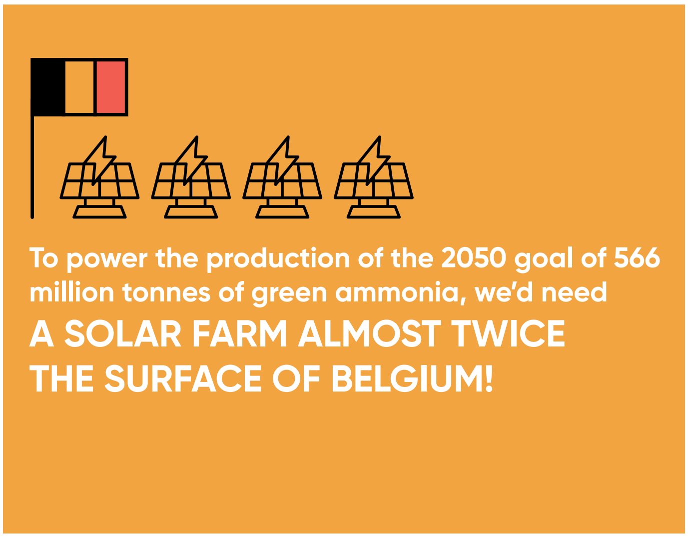
49 Lindstad et al.

50 Lindstad et al.

51 McKinlay, Turnock, and Hudson, 'A Comparison of Hydrogen and Ammonia for Future Long Distance Shipping Fuels'.

It is clear that, in the near future, a fuel mix consisting mainly of green ammonia has great potential to boost the decarbonisation of the shipping sector. To produce ammonia sustainably, however, changes must be made to the production process. All the energy should come from renewable energy sources, which can make air separation required to obtain nitrogen and the Haber-Bosch process through which ammonia is produced climate neutral. To obtain green hydrogen, steam reforming must be replaced by water electrolysis, which in turn is powered by renewables. An overview of the green ammonia production process is given below.

Producing more green ammonia will require more green power. Right now, there is only one green ammonia production plant in the world, located in Cusco, Peru.[52] There are more green ammonia capacity plans in the pipeline, but they only add up to 71 million tonnes per year.[53] More ambition, investment and concrete plans are needed to bring this green fuel to the forefront.



Visual by IKEM, 2022.

Active and planned green ammonia production plants.
Visual by IKEM, 2022.

52 Rouwenhorst, Travis, and Lefferts, '1921–2021: A Century of Renewable Ammonia Synthesis'.

53 Rouwenhorst and Castellanos, 'Innovation Outlook: Renewable Ammonia'.

A call for action

In summary, green ammonia potentially has major benefits, and the climate stakes could scarcely be higher. So, what needs to happen for green ammonia to scale up and for the market to take off? Here are some recommendations on where to start.

Policy

There is need for a clear political commitment to green ammonia, accompanied with targets and supporting regulatory mechanisms to create a stable investment climate and spur market growth. It is also crucial to ensure the certification of green production processes (similar to the Green Hydrogen Standard) so as to ensure that the additional ammonia is produced with renewable energy in a socially responsible manner.[54]

Renewable energy

To reach the green ammonia targets required for true climate change mitigation, there is need for much more renewable energy capacity. Countries must quickly increase their renewable energy capacities, and, beyond that, they must work to form new international partnerships to trade green fuels like hydrogen and ammonia.

International collaboration

An international common standard for green ammonia is needed to create a global, universally recognised market for production, refuelling and maintenance. The best way to achieve this is through international coordination, which could be supported by the International Maritime Organisation (IMO), for instance. Having already declared that 'the time is ripe for maritime ammonia', the IMO is expected to actually approve it as a maritime fuel in 2023.[55]

Technology & infrastructure

The existing infrastructure for the production, transport and storage of ammonia must be expanded and adapted to enable a much wider deployment of ammonia as fuel, beyond its current use in fertiliser.[56] This includes upgrades to ports, where more ammonia-ready bunkering stations to fuel vessels are needed.[57]

Employment

Renewables and green fuels offer great job creation potential. The hydrogen market alone is projected to create up to 30 million jobs throughout the global supply chain by 2050.[58] Tapping into these socio-economic benefits and ensuring flourishing markets, investments in innovation, R&D, and training will secure a thriving new employment sector.

Costs and carbon pricing

As early as 2030, green ammonia could become cost-competitive with the fossil-based kind.[59] Supporting mechanisms and incentives can help accelerate investments in green-ammonia infrastructure. A strong carbon price can redirect investments away from fossil fuels and towards funding to green alternatives, like ammonia, thus further levelling the playing field.[60]

54 Zhu and Wei, 'A Green Hydrogen Era: Hope or Hype?'

55 Zincir, 'Ammonia for Decarbonized Maritime Transportation'.

56 Salmon and Bañares-Alcántara, 'Green Ammonia as a Spatial Energy Vector: A Review'.

57 Nayak-Luke, Cesaro, and Bañares-Alcántara, 'Pathways for Green Ammonia'.

58 Taskforce, 'Economic Impact Assessment: Hydrogen Is Ready to Power the UK's Green Recovery'.

59 Rouwenhorst and Castellanos, 'Innovation Outlook: Renewable Ammonia'.

60 Rouwenhorst and Castellanos.

Final takeaway

Ammonia helped avoid a global food shortage crisis about a century ago and may now be pivotal in solving the biggest challenge of the current age: climate change. While renewable ammonia is not the only sustainable fuel, its promising characteristics mean it has the potential to help power the green economy of tomorrow. There is no single silver bullet – but with less than seven years left in our carbon budget to meet the goals of the Paris Agreement, green ammonia is a shot worth taking.

Assumptions

The average yearly production yield from a ground-mounted photovoltaic system in Germany was used for these calculations.[61] However, the ammonia production process requires a constant power feed in, and so a combination of renewables would be needed to provide the energy supply. Places in the world with both wind and solar potential are thus most suitable for large-scale ammonia production plants. For example, a planned project in Mauritania that uses a mix of renewable energy sources, needs only a quarter of the installed renewable capacity to produce the same amount of ammonia as would a comparable facility in Germany.[62]

61 Wirth and Schneider, 'Recent Facts about Photovoltaics in Germany'.

62 Rouwenhorst and Castellanos, 'Innovation Outlook: Renewable Ammonia'.

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