Appendix 3: 1112-00008A – Roadmap for Green Fuels in Transport and Industry Innomission 2 (2021)

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.

Roadmap for Green Fuels in Transport and Industry

Innomission 2 (2021)

Content

1 Abbreviation

AEC	Alkane electrolysis cell
Biofuel	Biofuel is fuels produced from biooils (see definition of biooil below)
Biogas	60% methane and 40% CO_2 based on production from biomasses via anaerobic digestion
Biooil	Biooil is oil produced from pyrolysis, liquefaction or the HVO process. Biooil also include oil from pyrolysis of plastic and tires as it is assumed that these with time will become 100 % biogenic.
BNG	Biogas upgraded to natural gas quality by removing CO_2 and other impurities, leaving primarily CH_4
CC	Carbon capture
CCU	Carbon capture and utilization
CCS	Carbon capture and storage
CH_2	Compressed hydrogen
CHP	Combined heat and power plant
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
DK	Denmark
DME	Dimethylether (C_2H_6O)
ENDK	Energinet Denmark
EtOH	Ethanol (C_2H_5OH)
EU	European Union
EC	Electrolysis cell
FAME	Fatty acid methyl ether (=biodiesel) (C_{16}-C_{81} esters)
FCEV	Fuel cell electric vehicle
Gasoline	Light hydrocarbons (C_4-C_{12}, typically C_7-C_{11}). Same as petrol.
GHG	Greenhouse gas
H_2	Hydrogen
HFO	Heavy fuel oil (typically C_{20}-C_{50})
HVO	Hydrotreated vegetable oil (typically C_{15}-C_{18})
Jet-fuel	Highly branched hydrocarbon, C_{10}-C_{13}, mostly kerosene
LCA	Life-cycle assessment analysis
LH_2	Liquefied hydrogen
LNG	Liquefied natural gas (primary CH_4)
LOHC	Liquid organic hydrogen carriers (H_2 carrier with the goal of making H_2 transport cheaper)
LPG	Liquefied petroleum gas (primary C_3-C_4)
M85	Methanol gasoline blend with 85 wt% MeOH
MeOH	Methanol (CH_3OH)
MGO	Marine gasoil (typically $<C_{35}$)
Mt	Megatonne (1.000.000.000 kg)
NG	Fossil natural gas (primarily CH_4).
NH_3	Ammonia
RE	Renewable energy
SMR	Steam methane reforming (eSMR=electric heated steam methane reforming)
SOEC	Solid oxide electrolysis cell (high temperature with high efficiency)
WtE	Waste to Energy plants

2 Executive Summary

This road map provides a consolidated call for action through three periods leading to 2023/24, 2030 and 2030-2050 respectively, on the approach to green fuels in transport and industry in Denmark, building on multiple workshops and interviews involving a large number of the most significant Danish stakeholders across research organisations, innovation and knowledge sharing institutions, trade organisations and companies including technology and energy providers and future off-takers of green fuels. The roadmap is to be seen in conjunction with Innomission 1: Capture and storage or use of CO_2.

A call for action. Key activities and workstreams build on identified goals, challenges and inflection points and provides guidance for stakeholders, that all are part of a green transition. One action remains the most immediate and prominent across the value chain – the need to act urgently and coordinated and to support more demonstration and up-scaling activities. Further delay or hints of indecisiveness, in the support of enabling a transformation, will have pronounced consequences to the ability of further curbing Danish greenhouse gas emissions according to both national and international goals, as well as the harnessing of the significant Danish socio-economic potential. A large number of Danish industry stakeholders are already planning a total of 3.7 GW (~53 PJ/y hydrogen production) significantly exceeding the expectations of the Danish Energy Agency during the period from 2024 to 2030 of 132 MW (~1.9 PJ/y hydrogen production). These plans provide an immediate and obvious launch pad for a strong Danish ambition within PtX as supported by this roadmap.

Reducing uncertainty. Key in the utilisation of hydrogen-based fuels and scarce renewable carbon resources in specific parts of the transport system and industry requires a scale of investment beyond the traditional willingness of the public sector. To succeed, a reduction in uncertainty and achievement of cost parity between alternative green and fossil fuels, is needed. This involves:

- A clear and stable path as to which fuels besides direct electrification to target, which preferably is already global commodity e.g. Hydrogen, Ammonia, Methanol and biooil.
- Drastically increasing the availability of green hydrogen as well as increasing its utilisation both directly and as a basis for production of green fuels. And in consequence increase availability of renewable power accordingly.
- Pooling the off-taking demand side and creating new value chains across energy and transport.

- Ensuring focus of public resources available for building large scale demonstration and test sites. Changes in regulatory framework conditions (i.e. CO_2 taxes, subsidies, CO_2-displacement requirements in a cap-and-trade system) and research into innovative business models.
- End-to-end large demonstrators and cost-out innovation activities with a strong focus on enhancing the efficiency in PtX and PtX-activities coupled with wind energy sources and technologies.

Technology leads the path to efficiency. In the subsequent steps technological development is equally vital in the bringing forth of a transition, in relation to the gradual cost-out of the production of fuels. In tandem with the development of the markets for green fuels, research and innovation will allow for more optimal combinations and scaling of existing technologies. On a longer term it could allow for the breaking of entirely new ground within the technologies by researching in optimization of electrolysis and catalytic processes. Research and innovation would entail:

- Optimal use of feedstocks across off-take sectors based on Life Cycle and substitution analyses, combined with studies into security of supply for feedstocks.
- Efficiency for new or retrofitted engines, new methods for modelling, forecasting, controlling and optimizing engines running on green fuel and safety in relation to operation.
- Pathways into a stronger integration of PtX plants with the broader energy systems by looking at modelling, control systems, new market design principles and monetization models to secure plant efficiency and a robust and balanced energy system enabled by a number of distributed PtX plants.
- New possibilities for utilisation of surplus heat and the use of biproducts from processing.
- Sector coupling of flexibility in both production and offtake of green fuels through among other digitalization, Artificial Intelligence, dynamic tariffs and through social science disciplines studying accept and behavioural adaptation in relation to PtX plants and new energy infrastructure facilities.
- Development and discovery of new catalysts and processes that are not limited by poor efficiency, low product selectivity, high cost, and rarity are needed.
- Fundamental research in CO_2 functionalization to generate platform chemicals, key building blocks in pharmaceutical industries and polymer chemistry, providing sustainable alternatives for petroleum-based chemicals.

Stay ahead. Denmark is already a world leader within shipping and maritime equipment as well as catalytic processing – combing large industry with a strong undergrowth of innovative SMEs. Furthermore, the Danish strongholds mirror the wind energy production capabilities and knowhow, which is second to none and offers cheap green power throughout the globe. In addition, the openness and trustfulness in the Danish research and innovation environment and in the related industry constitute the basis for unique collaborations across the entire value chain. By choosing timely to adhere to the necessity of making green fuels a key element at certain stages and in certain areas within transport and industry, Denmark's position in the lead of the global transition towards a sustainable future can be sustained. It will ensure that green fuel technologies in combination with carbon storage solutions will also be a substantial and increasing part of the economic activity of Denmark going towards 2030 and beyond.

2.1 PROCESS AND PARTICIPATING ORGANIZATIONS

Danish Center for Energy Storage (DaCES), six universities AAU, AU, SDU, KU, CBS, DTU, Energy Cluster Denmark (ECD) and Maritime & Logistics Innovation Denmark (MARLOG) have instigated the initiative to establish the partnership behind the Roadmap. With Professor Anker Degn Jensen, DTU Chemical Engineering as chair, the partnership has orchestrated this roadmap. Key partners and co-sponsors, the Danish Technological Institute, FORCE Technology, DBI and the Alexandra Institute, (RTO's), Vestas and Haldor Topsøe, have joined the initiative and are equally sponsors of the roadmap.

Three workshops, each hosting approx. 100 participants, has involved representatives of universities, industry, interest and business associations in identifying the challenges and possibilities. The workshops were involving and with a broad representation. The output was synthesized to decipher common denominators, gaps in the value chains and potential conflict of interests btw. stakeholders. Moreover, the synthesis includes insights from a number of key industry interviews, as well as input from the DACES Joint Working Group, the boards of both ECD and MARLOG on the subjects.

Table 2-1. Organizations participating with inputs to the roadmap

1st Mile	DNV	North Denmark EU Office
A.P. Møller Mærsk		Nordic Folkcenter for Renewable Energy
Dansk Shell	DTU	NORDPHOS
ADP AS	DynElectro	Ocean Team Scandinavia
Danish Academy of Technical Sciences (ATV)	En2save	Oiltanking Copenhagen
Alexandra Institute	Energinet	PFA Pension
Andel	Energy Cluster Denmark	Port of Hanstholm
AquaGreen	EnergySolution	Port of Rønne
Athco-Engineering	Everfuel	Port of Aalborg
Ballard Power Systems Europe	FORCE Technology	R&D Engineering
Bech-Bruun	Futurelab AS	Rambøll Management Consulting
Blue World Technologies	Goth Engineering	REEL
BP Transport	Green Hub Denmark	ReFlow
CBS	Green Hydrogen Systems	Region Midtjylland
Copenhagen Airport	GreenLab Skive	ReIntegrate
Copenhagen Capacity	Hafnium Labs	Semco Maritime
COWI	Haldor Topsøe	ShippingLab
DaCES	Port of Hanstholm	Simac
Danfoss	Hybrid Greentech	Siemens Gamesa
Danish Shipping	Hydrogen Valley	Stena Bulk
Danish Ship Finance	IFD	Stiesdal Fuel Technologies
DBI - The Danish Institute of Fire and Security Technology	Implement Consulting Group	SubC Partner
Danish Energy	Iveco Denmark	SulfiLogger
Dansk Energirådgivning	JG Maritime Engineering ltd	University of Sourthern Denmark, SDU
Danish Gas Technology Centre	Kalundborg Municipality	Danish Technological Institute
Danish Industry	Kvasir Technologies	Tärntank Rederi
Danish Transport and Logistics (DTL)	University of Copenhagen	Total
Danish Harbours	LINDØ port of ODENSE	Tuco Marine ApS
The Danish Maritime Industry	Lloyd's Register	Vestas
Danish Transport and Logistics Association	Lundgrens	Wood Mackenzie
DB	MAN Energy Solutions	Wärtsilä
DFDS	Marlog	Ørsted
DHI	Maskinmesterskolen København	Aalborg CSP
DHRTC	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping	Aalborg Portland
Disruptive Biotrading	Nature Energy	Aalborg University
		Aarhus University

3 State of the art

3.1 GOAL

To satisfy the 70%- CO_2-equivalent (CO_2e) reduction goal in 2030, the CO_2e emission must be reduced by an additional 11.8 Mton/y compared to the current frozen policy projection as shown in Figure 3-1. Both industry and transportation are sectors where a significant CO_2e emission reduction can be achieved and contributed to reaching the 70%- CO_2e reduction goal in 2030.

A key source for the CO_2e emission in industry and the transport sector is fossil fuels. The available energy sources to replace fossil are electricity from renewable sources (wind and solar power) and residue biomass and waste. This is shown in Figure 3-2, which provides an overview of the technology pathways for production of renewable fuels.

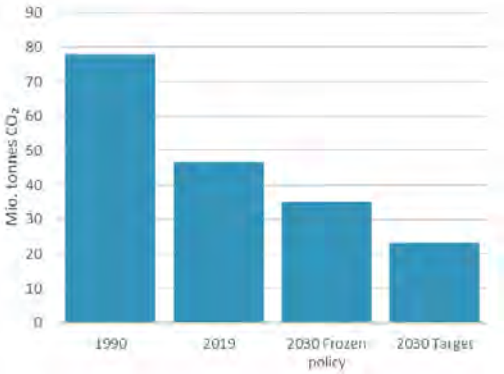


Figure 3-1: CO_2 emissions in Denmark from 1990 to 2030

3.2 ALTERNATIVE FUELS AND POSSIBLE PRODUCTION PATHS

Electricity produced from wind and solar power can be used directly by light-duty road transport or for heavy-duty road transport as a hybrid solution with other fuels. Alternatively, power can be converted to green hydrogen via electrolysis and be used directly in heavy-duty land transport or light-duty marine maritime transport. For heavy duty maritime and aviation, liquid fuel is optimal due to the need for high energy density.

Liquid fuels can be produced via either of the following routes:

1. **Methanol, DME**: Syngas is formed by combining green hydrogen with either:
    - CO_2 from carbon capture
    - Gasified biomass
    - Steam reformed biogas

   This Syngas can be converted to Methanol, DME or to a "crude alike oil" in a Fischer-Tropsch synthesis. These liquid fuels can be used to cover a variety of end users in the transportation sector. Additionally, they can be further converted into jet-fuel.
1. **Biogas:** Biogas is produced via anaerobic digestion. It can be used directly in combustion-based applications, upgraded to biogenic natural gas (BNG), or converted to Syngas (see point above)
2. **Ethanol**: Fermentation of biomass result in ethanol that can be blended into gasoline
3. **Biooil**: Biooil is oil produced from biomass through pyrolysis, liquefaction or the HVO process. Biooil also include oil from pyrolysis of plastic and tires as it is assumed that these with time will become 100 % biogenic. Biooil can be refined to liquid fuels for trucks, maritime and aviation
4. **Ammonia**: Nitrogen captured from air is mixed with hydrogen from electrolysis and sent to ammonia synthesis loop resulting in liquid ammonia

It is important to note that hydrogen is required for all the technology pathways mentioned. This makes the production of cheap and competitive green hydrogen via electrolysis crucial for the transition from fossil-based fuels to renewable alternatives.

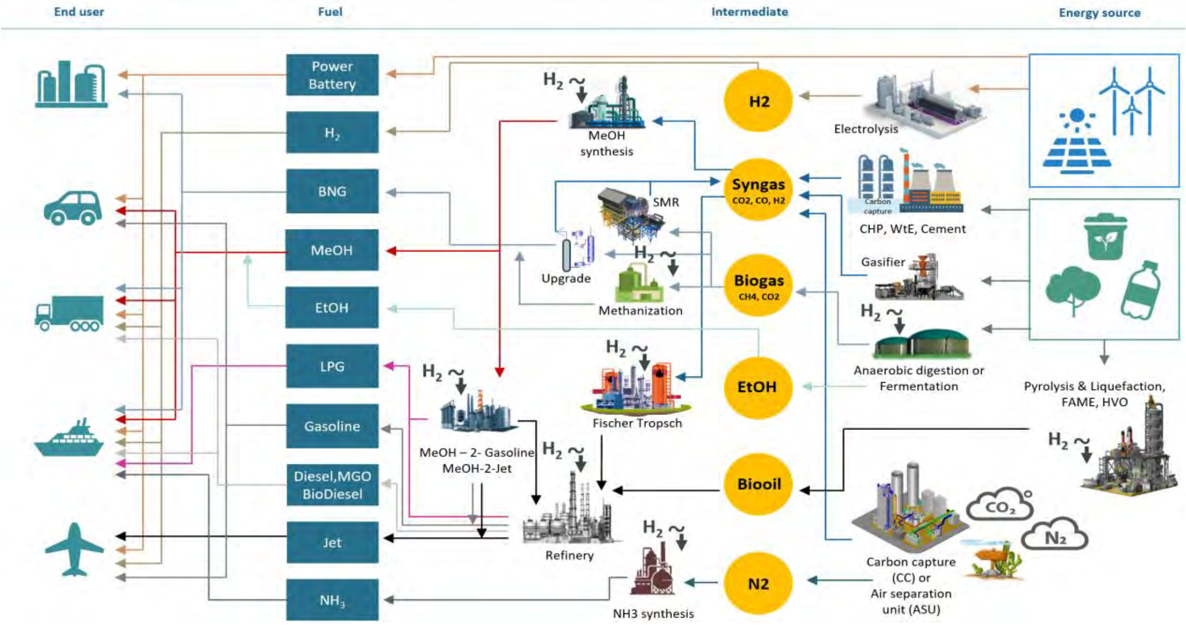


Figure 3-2: Overview of different pathways for production of renewable fuels (the black H_2 show the processes which need green hydrogen)

3.3 PTX PROJECTS AND ACTIVITIES

There is an ongoing massive global upscaling of hydrogen production. More than 30 countries have hydrogen roadmaps and 228 large-scale hydrogen projects have been announced (ref 1). There are already invested more than 80 billion USD globally in mature projects, meaning they have passed the final investment decision, with additionally 220 billion USD pledged in investments. Authorities worldwide have already pledged more than 70 billion USD in public funding.

In Europe, there is a target of 40 GW blue and green hydrogen production by 2030, with additional import of 40 GW. The eight largest announced European projects are set to commission more than 80 GW of electrolyser capacity by 2030 (Table 3-1). Denmark is missing an official target for hydrogen production but the power-production capacity goals for the energy islands are 2-3 GW at Bornholm and 3-10 GW in the North Sea.

It is important that the Danish projects in Table 3-1 receive the proper support, so that they will be realized by 2030, by setting up a national strategy and removing barriers. Development and demonstration of hydrogen, ammonia, methanol/DME, biooil refinery and jet-fuel projects are crucial to a successful roadmap for alternative fuels in transport and industry.

In addition to the PtX project listed in Table 3-1, DK have several companies that work with pyrolysis and liquefaction, producing a sustainable oil that can replace fossil. It is important quickly to ensure that our refineries become capable to take and refine these oils.

Table 3-1. Largest PtX projects of the world and Denmark (ref 2 and 3). Projects in DK are marked with light blue.

World's 20 largest green hydrogen projects	Cap. (GW)	Power Source	Products	Location	Year
HyDeal Ambition	67	Solar	H_2	Spain, France, Germany	2030
Asian Renewable Energy Hub	14	Solar and onshore wind	H_2 and NH_3	Australia	2027-2028
NorthH2	10	Offshore wind	H_2	Netherlands	2030-2040
AquaVentus	10	Offshore wind	H_2	Germany	2035
HyEnergy Zero Carbon Hydrogen	8	Wind and solar	H_2 and NH_3	Australia	2030
Murchison Renewable Hydrogen Project	5	Onshore wind and solar	H_2, green fuels	Australia	2028
Beijing Jingneng Inner Mongolia	5	Onshore wind and solar	Unknown	China	2021
Helios Green Fuels Project	4	Onshore wind and solar	H_2 (transported as NH_3)	Saudi Arabia	2025
Pacific Solar Hydrogen	3.6	Solar	H_2	Australia	-
Base One	3.4	Wind and solar	H_2	Brazil	2025
H2-Hub Gladstone	3	Renewable Energy	NH_3	Australia	-
Yellow Sea	2	Floating wind	Unknown	China	-
HyEx	1.6	Solar	NH_3	Chile	2024
Geraldton	1.5	Onshore wind and solar	NH_3	Australia	-
HNH	1.4	Onshore wind	NH_3	Chile	2026
Green Fuels for Denmark, Ørsted, CPH Lufthavne, Mærsk, DSV, SAS	1.3	Offshore wind	H_2 and e-fuels	Denmark	2023-2030
SeaH2Land	1	Offshore wind	NH_3, ethylene and transport fuel	Belgium and Netherlands	2030
Esbjerg, Maersk, DFDS, Arla, Danish Crown, DLG and Copenhagen Infrastructure Partners	1	Offshore wind	NH_3	Denmark	2025-2027
H2 Sines	1	Onshore wind and solar	H_2	Portugal	2030
Rostock	1	Offshore wind and other renewable energy	Undecided	Germany	-
Additional projects in Denmark	**MW**				
Siemens Gamesa, Green Hydrogen Systems	0.450	Onshore wind	H_2	Brande	2021
HySynergy – Shell, Everfuel	1000	Wind and solar	H_2	Fredericia	2022- 2030
Skovgaard Invest, Haldor Topsøe, Vestas	10	Wind and solar	NH_3	Ramme	2022
GreenLab, EuroWind, Everfuel, Eniig, E.ON, Energinet, GHS, DGC	12	Wind and solar	H_2 and e-fuels	Skive	2022
H2RES, Ørsted	2.1	Offshore wind	H_2	Avedøre	2022
DIOGENES: Danfoss, Green hydrogen, DTU	0.5	Grid + PV	H_2	Nordborg	2022
Green Hydrogen Hub, EuroWind, Corre Energy, Energinet	350	Wind and solar	H_2	Hobro/Viborg	2028

Regarding international efforts, it is important that Denmark align our efforts to what happening in Europe and globally, when it comes to:

- Global push for CO_2-taxes
- Alignment of sustainable aviation fuels (SAF) approval and certificated requirements
- The European Hydrogen Strategy
- Plans by multiple European transmission system operators to develop and operate hydrogen grids
- Renewable Energy Directive II (RED II) entering into effect on June 30th 2021 and the coming revision
- The Sustainable and Smart Mobility Strategy from the European Commission
- Funding opportunities in Horizon Europe and European year of rail

3.4 DENMARK'S RELEVANT ASSETS AND CAPABILITIES

Denmark has a strong energy system with diversified grids and world-class security of supply. Our strongest comparative advantages are:

1. *Energy source:*
    - **Wind power:** DK have world class offshore wind opportunities. The potential in the North Sea is estimated to be ~250 GW where 40-50 GW is with the Danish territorial. Denmark is also the leading wind-power producer per capita of the world.
    - **Biogas:** Denmark has a leading position in biogas.

2. *Offtake sector:*
    - **Maritime nation:** DK is today one of the world largest maritime nations and the home of many globally leading shipping and equipment companies
    - **Aviation:** Copenhagen airport has received multiple awards for being the best airport of northern Europe, while also being the largest in the Nordics
    - **Land transport:** DK has key players within the heavy land transport and freight forwarding
3. *Infrastructure, storage, and integration:*
    - **Electricity grid:** The Danish electricity system consists today only of 14% fossil fuels. It is one of the most sustainable power systems in the world, with competitive electricity prices, and high security of supply
    - **Gas grid:** The natural gas grid extends to most of the country and has the largest share of biomethane (20 % in 2020) in the world.
    - **District heating system:** The district heating system enables Denmark to increase the overall energy efficiency of chemical plants considerable (to an overall efficiency of 90-95%). This include PtX-units which could deliver heat to 1.8 million households through district heating (ref 4).
    - **Energy Storage**: The Danish underground is well suited for storing of gases, including hydrogen. We currently have one of the largest gas storage capacities of the world, measured per capita.
    - **Digitalization** - DataHub and transparency in data related to energy markets, for supporting of new, green business models
    - **Sector coupling**: Based on our assets and capabilities, we have a great foundation for achieving an efficient sector coupling among our different energy systems
4. *Ambitions and knowhow:*
    - **Industry and technology:** Denmark has world leading companies, industry organizations, universities, energy and maritime clusters, willing to work together within the PtX value chain
    - **PtX**: Leading in several PtX technologies (Figure 3-3)
    - **Environmental governance and management**: Denmark has a well-functioning environmental governance and management system characterized by high levels of co-operation and consensus.

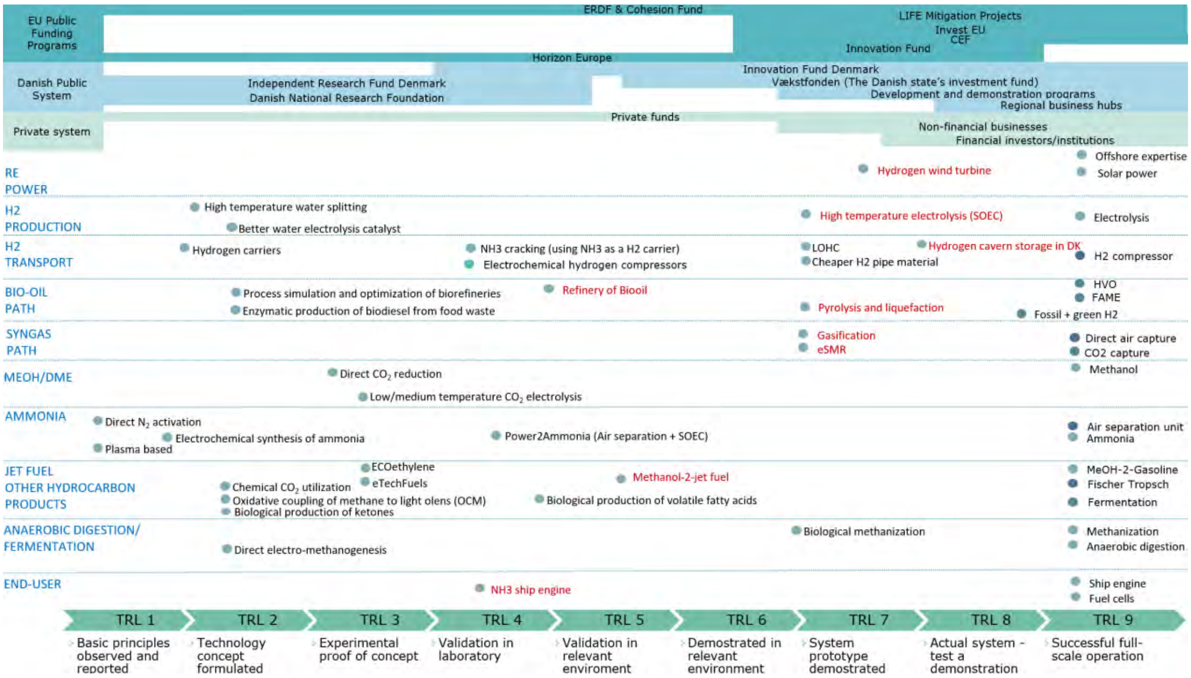


Figure 3-3: Various PtX technologies vs TRL and funding. Read text are considered very important to focus on in the near future.

There are several world-leading Danish companies involved in coming Danish PtX-projects, who drives the Danish stronghold in the area. First of all, these include the off-takers and world-class logistics companies such as **Maersk, SAS, DSV Panalpina, DFDS and MAN Energy Solutions**, which are highly specialized in international transportation of freight and passengers and equipment. **Ørsted and Vattenfall** are among global leaders in managing large renewable energy projects and infrastructures. **Copenhagen Infrastructure Partners** are among the leading investors in renewable energy. **Vestas** and **Siemens Gamesa Renewable Energy** are among the leading wind turbine manufacturers. **Everfuel** is the leading operator of hydrogen refueling stations. **Haldor Topsøe** is leading in SOEC electrolyzers and chemical processing related to PtX. **Siemens Energy** and **Danfoss** are among the leading providers of technologies for PtX-plants. **Green Hydrogen Systems** designs and manufactures modular electrolyzers. **Energinet** is a world-class Danish transmission system operator in power, gas and hydrogen. **Ballard** is a leading provider and manufacturer of fuel-cell solutions. **Shell** owns and operates the largest refinery in Denmark. In addition to these companies, Denmark also has several leading universities with expertise in PtX, LCA and business modelling, including **DTU, AAU**, **CBS, AU, KU and SDU**. Finally, the Danish stronghold also consists of a strong open, trusting and collaborative culture across the value chains and an ability and experience of reducing costs in the renewable energy sector.

4 Technology paths – basis for roadmap

4.1 AVAILABILITY OF RENEWABLE ENERGY FOR FUEL PRODUCTION

4.1.1 Availability of wind and solar power

The Danish electricity system is strongly integrated into the northern European electricity market, and historically the balance between domestic electricity production and electricity imports has fluctuated depending on market conditions (such as precipitation, solar irradiation, temperature and wind) (ref 5). In a frozen policy scenario, the Danish Energy Agency expects that there will be years of net electricity exports and years of net electricity imports towards 2030, as shown in Figure 4-1. Any large-scale production of PtX before 2030 will increase Danish imports of electricity. Thus, the carbon footprint of the fuels will depend on the carbon footprint of the imported electricity blend. However, according to Danish Energy, 86% of imported electricity is renewable (ref 6).

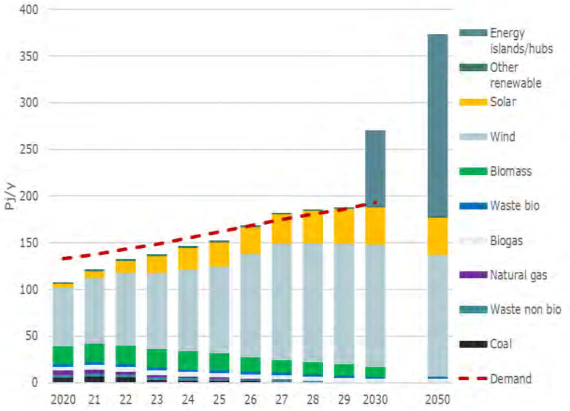


Figure 4-1: Available power and power usage towards 2030

The realization of the energy islands/hub in 2030 is expected to significantly affect Denmark's electricity balance, and provide a 74/y PJ surplus of green electricity, which can be used for electrification of other sectors (e.g. via PtX) or exported to Denmark's neighboring countries (ref 7 and 8).[1] Assuming that electricity consumption in other sectors is kept constant towards 2050 (or excess consumption is met by solar/wind projects not yet in pipeline), increased capacity from the energy island/hub in the North Sea will give a surplus of 195 PJ/y.

4.1.2 Availability of hydrogen

In a frozen policy scenario the Danish Energy Agency expects an expansion of electrolysis capacity to 132 MW (~1.9 PJ/y hydrogen production) during the period from 2024 to 2030 (ref 5). However, according to the actors in the industry, 3.3 GW (~48 PJ/y hydrogen production) is currently being planned (summary of Danish projects in Table 3-1).

4.1.3 Availability of biomass

In 2010, the Climate Commission calculated the total energy potential from Danish land-based biomass resources to 174 PJ/y towards 2050, provided that no additional area is included to produce energy crops (ref 9)[2]. We assume that other sectors (mainly construction) will use 24 PJ/y biomass in 2050. This leaves 150 PJ/y available for fuel production.

---

[1] Political decisions have not yet been adopted on measures that can contribute to a significant increase in electricity consumption in the context of the energy islands, nor have specific foreign connections and capacities been agreed by those who import electricity abroad.

[2] Own calculations for 2050 based on a linear projection,

4.1.4 Availability of biogenic point source CO_2

Biogenic CO_2 from carbon capture from point source (mainly CHP, WtE and industrial boilers) can be a carbon source for green fuels production. According to Dansk Energi (ref 10), we have almost 16 Mt. biogenic CO_2 available today. A big amount of this CO_2 comes from imported biomass, which is expected to be reduced towards 2050.

Table 4-1. Point source biogenic CO_2 availability (COWI calculations)

2020	2030	2050
15.6	12.7	6.0

4.2 PATHWAY FROM END USER PERSPECTIVE

In the following sub-chapters, key propellants and their associated production paths is given for the following end-users:

1. Industry
2. Light road transport
3. Heavy-duty road transport
4. Maritime
5. Aviation

Based on these parts, we will identify key fuels and outline an optimal roadmap for the green transition.

4.2.1 Industry

The current and future expected energy sources and consumption levels are shown in Table 4-2 and Figure 4-2.

Units are in PJ/y	2020	2025	2030
Internal transport	1.4	1.3	0.7
Electric motors and ventilation/cooling	21.4	22.5	23.1
Light and electronics	3.0	3.3	3.3
Heating	12.9	10.5	9.1
Process heat - high temperature	19.8	21.2	21.9
Process heat - medium temperature	34.2	30.7	28.6
Electricity- and district heating production	2.6	2.6	2.6
Total	95.3	92.1	89.4

Table 4-2: Energy used in industry divided into areas

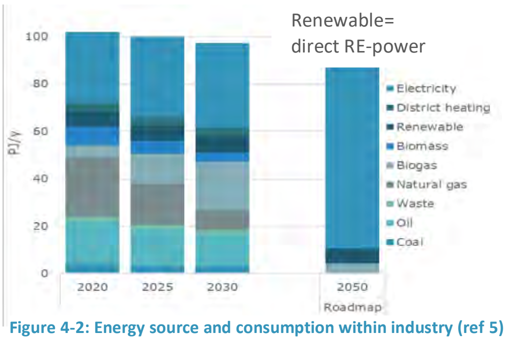


Figure 4-2: Energy source and consumption within industry (ref 5)

According to the Climate Partnership for Industry (ref 11), industry will aim for increased efficiency, carbon capture and electrification with the exception for high temperature applications, where considerable reduction in power price is required for electrification to be economic attractive. Until then, industry would like to solve their 70%-CO_2 reduction goal by using gas from the natural gas grid, which is expected to become fossil free by 2050 (Figure 4-3).

Most of the industry requiring high processing-temperatures, is connected to the existing natural gas grid, especially when the new natural gas pipeline to Lolland/Falster is constructed. Thus, converting high temperature applications to biogenic natural gas is considered a cost-effective way to reduce the CO_2 emission within industry.

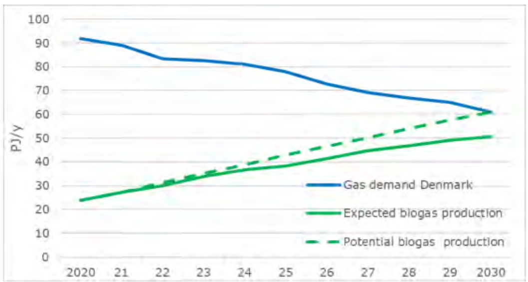


Figure 4-3: Expected NG consumption and % biogenic

As biomass likely will become a limited resource and as direct electrification is the most energy efficient pathway, it's desirable that industry focus on electrifying their processes, especially when commissioning new units. As biomass likely will become a limited resource and as direct electrification is the most energy efficient pathway, it is desirable that industry focus on electrifying their processes, especially when commissioning new units. Legislation should ensure that electrification is economically favorable in most cases.

The technology pathway for industry is depicted in where key focus is to increase the electrification and replace fossil with natural gas that over the years will become 100% biogenic. Green hydrogen (or any other green fuels) is not foreseen, as direct electrification is considered a more economically attractive path than green hydrogen/fuel.

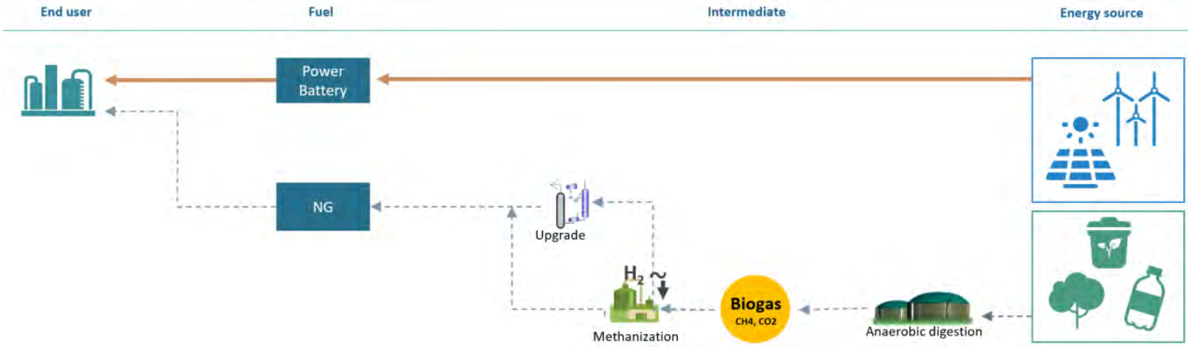


Figure 4-4: Dashed lines indicate an intermediate stage going towards 2030 while the full line is the major situation in 2050.

4.2.2 Light-duty road transport

In a frozen scenario, current and future expected energy sources and consumption levels are provided in Figure 4-5.

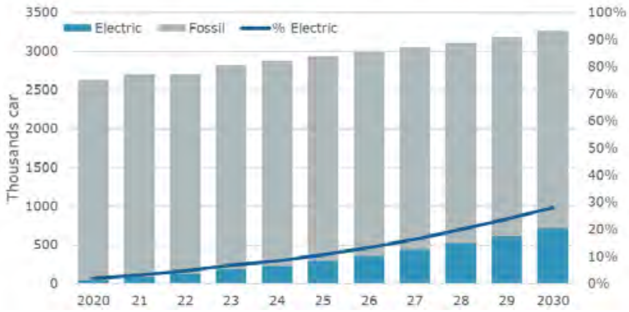


Figure 4-5: Energy source and consumption by cars

The highest obtainable energy efficiency in the entire chain from "electric production" to "wheel" is via direct electrification (see Figure 4-6). Thus, the optimal propellant for light and short distance transportation is electricity.

As most cars sold today are still gasoline/diesel-based, it will take several years before the majority of cars are electrified (see Figure 4-5). Thus, to satisfy the 2030-70% CO_2 emission goal, a green fuel that can be used within existing vehicles must be found. Fuels that can be used within existing vehicles are:

1. Gasoline engine: Gasoline, MeOH[3], EtOH
2. Diesel engine: Diesel, DME, FAME (=biodiesel), HVO/BioFuel

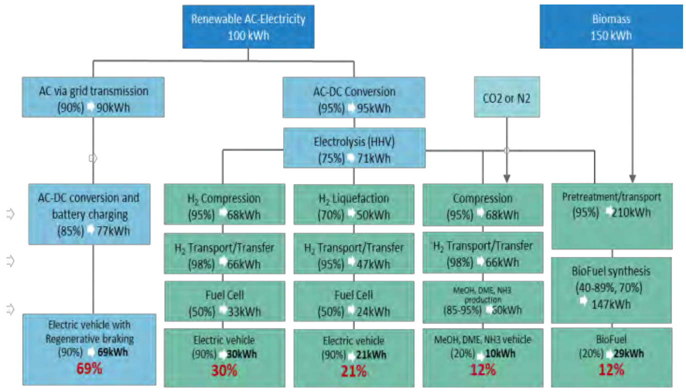


Figure 4-6: Indicative overall energy efficiency – from source to wheel. The electrolyze efficiency might increase from 75% (2021) to 90% (2030) which will improve the overall efficiency of green fuel. Additionally, the loss in electrolysis can be used for district heating which is not incorporated in the overall given efficiency figures.

MeOH/DME is cheaper and less complex to produce than synthetic Gasoline and synthetic Diesel. The carbon source can be CO_2 capture from point sources (thus, there is a synergy with the need for capture CO_2 from point sources). **FAME** and **EtOH** is today primarily based on first generation biomass which is not considered as an option for large scale production as it competes with food productions. There are considerable developments within **HVO/BioFuel**, which is expected to become competitive.

This gives the technology pathway for light-duty transportation shown in Figure 4-7.

---

[3] Installation of a FFV (fuel flex vehicle) device on the motor to electronic adjust the combustion cycle time so it drives optimally on MeOH.

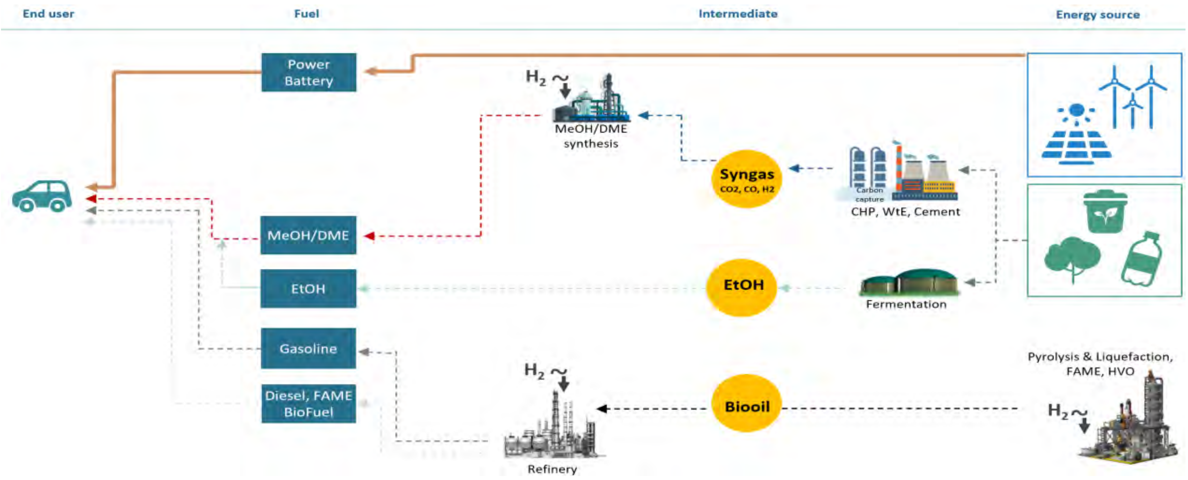


Figure 4-7: Dashed lines indicate an intermediate stage going towards 2030 while the full line is the major situation in 2050.

Additional advantage with both the MeOH/DME path and the HVO/BioFuel path are:

- easy to transport and can be transported and distributed by the existing infrastructure
- can be further synthesized/refined into aviation fuel when the existing vehicle package become electrified

4.2.3 Heavy duty land transport

Current and future expected energy sources and consumption levels are provided in Figure 4-8.

Despite the higher efficiency of electric engine, the following factors makes electrification of heavy long-distance transport less attractive:

1. Weight of today's batteries: Batteries will take up a major part of what is available for freight (see Table 4-3).
2. Charging time of today's batteries: Is several hours. This could be solved by battery swapping, but the batteries will be big and heavy, i.e. special swapping-machinery will be required.

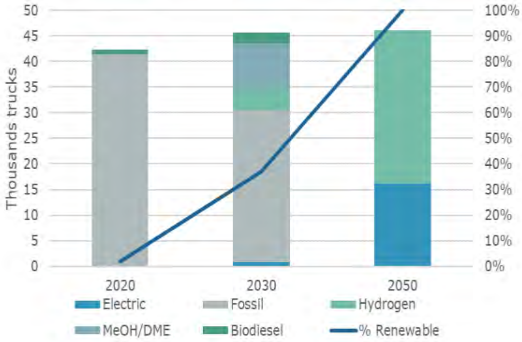


Figure 4-8: Energy source and consumption by heavy land

The most efficient propellant after electricity is hydrogen in FCEVs (see Figure 4-6).

It is believed that heavy-duty transport will be a combination of hydrogen an electricity. The weight of the batteries strongly depends on the distance and power use between refueling. Electric road system (ERS) with continuous electricity supply, which is considered in Sweden and Germany, as well as battery improvements will decrease the required size batteries.

As with light-duty road transportation, there will be a transition period where trucks are changed to new hydrogen-based fuel-cell-electric-vehicles (FCEV) driven trucks. Within this transition period the same intermediate fuel as used for diesel engine light-duty transportation can be applied.

Table 4-3: Gasoline/diesel tank sizes vs battery sizes required (used: battery energy density = 0.612 MJ/kg, Electric efficiency of electric engine=90%, energy density of CH_2=4.8 MJ/l (700 bar), energy density of LH_2=9.6 MJ/l, Efficiency of H_2-FCEV=50%)

Column1	Tank size [l]	Eff. Combustion	Fuel density [kg/l]	Max Fleet weight [ton]	Max cargo weight [ton]	Fuel weight [ton]	Battery weight [ton]	Hydrogen weight [ton]	Actual Hydrogen volume (CH_2) [m^3]
Car	45	35%	0.85			0.038	1.1	0.01	0.14
	70	35%	0.85			0.060	1.7	0.01	0.22
Truck	475	35%	0.85	24		0.404	11.7	0.09	1.49
	1 000	35%	0.85	40	36	0.850	24.6	0.19	3.14
Big tanker ship	5 000 000	49%	1.01		150 000	5 050	204 861	1 590	26 120
	17 000 000	49%	1.01		500 000	17 170	696 526	5 408	88 807
Plane 1h flight	15 000	35%	0.85	70		12.8	369	2.9	47
10h flight	150 000	35%	0.85	350		127	3 694	28.7	471

This gives the technology pathway for heavy-duty road transportation shown in Figure 4-10.

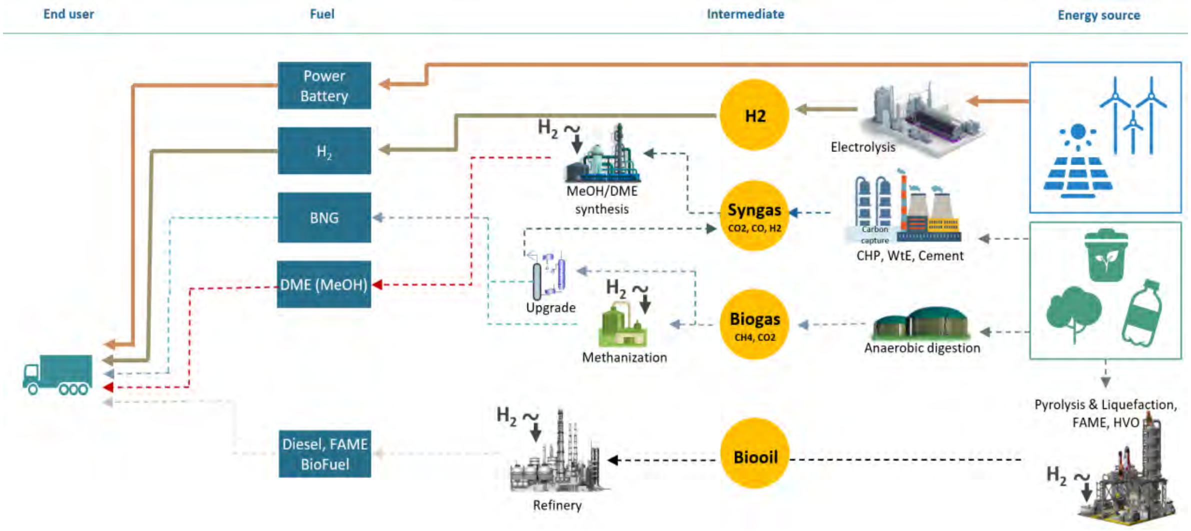


Figure 4-10: Dashed lines indicate an intermediate stage going towards 2030 while the full line is the major situation in 2050.

4.2.4 Ships

Current and future expected energy source and consumption are given in Figure 4-10

Long distance transport requires huge amounts of energy (see tank sizes in Table 4-3). Thus, **power** and **hydrogen** are only an option for short distance light ship transport.

Ammonia seems to be an optimal marine fuel as:

1. Ammonia can be produced where there is RE source but no carbon source, i.e. in the solar-rich-desert and on wind-rich-ocean
2. A major part of sustainable available biomass must be assigned to production of aviation fuel (see discussion in next chapter)

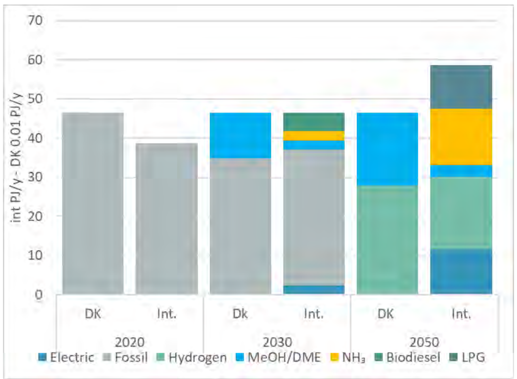


Figure 4-9: Energy source and consumption by marine transport.

The disadvantages of NH_3 is that is has a low energy density, burn slowly and is toxic. That it burns slowly makes NH_3 not feasible on medium and high-speed engines (4-stroke engine) while suitable on slow large big container vessels (2-stroke engine). Cracking NH_3 to H_2 for use in an auxiliary engine is considered to facilitate speed when needed.

LNG: Today it seems to be larger focus on LNG as marine propellant. However, there is not enough biogenic NG for ensuring both zero emission industry and zero emission maritime sector. Fossil LNG emits ~28% less CO_2 than bunker fuel/HFO/MGO, so using fossil/biogenic-based NG is a CO_2 reducing solution in a transition period. However, boil-off gas from LNG carriers and emission of un-combusted methane gas in the exhaust from LNG vessel is large which may vanish the above saving as methane is a much stronger GHG than CO_2. The problem can be decreased by flaring the vented gas. Due to the boil-off and the methane slip and since NG is a limited resource, LNG is not considered as an optimal fuel.

Cracking and associate hydrogenation of bunker fuel/HFO/MGO: In an initial transition period, hydrocracking of heavy marine fuel with green hydrogen is a low-cost solution that can assist in creating a hydrogen marked and making the maritime fuel partly green. As none of the Danish refineries have a FCC-unit (Fluid catalyst cracking), this option will not be considered in this roadmap.

LPG: A byproduct in the production of synthetic aviation fuel may be LPG. Thus, when larger amount of aviation fuel will be produced, large amount of LPG might be produced. Competition will determine whether it is optimal to convert LPG into aviation fuel or us it as marine fuel.

MeOH/DME: DME can be used in today's diesel engines and it is cheap/simple to convert MeOH to DME. MeOH require minor engine development.

BioFuel: Oil produced from biomass/waste/plastic/tire is expected to be applicable after minor refinery processing in today's ship engine (required R&D). As ship engine normally is quite robust and as they often are equipped with downstream DeNOx, the requirement to the fuel quality is often less meaning that it is optimal to use BioFuels in ship engine in the transition period where refineries convert from fossil fuel as feedstock to Biooils as feedstocks.

Hydrogen and electricity: If alternative to hydrocarbon-based aviation fuel is not found/approved, maritime will compete with the aviation getting the limited hydrocarbon-based fuel. This will most likely favor use of electricity and hydrogen as propellent on small and medium size ships where NH_3 is not appropriate.

This gives the technology pathway for near-shore and international marine transportation shown in Figure 4-11.

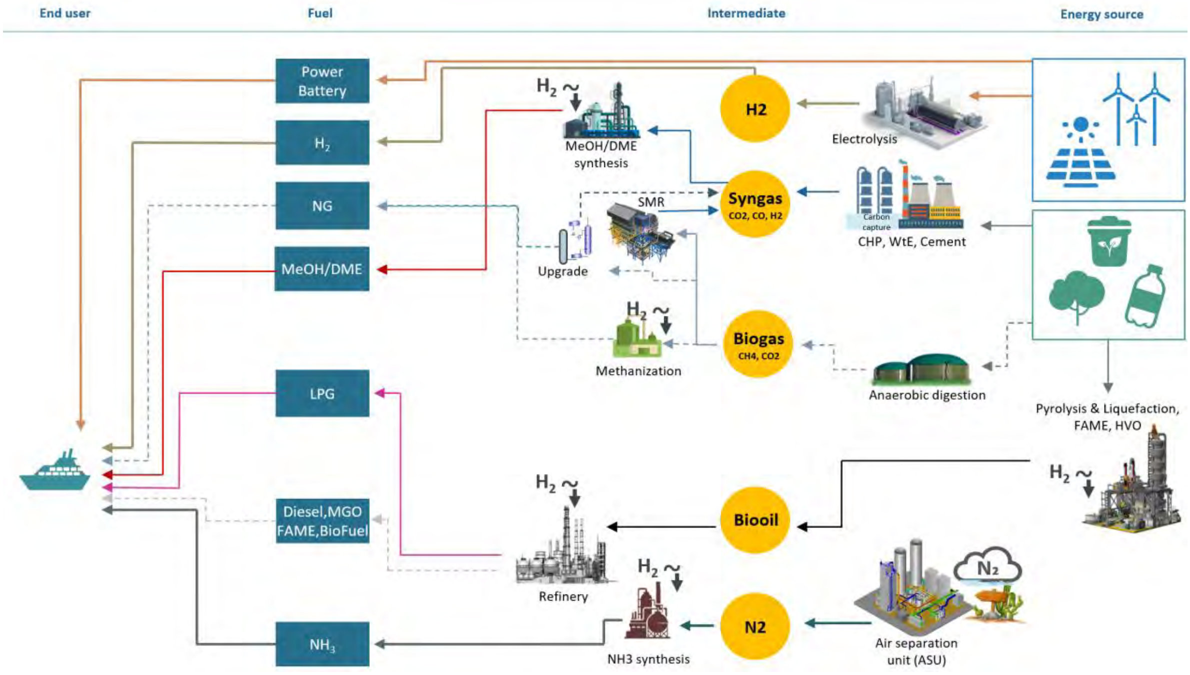


Figure 4-11: Dashed lines indicate an intermediate stage going towards 2030 while the full line is the major situation in 2050

4.2.5 Aviation

Current and future expected energy sources and consumption levels are given in Figure 4-12.

Electrification of small planes (7 passengers today, 28-30 passengers by 2030) is possible. However, due to the weight of batteries, it is unlikely that very large planes will become electrified within the near future. But hybrid planes may become important.

Synthetic aviation fuel (SAF): Fuels for aviation is subject to very strict regulation, including:

1. High energy density (ensure less fuel weight and thereby less fuel consumption)
2. Low cold fluid properties as very cold in 10 km altitude
3. Explosion limits (safety)

These requirements restrict aviation fuel to highly branched C_{10}-C_{13} hydrocarbons. For cargo and military flight, the requirement to point 3 is less strict, allowing a blend with 70% gasoline (Jet-B).

Syngas to SAF: Synthetic production of aviation fuel can either follow the Fischer-Tropsch route or a MeOH/alcohol route (see Figure 4-13). The MeOH/alcohol route seems more optimal as the product distribution is limited by the catalyst pore size making the recovery within a specific range much higher than for the Fischer-Tropsch route.

Additionally, the MeOH route make synergy with using MeOH as intermediate fuel for light transportation (i.e. building the MeOH plants in a first step and then later adding the jet-fuel-synthesis step). Conversion of MeOH-to-Jet have a TRL of 5, i.e. R&D is required. Alternative, it should be investigated whether it is possible to approve Jet-B as passenger fuel as MeOH-2-gasoline is expected to have a higher recovery than MeOH-2-Jet and has a TRL=9. However, approvement of Jet-B will require international acknowledgment and approval.

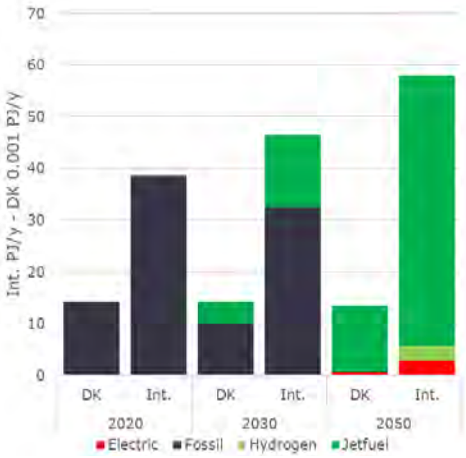


Figure 4-12: Energy source for Danish and international aviation

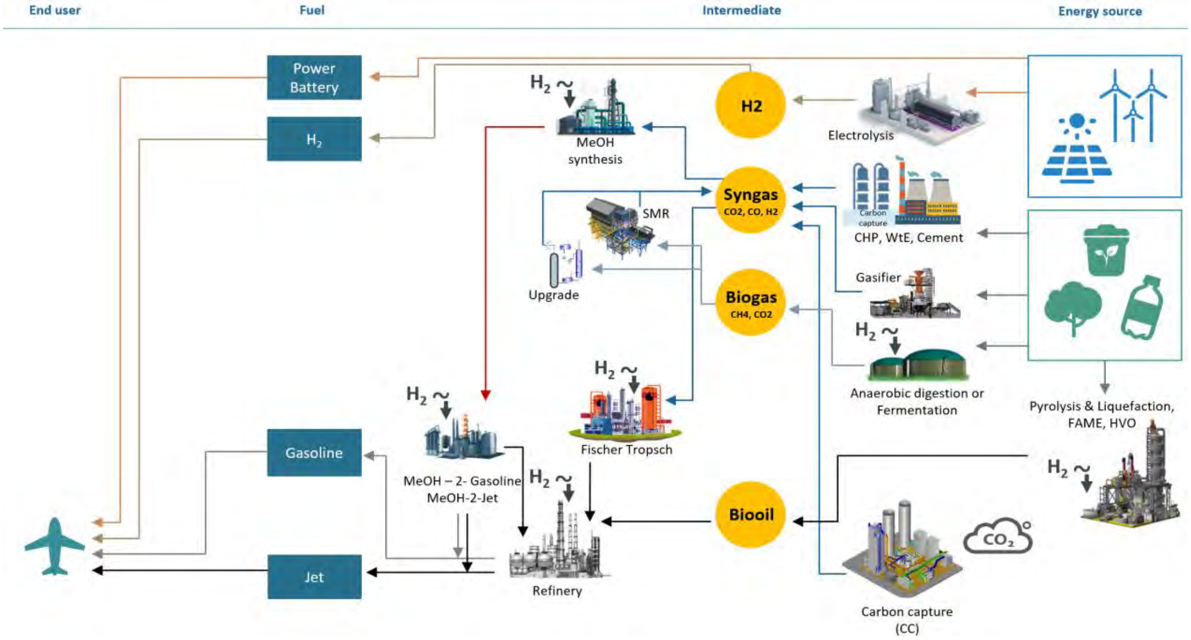


Figure 4-13: Technology pathways for aviation

Biooil to SAF: As huge amount of aviation fuel is needed, both the syngas route and the biooils route to produce aviation fuel must be matured. Thus, development and approval of refining of biooil to SAF is very important.

Hydrogen: The big aviation producers are looking into hydrogen planes. Liquefied hydrogen seems feasible and do to it very light weight, smaller wings are required. However, it has a very low volumetric energy density, is very explosive, and need extremely cryogenic storage facilities. Thus, hydrogen planes will include huge development, new infrastructure, approval, and tests before approved as passenger transport.

This gives the technology pathway for aviation shown in Figure 4-13.

4.2.6 Life cycle analysis (LCA)

To evaluate whether an alternative fuel can support the reduction of Danish emissions, we need to assess not only the end-use of alternative fuels, but the entire value chain. Using other feedstocks and fuels will only lead to real climate gains, if there are no alternative forms of utilization that can contribute to greater climate gains.

When assessing the environmental and climate footprint of transportation, all relevant emissions and resource consumption must be included. Both the direct and indirect environmental and climate impacts of using other fuels must be measured.

Research and innovation are thus required into the optimal use of feedstocks for green fuels in transportation, compared to other downstream sectors, based on LCAs and substitution analyses. The supply of feedstocks is critical, and it is therefore important to ensure that each feedstock is used where it has the greatest effect. The environment and climate impacts associated with feedstocks are typically associated with the production phase, but distribution and storage can also lead to significant emissions. In particular, land use associated with feedstocks is of environmental and climate significance. If feedstock, such as biomass, is already being used for other purposes, then the production of green fuels from the same biomass will cause indirect climate impacts.

4.3 SUGGESTED PATH FOR THE GREEN FUELS ROADMAP

Based on the expected dominant paths, we have evaluated the %-distribution of fuels for each end-user (see Table 4-4). The calculations are based on the following assumptions:

1. There will be no consumption of fossil fuels in 2050
2. From a CO_2/environmental perspective, a vehicle/fleet should not be replaced before its end-of-life. It takes time (10-30 years) to change our assets and fleets, thus intermediate green fuel alternatives must be used in our existing assets/fleet
3. Hydrogen and electric planes are limited before 2050, which means that aviation fuel must be carbon based
4. Max biomass consumption in 2050 is ~150 PJ/y (this is what we have of residual/waste – see subsection 4.1.3)
5. DAC (direct air capture) is not a competitive technology in 2050
6. NG will in 2020 be partly fossil based but will be 100% biogenic in 2050

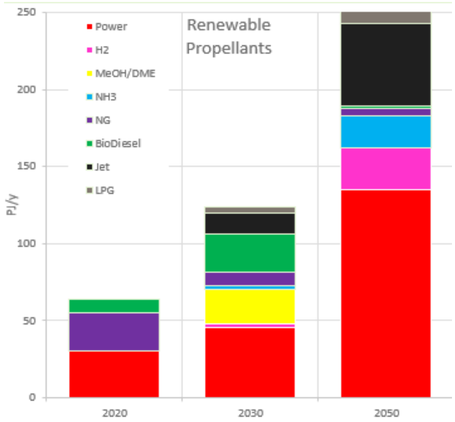


Figure 4-14 Expected total consumption of renewable fuels 2020, 2030 and 2050

Table 4-4: Expected % distribution of fuels in 2020, 2030 and 2050

	CAR			VANS			TRUCKS			BUS			TRAIN			FERRIES		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
Fuel distribution, %																		
Power		22	100		16	80		2	35		27	52		68	68		0	25
H2					10	20		10	65		10	48			32			45
MeOH/DME		15	0		5	0		20	0		5	0		10	0		10	
NH3																		30
NG																		
Bio NG (industry)																		
BioDiesel	2	15	0	2	0	0	2	5	0									
Jet																		
LPG																		
Biomass and waste																		
Fossil	98	48	0	98	69	0	98	63	0	100	58	0	100	22	0	100	90	0

	Kattegat			Spare time Boats			Fhising boats			Jetmotor			Turbopropelfly			Int. Marine			Int Aviation			Industy		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
Fuel distribution, %																								
Power		0	0		0	0		0	0			5			5		5	20			5	30	37	88
H2			60			60			60									37			5			
MeOH/DME		25			25			10									5							
NH3			40			40			40								5	25						
NG																						24	9	5
Bio NG (industry)																						5	21	
BioDiesel																	10					6	7	2
Jet											30	90		30	90					30	90			
LPG																	0	19					4	5
Biomass and waste																						10	6	
Fossil	100	75	0	100	75	0	100	90	0	100	70	5	100	70	5	100	75	0	100	70	0	25	17	0

The total consumption of each of the expected fuels is plotted in Figure 4-15. Based on the consumption, we have calculated the required:

1. Renewable energy
2. Residue and waste
3. Hydrogen
4. CO_2 from point source (the intermediate consumption is not subtracted from residue/waste as a major part will be imported biomass)

To ensure that Denmark is sustainable we have compared the required values with what is available in Figure 4-15. The figure shows that we expect an intermediate scarcity in sustainable biomass/residue in the future, in particular carbon, which is supported by a recent publication by Danish Energy (ref 10).

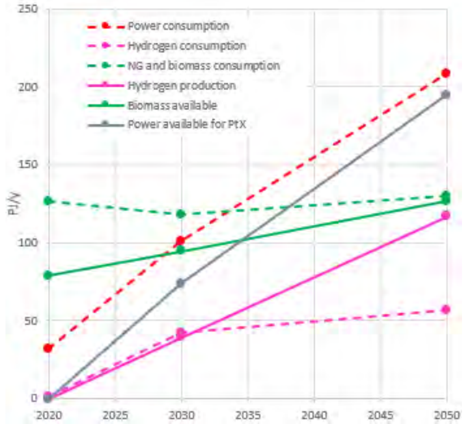


Figure 4-15: Expected availability and consumption of renewable energy, hydrogen and carbon in 2020, 2030 and 2050

This leads us to the following conclusion: If we are to be fossil free in 2050, and the major part of the aviation is still hydrocarbon-based fuel, then a big part of the available biomass/residue must be used for producing aviation fuel in 2050, thus, all other must to the extent possible use other than C-based fuel.

Provided the above assumptions, an optimal path that aims at using most of the available biomass/residue for production of aviation fuel in 2050 should be developed. Thus, a suggested path is a path where biomass/residue/CO_2 based carbon source is first converted to intermediate fuels that can be used in our existing vehicle/truck/marine package and then later converted to aviation fuels.

MeOH/DME and biooil/biodiesel are intermediate fuels that can be used in our existing fleet and then from 2030-2050 can be further converted to aviation fuel while our fleet is getting more electrified or converted to H_2 and NH_3. For marine, some LPG might optimally be available as this is a byproduct from the production of aviation fuel. However, it can be discussed whether this LPG optimally should be refined to aviation fuel to leaving some MeOH/DME for maritime use.

Methane/biogas/NG should be reserved for high temperature industries and while this is becoming more electrified, biogas should also be converted to aviation fuel.

In conclusion, this leads us to the following three main tracks in the roadmap:

1. Green hydrogen (for heavy duty land transport)
2. Intermediary fuels (MeOH/DME and Biooil)
3. Green fuels for shipping and aviation

5 Roadmaps

5.1 TECHNOLOGICAL ROADMAP

Within this subsection the technological implementation of the following three tracks in the roadmap is given:

1. Green hydrogen (for heavy duty land transport)
2. Intermediary fuels (MeOH/DME and Biooil)
3. Green fuels for shipping and aviation

The description of each track includes:

1. A table based on the implementation workshop where suggested action points are given. The action points contain specific goals, critical gaps/challenges and actions needed
2. Key actions are extracted from the table and plotted in a timeframe

5.1.1 Green Hydrogen (for heavy duty land transport)

Table 5-1 includes suggested action points for the technological implementation of the roadmap. The key action points are described below and shown in Figure 5-1.

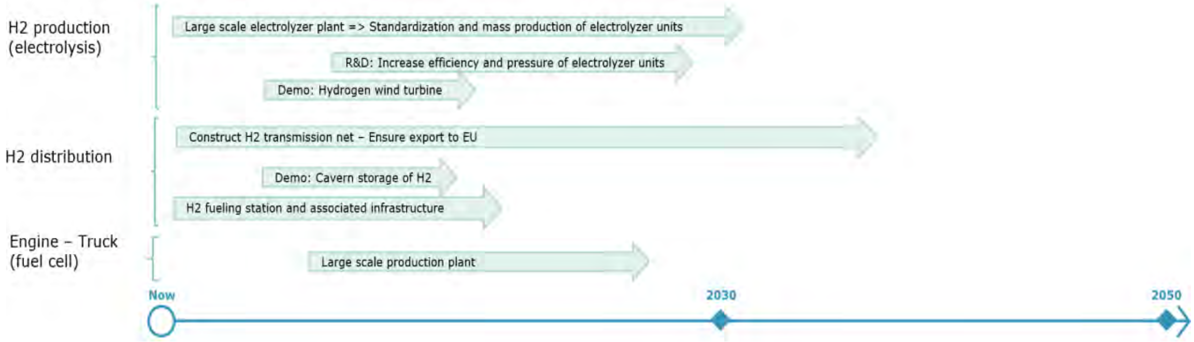


Figure 5-1: Key actions within the implementation roadmap for green hydrogen

To "kick-start" the green hydrogen marked, the following actions should be taken:

1. Large-scale electrolysis plants (see list of Danish projects in Table 3-1) that will push development both with respect to mass production, scale, standardization as well as R&D that will increase the efficiency and pressure in the electrolysis unit as well as reducing the plant cost
2. Hydrogen fueling station and associated infrastructure
3. Construction of hydrogen transmission net (both on and offshore) and associated cavern storage
4. Demonstration of offshore hydrogen wind turbine

Table 5-1: Technological implementation of green hydrogen

TECHNOLOGY		TODAY	GOAL/POSSIBLE*	KEY CHALLENGE/GAPS/SOLUTIONS	ACTION/IMPLEMENTATIONS
Marked	Heavy-duty road	None	Larger fraction of truck in DK drive on H_2.	Hydrogen is still too expensive	Legislation that make it beneficial until price get down
				Distribution network, Safety	H_2 infrastructure and vehicles
	Export to EU	None	Export of hydrogen to EU	Need to compete with hydrogen from north-Africa and blue hydrogen	Construct a hydrogen transmission line to Germany
H_2 production	Efficiency of electrolysis[4]	75-88 % (HHV basis)	90-95 % (HHV basis)	Resistance in cell, material degradation, sluggish electrode kinetics	R&D
	Increase pressure in electrolysis	1-50 bar	80-100 bar	High pressure industrial scale components Mechanical stability of SOEC at high pressure	R&D Expand marked and increase robustness for high hydrogen pressure components
	Production of electrolysis units	Few MW	Up to 5 GW 2030 Up to 13 GW 2050	Fast increase in production facility	Production should focus on taking outdated unit back to reuse materials
	Decrease cost of electrolysis unit (€/kgH_2)	4-8 (depend strongly on operation hours)	2 (2030) 1.5 (2050)	Decrease cost of RE-power	Legislation (decrease taxes)
				Increase operation hours	Increased sector coupling Increase storage
				Mass production & Standardization	Scale production
	Hydrogen wind turbines	10-12 % AC-DC conversion and distribution loss	1-2%	Offshore maintenance of electrolysis	Demonstration plant
	High temperature water splitting	TRL 2-5	TRL 9	Short lifetime, High CAPEX	R&D
Hydrogen distribution	Compression		Decrease compression loss	More efficient compressors are under development	R&D: Development of electro-chemical hydrogen compressor
	Pipe	None	Pipe from offshore wind farm to Germany as fast as possible	Expensive Local resistance	Use part of existing net R&D – cheaper piping material
	Offshore integration - Island/hub	None			R&D - System integration
	Storage-Cavern	None	Large-scale cost-efficient storage	Local resistance	Demonstration plant
	Refueling stations	Few	Several distributed in DK	Trust that hydrogen is the way to go and safety	
Fuel cells	Increase efficiency			Sluggish kinetic at electrodes, high cost	R&D
	Decrease production cost			Mass production & Standardization	

5.1.2 Intermediary fuels (MeOH/DME and biooil)

In Table 5-2, suggested action points for the technological implementation roadmap are listed. The key action points are described below and shown in Figure 5-2.

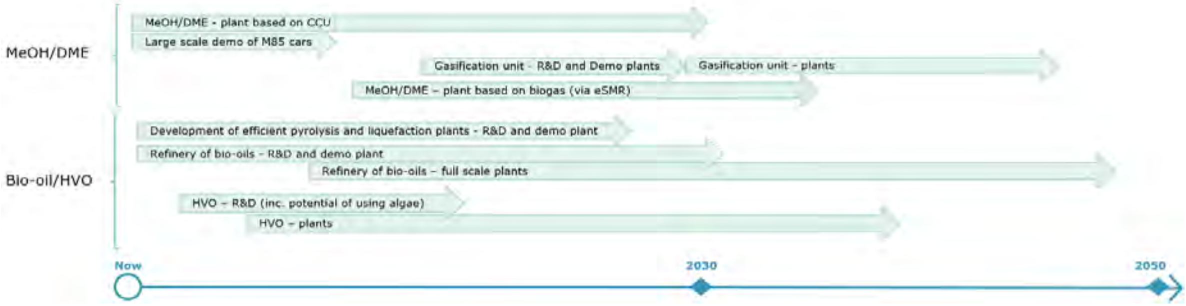


Figure 5-2: Key actions within the implementation roadmap for intermediate fuels

---

[4] The efficiency is given on HHV basis to clearly indicate how much energy that is left for district heating.

Natural gas:

High temperature applications in industries will, until the power price is considerably lower and efficient electrification of high temperature process have been developed, use natural gas. Applications that uses coal or naphtha will convert to natural gas in a transition period. This conversion is already taking place and is not covered here.

NG for transportation: In 2050 most of the available biogenic natural gas should be used for production of aviation fuel. Thus, use of natural gas in the transport sector should be an intermediate solution. As natural gas cannot be used in existing vehicles it is questionable whether it is optimal to invest in infrastructure that support natural gas for land transport.

MeOH/DME and Biooil:

The transition to electrical cars will not be fast enough. Thus, a green alternative is needed in the transition period. As per subsection 4.2, MeOH/DME and Biofuels are optimal intermediate fuel as:

1. Only minor changes of existing infrastructure and vehicle engines are required
2. They can be further synthesized/refined into aviation fuel when the existing vehicle package become electrified
3. There is a synergy between the need for intermediate CO_2 capture from point sources (heat and powerplants that may be outdated when not able to compete with RE-production)

Key actions in the implementation roadmap are:

1. MeOH/DME - plants based on CCU (e.g. Green Fuels for Denmark project – see Table 3-1)
2. Large scale demonstration of M85 cars
3. Refinery of pyrolysis/liquefaction oil – R&D and demo plants
4. HVO – R&D (include potential of using algae)

Table 5-2: Technology implementation of intermediate green fuels

TECHNOLOGY		TODAY	GOAL/POSSIBLE*	KEY CHALLENGE/GAPS/SOLUTIONS	ACTION/IMPLEMENTATIONS
MeOH/DME	Gasoline engine: Convert to M85	Have been used previous in CA in 80'	Install FFV (Flex fuel vehicles)	1. Enough green MeOH 2. Insurance (new fuel type is not covered by car insurance)	1. Ensure that green MeOH can compete (CO_2 tax, cheap H_2) 2. Large scale demo
	Diesel engine: Can run on DME	None	No/little modification is required	1. None	No action required (if MeOH marked, DME marked will automatically follow as conversion from MeOH to DME is cheap)
	CO_2 infrastructure	Covered under mission 1 – Capture and storage of CO_2			
	Production – based on captured CO_2	TRL=9	Cheap	1. Hydrogen is expensive 2. Only biogenic CO_2 must be applied	Cost comparison of CCS vs CCU – evaluate calculation procedure
	Production – based on biomass - gasification	TRL=8	TRL=9	1. Gas cleaning is expensive	1. R&D to develop cheap high temperature gas cleaning 2. Demo of the technology on large scale
	Production – based on biogas - SMR			1. Anaerobic digestion is an inefficient process 2. Seems like an optimal route to make biogas to MeOH instead of methane (better business case)	Demo
Bio-oil	HVO	TRL=9	Cheap	1. Hydrogen is expensive 2. Limit source of oil. Could be extended with algae	Cheap hydrogen (see chapter 5.1.1)
	FAME			1. Use first generation biomass	
	Pyrolysis/ solvent liquefaction	TRL 5-7	TRL=9 Cheap oil	1. Gab between produced oil and what refinery can take today 2. Removal of oxygen use large amount of expensive hydrogen 3. Optimize process 4. Scale production	1. Cheap H_2 (see chapter 5.1.1) 2. R&D 3. Demo plants 4. Legislation that make it beneficial to use biooil instead of fossil in a transition period
	Fermentation (DME/OME)		TRL=9	Low TRL	R&D

Natural gas (NG)	Industry	Fossil	Replace with NG/power	Power price need to be much lower for high temperature applications in industry	Convert fossil consumption in industry to NG consumption that over time will be converted to biogenic
	Biological methanization	Demo plant	Full scale plant	Hydrogen is expensive Do not need gas-cleaning (advantage)	

5.1.3 Green fuels for aviation and shipping

In Table 5-2, suggested action points for the technological implementation roadmap are listed. The key action points are described below and shown in Figure 5-3.

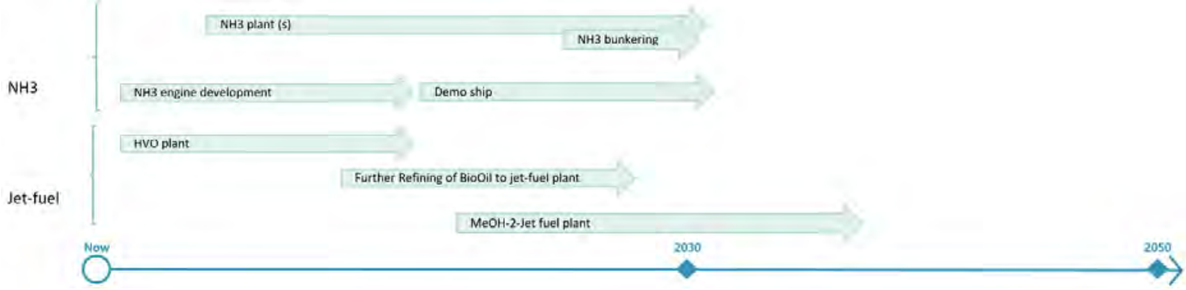


Figure 5-3: Key actions within the implementation roadmap for green fuel aviation and shipping

Key actions in the implementation roadmap are:

1. NH_3 engine – get it to work and approve NH_3 as a marine fuel
2. NH_3 large scale demonstration plant in harbor in DK (e.g. Esbjerg and Skovgaard Invest project – see Table 3-1) i.e. and associate bunkering facility
3. R&D on MeOH-2-jet process or get gasoline approved as jet fuel. MeOH-2-gasoline has TRL=9 and is believed to have higher efficiency than both Fischer-Tropsch and MeOH-2-jet.
4. MeOH-2-jet fuel demonstration plant

Table 5-3: Technology implementation of green fuel for aviation and shipping

TECHNOLOGY		TODAY	GOAL/POSSIBLE*	KEY CHALLENGE/ GAPS/SOLUTIONS	ACTION/IMPLEMENTATIONS
NH3	Production	None	Plant in 2030 Demonstration of technology for export	Expensive to produce in DK compared with middle east/north Africa	Large scale demo plant
	Engine – ICE-2-strocke	None	One in 2025	NH_3 is toxic/low flammability/safety	Focus on safety especially on first demo ship
				Many different fuels	1. An engine should be able to operate at several fuels 2. Try to limit the number of different types of fuels – will impose cheaper infrastructure and refueling logistic
				Retrofitting existing ships	
	Direct NH_3 fuel cell	Eff=50%	Eff>65%	Low TRL	R&D
	Demo ship	None	Bornholm ferry		
MeOH/ DME	Production	See Table 5-2			
	Engine	Is developed		Retrofitting of existing engines	Duel fuel operation
	Demo ship		2023 (Mærsk)		
BioFuel	Production	See Table 5-2			
	Engine	Most BioFuels can with minor refinery enter existing engine (pilots with lignin from biomass is currently ongoing)			
	Demo ship				
	Approved as jet	Only HVO	All biomass/residue type should have a route to jet-fuel	Low TRL	R&D
Jet fuel	General			Can danish production become competitive	
	Fischer-Tropsch	None in DK		Low recovery	
	MeOH-2-gasoline	Some plants but none in DK	Approve Jet-B as jet fuel as this path is believed to be optimal	Jet-B is not approved for passenger transportation	Investigate whether it can be approved
	MeOH-2-jet	TRL=5	TRL=9, Approve	Lower expected recovery than MeOH-2-Gasoline. Higher expected recovery than Fischer-Tropsch	R&D

Other	Production		Export danish technologies		1. Needs for green certificates 2. Need for support/subsidies until technologies are more mature and competitive

5.2 IMPLEMENTATION ROADMAP

A successful market implementation of green fuels contains several generic elements, irrespective of which fuel is sought implemented, as described in sections 5.2.1 and 5.2.2 below. Thereafter, we will consider specific challenges related to the market implementation of green hydrogen for trucks, methanol for passenger cars, and green fuels for shipping and aviation.

5.2.1 End-to-end demonstration projects

A crucial element for implementation is to convince all actors in the ecosystem that the product can both reach the market and be used effortlessly by consumers. As a considerable behavioral challenge, consumers - especially private consumers - are generally skeptical towards alternative fuels and must be convinced that these are both functional and safe. We therefore need in-depth case studies of what caused early mass public acceptance of alternative fuels (such as ethanol in Brazil or electric cars in China and California). This requires interdisciplinary research bringing together the social sciences and humanities. Moreover, there is a pressing need for end-to-end demonstration projects that represent the full value chain, from energy provider, over fuel production to distribution and consumption (see Table 3-1 for Danish flagship projects which also include end-to-end demonstration). It is advised to showcase the technology through demonstration projects with specific public sector institutions (e.g. deliveries to all hospitals in a region) by the use of public procurement agreements. Also, certain private companies have set very ambitious sustainability targets (e.g. Novo Nordisk) meaning that they accept paying a premium for low/no emission transports. Such private companies should also become partners in these demonstration projects. From experience, positive news of such successful applications spreads quickly, and helps convince consumers. Moreover, demonstration projects are a good opportunity to showcase Danish technological know-how and illustrate the commercial viability at industrial scale, thus supporting future export potentials.

5.2.2 Framework conditions

5.2.2.1 Strategic direction, including a clear infrastructure plan

Actors are awaiting a clear strategy from the Danish state, which displays an understanding of the industry and a commitment to the effort of introducing green fuels. This is seen as a challenge for the industry to proceed, and considered a key goal within the first year of the roadmap. The strategy should include a plan for green fuels infrastructure expansion as an integrated part of strategies for renewable energy. Currently, one of the main challenges of the sector is easy distribution of commodities in the ecosystem. This is exacerbated by the fact that infrastructure projects have a long duration – both in terms of planning and implementation. One infrastructure element, which is regarded specifically crucial for the market, is a hydrogen grid, either as a new pipeline or by retrofitting the current gas pipeline. Extent and location of this grid must be thoroughly analyzed benchmarking it against solutions where hydrogen is converted to methane to re-use existing infrastructure and where green hydrogen is upgraded locally to value added products like methanol/ammonia to benefit from co-location of electrolysis units and fuel-synthesis plants. A thorough analysis of this involving key stakeholders is important at national level. When planning the hydrogen grid, it is crucial to ensure both 3rd party access, and transparent usage regulation. The precise analysis of the various regulatory options entails an international political economy analysis that looks at winners, losers, side packages and incentives using both qualitative and quantitative methods. Until the hydrogen grid is at least partly functional, actors expect most projects to be on a demonstration level. Having the grid in place is regarded as a crucial inflection point to unlock scale in the green fuels market. Moreover, it is thought to give Danish companies a competitive edge in attracting international investments and help secure Denmark's position as a net exporter of hydrogen and hydrogen-related technology. Finally, as we have seen with data centers in relation to the well-functioning electricity grid in Denmark, a hydrogen grid might also open up for investments in other industries.

5.2.2.2 Financial incentives for the market

The government needs to ensure financial incentives for the end-user to use sustainable alternatives to fossil fuels, either by implementing a cap-and-trade system, tradable blending requirements or in terms of subsidies and taxation. A system which is transparent, technology neutral and ensures price comparability between green and fossil fuels within all areas of transportation and industry is regarded as an inflection point for market implementation. Such a system would require a certification mechanism for all sustainable fuels linked to life cycle assessments, to ensure traceability of inputs, and to allow the market to reward CO_2-reductions, and possibly other characteristics which are of benefit to society. Discussions with the industry have shown that most actors are in favor of a CO_2 tax as one of the most efficient tools to support green fuels. Thus, a key workstream within the first 1-2 years is to undertake a full comprehensive analysis of the broader strategic impacts of the various options (using e.g. multi-criteria decision analysis).

Consumers will presumably be willing to pay a premium for green fuels. The size of this premium will most likely differ from one end-user group to another. Some end-user groups are also more affected by global prices than others. International shipping and aviation will for instance have the opportunity of bunkering elsewhere, if prices for green fuels are comparatively high in Denmark. Thus, studies are needed into consumer willingness to pay to maximize the premium potential for each end-user group, and thereby minimize market distortions by subsidies and taxation.

Finally, on the input side, PtX producers are seeking a redesign of distribution tariffs. Dynamic electricity tariffs could be introduced to increase the potential for green hydrogen production to balance the electricity grid. Further, electricity distribution tariffs are charged on the cables, which connect electrolysis plants with renewable energy plants within the same project. This constitutes a large economic burden for PtX producers. The distribution tariffs could be redesigned so it is possible to opt-out of electricity consumption from the public grid and utilize its own sustainable power production plant for free.

5.2.2.3 Social acceptance of green fuel technologies

The diffusion, effect and final content of technological change depends on how it interacts with the organization of the social fabric, and the way in which measures contribute to solving major societal challenges depends on how they reflect the dynamics of change at the micro levels of the economic system. In this context, the micro level includes both the end-user and citizens. Considerable challenges to end user and citizens' acceptance of green fuel technologies is posed by concerns about the safety and functionality of the fuels as well as Not-In-My Backyard (NIMBY) attitudes. These must be tackled in a joint effort by the government and relevant companies. Innovative ways of channeling the general agreement on the need for climate-tackling activities into incitement for local green fuel projects should be explored. For instance, involvement of citizens and stakeholders in processes of energy transition may improve legitimacy and efficacy of green energy solutions. The involvement can take place at different scales, such as in the national public sphere or in local arenas, or in specific thematic contexts. Moreover, it can unfold in different media and communication formats such as public hearings, surveys, or future workshops. Other options, such as local co-ownership of production facilities, could also be considered to ensure legitimacy and social acceptance. A comprehensive strategy for affecting end-user behavior and citizens' concerns should be developed within the first years of the roadmap, based on existing knowledge within the social sciences and humanities (SSH) field.

5.2.3 Green hydrogen for trucks

A crucial aspect of market implementation of green hydrogen for trucks is to develop and enforce industry standardization of green hydrogen producing equipment and output quality, for which there are currently no national guidelines. If, for instance, the hydrogen is to be used in fuel cells, there are high demands for quality, and standards for allowed levels of water in pure hydrogen must be determined. Denmark should seek to align these standards with the EU so that a European regulatory system for hydrogen may come into place.

The composition of the industry for land transport of goods is complex, and actors sometimes have opposing interests. While companies buying transportation of goods push for greener options, distributors have a hard time finding haulers willing to risk investment in trucks run on green fuels, especially given the low margins in the industry. Trucks are expensive, so haulers, which will most often be smaller companies with 5-10 vehicles, will not replace them until necessary, and when doing so will think mainly in economic terms. With a fairly long lifespan (7-8 years), replacement of old trucks is a slow process. Moreover, producers are not expected to have models ready for large-scale distribution until 2028. Since there are no major truck producers in Denmark, implementation is dependent upon international demand. Technological advances, which increased energy efficiency of trucks, and thus the number of kilometers traveled per charge, might help to increase demand so that commercially available trucks are available on a large scale at an earlier date.

Filling stations with pressurized tanks will need to be established along the main road network, both in Denmark and in the rest of the EU. Furthermore, given the explosive nature of hydrogen, a specific effort is needed to smooth citizens' and consumer concerns during the market introduction. In sum, the societal readiness level of green hydrogen for trucks is currently deemed at a medium to low level (3-4).

5.2.4 Intermediary fuels for road vehicles

Methanol use in private vehicles has a high technological readiness level and could be distributed from the producer to the end-user through the established network of pipelines and filling stations. Nevertheless, promoting intermediary fuels such as methanol in the market for private vehicles, has both a technical, behavioral and financial challenge. As a technical challenge, for the gasoline engine to run smoothly on high levels of methanol, it must either be equipped with an additional device (Flex Fuel Kit) or undergo changes to the engine map. Demonstration projects by Danish Technological Institute have shown that a blend of 85% methanol can be used in existing gasoline engines with only minor adjustments. The device/modification must be available on a large scale in a standardized version, and mechanics across the country must be instructed in the application. This is regarded as a first goal for market implementation. The behavioral and financial challenges relate to concerns that the vehicle will be damaged, and whether this will entail additional cost for the consumer. To handle this, the government could engage in dialogue with car producers, to expand engine guarantees to cover installation of the engine device and use of methanol. If this is not possible, other market actors, i.e. insurance companies, could be incentivized to cover any damages to the engine caused by installation or use. When both the technical, behavioral and financial challenges are overcome, a critical mass of consumers would be expected, which could be seen as an inflection point for the market. The market for private vehicles is estimated to have a high societal readiness level (7-9), although further studies into behavioural modeling of individual consumers are needed.

5.2.5 Green fuels for aviation and shipping

The shipping industry has a high readiness level to adapt green fuels. The large amounts of fuels which ships offtake means that a few ships will be able to kick-start a large demand. Moreover, ship owners have a desire to go green, vessel engines have a high acceptance for fuels, and there is ongoing research into engines that are tailored for, e.g. ammonia, to improve energy efficiency. The shipping industry is even ready to put a price tag on their engagement. According to actors in the industry, a specific goal for the market would be that fuels are available in 2025, with a 20 % price premium difference between black and green fuels. Perhaps a transition can be achieved by requiring a certain blend-in of green fuels to the current fuels or e.g. grey ammonia.[5] The use of ammonia in shipping is deemed to have a medium to high SRL level (6-7).

Nevertheless, there are challenges to overcome. As a test before market introduction, end-to-end demonstration projects of the use of green fuels are crucial to improve consumer acceptance. Further, fuels need to be ready in large quantities to ensure sufficient bunkering opportunities. Vessels, especially ocean-going vessels, offtake large quantities of fuel when bunkering, and some fuels need to be stored in pressurized tanks. Thus, a considerable obstacle to market implementation of green fuels for shipping in Denmark is infrastructure readiness to operate and store large quantities of fuels. Related to this challenge are issues of determining operating standards and safety procedures, as well as securing port authorities' acceptance of bunker infrastructure.

Further, given the international nature of shipping, there is considerable skepticism from the industry on whether Danish production of green fuels for shipping will be sufficiently cheap to compete with international products. In

---

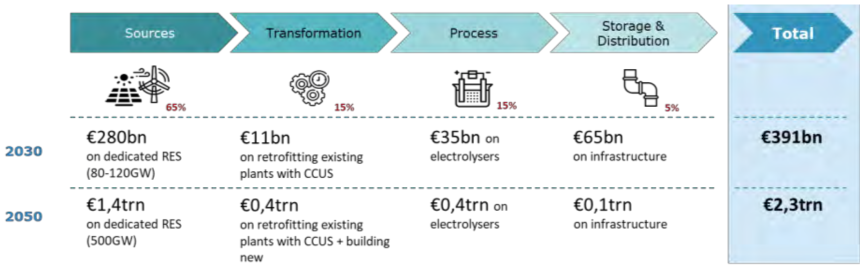
[5] Fossil ammonia where CO_2 is captured and stored

any case, the industry expects no export potential of production. However, the industry further agrees that there is a considerable export potential of fuel-related know-how and technologies, both regarding fuel production and engine technology.

Another considerable challenge to overcome regarding implementation of green fuels for aviation and shipping concerns the regulatory barriers related to fuel requirements, which are particularly strict for aviation. These requirements are agreed upon on an international basis through the International Maritime Organisation (IMO) and the International Air Transport Association (IATA). Thus, for successful market implementation, the Danish government should consider active engagement in IMO and IATA to purposely transform these requirements.

5.3 FINANCIAL ROADMAP

The investments needed to convey a green transition through utilization of green fuels are significant. Following EU's Investment agenda €320-458bn is to be invested in hydrogen until 2030 and expected addressable market of €2 trillion until 2050. A significant part of the investment is related to the build out of renewable energy sources. Hence underlining the substantial effects by increasing efficiency in transport technology – as this will lower the need for installed power capacity. Investments alone for the energy island in the North Sea can be estimated to approx. 8 bn EUR.



	Sources	Transformation	Process	Storage & Distribution	Total
	65%	15%	15%	5%	
2030	€280bn on dedicated RES (80-120GW)	€11bn on retrofitting existing plants with CCUS	€35bn on electrolysers	€65bn on infrastructure	€391bn
2050	€1,4trn on dedicated RES (500GW)	€0,4trn on retrofitting existing plants with CCUS + building new	€0,4trn on electrolysers	€0,1trn on infrastructure	€2,3trn

Figure 5-4: EU's investment agenda for hydrogen

5.3.1 Investments in demonstration and infrastructure

Creating a market for hydrogen is among the immediate actions of the proposed roadmap. This require investments in large scale demonstration plants (as listed in Table 3-1), transmission abilities and storage, and will include the deployment of both large industry and SMEs. Private investments are envisioned having a significant role here. De-risking these massive private investments is of crucial importance sparking the development in this area, therefor also public financial support is envisioned to have an initial role.

Several aspects play a significant role in lowering the risk to the investor. Initial public co-financing of large demonstration plants is a strong contribution in this respect. Focusing available public funding for large demonstration plants, transmission and storage infrastructure is important. Another aspect is ensuring a stable off-take. Creating a significant market for f. ex methanol for light transport through legislative measures is thus important. Bundling investments across the value chain – including both the production, distribution and use of the green fuel – could also prove as efficient means to ensure off-take. Additional initiatives could be applying public procurement as a catalyst for the use of the green fuels by f.ex. offtake for public transportation.

Lowering the complexity in fuel solutions would also support the ability for investors to navigate – a scenario focusing on Hydrogen, Ammonia and Methanol would therefore have positive effect for the investor outlook. Similar if it would be possible to pool the demand by off-takers – to get more certainty on market sizes.

Even though there is a willingness in some markets to pay a premium on green solutions, a very significant contribution to the de-risking of investments, is to narrow the price gap between grey, blue and green hydrogen. This will in the longer run be obtained through scale-up production and research, and in the shorter run though economic incentives either increasing the cost of fossil-based fuels through a CO_2 tax or provide subsidies or alleviating other taxes applied to green fuels. In this respect it must be taken into account that electricity makes up 50% of the cost of green hydrogen production and tariffs another 20% – the price of electricity thus has a large impact on the price of hydrogen. Focusing on developing innovative business models that cater for a market for green fuels is therefore important.

User acceptance and behavior is also important to consider. Engagement and focus on benefits for end users/citizens is important in aiding the transition for both construction and operation of facilities and in the end positively affect demand. Utilizing existing assets by retrofitting fossil-based infrastructure (refineries, gas transmission, storage etc.) could also prove a faster way to reduce the investment requirements and the price of green fuels.

During the later years there have been an increasing focus towards sustainable investments (e.g. ESG) currently also driven by the introduction of the EU taxonomy. Green fuels are to benefit from this focus. But it will also call for transparency in the declaration of fuels. Introducing digital solutions like block-chain which is currently applied in development tools for reporting, would add to the transparency of the markets.

Projects that would require investments following the road map include:

1. Planned PtX demonstration projects with a 2030 horizon
2. Hydrogen (heavy vehicles) and M85 (light vehicles) fueling stations and associated infrastructure
3. Hydrogen transmission net – pipe to Germany for export
4. HVO: Medium scale plant
5. Hydrotreating of bio-oils: Medium scale plant on refinery
6. MeOH/DME: Large scale plant based on CCU
7. NH_3: Large scale NH_3 plant (at harbor) and associated NH_3 bunkering and maritime off-take
8. Offshore hydrogen wind turbines
9. Gasification with downstream MeOH and MeOH-2-jet: Medium scale plant

Demonstration projects often require public funding to support the business case for the involved actors. An example of this is the recent political agreement to set up a pool of DKK 200 million, earmarked for the green transformation of municipal ferry operation in Denmark.[6]

5.3.2 Public financing of Innovation and R&D

Besides initial co-financing, public funding also has a significant role in relation to technology development which is assumed to be ongoing towards 2050. The current road map identifies following key technologies which ought to be addressed:

1. NH_3 engine and retrofitting diesel engines for dual fuels
2. Refinery of Biooil (from pyrolysis and liquefaction)
3. Improve electrolysis – catalysts, efficiency, material degradation, and increase pressure
4. Improve fuel synthesis processes – better catalysts and more efficient processes
5. Methanol-2-jet (or approve jet-B as jet fuel for passenger aviation)
6. Improve pyrolysis and liquefaction process
7. Hydrogen wind turbine
8. Hydrogen storage in caverns in Denmark
9. Improve gasifier incl hot cleaning of syngas

According to the level of maturity of the identified technologies (Figure 3-3), specific relevance of national funding applies to the Innovation Fund: Grand solutions and Innobooster, EUDP and ELFORSK and in some cases even a facility like the Export Credit Foundation. But compared to the investment sizes needed, additional funding is highly relevant to consider. Several European funding possibilities apply during 2021-27. Most relevant is Horizon Europe with a budget of 15 bn EUR for climate, energy and mobility (i.e. InnovFin EDP Facility, which provides loans to commercial-scale industrial demonstration projects (TRL 7-8) for renewable energy, fuel cells and hydrogen. The EU Innovation Fund awards grants of 10 bn for demonstration or scaling up innovative technologies including PtX technologies. Other European options include Connecting Europe Facility with 5 bn EUR for grant and risk mitigation instruments for energy transmission infrastructures of European importance. Invest EU with a budget of 9 bn for guarantees for bankable investments in sustainable infrastructure, and LIFE with 1 bn EUR for demonstration projects in clean energy transition ready to be implemented close to market

---

[6] https://www.trm.dk/nyheder/2021/aftale-om-200-millioner-kroner-til-groenne-faerger-i-danmark/

condition at industrial scale. In addition is to be consider EU funded programs implemented at the member state level (ERDF, Cohesion Fund and the Recovery and Resilience Facility). Of specific interest is also the dedicated instrument Important Project of Common European Interest (IPCEI) which is currently being applied on hydrogen throughout Europe, endowing selected projects with unique exceptions from state aid rules.

6 Integration of PtX with the broader energy system

The energy system stands before a transformation as it adapts to the introduction of the hydrogen value-chain of PtX, which embraces all energy consuming sectors. It is important to utilize the strengths of the individual system for optimal implementation of PtX fuels, while also ensuring efficient interfaces between different energy sources into the energy systems.

Despite the highly developed Danish energy system, it faces several challenges and opportunities with the introduction of the PtX value-chain. The challenges and opportunities are of technical, market, systemic and regulatory character and include:

- Availability and allocation of resources
- Development of energy system models to include PtX and co-optimization of energy grid infrastructures
- Balancing of electricity grid with increasing share of wind and solar power with PtX-plant flexibility and the associated energy storage capacity (e.g. Hydrogen storage)
- Development of hydrogen infrastructure, including offshore grids and energy islands
- System services and integration of PtX-plants in low-inertia, converter-based power systems
- Hybrid plants combining PtX with Energy storage, Wind Turbines, and Solar Panels
- Integration of electricity, electric infrastructure, reuse of heat surplus, district heating, hydrogen, gas, biomass and carbon markets.

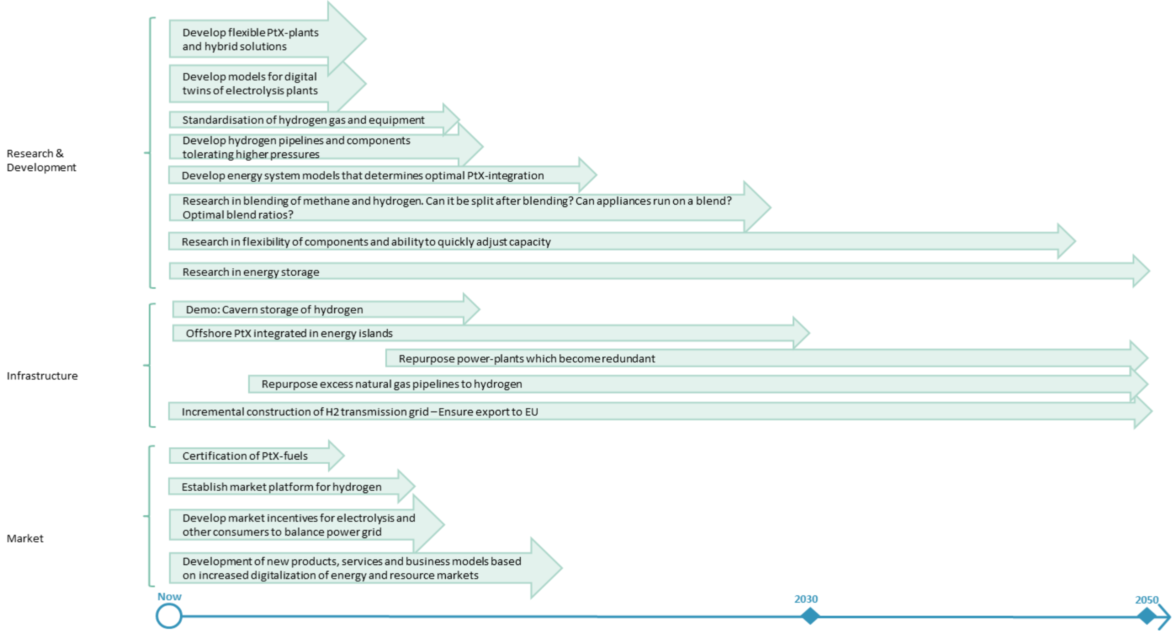


Figure 6-1. Key activities and workstreams for integration of PtX with the broader energy systems

There are several gaps in the current energy systems which leads to suboptimal integration of alternative fuel production, distribution, and consumption. A number of key activities and work streams have been identified to close the gaps. The goal is to do so optimally, by implementation of existing technologies and smarter regulatory frameworks, while other gaps require further research and development.

6.1 TECHNOLOGICAL IMPLEMENTATION

Balancing of the electricity system is a key focus area for technological market implementation. This can be achieved by development of hydrogen infrastructure with storage of hydrogen in underground caverns. The technology for hydrogen storage is mature but scaling and proof-of-concept is needed on a large scale. A big demonstration plant for hydrogen storage would allow shifting excess power production from wind power to periods with low production and high consumption of energy, increasing the agility of our energy system and put Denmark in a leading international position in renewable-based energy systems with PtX. Digital twins will enable optimal design and operation, and optimization of PtX-plants for various use cases. It is also essential that the development of the energy islands in the North Sea and Baltic Sea includes support for PtX-production.

Research and innovation are required to provide the pathways for stronger integration of PtX with the broader energy systems. It also opens for further development of flexibility in both production and offtake of green fuels through e.g. digitisation, market solutions and behavioural adaptation. By increasing the flexibility, efficiency in turn will increase adding to further lowering of cost and the overall uncertainty related to green fuels and provide better possibilities for balancing and ensuring stability of the electricity system with an increasing share of intermittent power. Research and innovation in flexibility should focus on the ability of components in the PtX energy system to be able to deliver system services for the electricity grid, by being able to quickly adapt to the price signals of the electricity market. Research and innovation should also focus on developing energy storage technologies, so they can become viable options for the energy system and for hydrogen production for both short- and long-term storage. Another aspect could be evaluating and handling the potential long-term risk for the Danish power and energy system, when there is large-scale deployment of PtX and increased level of cross-border fuel trading and transportation activities.

The industry opportunities by combining PtX-plants with wind turbines should be prioritized. This involves new control concepts, hybridization, simplified equipment, ancillary components, combined power and hydrogen transmission etc. Research and innovation about PtX and related technologies (incl. energy system models) for offshore applications shall also be prioritized to achieve optimal design, planning, implementation and operation of GW-scale offshore plants, e.g. via offshore energy islands. This will create a sustainable market for Danish technologies and stakeholders.

Key research and innovation activities are also needed in blending of hydrogen and methane. Research and innovation could provide options for splitting of these blended gases or for conversion of existing appliances connected to the grid to run on a hydrogen and methane mix. Research and innovation are also needed to increase the pressure of hydrogen in pipelines to excess of 30 bar. The higher pressure that can be achieved, the more energy can be transported in the hydrogen grid, increasing the flexibility of the energy systems.

Key innovation workstreams in repurposing natural gas pipelines for hydrogen must be carried out, as well as key activities in repurposing and reintegration of obsolete power plants into the PtX energy system, for example as hydrogen power plants. Also, the costs of repurposing the gas pipeline system for hydrogen and hydrogen cavern storage must be benchmarked with respect to overall economy versus a process, where hydrogen is converted to methane enabling re-use of existing infrastructure. Detailed analyses of the cost of the various routes must be benchmarked involving all key stakeholders.

Energy system models should be further developed and integrate the PtX value chain in both short- and long timescales. They should allow actors and regulators to determine optimal locations of new plants based on grid capabilities, market forecasts, biomass and carbon availability and include sector coupling and co-optimisation of gas, electricity, hydrogen and district heating. Energy system models should also incorporate digital twins of electrolysis plants for optimisation of energy systems. Furthermore, the advances in artificial intelligence and machine learning must be adopted in the energy system models, to provide valuable data analysis, insights and forecasting of energy markets. The models should provide socio-economic analyses assisting in prioritising e.g. biogenic CO_2 for CCS or fuel production, biogas for industry or methanol, offshore wind power for export of electricity, hydrogen or liquid fuels, taking into account the national resources and environmental goals.

6.2 MARKET IMPLEMENTATION

There is a need to establish a hydrogen grid as soon as possible, as this will drive the market implementation for the hydrogen economy and establish cost-efficient transport of hydrogen to where it is needed. The hydrogen grid will be a magnet for PtX-projects which will gain access to cheap hydrogen for further processing into PtX-fuels and will allow actors to focus on key expertise areas.

However, some technologies are best co-located such as high temperature electrolysis and down-stream synthesis to e.g. ammonia or methanol, as very high overall efficiencies can be achieved with correspondingly low cost. Thus, distribution will be most beneficial for export and distribution for transportation uses (trucks and short distance maritime transport).

To implement PtX-fuels in the energy markets further digitalisation is needed. Market actors are currently acting bilaterally due to a lack of centralised market platforms for particularly PtX-fuels, hydrogen, biomass, and carbon. A goal for market implementation of PtX-fuels in the broader energy system is to further digitalise energy markets. Key work streams should identify the possibility of implementation of blockchain technology in market designs as a tool to facilitate efficient and transparent market design and tracking of certificates providing guarantees of origin for hydrogen and PtX-fuels. Digitalisation should also integrate the trading of certificates with physical products. Digitalisation must also provide possibilities for utilisation of surplus heat and the use of biproducts from PtX processing plants. The market design should allow for consumers to be responsive regarding grid balancing and act dynamically on both production and distribution capabilities of the electricity grid. The PtX value chain must utilise the potential for balancing the electricity grid, which will allow Denmark to use cheap wind-power instead of exporting it to neighbouring countries. It is crucial that we reclaim the value of cheap wind-power.

Digitalisation must be seen as a new type of infrastructure similar to transmission grids. It is going to be one of the key pillars of the market development and will bind together the PtX-markets and make Denmark leading in green energy to sectors which are difficult to electrify. Thus, a goal is to test, develop and implement new digital and cyber-secure infrastructure and market solutions that can support the future PtX market, by securing the value of renewables in the entire value chain, across sectors and borders. It will allow actors increased access to market and utility data in a transparent and cyber-secure manner, which will reduce entry barriers for new and existing actors. Digitalisation will secure an efficient utilisation of existing and new energy infrastructure, which will minimise costs and issues related to the transition to sustainability. It will release the potential for sector coupling and introduce the necessary flexibility for balancing the electricity system.

7 Contribution towards the Vision

7.1 CO_2-REDUCTIONS

Climate projections from the Danish Energy Agency show that under a frozen policy scenario, total net emissions are expected to fall to 35 mt CO_2e in 2030, corresponding to a reduction of 55% compared to the 1990 level. The projections thus show that at present there is an estimated reduction shortfall of 15 percentage points, corresponding to 11.8 Mt of CO_2e in relation to the Danish Climate Act's 70% target (ref 5). Assuming full implementation of the proposed roadmap, initial estimations show that the roadmap has a potential to reduce CO_2e by a further 4.9 Mt in 2030. Thus, the roadmap covers 41% of the reduction shortfall to reach the Danish climate goal.

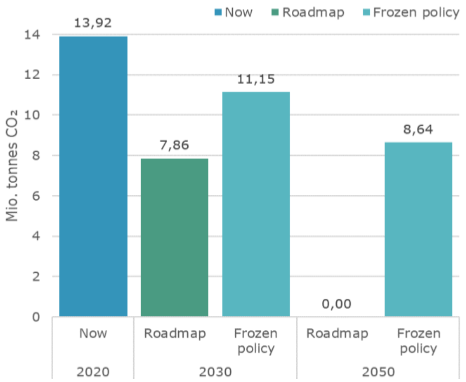


Figure 7-1: National emissions from transport (Mt CO_2) in 2020, 2030 and 2050 as frozen policy and roadmap scenarios

The main part of the CO_2e reductions are expected from the transport sector. Despite an increase in conducted transportation, CO_2e emissions from the transport sector are expected to fall by 2 mt from 2019 to 2030 in a frozen policy scenario, which means that the sector is expected to emit 11.5 mt of CO_2e in 2030. This is roughly at par with emissions in 1990. More than half of this reduction is from the transition to electric passenger cars (ref 12). By implementing the roadmap, emissions in 2030 are estimated to be further reduced by 3.3 Mt CO_2e so that the sector emits 7.9 Mt CO_2e. These estimations only include national transportation, in line with the Danish Climate Act's 70% target. Although the roadmap does not propose full-scale Danish production of ammonia for shipping, expected reductions from shipping are included. Given the right framework conditions, and opportunitiy for full-scale demonstration of the technology, shipping is expected to convert to green fuels, irrespective of the origin.

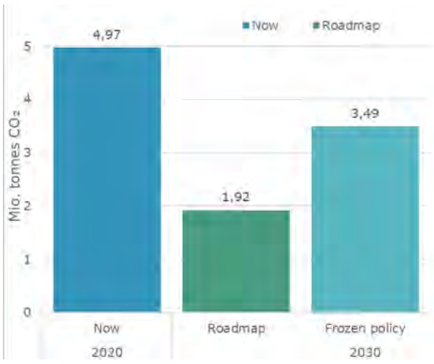


Figure 7-2: Emissions from industry (Mt CO_2) in 2020, 2030 and 2050 as frozen policy and roadmap

In sum, the roadmap presents an estimated 33% reduction of the emissions in the transport sector compared with 1990 levels. This should be held up against a sharp increase in transportation conducted. It also exceeds expectations according to the Climate Partnership for Energy and Utilities Sector (ref 13), which estimated the CO_2e reduction potential from PtX in the transport sector to be 1.9 Mt. Moreover, it is in the high end of government estimations in the Climate Programme for 2020 (ref 12).

In a frozen policy scenario, emissions from the industry (manufacturing and construction) are expected to fall by 1.5 Mt CO_2e in 2030. The emissions from manufacturing and construction come from both the sector's energy consumption and process emissions (ref 5). The reduction is mainly due to a reduction in the manufacturing industry's energy-related emissions, while the decrease in process emissions is significantly smaller. By implementing the roadmap, emissions are estimated to be reduced by a further 1.6 Mt CO_2e compared to the frozen policy scenario. This constitutes a 76% reduction in CO_2e emissions from the sector.

Finally, we expect a 1.1 Mt CO_2e reduction from 2020 to 2030 from the Danish share of international shipping and aviation. These reductions do not contribute towards the 70% reduction target. The reduction will occur despite a considerable increase in transportation conducted by these modes. The estimations are uncertain, due to different methods of calculating the Danish share of international aviation and shipping. Nevertheless, the estimations are in line with the long-term reduction potential estimated in the government's Climate Programme for 2020 (ref 12).

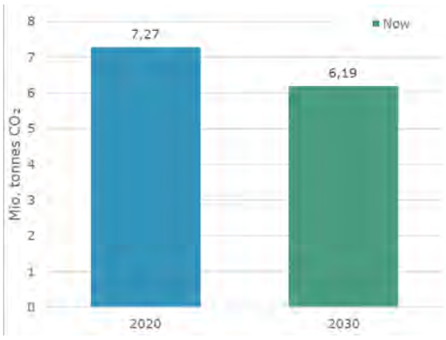


Figure 7-3: Emissions from international maritime and aviation transport (Mt CO_2) in 2020 and 2030 roadmap

The above calculations focus solely on transportation and industry, and not on national or international effects in other sectors. For instance, surplus heat from PtX can support the Danish district heating supply. Also, Danish power from sun and wind would arguably have a greater climate effect if it is exported in the European electricity system, where it would displace fossil-based electricity production. Finally, the calculations do not consider any possible rebound effects due to tighter regulation.

7.2 EXPORT

Denmark has a long tradition of exporting energy raw materials, primarily based on oil and natural gas. From the end of the 1990s onwards, exports increased markedly and peaked in 2008 at approx. 76 billion DKK in export earnings (ref 5).

The export potential of PtX products is dependent upon the composition and characteristics of the product. PtX products that are difficult to transport over long distances, or consist of raw material that is geographically constrained, will have a better potential for exportation to other European countries than other products. For easily transportable PtX products, the market is expected to be saturated by cheaper products from areas with lower electricity costs (i.e. Australia or Saudi Arabia). Thus, the export potential of PtX commodities is focused mainly on Denmark's neighboring countries and the EU. The export of new PtX technologies and services has a huge potential for boosting the already existing export-intensive businesses within energy and transport given that commercial viable technologies are demonstrated.

For the proposed roadmap, it seems realistic that there will be a considerable export potential for green hydrogen. The existing hydrogen consumption in industry and refineries is approx. 1440 PJ in Europe, which is today largely produced from fossil fuels, i.e. natural gas and coal. Some of this could potentially be replaced by electrolysis-based hydrogen from Denmark. The increasing green hydrogen demand from Germany, and ongoing discussions of an EU hydrogen backbone, are good indications of a growing demand from Denmark's neighboring countries.

Medium term export of methanol also seems realistic, although to a less extent than hydrogen. Due to imports of biomass, Denmark has considerable access to carbon, which is used in methanol production.

Conversely, the industry does not seem convinced that production and export of ammonia is a viable option for Danish producers, as this may be produced with less cost in other countries and imported to Denmark. For this reason, the roadmap does not include a large-scale ammonia production facility placed in Denmark, although smaller scale facilities may be set up in order to test the technology.

An additional effect of the roadmap is the lost opportunity to transport electricity from the energy islands to the European electricity system. Indeed, Denmark will be a net importer of electricity, even when the North Sea energy island is operating at full capacity.

Nevertheless, besides satisfying a local market, Danish production of PtX fuels still plays an important role in building technologies and know-how, which may be exported on a large scale, as is the case with wind energy. Many years of active Danish energy and climate policy has ensured a good business starting point for the development of green technology in Denmark (ref 13). Today, more than 32.000 people work in the wind energy industry, and wind technology and services make up approx. 5% of Denmark's total exports, corresponding to more than DKK 66 billion (ref 14). At the same time the maritime industry employs 60,880 people directly and exports goods and services for just over DKK 287 billion accounting for 26.5% of the total Danish exports. On top of that more than 25.000 are employed within land transport in Denmark. In continuation of this, the 70% target in 2030 can be leveraged for Danish consumers and companies to use energy-efficient solutions, which at the same time will lead to increased demand for energy technology. This supports the energy technology innovation in Denmark, which contributes to Danish companies having good conditions for continuing to develop and export competitive energy technology solutions. In fact, according to actors in the industry, this is where the main export potential is expected, and thus should not be underestimated.

This PtX road map suggests actions to among others support the realization of 3.7 GW already planned PtX projects for 2030. These already planned projects are likely to become the first fast steppingstone for Denmark to grow a global export of technologies and solutions in PtX. This export will come on top of the increased export of wind turbines from Denmark as a consequence of PtX requiring more renewable power on a global scale in the coming decades.

7.3 EMPLOYMENT

The calculations of employment effects by the investments in the roadmap, is based on a breakdown of the investments in:

- expected labor purchase
- purchase of non-standard components/plant
- purchase of goods and services in general
- information on the timing of the individual investments

Table 7-1. CAPEX investments (bill. DKK) needed for fuel production in 2020-2030 and 2030-2050 (COWI calculations)

	2020-2030	2030-2050
H_2	1	7
MeOH/DME	19	0
Jet	15	14
Total	35	22

This information has been obtained by experts from COWI's and external experts. Based on this information and COWI's calculation model, COWI has calculated the demand for labor measured in number of man-years and divided into years and occupational groups.

The demand calculations are based on expectations for CAPEX projections for green hydrogen, methanol/DME and jetfuel shown in Table 7-1. CAPEX estimations only cover production facilities, and further investments will be required for the distribution and bunkering of the fuels. Moreover, we assume that the cars, vans and trucks on Danish roads will be imported from abroad, regardless of which fuel they run on. This relatively large investment is therefore expected to have limited direct employment effects.

This also implies that the calculations do not additionally include demand due to technological export. This is important, as expectations for technological export are high, as mentioned in section 7.2. In fact, actors in the industry expect technological export to be the main driver behind job creation.

The estimated demand from CAPEX projections includes both the direct and the indirect employment effects, and thus both the labor demand that investment creates in connection with the actual implementation of the investment and acquisition of the components/plants that are not standard solutions (the direct effect) and the labor demand generated by investment in suppliers of goods and other services (indirect effect).

Based on expectations for CAPEX projections for green hydrogen and methanol, combined with the suggested development of consumption of biofuels in industry transport, it is expected that PtX CAPEX investments of 35 billion DKK is required between 2021 and 2030 , and a further 22 billion DKK towards 2050 to make transport and industry independent of fossil fuels by 2050.

Figure 7-4: Total employment effect (thousand man-years) for 2020-2030 and 2030-2035

The total employment effects for the periods 2020-2030 and 2020-2050 are shown in Figure 7-4. As the table shows, COWI foresees a high demand for unskilled labor, blacksmiths and shipbuilders and plumbing and gas-technicians.

While construction of production facilities mainly requires unskilled or lower-education labor, it could be expected that the significant labor demand created due to export of PtX technologies would be directed more towards higher education employment.

In order to meet employment demands with a national workforce, it is crucial to ensure the right education of potential employees. This process must be initiated now, so that new graduates are ready by before 2030.

8 Reference list

1. Hydrogen Council (2021). Hydrogen Insights 2021.
2. Recharge News (2020). Growing ambition: the world's 20 largest green-hydrogen projects. December 2020.
3. Dansk Gasteknisk Center (2020). Power-to-X projekter i Danmark, november 2020.
4. Danish District Heating Association (2021). Nye forbrugere strømmede i rekordstort antal til fjernvarmen i 2020.
5. Danish Energy Agency (2021). Klimastatus og -fremskrivning 2021 (KF21).
6. Dansk Energi (2020). Rekordår: Strømmen har aldrig været grønnere.
7. Danish Energy Agency (2021). Klimastatus og -fremskrivning 2021 (KF21): Havvind. Forudsætningsnotat nr. 4B. Opdateret april 2021.
8. Danish Energy Agency (2021). Klimastatus og -fremskrivning 2021 (KF21): El og fjernvarme. Sektornotat nr. 8A.
9. Klima-, Energi- og Forsyningsudvalget 2019-20 (2020). KEF Alm.del - endeligt svar på spørgsmål 305.
10. Dansk Energi (2020). Potentialet for CO2-fangst i Danmark til den grønne omstilling.
11. Regeringens klimapartnerskaber (2020). Partnerskab for energitung industri.
12. Danish Government (2020). Climate Programme 2020
13. Climate Partnership for Energy and Utilities sector (2020). Powering Denmark's Green Transition.
14. Danish Energy (2020). Recommendations for a Danish Power-to-X strategy