

Appendix 4: 1112-00012A - Innomission Roadmap Leveraging Danish strengths to mature and scale up e-fuels for transport

Roadmaps for mission-driven green research and innovation partnerships (Innomission-roadmaps)

Innomission partnerships: Translating mission roadmaps into sustained actions

The call for mission-driven green research and innovation partnerships is the second phase in Innovation Fund Denmark's (IFD) Innomission program. Phase one generated roadmaps for each of the four missions (<https://innovationsfonden.dk/da/programmer/groenne-missioner>). Phase two now asks for proposals to form Innomission partnerships to drive action based on the directions outlined in the roadmaps.

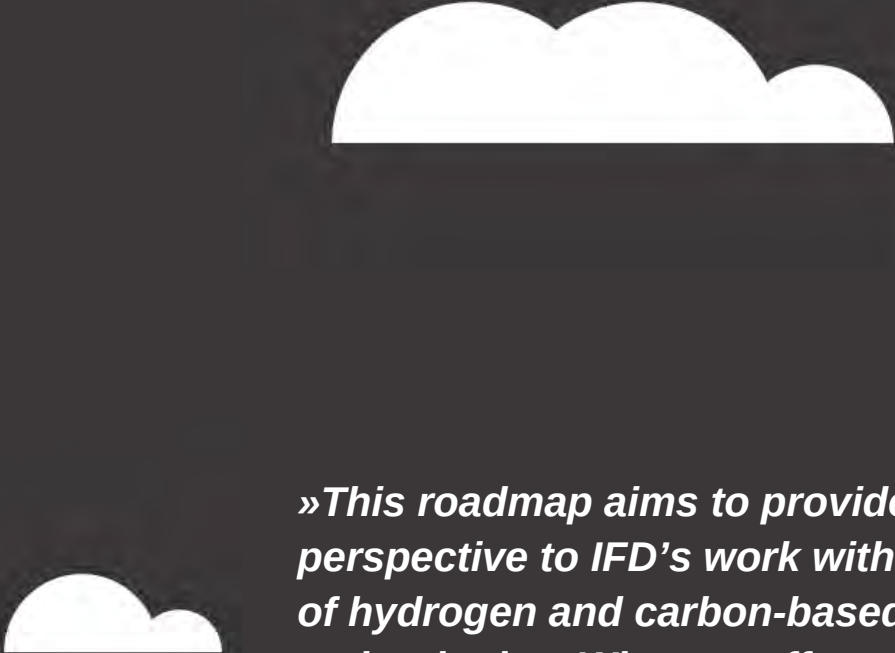
During phase one Innovation Fund Denmark received 12 roadmaps within the four mission areas. Of these 12 roadmaps, six roadmaps were selected by the IFD Board of Directors to provide direction to the partnerships in designing action plans. The six roadmaps are described in the call for innomission-partnerships and shown in its full length in these appendices.

INNOMISSION ROADMAP

Leveraging Danish strengths to mature and scale up e-fuels for transport

Proposal for Innomission Roadmap 2: Green Fuels for Transport and Industry

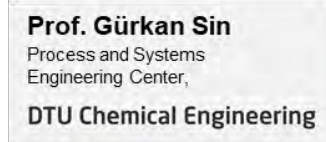




»This roadmap aims to provide an industry perspective to IFD's work with focus on a range of hydrogen and carbon-based power-to-x technologies. What we offer are a set of key elements to include in IFD's strategic work. In other words, this is not a comprehensive map. Instead, it is a set of proposed technological pathways towards 2030 and 2050 and an outline of the immediate first steps on the way«



Partners contributing to the proposal (in alphabetical order)



MAERSK



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Introduction: Decarbonising heavy transport.

In the global efforts to limit climate change and mitigate manmade greenhouse gas (GHG) emissions, transport is front and center. Prior to the COVID pandemic, transportation made up 15% of global GHG emissions. Since 2000, emissions have been steadily increasing at a pace of app. 2% per year. In Denmark, transport constitutes app. 30% of national emissions^{1,2}.

Over the past decade, direct electrification of passenger transport has made great strides, leveraging from diminishing costs of renewable electricity and from advances in battery technology and production. However heavy road transport, deep sea shipping and aviation remain a significant challenge. As they cannot all feasibly be electrified, they remain dependent on fossil fuels for energy.

Here, green fuels are needed instead. While oil can in part be replaced by advanced biofuels, the global supply of biomass for biofuels simply cannot match the future need for fuels and feedstock for transport and industry without converting significant amounts of agricultural land to energy crops. In addition, there are some challenges with respect to the economics and sustainability of advanced biofuels production. Large scale production of e-fuels, based on renewable hydrogen and sustainable carbon, remains the most obvious option to decarbonise heavy transport globally.

Denmark holds a unique opportunity to become a global center for technology development and production of such sustainable e-fuels for transport. Here, all the major requirements for large-scale development, production and offtake of fuels and feedstocks based on renewable hydrogen and sustainable carbon are present:

- **Denmark has the renewable energy potential**, including from the very large potential for offshore wind generation in Danish waters, enabling a steady scale up of energy production to match increasing offtake for electrolysis and further fuel synthesis.
- **Denmark has the offtaking sectors**, as one of the world's largest ship owning nations, with Skagen as an important bunkering port, and with a broad group of highly ambitious shipping lines, airlines and logistics companies who are all on the leading edge in the green transformation of their industries.
- **Denmark has the infrastructure** to enable coherent and large-scale sector coupling leveraging from power-to-X technologies. This includes both a highly efficient and extensive district heating system to offtake surplus heat, an advanced and mature bioeconomy, as well as modern CHP plants based on biomass and waste and biogas plants, which serve as a source for sustainable carbon.
- **Denmark has the ambition**, long having led by example in the global fight to limit climate change and with a national climate target of at least 70% reductions in national GHG emissions by 2030 and a net-zero emission by 2050, the political commitment to helping new, green solutions take roots helps fertilise the grounds for investments along the entire supply chain.
- **Denmark can produce the know-how**, with an extensive and tested research infrastructure, combining high-ranking universities, Research and Technology Organisations and clusters with SMEs, green technology companies and OEMs, including world-leading companies in electrolysis and fuels synthesis, and large utilities and developers to both develop and test new solutions – and to implement them at scale, driving industrialization and cost-out.

While Denmark is ideally suited to be a future hub for power-to-X technology, services and commodities, other European and global players are working quickly towards the same goal. Sustainable fuels, based on hydrogen produced from solar and wind energy and sustainable carbon from biogenic sources is an

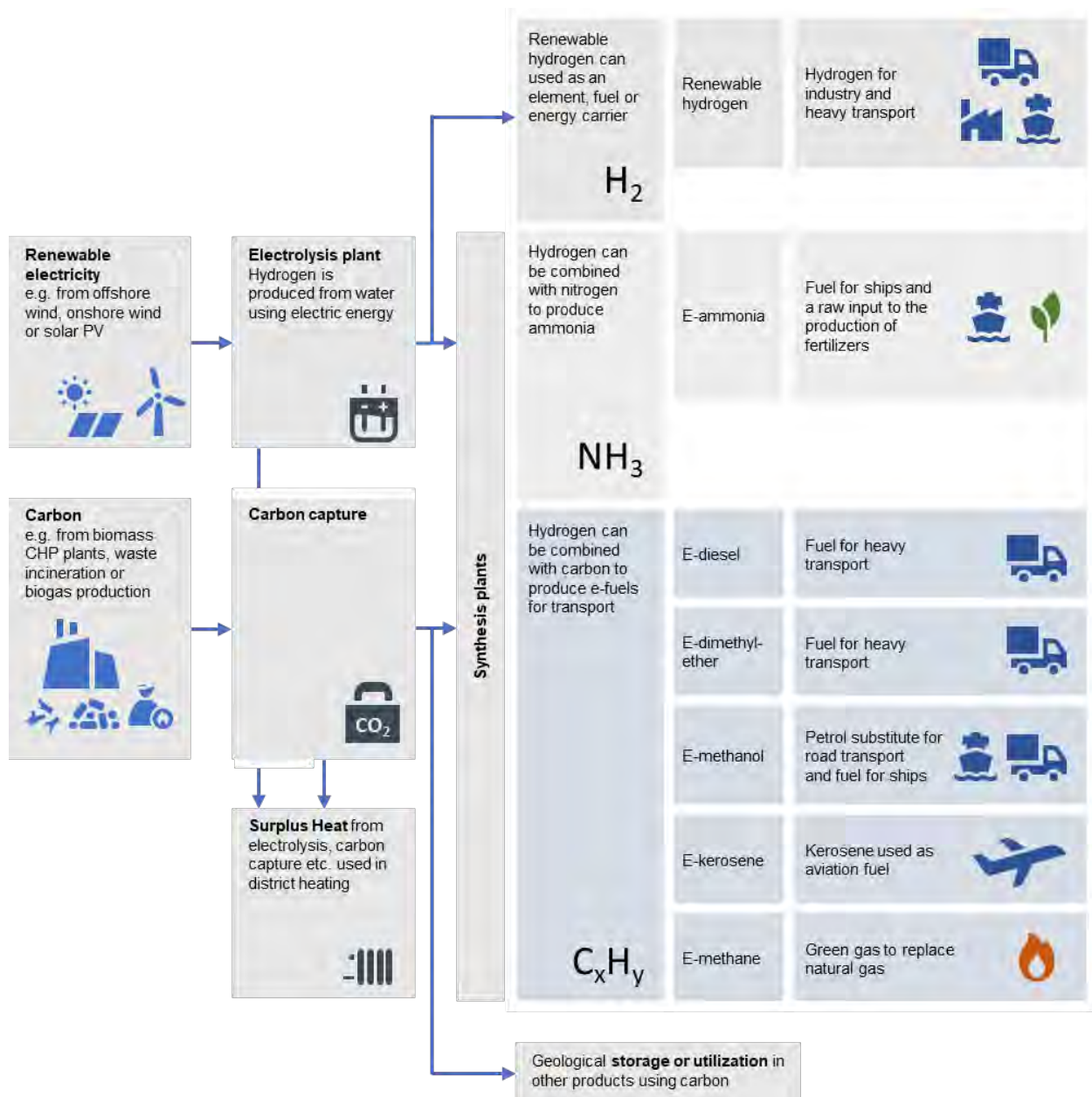
¹ Own calculations based on CAIT/WRI.

² Denmark 2021 National Inventory Report. Excluding LULUCF.

inevitable part of any tangible global solution to the climate crisis – the technologies will come. What Denmark stands to gain from this development, hinges on our ability to innovate and scale solutions quickly, and to provide an environment where commercialization of technology – including validation and de-risking – can happen efficiently.

Schematic overview of pathways, resource and energy streams for PtX and CCU/S applications.

Adapted from Dansk Energi 2020: Recommendations for a Danish Power-to-X strategy



A focused roadmap for hydrogen and power-to-X – with perspectives on carbon capture

This roadmap answers the call of Innovation Fund Denmark for mission-driven green research and innovation partnerships. It describes the main technological pathways for renewable hydrogen and power-to-X and details the potentials and hurdles towards 2030 and 2050. As such, it is a focused roadmap in terms of scope and vision. The aim is to offer a new – predominantly industrial – perspective on what it will take to make Denmark a global leader within power-to-X. This is structured around three key messages:

- 1) Significant synergies can be leveraged through a ‘flagship’ approach.
By encompassing the entire value chain to promote development and uptake of new technologies to produce, store, distribute, bunker, dispense or tank and use new green fuels, several synergies can be leveraged. This way, the challenge of combining the many components and technologies along the value chain and optimizing overall efficiency can be overcome by a holistic system level focus to achieve a low cost and feasible pathway. And by engaging both producer and consumer, demand and supply can be scaled in parallel, alleviating the ‘chicken and egg’ issue of new fuels and infrastructure. Also, in terms of signaling to global OEMs to invest in bringing new vehicles, vessels and drivetrains to market. Hence, green e-fuel pathways with relatively high technology readiness levels (TRLs) can benefit from being promoted by means of fewer, larger ‘flagship’ projects.
- 2) It is not just about getting to 2030. It is about doing it in a way that gets us to 2050.
Reaching 70% emissions reductions by 2030 is an immense challenge and will be transformative to all of society, not least transport. But positioning Denmark to reach the long-term goal of 2050 is equally important. Considering the long investment cycles of heavy transportation – often measured in decades – technologies must be aligned with the 2050 net-zero target already in 2030. This means, Denmark must already today start developing, validating and maturing the technologies, infrastructure, and regulation necessary to reach net-zero by 2050, including renewable energy buildout, hydrogen electrolysis and supply of sustainable CO₂ for power-to-X.
- 3) Denmark’s window of opportunity to become a leader is closing fast.
Denmark is well positioned to become a regional, even global, leader in power-to-X technologies, benefiting from exports of both services, knowledge, hardware and commodities. But other European countries, such as Germany and the Netherlands, have high ambitions – backed by regulatory and policy support. And while there is presumably ample space still in the future market for green e-fuels – Denmark will have to accelerate its rollout and ramp up of power-to-X projects not to fall behind in the race.

The roadmap is given as input to Innovation Fund Denmark’s strategic work, designing the future mission-driven green research and innovation partnerships. While this roadmap specifically answers, and is formally submitted to, the call for Innomission 2: “Green fuels for transport and industry”, the large overlap with carbon capture and utilization technologies also makes it suited as input to the call for Innomission 1: “Capture and storage or use of CO₂”, as this roadmap also brings perspectives related to CCUS. *It is the hope of the partners behind this submission that it will be considered in the work on both Innomissions going forward.*

A large container ship is shown from a low angle, sailing on the ocean. The ship's hull is white with a red bottom. The deck is loaded with many colorful shipping containers in shades of green, blue, and red. The ship is moving towards the right, leaving a wake in the water. The sky is a mix of orange and blue, indicating sunset or sunrise. In the distance, a small island or headland is visible on the horizon.

Section 1: **THE VISION**

A vision for 2030: Denmark as world leader in e-fuels for heavy transport

In 2030, Denmark has reduced its yearly emissions with 70% compared to 1990 and has reached its climate target accordingly. Equally important: Denmark now has laid the foundation to decarbonise heavy industry and transport sectors, paving a way forward towards 2050.

The primary driver for reductions from 2020-2030, responsible for app. 10 out of 22Mt/y CO₂e, have been the phasing out of fossil fuels; coal from central CHP plants, natural gas from district heating and individual oil and natural gas boilers have been replaced – for the main part by district heating in urban areas, heat pumps in rural areas. This is combined with energy savings and energy efficiency in buildings as well as electrification of industry. On the roads, 1.5mn electric vehicles now make up app. half of the of the fleet, mitigating a further app. 2Mt CO₂ per year. Within heavy transport, hydrogen and hydrogen-based e-fuels or electrofuels have reduced a further app. 1-2Mt CO₂ per year³.

Since 2020, Denmark has more than quadrupled its installed offshore wind capacity to at least 7GW. Combined with 5GW onshore wind and at least 5GW of solar PV⁴, Denmark now sources the bulk of its power from solar and wind energy and has become net exporter of electricity.

Hydrogen electrolysis installations have scaled 2-3 orders of magnitude from a few megawatts to hundreds, with some even beyond a GW in size. Denmark now has a total capacity of 1-4GW electrolyser capacity, using some 10TWh electricity in order to produce some 200kt renewable hydrogen per year. These large electrolyzers are located strategically, close to specified points where large amounts of offshore wind energy is fed in connected to the grid, close to the central district heating systems to better utilise waste heat and in relative proximity to sustainable sources for CO₂. By 2030, such surplus heat can cover app. 10-25% of Danish district heat demand. In these places, 'hydrogen clusters' have emerged, combining relevant value chains and resource flows – including captured sustainable carbon from biomass, biogas or organic waste – to produce renewable hydrogen and e-fuels for heavy transport and as industrial feedstocks, as well as ammonia for ammonium nitrate fertilizer. A total of 4-6 Mt/y CO₂ is available from carbon capture facilities, of which app. 1Mt are combined with hydrogen to produce e-fuels, mainly e-kerosene and e-methanol, while the rest is stored in geological formations.

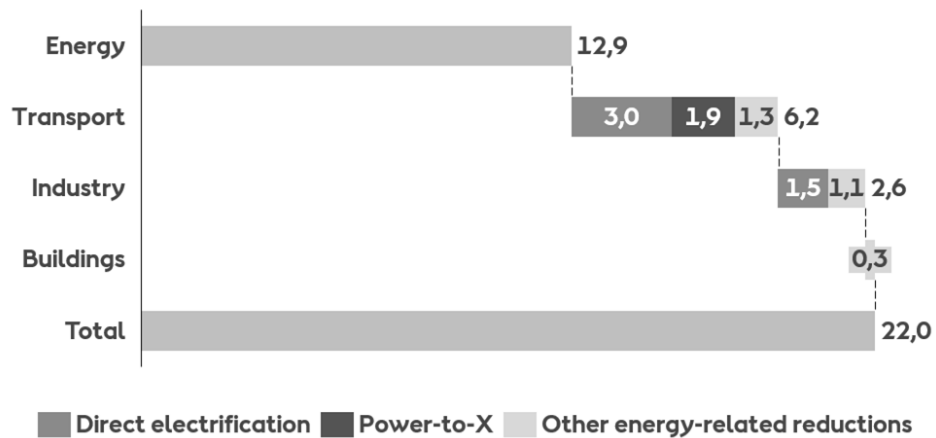
A Danish industry for power-to-x has emerged. Closely integrated – in some places even interconnected – with similar industry clusters in neighboring countries such as Germany, the Netherlands and Norway, Danish service providers and OEMs have evolved into a major export industry, supplying both hardware, software and services for power-to-X facilities abroad. In addition, a strong industry-academia collaboration provides both training and education, along with applied research and innovation within power-to-X technologies.

³ Klimapartnerskabet for Energi- og forsyningssektoren + own calculation.

⁴ Rounded numbers from *IDA Klimasvar*. For offshore wind: Existing capacity + Kriegers Flak, Vesterhav S+N, Thor(1GW), Hesselø (1.2GW), Bornholm (1GW) + open door (0.3GW).

Emissions reductions across sectors towards 2030

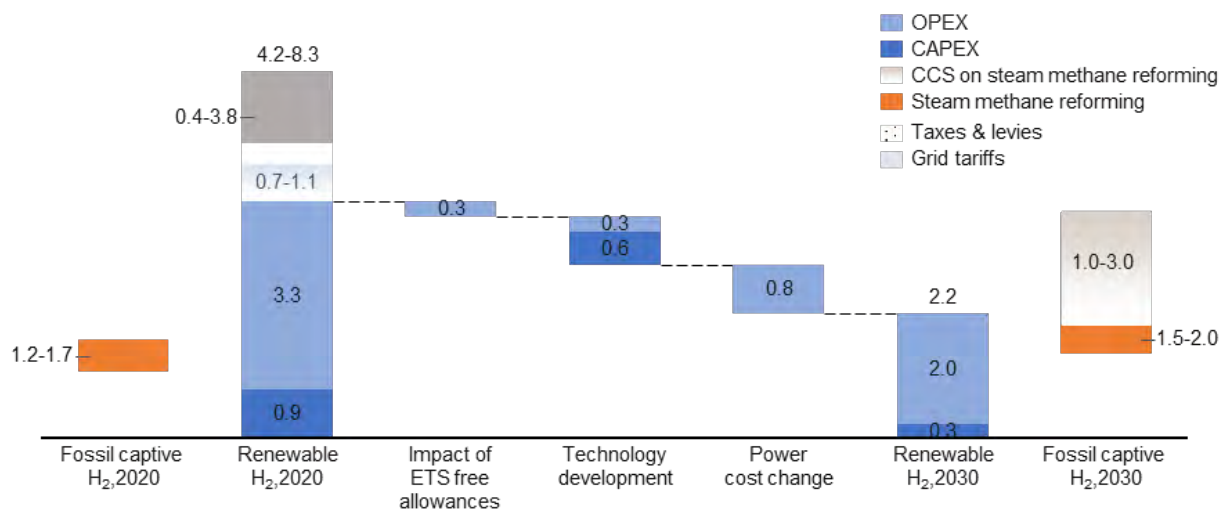
Mt CO₂e. Reductions from CCS included in 'Energy'.
Based on Climate Partnership for Energy and Utilities.



By 2030, renewable hydrogen can become cost competitive in Europe

EUR per kg pure hydrogen Illustrative example of a generic European electrolyser⁵

Source: Ørsted



⁵ Assumed electricity price is the same for all markets, based on BNEF LCOEs forecasts for offshore wind, with FID 2020 and 2030 (1H 2020 update; we assume 4 years from FID to COD). A faster cost-out of offshore wind would therefore show lower costs of renewable hydrogen. Cost ranges for fossil hydrogen with CCS based on independent, external studies and Ørsted estimates. Estimates vary significantly across external publications, and current costs are highly uncertain. We therefore only include a cost range for 2030.

A vision for 2050: A climate neutral Denmark is a significant exporter of power-to-X technology, services and commodities

By 2050, the energy system known today has transformed beyond recognition. Across Europe, electricity is now the dominating energy carrier, used in heavy industry, heating and for electrified transport. European power production – which has more than doubled since 2020, is now provided primarily by renewable energy – with wind alone taking up half⁶. To this end, hydrogen production has added increased demand side flexibility to the grid, enabling very high penetrations of variable power production regionally, including +100% wind penetration in Denmark.

Danish waters are home to some 30 of the almost 400GW of offshore wind installed in European waters⁷. Denmark is now a significant net exporter of renewable energy, both as electrons through the significantly expanded interconnected off- and onshore transmission grid, and in the form of molecules, mainly hydrogen of which is produced 1-2Mt per year in Denmark from 15-20GW electrolyser capacity – of which app. half is placed offshore.

The Danish hydrogen clusters which emerged by 2030 have since been connected to the European hydrogen transmission grid, which gradually emerged from 2030-40, connecting especially offshore wind resources in Northwestern Europe to heavy industrial users in the German and Dutch heartland and fueling hydrogen-based transport elsewhere throughout Europe.

Denmark is now completely climate neutral. All significant point sources for carbon – CHP plants, waste incineration, industry and biogas – has carbon capture facilities. As a general rule – depending on local conditions and infrastructure – unavoidable emissions, e.g. from cement production are stored geologically, while biogenic carbon is utilised to produce sustainable e-fuels or other commodities, e.g. biodegradable e-plastic.

The global market, now of 500-800Mt hydrogen per year⁸ is dominated by hydrogen produced from renewable energy. Denmark – while punching above weight in terms of yearly H₂ production – will only be a relatively small player in the global commodity market for hydrogen and hydrogen-based fuels. However, Denmark leverages its large seabed area and good offshore wind conditions to become a major green commodity exporter of green electricity, PtX fuels and chemicals on a regional level.

Danish know-how and technology export contributes significantly to national value creation. Danish shipping and logistics firms – now fully climate neutral – have achieved a competitive advantage from their global leadership in decarbonising their activities, as consumers increasingly call upon companies to address scope 1, 2 and 3 emissions, including transport. Industries are relocating to Denmark to benefit from cost competitive renewable energy, fuels and feedstocks, and Denmark is attracting international talents seeking training or work within the field of power-to-X.

⁶ European Commission 2030 CTP IA - MIX

⁷ Wind Europe – Our Energy, Our Future, 2019. App. half will in practice be dedicated commodity export.

⁸ ETC: Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy. 2021



Section 2: **THE POINT OF DEPARTURE** and **NEXT STEPS**

The technologies are known – now they must be implemented

In its essence, power-to-X is the exercise of converting moving electrons to molecules. And generally, the methods and technologies to do so are well known. Producing hydrogen from electrolysis, for instance, has been done for more than 200 years. Other common processes, such as Fischer-Tropsch (producing hydrocarbons from hydrogen and carbon monoxide) or Haber-Bosch (producing ammonia from hydrogen and nitrogen) carry names from the scientists who first described them a century ago.

While newer paths from electron to molecule have since been explored – and as component costs and process and plant efficiencies are incrementally being improved – the central technologies to power-to-X are generally known, as is demonstrated by their respective TRLs.

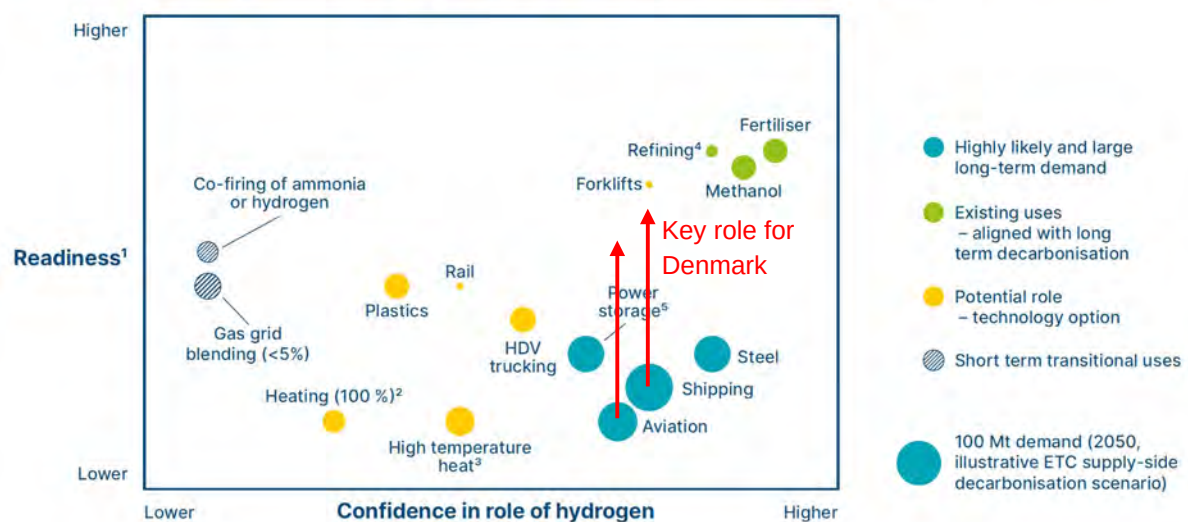
The pathways to maturing power-to-X is to a large extent a challenge of 'making the pieces fit together', holistically integrate system components and increasing overall system efficiency towards commercialization, validation and de-risking to increase confidence in the technology and achieve cost-competitive solutions. In effect, this includes feasibility and FEED studies, as well as demonstration projects to identify and address the technical, economic and regulatory challenges that comes with implementing power-to-X and carbon capture and utilization in real life.

For Denmark, the challenge and opportunity is in kick-starting this implementation track – with a special focus to heavy transport sectors. This is needed to reach the current climate targets – and to bolster Denmark's global position as a hub for leading clean tech industries and sustainable logistics and transport companies.

Denmark well positioned to increase overall readiness of two major hydrogen and e-fuel pathways

Illustrative opportunity space for Denmark, leveraging form existing industrial and academic strengths.

Adapted from Energy Transitions Commission: Making the Hydrogen Economy Possible, 2021



Supply side technologies

Hydrogen electrolysis

Three major electrolysis paths exist, Alkaline (AEC), Proton Exchange Membrane (PEM) and Solid oxide (SOEC). AEC is a mature technology (TRL 9). Recent efforts have focused on pressurised AEC systems, scaling production and increasing efficiency, with indications of potential for further significant cost reductions. PEM is a newer but mature (TRL 8-9) and may achieve higher theoretical efficiencies than AEC. However, it suffers from the use of the rare earth metal iridium, which may limit long term build out. SOEC promises the highest efficiency but lacks durability and development (TRL 6-7) before being commercially available. Several vendors claim to have developed 20MW systems, but these consist of several smaller modules and are not yet commercially proven. While AEC and PEM electrolyzers have been demonstrated in industrial (10MW+) scale applications, ramping up the supply chain and reducing unit costs remain a barrier to commercialization. Similarly, optimizing efficiencies on a plant level, including utilization of highly variable loads and integration with district heating to increase overall efficiency, is relatively new grounds.

	CURRENT TRL / SRL ⁹
Hydrogen electrolysis (AEC)	TRL: 9
Hydrogen electrolysis (PEM)	TRL: 8-9
Hydrogen electrolysis (SOEC)	TRL: 6-7
Hydrogen electrolysis system integration	SRL: 6-7 – Pre commercial demonstration

Main challenges towards 2030: Scaling up supply chain for electrolyser stacks. Integration of large-scale hydrogen electrolysis in Danish energy system, including utilizing surplus heat. Demonstration of project economy and feasibility of frequent ramping production up and down to match the output of a variable power sources. Energy market design and regulatory incentives to enable commercialization of renewable hydrogen. Ensuring geographical locations of electrolyses and power2X that enable synergies with the electricity and district heating grids as well as reduces the need for large-scale hydrogen storage.

Main challenges towards 2050: Improved cost performance of electrolyser plants. Retrofitting or converting existing gas infrastructure to accommodate a continental hydrogen market. Market design to enable electrolyzers to supply ancillary services and potentially run at fewer full load-hours.

⁹ 1. Technology readiness level common framework to assess technology maturity: 1 Basic research; 2-4 technology development; 5-8 Demonstration; 9 Commercialisation. See Innovation Fund Denmark TRL and SRL definitions.

Carbon Capture

Carbon capture (CC) can generally be divided in three types of technology: Pre combustion, post-combustion CC and oxy-fuel CC. Post combustion capture can be retro-fitted to existing installations, while oxy-fuel and pre-combustion capture should generally be installed together with the installation of the plant. Post-combustion CC based on an amine solution is a mature technology used across the world at industrial scale. There are other alternatives to amine solutions that promise better overall efficiency and a reduced negative environmental impact. One example is chilled ammonia, which is being developed by Baker Hughes.

Carbon capture can generally achieve a 90% carbon capture rate, i.e. capture 90% of the CO₂ in the flue gas. Going above 90% is possible, but the cost increases significantly above this level. The maximum feasible capture rate is expected to increase to around 95% in the future (2030+). Carbon capture requires energy in the form of steam, and hence the actual capture rate at a specific site may be lower than 90% depending on what energy sources are available. Utilization of waste heat to increase to overall efficiency at plant level is yet to be demonstrated.

	CURRENT TRL / SRL
Carbon capture (CC)	TRL: 9 – Integration at scale
Carbon capture and storage (CCS)	TRL: 7 – Pre commercial demonstration
Carbon capture and utilisation (CCU)	TRL: 7 – Pre commercial demonstration
Utilisation of waste heat	TRL: 5 - Demonstration
CCU/S System integration	SRL: 5 – Proposed solutions validated by feasibility study

Main challenges towards 2030: Full scale integration with CO₂ point sources (CHP- and WtE plants) and eventually fuel synthesis plant. Perform system level integration (heat and process integration) and optimization to ensure low cost and efficient solutions on overall system level. Scaling carbon capture and interface with offtaking solutions, both utilization and storage. Develop regulatory framework that incentivizes carbon capture on sustainable biogenic emission sources with subsequent use of CO₂ for PtX.

Main challenges towards 2050: *Ensure long-term supply of sustainable CO₂ from biogenic- and atmospheric sources for use in production of green fuels through PtX, while maintaining a focus on sustainable use of bioenergy in CHP plants.*

Carbon capture on biomass heat- and power plants

Carbon capture is a prerequisite for reaching the ambitious national and international climate targets, both in order to avoid CO₂ emissions from unabatable fossil sources, but also for decarbonizing hard-to-abate sectors where a carbon-fuel is required, such as aviation and shipping. The only way to produce truly renewable e-fuels with carbon content is to combine hydrogen from electrolysis based on renewable electricity with sustainable CO₂ from biogenic sources or direct air capture (DAC). Until DAC becomes commercially available at scale, sustainable carbon will be a scarce resource and should be captured and used for the purposes where it brings the highest climate value.

Different sources of sustainable CO₂ will have different costs for installing carbon capture due to e.g. concentration of CO₂ in the flue gas, proximity to logistics infrastructure, scale of plant, number of annual operational hours, remaining plant lifetime, etc. Hence, some plants will be able to supply carbon at relatively low additional costs, while others will be more expensive. However, due to the large volume of sustainable CO₂ needed to decarbonise aviation alone, it will be necessary to install carbon capture on most or all installations where it is technically and economically feasible.

For example, decarbonizing all of EU aviation (domestic and international) will require around 170Mt of CO₂ per year when assuming that all current jet fuel consumption is replaced with sustainable jet fuel¹⁰. The total capturable potential in EU today is only around 140-200 million tonnes, however some of these units may not be feasible for carbon capture due to size, location, short remaining lifetime, or other reasons. Recalling also that sustainable carbon may be necessary to decarbonise parts of long-distance shipping, as well as for creating negative emissions for reversing climate change, all sustainable CO₂ that can be captured, should be captured.

¹⁰ EASA, EEA and Eurocontrol, European Aviation Environmental Report 2019

Aviation fuel (and the methanol path, more generally)

Commercial aviation fuel in use today is almost exclusively in the form of kerosene. Among others, kerosene is used in aviation due to its high energy density. Due to a need for high energy density for long-duration flights it is generally expected kerosene-like fuel will continue as the prevailing fuel type in aviation. Sustainable aviation kerosene can be segmented into two overall types; bio-kerosene and e-kerosene. Biofuel is in use today, but at a global scale, biofuel has limitations due to limited feedstock availability, sustainability and competing demand. E-kerosene is less restricted with regards to feedstock availability, can be produced at scale and generally expected as the long-term solution.

To produce e-kerosene requires CO₂ and hydrogen as feedstock. Two main paths exist to convert CO₂ and hydrogen to aviation fuel: Fischer-Tropsch (FT) and Methanol (MeOH).

For FT, CO₂ must be converted to CO in a high temperature reactor called syngas preparation, which has been demonstrated (TRL 6). There are several alternative process configurations for the preparation of syngas from CO₂, which needs to be integrated holistically with electrolysis unit to ensure highest efficiency and the lowest cost seen from overall systems level. The FT process is in commercial operation in several large-scale plants. Pre-commercial reactors suitable for projects in a smaller size, suited for short and medium term projects combined with renewable hydrogen production (e.g. ~250MW range) have been demonstrated e.g. by Velocys and Sasol (TRL 6). The FT process produces a synthetic crude oil, which requires further processing to produce kerosene. Final fuel refining can be performed in retrofitted refinery processes, which are commercially proven by Sasol, Shell, and Topsoe (TRL 9).

For the MeOH pathway most commercial MeOH plants convert CO+H₂ to MeOH. However, using a feed gas of CO₂ and hydrogen has been proven (e.g. at Iceland, CRI) TRL 8-9, and Topsoe has with Dupont Beaumont Methanol in Texas operated with CO₂ import resulting in a similar feed gas since 1985 (TRL 9). Conversion of methanol to jet fuel takes first MeOH-to-Olefin (MTO), which is commercialised (TRL 9). The next step is Olefin-to-Distillate which has been demonstrated, e.g. by ExxonMobile (MOGD) TRL 6. For the MeOH pathway, commercialization is contingent on approval by the US approval organization ASTM.

In the longer term, such power-to-liquid exhibit the largest cost reduction potential and is expected to make up the largest volume of sustainable aviation fuels (SAFs) in the mid- to long term, from mid 2030s onwards. Before 2050, it is expected e-kerosene from power-to-X will be cost competitive vis-à-vis both fossil kerosene and bio-SAF¹¹.

It is however the expectation, that the full expanse of SAF production pathways is necessary to phase out fossil fuels from the aviation sector, as no single sustainable fuel type will be able to meet the increasing demand for aviation fuels in Europe.

	CURRENT TRL / SRL
Fischer-Tropsch (efficient, smaller scale)	TRL: 6 – Pilot demonstrated
Fischer-Tropsch (industrial scale)	TRL: 9 – Commercial operation
Refining	TRL: 9 – Commercial operation
Methanol	TRL: 6-7
System integration	SRL: 5-6. Clear declaration of intent from stakeholders. Standardisation body approval pending

¹¹ Destination 2050: A route to net zero European aviation. Roadmap prepared by five major European Aviation Industry Associations (A4E, ACI Europe, ASD Association Europe, ERA, CANSO)

Main challenges towards 2030: Integrate hydrogen electrolysis, carbon capture, methanol synthesis and aviation fuel production to improve efficiency and create plant synergies, including heat and process integration to ensure low cost and efficient solutions on overall system level. End-to-end integration of the chemical synthesis process steps towards aviation fuel. Develop a regulatory set up supportive of sustainable aviation fuel offtake and ensure fuel type approval by the relevant industry bodies.

Main challenges towards 2050: Continuously realise cost reductions to ensure competitiveness, together with bio-kerosene, against fossil kerosene. Continue ongoing work to develop international regulatory framework capable of addressing international aviation emissions, which currently do not count towards Denmark's 70% target.

Ammonia

Ammonia (NH₃) is the second most produced chemical in the world and is commonly used as a base chemical and in the production of nitrogen fertilizers. The ammonia molecule is comprised of one nitrogen and three hydrogen atoms, hence the ammonia molecule itself is carbon free. Nitrogen in the form of nitrogen molecules (N₂) is the most common molecule in atmospheric air (78%). In its simplest form the production of ammonia is done by combining nitrogen atoms from atmospheric air with hydrogen atoms. Production of ammonia, by means of combining nitrogen and hydrogen, typically takes place through a chemical process known as Haber-Bosch. Today, most of the hydrogen going into the Haber-Bosch process is produced by steam reforming of fossil fuels, while the nitrogen is produced through separating nitrogen from the remaining constituents of atmospheric air in what is known as an air separation unit.

In addition to its current use as a chemical, ammonia has been widely suggested as a future sustainable fuel. This is due to several reasons. Firstly, sustainable ammonia is not limited by feedstock availability since the inputs required for production are nitrogen from atmospheric air, water for hydrogen electrolysis and renewable electricity to run the electrolysis process. Secondly, it can be stored in liquid form at ambient temperature if pressurized to around 10bar with reasonable energy density in comparison with conventional liquid fuels. One drawback of ammonia is relatively high toxicity for humans and the environment in case of a spill. For these reasons, ammonia is mainly considered as a fuel for heavy duty applications such as marine shipping and potentially for stationary power generation.

Because of the use of fossil fuels in the production of hydrogen for Haber-Bosch synthesis, the production of ammonia is today very carbon intensive. However, the fossil hydrogen can be replaced by hydrogen produced by water electrolysis using renewable electricity, whereby the produced ammonia becomes sustainable. In principle, a conventional Haber-Bosch ammonia plant would only need to exchange the fossil fuel-based steam reforming step with electrolysis to produce sustainable ammonia. However, typical ammonia plants today are at massive scale compared to the scale of today's electrolysis units; in part driven by large scale benefits of air separation units. For this reason, there is a need for further development of ammonia plants capable of efficiently producing ammonia based on electrolysis at small scale. Efforts into improving efficiency at small scale is being made by industry. One such example includes the concept of avoiding an air separation unit altogether by using the specific characteristics of high-temperature SOEC electrolysis technology. The SOEC makes possible simultaneous production of hydrogen and separation of nitrogen from air to yield a suitable ammonia synthesis gas for subsequent Haber-Bosch ammonia synthesis. However, this concept is still at an early development stage.

	CURRENT TRL
Haber-Bosch synthesis	TRL: 9 – Integration at scale
Integration of proven electrolysis in way of steam reforming in Haber-Bosch	TRL: 7 – Pre commercial demonstration
Ammonia synthesis gas production using SOEC	TRL: 4-5 Technology validated in lab

Main challenges towards 2030: Integrate electrolysis-based hydrogen production at scale in retrofitted ammonia plants to gradually displace steam reforming. Create an efficient electrolysis-based green-field ammonia plant design minimizing current advantage of scale.

Main challenges towards 2050: Develop an end-to-end electricity-based production process for ammonia optimized for electrolysis integration and variable renewable electricity generation as the energy source.

Key demand side technologies

Aviation

Aviation, due to its high volumetric and gravimetric energy density requirements, is considered one of the hardest sectors to decarbonise today. However, seven overarching pathways for sustainable aviation fuels SAFs are currently being explored. Leaving out solutions based on biofuels (HEFA, waste, used cooking oils etc.), cf the discussion on availability above, these are: direct electrification using batteries, pure hydrogen and e-kerosene – as well as hybrid solutions of the above.

Smaller battery electric airplanes have been demonstrated to carry a few passengers at inter-regional distances of a few hundred kilometers, and newer models are expected. However, owing to the relatively low energy density of batteries, electrification of overseas and long-haul aviation is hardly realistic.

Indirect electrification using pure hydrogen has been proposed to (partially) overcome the challenge of carrying sufficient energy for a long flight on a plane. One such example is Airbus' ZEROe program, aiming to introduce the world's first commercial airliner powered by gas turbines burning hydrogen by 2035.

However, before then, and likely long after, given the 25+ years investment cycle of commercial aircrafts, SAFs based on e-kerosene is likely to be a main pathway for SAF production in the medium-to-long term.

E-kerosene based on renewable hydrogen and sustainable CO₂ from biogenic sources will have the same composition as fossil kerosene – essentially making it a 'drop in' fuel, requiring very limited to no adaptation on the demand side.

While more evidence is needed, preliminary results from measurements using SAF, and laboratory experiments indicate certain SAF compositions come with the added benefit that they can reduce the overall radiative forcing from aviation (the 'non-CO₂' related effects from e.g. contrails and particles and soot), which also carry a significant part of the climate impact from aviation.

Path	CURRENT SRL
Distribution and utilization of e-kerosene (from Fischer Tropsch pathway)	SRL: 8 – No new technological requirements
Distribution and utilization of e-kerosene (from e-methanol pathway)	SRL: 8 – Contingent on approval by ASTM

Main challenges towards 2030: No new technology required. Cf supply side challenges.

Main challenges towards 2050: -//-

Why not just continue with fossil business as usual - and offset with CCS?

One theoretical way to indirectly decarbonise the hardest-to-abate heavy transport in the long run could be to continue business as usual – and then offset the fossil emissions through e.g. CCS based on biogenic carbon.

This path, however, is an unfeasible alternative to replacing fossil jet fuels with SAFs for at least three reasons:

- Firstly, emissions from end use fuel combustion are only part of the problem. Along the supply chain for fossil fuels there is further (fossil) energy consumption and leakages, all contributing to diminishing the global carbon budget – but not being accounted for by the end user and hence not 'captured'.
- Secondly, even if the supply chain emissions and leakage can be robustly accounted for, negative emissions and nature-based solutions are already projected to play an important role to stay below 1.5°C by end-century. Continuing the current fossil practice in select sectors would put further pressure on a limited carbon sink, jeopardizing the global efforts to stay within the planetary boundary.
- Thirdly, like all other industries, aviation has an urgent need to perform reduced climate impact. Continuation with fossil fuels will be detrimental to the aviation industry - both business customers and leisure travelers require future sustainable aviation.

Maritime shipping

Like aviation, deep sea shipping remains challenged by the high energy density requirements needed to ship goods over longer distances. And just as with aviation, advanced biofuels will eventually come with supply bottlenecks, leaving this option only partially feasible in the long term.

Instead, energy carriers such as synthetic e-methanol and e-ammonia have been proposed as two sustainable shipping fuel candidates for global maritime shipping. A third is hydrogen fuel cell electric drives. Vessels powered by hydrogen fuel are beginning to become commercially available but are generally reserved for shorter, fixed routes, due to both high volumetric space required to carry sufficient hydrogen fuel and the high-tech refilling infrastructure not being universally present when docking at ports.

Both e-ammonia and e-methanol will require new engines and infrastructure. The 2-stroke diesel engine technology in use in the majority of maritime deep-sea vessels, is generally capable of burning ammonia and methanol as fuel, but this requires modifications to the design. For e-methanol, 2-stroke engines became commercially available in 2016, whereas the 4-stroke medium speed engines are still in the development phase. Deployment in vessel conversions have also been seen, e.g. the conversion of 4 main Wärtsilä 8ZAL40S engines of the STENA Germanica (2015) and in newbuild vessels like the Taranaki Sun chemical tanker equipped with MAN B&W ME-LGIM dual fuel engines (2016). Deployment has historically been limited, but 2021 has seen commercial interest pick up. For ammonia, marine engines are currently not available, but engine designers are working towards making them available. The world's largest 2-stroke engine designer, MAN ES, is currently working on a two-stroke ammonia engine intended for first commercial deployment in 2024. Wärtsilä is similarly working on a 4-stroke ammonia engine, which is expected to be commercially available before 2024.

In addition to reciprocating engines, solid oxide fuel cells (SOFC) and direct methanol fuel cells, may in time play a more prominent role in marine propulsion. However, demonstration and balance of plant trials on large scale are needed, and the perspectives for large scale deployment goes beyond 2030.

As the fuel types are similar, e-methanol and e-ammonia are relevant marine fuels across propulsion engine types. Before deployment can begin to accelerate, feasibility and design studies are needed, as well as a need for scaling and marinizing SOFC technologies. This includes vessel-side investment, OPEX and HSE, but also analysis into fuel availability, bunkering, route planning, supply bottlenecks and sustainability.

Main challenges towards 2030: Ensuring bunkering infrastructure is in place and ample fuel supply is guaranteed to avoid stranded assets. Commissioning of new ships and conversion of engines compatible with new fuel types supported by technical approval by Class Societies, Flag states and IMO. Reducing cost gap to fossil bunker fuels, including through scale and optimization of process efficiencies along the supply chain. Ensure end markets with gradually more ships using e-ammonia. Continue the development of X to power technology including fuel cells.

Main challenges towards 2050: Establishment of global bunkering network. Closing cost-gap to fossil bunker fuels. Establish well-to-wake GHG transparency of transport to end consumer to incentivise uptake of green shipping.

Path	CURRENT TRL
E-ammonia	TRL: 6 – pre-commercial demonstration
E-methanol	TRL: 8 – pre-commercial demonstration
Bunker infrastructure and system integration	SRL: 6 – Solutions proposed but not demonstrated

Heavy road transport

The past decade has seen a rapid transformation of light duty (passenger) road transport, fueled by efficiency gains and cost reductions in modern li-ion batteries. Today, most analysts agree battery electric vehicles (BEVs) are now mature and will increasingly render internal combustion engine vehicles obsolete (ICEVs).

However, while the same story may to an extent also become the case for heavy duty road transport, batteries-electric drives are still relatively heavier compared to BEV and fuel cell electric (FCEV) counterparts. Furthermore, they come with the challenge of relatively long charging times – especially if operating without access to a fast-charger. For these reasons, indirect electrification using fuel-cell electric drives (FCEVs) fueled by renewable hydrogen from electrolysis are considered an alternative pathway to decarbonise heavy road transport.

Both technologies have been demonstrated at large scale and are now commercially available – albeit still at a CAPEX cost premium, which must be recuperated through OPEX efficiencies. To logistics operators, this leaves the task of establishing own experiences with either of the two alternatives, to test its fleet integration, infrastructure requirements and potential OPEX gains. Such initial experience building with FCEV trucks will also entail establishment of dedicated hydrogen dispensing stations and associated infrastructure at strategic locations. Such infrastructure will in addition help quantify potential benefits of hydrogen infrastructure at a system level, including reduced needs for grid reinforcements compared to e.g. battery-electric.

Furthermore, while FCEV drivetrains are commercially available, including for heavy-duty, long haul road transport, the selection and market volumes remain limited. As such, a further challenge is in unlocking further FCEV supply chain investments among heavy transport producers. While the Danish market is relatively minor in the global scale of heavy land transport, developing solutions to produce and dispense cost competitive hydrogen will send a clear market signal calling for fuel cell drivetrains.

	CURRENT TRL / SRL
FCEV drivetrains	TRL: 8 – commercially demonstrated
FCEV fleet integration and infrastructure	SRL: 7-8 commercially demonstrated

Main challenges towards 2030: Reducing total cost of ownership to end-users to enable and de-risk experience building. Increasing FCEV selection and market volume. Increasing storage capacity of high-pressure (700-bar) tanks to increase operational range. Optimizing fleet logistics. Establishing and optimizing hydrogen distribution infrastructure, including cross-border.

Main challenges towards 2050: Buildout of dispensing infrastructure. Reducing CAPEX cost of vehicles through scale.

Smart energy systems and System Integration

The Danish energy system has a long history of integrating value and resource streams to increase overall system efficiency. Waste becomes a resource when it is utilized for energy, combined power and heat generation feeds into a highly efficient district heating system, surplus heat from industry is often utilized - and when strong winds are blowing and power prices low, electricity can be stored in heat accumulators or in the district heating grid using electric boilers and heat pumps.

These smart energy system and 'sector coupling' interfaces are in part what has made the Danish energy system efficient, stable and well suited for renewable energy. With the introduction of carbon capture and power-to-X technologies at scale, even more interfaces between resource, energy and value streams become visible – offering further potential for efficiencies and synergies.

As illustrated on page 6, both carbon capture, electrolysis and fuel synthesis processes generate surplus heat which can in time deliver a significant share of Danish district heating demand. Captured carbon can be combined with hydrogen electrolysis to create renewable fuels and other feedstocks for industry. And in the longer run, renewable hydrogen can create a bridge between variable power generation and a future dedicated hydrogen grid.

All such synergies must be identified and realized, to increase the overall cost performance and efficiency along the future value chains for power-to-X, in order to quickly scale and commercialize the new technologies. This requires a strategic and sector-integrated approach to developing smart energy systems. Both when designing future regulation and policies – and when promoting innovation and development of new technologies. By developing technologies independently and in 'silos', the important interfaces between projects risk being missed, potentially leading to a slower, sub-optimal development of green fuels and jeopardizing the vision of a Danish power-to-X industry laid out in this roadmap.

An aerial photograph of a multi-lane highway bridge spanning a body of water. The bridge has several lanes in each direction, separated by a central median. A large white truck with a blue trailer is traveling in the left lane, and a dark-colored car is in the adjacent lane. The water is dark blue, and the bridge structure is visible on the right side.

Section 3: **A ROADMAP TOWARDS 2050**

Overview: Roadmap and milestones towards 2050

Pathway	2021-2025	2025-2030	2030-2035	2035-2040	2040-2050
Hydrogen electrolysis (AEC PEM, SOEC)	Scale up to ~200MW stacks in flexible operation with use of excess heat in district heating	2-2.5GW electrolyser Renewable hydrogen cost competitive to fossil hydrogen + CCS	4GW electrolyser Renewable hydrogen cost competitive to fossil hydrogen	8GW electrolyser capacity in Denmark, app. half offshore	15-20GW electrolyser capacity in Denmark, app. half offshore
Storage, transport and distribution	Demonstration of CO ₂ -storage in combination with e-fuel production. Demonstration of hydrogen distribution and tanking	Large-scale storage and distribution of e-fuels Hydrogen and CO ₂ transmission lines e.g. connections to Northern Germany	Expanding hydrogen and CO ₂ grids in Europe Heavily expended markets for e-fuels and hydrogen	Fully connected European e-fuels and hydrogen market E-fuels and hydrogen dominates in shipping and aviation	Heavy duty transport is fully decarbonized
Carbon Capture	Pilot plants emerging at waste incineration plants, industrial plants and biomass CHP	First full-scale plants in Denmark, mostly centered around Copenhagen. First CCU applications 0.5-1Mt/y CO ₂ captured	All significant point sources for carbon have CC plants. Renewable (biogenic) carbon being used in PtX applications. 4-6Mt/y CO ₂ captured.		Biogenic carbon potential of 3.5Mt/y Direct Air Capture (DAC) combined with both CCU and CCS
E-Methanol		2027: First large-scale E-methanol production in Denmark	2030: E-methanol based on renewable hydrogen form basis for decarbonization of domestic and regional shipping	Danish ports part of global e-methanol bunkering network. Large share of deep sea shipping on e-methanol	Danish shipping sector completely climate neutral, based mainly on e-methanol and e-ammonia
Aviation (E-kerosene)	Scalable technical solutions to produce e-kerosene demonstrated from 2023 onwards	~0.2Mt renewable e-kerosene produced in Copenhagen, covering some ~25% of Danish consumption		All Danish aviation fuels provided by power-to-X	
Shipping (E-ammonia)	2023-2024: First commercially available ammonia engine (2- and 4 stroke). Continuous: Denmark to endorse ambitious regulation through IMO that can ensure a level playing field and promote innovation.	First large-scale e-ammonia plant in Denmark. Ammonia bunkering in several ports Danish flag state as front-runner on regulation and guidelines for use of ammonia as fuel on IGC and IGF-code ships			Danish shipping sector completely climate neutral, based mainly on e-methanol and e-ammonia

Need for a prioritised 'flagship' approach to mature power-to-X

Costs of renewable hydrogen production is expected to decrease dramatically towards 2030 and beyond through scaling the technology. This cost-out journey, as well of the development and technological maturing power-to-X technologies, can be accelerated if promoted through a 'flagship project approach', focusing on projects that encompass the entire value chain, with an emphasis on end users.

Specifically fostering joint ventures between supply and demand for future research and innovation partnerships comes with several advantages:

- 1) Plays to a specific Danish strength of being able to develop technical, economic and regulatory solutions *along* the value chains and not just focus on developing technologies in silos
- 2) Helps overcome the chicken and egg challenge for investors, when both demand and supply side are on board.
- 3) As maturing power-to-X applications also depends on regulation, flagship projects backed by the IFD can potentially be a regulatory sandbox, where regulation can be tried or dispensed.
- 4) Provides a good point of departure from where projects can continue on a growth trajectory in later stages, both in terms of throughput volumes and for continuous innovation, improvement and optimization, even after going commercial.

Example of a flagship project: A joint venture for a ground breaking power-to-X project in the Copenhagen area

The Green Fuels for Denmark (GFDK) project brings together leading Danish companies representing the demand and supply side of sustainable e-fuels behind a vision to establish an ambitious sustainable fuels production facility. The project aims to establish a 1.3 GW electrolyser in 2030 powered by 2-3 GW offshore wind from the Bornholm energy island, which holds the potential to replace >270.000 tpa. of fossil fuel consumption in 2030, equivalent to a 1.77% reduction in Danish CO₂ emissions. The project is intended to be established in three phases:

- Phase 1 (2021-2023): Establishing a single electrolyser module of 10MW producing renewable hydrogen for use in fuel cell buses and trucks in Denmark.
- Phase 2 (2023-2027): Scale-up and commercial operation of a 250MW electrolyser coupled with offshore wind, CO₂ capture and chemical synthesis to produce sustainable renewable e-methanol for maritime transport and renewable e-kerosene for aviation.
- Phase 3 (2027-2030+): Further scale-up to reach a combined electrolyser capacity of 1.3GW to be combined with app. 1Mt/y carbon capture, corresponding to 30% of Copenhagen Airport's fuel consumption, a large proportion of truck and bus operations in Greater Copenhagen and a full-sized container vessel.

Copenhagen Airports, A. P. Moller-Maersk, DSV Panalpina, DFDS, SAS, Everfuel, NEL, Molsslinjen, Haldor Topsoe, COWI, the Municipality of Copenhagen, Denmark's Capital Region and Ørsted have formed the first partnership of its kind which combines leading competencies across the value chain. The project aims to draw upon these to become a frontrunner for a large industry-coordinated heavy-duty transport sector decarbonization. The project holds the potential to establish new solutions to global challenges in relation to energy, climate and transport.

