Roadmap for Green Fuels in Transport and Industry

Danish Roadmap 2024

MISSION
GREEN FUELS

About this publication:

The Roadmap for Green Fuels in Transport and Industry is developed and published by MissionGreenFuels in collaboration with Ramboll. MissionGreenFuels is one of four state-initiated mission-driven green research and innovation partnerships supported by the Innovation Fund Denmark and Next Generation EU.

MissionGreenFuels
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Secretariat

The MissionGreenFuels secretariat consists of Aalborg University (Lead), Energy Cluster Denmark and Danish Center for Energy Storage

AALBORG UNIVERSITET

energy CLUSTER DENMARK

DaCES Danish Center for Energy Storage

Aalborg University Denmark
Danfoss
Green Hydrogen Systems
DTU Technical University of Denmark
SDU University of Southern Denmark
CIP Copenhagen Infrastructure Partners
TOPSOE
Aarhus University
University of Copenhagen
Danish Technological Institute
Alexandra Instituttet
Dynelectro
European Energy
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Blue World Technologies
Emery Oleochemicals
TECNOLOGY
BlueNord
Copenhagen Energy Partners
GreenLab
Erhvervshus Sydjylland
Greenhub Denmark
Crossbridge Energy Fredericia

+ Additional input from Danish business lighthouses "erhvervsfyrtårn"

GESEK
Fyrtårn Sydjylland

Baltic Energy Island
Fyrtårn Bornholm

CO2Vision
Fyrtårn Nordjylland

Water Technology
Fyrtårn Midtjylland

Contents

List of Abbreviations

AEC	Alkaline Electrolysis Cells
AF	DEA Analysis assumptions for Energinet
ASTM	American Society for Testing and Materials
AtJ	Alcohol-to-Jet
BAU	Business as usual
BOP	Balance of Plant
CAGR	Compound Annual Growth Rate
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilisation, and storage
CH4	Methane
CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRI	Commercial Readiness Index
DAC	Direct Air Capture
DH	District Heating
DME	Dimethyl ether
EC	European Commission
EJ	Exajoule
ETS	Emissions Trading System
FAME	Fatty Acid Methyl Ester
FCEV	Fuel Cell Electric Vehicle
FEED	Front End Engineering Design
FID	Final Investment Decision
FOG	Fats, Oils, and Greases
FT	Fischer-Tropsch
G/FT	Gasification/Fischer-Tropsch
GDP	Gross Domestic Product
Gt	Gigatonne
GW	Gigawatt
H2	Hydrogen
HEFA	Hydroprocessed Esters and Fatty Acids
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
HTL	Hydrothermal Liquefaction
HVO	Hydrogenated Vegetable Oil
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMO	International Maritime Organization
IPCEI	Important Projects of Common European Interest
KEFM	Danish Ministry of Climate, Energy and Utilities
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
LHV	Lower Heating Value
LNG	Liquified natural gas
LOHC	liquid Organic Hydrogen Carrier
LPG	Liquified Petroleum Gas
LSFO	Low Sulphur Fuel Oil
MDO	Marine Diesel Oil
MeOH	Methanol
MGF	MissionGreenFuels
MSW	Municipal Solid Waste
Mt	Megatonne
MWh	Megawatt-hour
NG	Natural Gas
NH3	Ammonia
NOx	Nitrogen Oxides
NZIA	Net Zero industry Act
OEM	Original Equipment Manufacturer
OFMSW	Organic Fraction of Municipal Solid Waste
OFW	Offshore Wind
PEM	Proton Exchange Membrane
PPA	Power Purchase Agreement
PS	Point source (CO2 capture)
PtG	Power-to-gas
PtL	Power-to-liquids
PtX	Power-to-X
PV	Photovoltaic
R&D	Research and Development
RES	Renewable Energy Sources
RWGS	Reverse Water Gas Shift
SAF	Sustainable Aviation Fuel
SNG	Synthetic Natural Gas
SOEC	Solid Oxide Electrolyzer Cell
SOFC	Solid Oxide Fuel Cell
SPK	Synthetic Paraffinic Kerosene
STEM	Science, Technology, Engineering, and Mathematics
TRL	Technology Readiness Level
TTW	Tank-to-Wake
TW	Terawatt
TWh	Terawatt-hour
WTT	Well-to-tank
WTW	Well-to-wake

Foreword

Green fuels represent one of the key levers to decarbonize our energy system, alongside renewables, electrification, and energy efficiency measures. In “hard to abate” industries like heavy transport, shipping, and aviation, where fossil fuels have long been dominant, green fuels offer a path forward. Derived from green hydrogen or bio-resources, these fuels are poised to play a central role in overcoming the complex challenges of the global energy transition. However, the journey to fully integrate these fuels into our existing energy systems is not without its hurdles. Scaling green fuels production, integrating them into our current infrastructure, and lowering the cost requires innovation, collaboration, and coordinated action.

For Denmark, green fuels present a strategic opportunity beyond national-level decarbonization efforts. By advancing innovation and development in areas like electrolysis and efuel synthesis, systems integration, carbon capture technologies, and sustainable biofuel production, Denmark can position itself as a global leader in green fuel technology. This leadership could boost energy exports, create thousands of clean jobs, and strengthen Denmark's economic competitiveness. Moreover, by exporting its technology and expertise, Denmark can help other nations accelerate their shift to green fuels, contributing to a more rapid and coordinated global transition to low-carbon energy systems

This roadmap is designed to guide Denmark towards these goals, aligning with the government's ambitious targets of reducing carbon emissions by 70% by 2030 and reaching full decarbonization by 2050. Originally introduced in 2021, the roadmap has been updated to reflect the latest national and global developments, ensuring it remains a relevant and tool for researchers, policymakers, and other central stakeholders.

The roadmap, developed by MissionGreenFuels in collaboration with key partners, provides a comprehensive framework to address technical, commercial, regulatory, social, and sustainability challenges that impede the widespread adoption of green fuels. The document identifies critical activities across these domains, with a focus on advancing technology readiness, scaling production capabilities, and improving market competitiveness of green fuels.

This document explores the following dimensions:

- **Technical innovations:** Advancing production, storage, distribution, and offtake technologies to enhance efficiency and scalability.
- **Commercial strategies:** Lowering costs and improving market competitiveness to ensure economic viability vis-à-vis conventional fossil-based fuels.
- **Regulatory frameworks:** Supportive policies that incentivize the growth and integration of green fuels into the broader energy system.
- **Social considerations:** Public perception, community engagement, and workforce development to foster broad societal support and a social license to operate.

By taking a holistic approach, this roadmap outlines clear priorities and actionable steps for green fuels stakeholders. It aims to drive immediate actions and guide long-term strategies to position Denmark as a leader in green fuels, supporting both national and global climate goals.

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Executive Summary

Roadmap for Green Fuels in Transport and Industry 2024

Green fuels are critical in meeting climate targets

Green fuels **will significantly contribute** to the Danish climate goals and the global ambitions of a green transition.

Green fuels offer a substantial opportunity for **Danish technologies and exports to support other countries in achieving their climate goals**. This could be via export of Danish-born innovation and technologies, or export of fuels to neighbouring countries.

MissionGreenFuels drives the development of the green fuels value chain by supporting R&D projects that address key needs such as technological innovation, systems integration, cost reduction, and processes optimization.

MissionGreenFuels also emphasizes **research on social, sustainability, safety, and market aspects** related to green fuels.

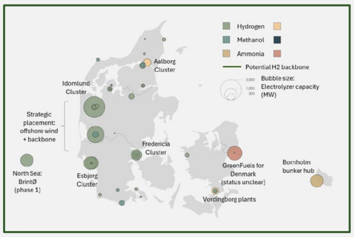
The Danish roadmap for green fuels guides the way

The **roadmap highlights the necessary pathways** to advance the adoption of green fuels in Denmark's transport and industrial sectors.

The roadmap examines several important topics:

- **R&D in production, user, and distribution technologies** to enhance efficiency and scalability of green fuels technologies
- **Strategies for reducing costs and improving market competitiveness**
- **Policies and frameworks necessary** to support the growth and integration of green fuels into the energy system.
- **Public perception, community engagement**, and workforce development to foster broad societal support.

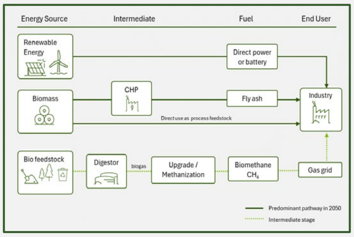
Reading Guide



Introduction and Context

New to green fuels? Start here for an introduction to green fuels and an overlook of recent national strategies, projects, and infrastructure plans.

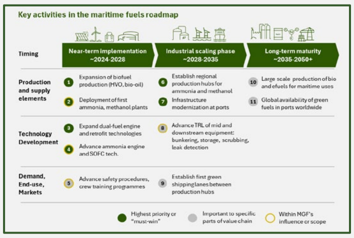
Green Fuels Introduction | Danish potential | Innovation Ecosystem | Systems Integration | Social and Sustainability



Sector Pathways

How will green fuels assist in transitioning certain sectors? For a look at sectoral level decarbonization pathways for industry, road transport, and the aviation and maritime sectors, please refer to Chapter 7.

Industry | Road Transport | Maritime | Aviation



Fuel Roadmaps

How do we get there? For a look at the key short- and long-term activities to advance green fuels, as identified by MGF stakeholders, please refer to chapter 8.

Green Hydrogen | Intermediary Fuels | Maritime Fuels | Aviation Fuels

Insights from the Green Fuels roadmap

In the roadmap, key activities in the short-and-long term are identified across various themes including technical, commercial, regulatory, and financial, and social elements. Timing of when activities will happen is informed by the latest developments in industry and policy. Key takeaways are shown below:

Availability of sufficient quantities of green power is identified as the most important prerequisite for developing H2-based green fuels. Without it, the sector will fail to launch.

Infrastructure development should be prioritized: Integration with existing and future energy systems, including electricity grids, district heating networks, gas/H2 pipelines, and CO2 supply chains, is critical for the success of green fuels.

Advancement of low-TRL technologies in biofuel and efuel production is essential for new synthesis pathways that use advanced/sustainable feedstocks.

The energy transition requires efuels, but its success hinges on the successful deployment of other technologies that are still nascent and expensive, such as green hydrogen and carbon capture technologies.

First movers and reference projects are needed: Companies that take risks and innovate can set a strategic direction quickest and can position themselves to capture the most attractive elements of the value chain and take those learnings forward.

From CCS to CCU: Utilization, not storage, of biogenic CO2 will be needed long-term to provide carbon feedstock for efuels production. Long-term direct air capture (DAC) will likely be needed as sources of biogenic CO2 will be tapped.

Research and innovation is cornerstone: Denmark's strong innovation ecosystem, supported by government, industry, and academia, is fundamental to driving the commercialization of green fuels and maintaining Denmark's leadership position.

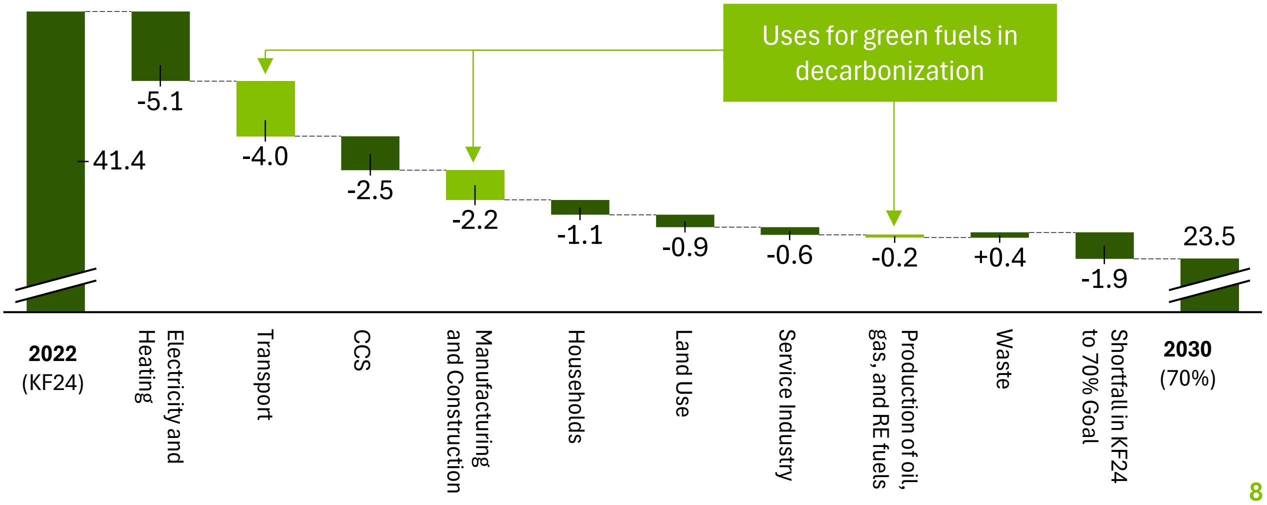
Social aspects should not be overlooked: Ensuring the social license to operate is critical. This requires community engagement, transparency, and broad stakeholder involvement.

Green fuels important contribution to emission reductions in the short and long term

Short term: Emissions reductions via green fuels will primarily come from fuel switching (biomethane injection, fossil-to-bio drop-in replacement, renewable biodiesel fuel blending) and niche applications of green hydrogen in transport and industrial uses.

Long term: Build-out of methanol, ammonia, and sustainable aviation fuel (SAF) production facilities with their usage in decarbonizing the maritime and aviation sectors, both domestically and for international routes.

Danish GHG reduction measures 2022-2030, Mt CO2e (KF24)



Driving Denmark's green future: MissionGreenFuels' Roadmap to green fuels leadership

This roadmap provides a structured and urgent call to **action for advancing the adoption of green fuels in Denmark's transport and industrial sectors**, guiding stakeholders through key milestones from now until 2050.

The roadmap is **developed through extensive collaboration with Danish stakeholders** and emphasizes the importance of coordinated action and the necessity to support demonstration and upscaling activities immediately to meet both national and international climate goals.

MissionGreenFuels plays a central role in developing and driving the implementation of the roadmap for green fuels in Denmark. As a state-initiated, mission-driven partnership supported by Innovation Fund Denmark, **MissionGreenFuels brings together key stakeholders across research organizations, industry, and government** to address the challenges and opportunities associated with green fuels in transport and industry.

The roadmap serves as a **strategic guide, developed by MissionGreenFuels in collaboration with experts and stakeholders, to align research and innovation efforts with Denmark's ambitious climate targets**. It outlines clear pathways for technological advancement, infrastructure development, and policy support, all of which are crucial for scaling up the production and use of green fuels.

MissionGreenFuels uses the roadmap to identify critical inflection points, set priorities, and coordinate actions across the value chain, ensuring that Denmark remains at the forefront of the global green energy transition.

Through this roadmap, MissionGreenFuels aims to reduce uncertainties, support large-scale demonstrations, and drive the commercialization of green fuel technologies, ultimately contributing to Denmark's 2030 and 2050 climate goals.

Denmark's ability to attract private investments will be crucial, requiring a clear strategy that highlights the country's strengths in renewable energy and leadership in clean energy technologies.

There needs to be a focus on green fuels and PtX technologies, aiming to **make PtX the next "wind adventure**". This would involve significant investment in innovation, infrastructure, and partnerships, both within the EU and globally.

Denmark could not only sustain its leadership in renewable energy but also **become a pioneer in the next generation of green technologies**, securing long-term economic and environmental benefits.

The roadmap is strategically designed to align research, development, funding, and policy initiatives with Denmark's ambitious climate goals for 2030 and 2050

Guiding funding and investments: It identifies key areas where investment is needed, such as infrastructure development, technological innovation, and scaling of green fuel production. By highlighting these areas, it helps direct both public and private sector investments to projects that will have the most significant impact on achieving Denmark's climate targets.

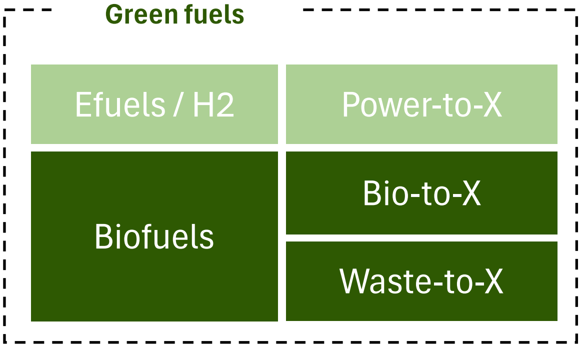
Shaping research and development: The roadmap outlines technological pathways and innovation needs. It serves as a framework for researchers and industry partners to focus their efforts on overcoming the technical challenges associated with green fuel production, storage, and distribution.

Informing policy development: Policymakers can use the roadmap to design regulations and incentives that support the green fuel industry. It provides a clear understanding of the regulatory needs and the types of policies that could accelerate the deployment of green fuels, ensuring they are integrated effectively within Denmark's broader energy system.

Strategic planning for infrastructure: The document emphasizes the importance of infrastructure integration, such as the development of hydrogen backbones and connections to renewable energy, water, CO2, and district heating systems.

1. Introduction to Green Fuels

Green fuels, also known as renewable or sustainable fuels, are produced using renewable or low-carbon energy sources and can serve as a substitute for fossil fuels. Depending on their production pathway, they can be carbon-neutral or even carbon-free. The input renewable energy can for example be wind and solar energy or organic material (biomass). Broadly, they are split into two categories: biofuels, based on biogenic sources, and synthetic fuels (efuels), based on low-carbon hydrogen derived from the electrolysis of water using renewable electricity. This combined process is commonly referred to as Power-to-X (PtX) where the "X" could be hydrogen, or a hydrogen derivative used for fuel, mobility, heat, or storage applications. Sometimes, hydrogen and efuels are also referred to as "indirect electrification", wherein electricity can be stored in chemical bonds of these molecules and used later for energy purposes. This differs from direct electrification where electricity is used directly, without any conversion steps.



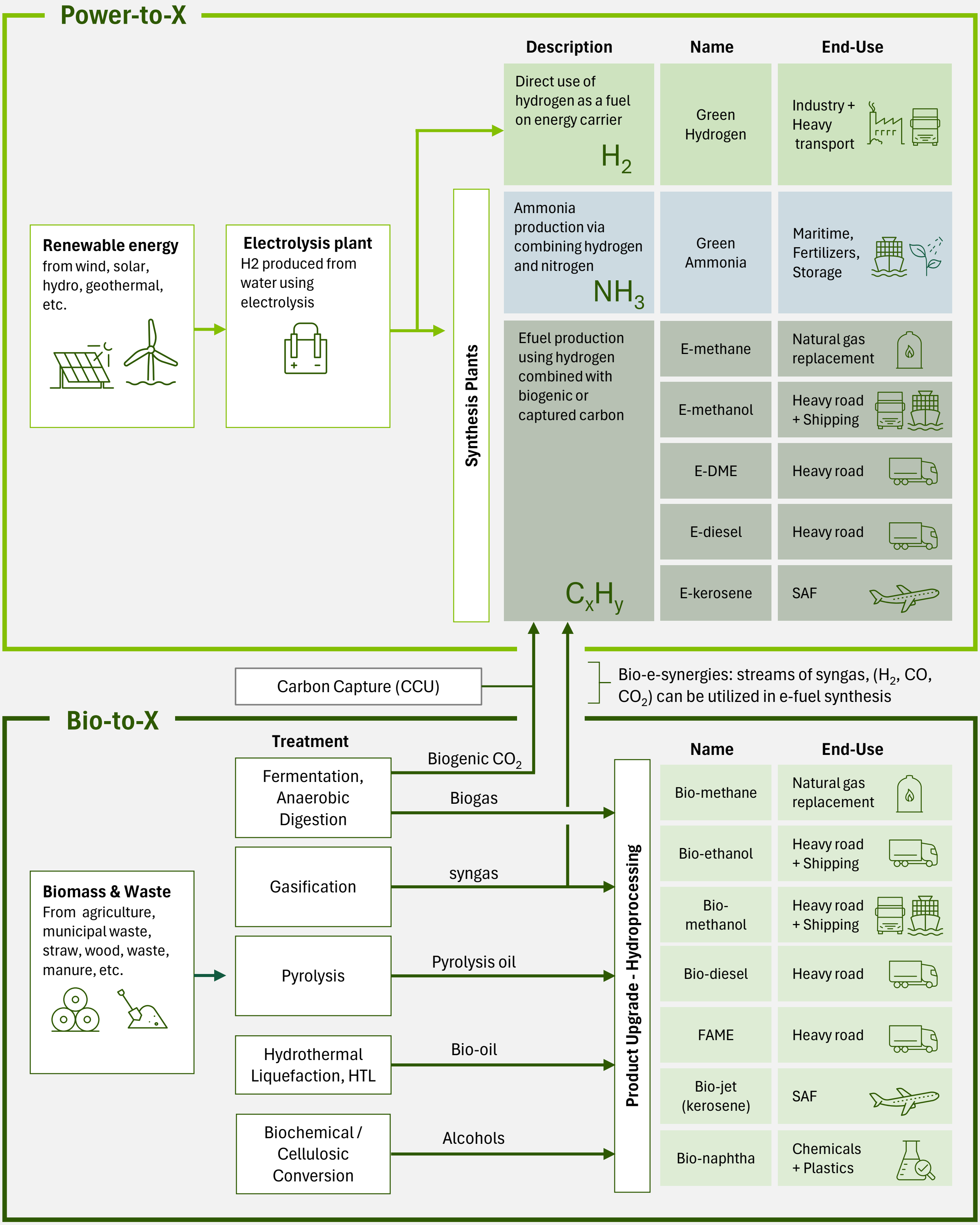
Each fuel, either liquid or gaseous, will have properties that make them technical replacements for conventional fuel sources. Depending on their energy densities, transport and handling properties, carbon inputs, combustion characteristics, existing infrastructure, some fuels are more attractive that others in certain applications. For example, biogas upgraded to biomethane can be directly injected into the existing gas grid and used in industry, however ammonia cannot be used in existing maritime engines and would require specialized engines, or fuel cells, that can use this type of fuel. These facts influence the timing of when green fuels can ultimately replace their conventional counterparts due to the fuel requirements of existing fleets or trucks, ships, or airplanes.

Other terminology used

- **Intermediary fuels:** serve as transitional fuels that facilitate the integration and utilization of renewable energy within the existing energy infrastructure and vehicle fleets (MeOH/DME and bio-oil, for example)
- **Drop-In fuels:** Renewable fuels compatible with existing infrastructure and engines without requiring modification
- **Bio-to-X:** Process of converting biomass into various forms of fuels or chemicals, such as biofuels, biogas, or biochemicals.
- **Waste-to-X:** Process of converting waste materials (e.g. plastics, OFMSW) into useful products like fuels or chemicals

There is lively debate between energy experts and policymakers about the extent that green fuels will play in future energy systems in both 2030 and 2050. Projections for hydrogen demand in 2050 differ greatly between various publications (based on key assumptions on end-use viability and adoption rates), however it is generally accepted that H2 will amount to 10%[1] to 26%[2] of primary energy in 2050. Regardless, both the low-end and high-end of these projections result in massive investment and scaling needs.[3] The levers that will impact this involve electrification, how much hydrogen is used for derivative applications such as sustainable aviation fuels (SAF) and maritime fuels, availability of sustainable biomass feedstocks, and how quickly price parity can be reached with conventional fuels, alongside demand-side, behavioral, and social aspects.

Figure 1.1: Green fuel production and end-use



Description	Name	End-Use
Direct use of hydrogen as a fuel on energy carrier H_2	Green Hydrogen	Industry + Heavy transport
Ammonia production via combining hydrogen and nitrogen NH_3	Green Ammonia	Maritime, Fertilizers, Storage
Efuel production using hydrogen combined with biogenic or captured carbon C_xH_y	E-methane	Natural gas replacement
	E-methanol	Heavy road + Shipping
	E-DME	Heavy road
	E-diesel	Heavy road
	E-kerosene	SAF

Name	End-Use
Bio-methane	Natural gas replacement
Bio-ethanol	Heavy road + Shipping
Bio-methanol	Heavy road + Shipping
Bio-diesel	Heavy road
FAME	Heavy road
Bio-jet (kerosene)	SAF
Bio-naphtha	Chemicals + Plastics

Note: This is a non-exhaustive list and a simplification of often complex multi-step production processes. There are other lower TRL technologies and pathways not shown in the above diagram.
Source: Adaption of Green Power Denmark's "Recommendations for a Danish Power-to-X Strategy"[4], Ramboll analysis

Intermediary fuels

In the original roadmap, the term intermediate or intermediary fuel was used to denote certain fuels that will serve a transitional or interim purpose. These are fuels that can be used in existing vehicle packages such as internal combustion cars or marine engines with minimal to no modification. The reason that they are intermediate is A) the transition to road transport electrification will not be quick enough based on current trajectories and existing asset lifetimes of for example lorries, vans, etc and an "intermediate" fossil fuel replacement is needed B) developing methanol, DME, or bio-oil production now for uses in existing engines allows the production and technology to scale to aviation fuels in the long term wherein carbon based fuels must be diverted to aviation purposes because of biomass/biogenic CO2 constraints. This is covered in greater detail in Chapter 7. The term intermediate fuel will also be adopted in this roadmap.

RFNBOs: Renewable Fuels of Non-Biological Origin

The EU refers to RFNBOs as liquid or gaseous fuels utilized in the transport and industrial sectors. These fuels differ from biofuels or biogas because their energy content is derived exclusively from renewable sources other than biomass.

Production pathways for green fuels

For both PtX based efuels and biofuels the feedstocks must be sustainable for these solutions to be truly green. For PtX, renewable energy is the input and for Denmark this is primarily onshore and offshore wind and solar. For biofuels, the feedstocks typically consist of organic fraction of municipal solid waste (OFMSW), manure, agricultural residues (straw, husks, etc),wood wastes, waste oils and fats. It is important to note that to be considered sustainable, the bio-feedstocks must align with the EU RED III rules for "advanced" feedstocks and must not include energy crops or crops grown for food.

The main technology for PtX is electrolysis used to produce green hydrogen. Further synthesis steps such as the Haber-Bosch Fischer-Tropsch process can combine hydrogen with various carbon and nitrogen steams to produce ammonia or other longer chained hydrocarbons. For biofuels, the main technologies are anaerobic digestion, fermentation, gasification, pyrolysis, and hydrothermal liquefaction (HTL). Each fuel production process can have either one of several synthesis steps, each adding complexity, cost, or inefficiencies (thermal losses) into the conversion process.. A simplified production and end-use diagram is shown in Figure 1.1 with the main green fuels shown with the production steps and potential end-uses.

The technology readiness levels (TRLs) of the key green fuels technologies and additional detail on the main challenges and opportunities are covered in Chapter 8 and Appendix 1.

The best use of green fuels

Electrification will play a major role in decarbonizing large portions of the transport and industrial sector. In the Danish government's PtX strategy[5], it is assessed that the majority of national transport can be directly electrified in the long run, particularly light road or heavy transport traveling shorter distances. Hydrogen, efuels, and biofuels, should be reserved for cases in which electrification is not viable due to technical or economic requirements. This means that hydrogen and its derivatives will be utilized mostly in heavy transport, shipping, and aviation.

Identifying the correct use cases for green fuels is crucial. It is known today that battery technologies are advancing at a rapid pace, have experienced fast cost reductions on the learning curve, and are seeing mass adoption as the consumer EV market becomes mature. Therefore, it would be incorrect to apply green hydrogen for light mobility and place it in the roadmap. Similarly, if we know that heat pumps for residential and commercial low-temperature heating are seeing successful adoption, it would be incorrect to label hydrogen as the heating fuel of the future. There are of course exceptions to each of these examples, but generally speaking, green fuels will see little practical use in light-mobility or low-temperature heating.

Scare renewable energy resources should be used wisely as the more green energy is needed for green fuels, the more land or ocean resources must be exploited. This results in more environmental impact, more raw material use in PV panels and wind turbines, and additional negative impacts on terrestrial and marine biodiversity. For more on sustainability aspects, see chapter 5.

Green fuels in the energy trilemma

Green fuels are central in addressing the energy trilemma by enhancing energy security and sustainability. They reduce dependency on imported fossil fuels by utilizing local renewable resources like biomass, wind, and solar power, thus bolstering energy security. Sustainability is a key advantage, as green fuels significantly reduce greenhouse gas emissions and can support the circular economy by utilizing waste streams. Technologies like PtX enable the production of hydrogen and synthetic fuels using renewable electricity, achieving zero or near-zero emissions.

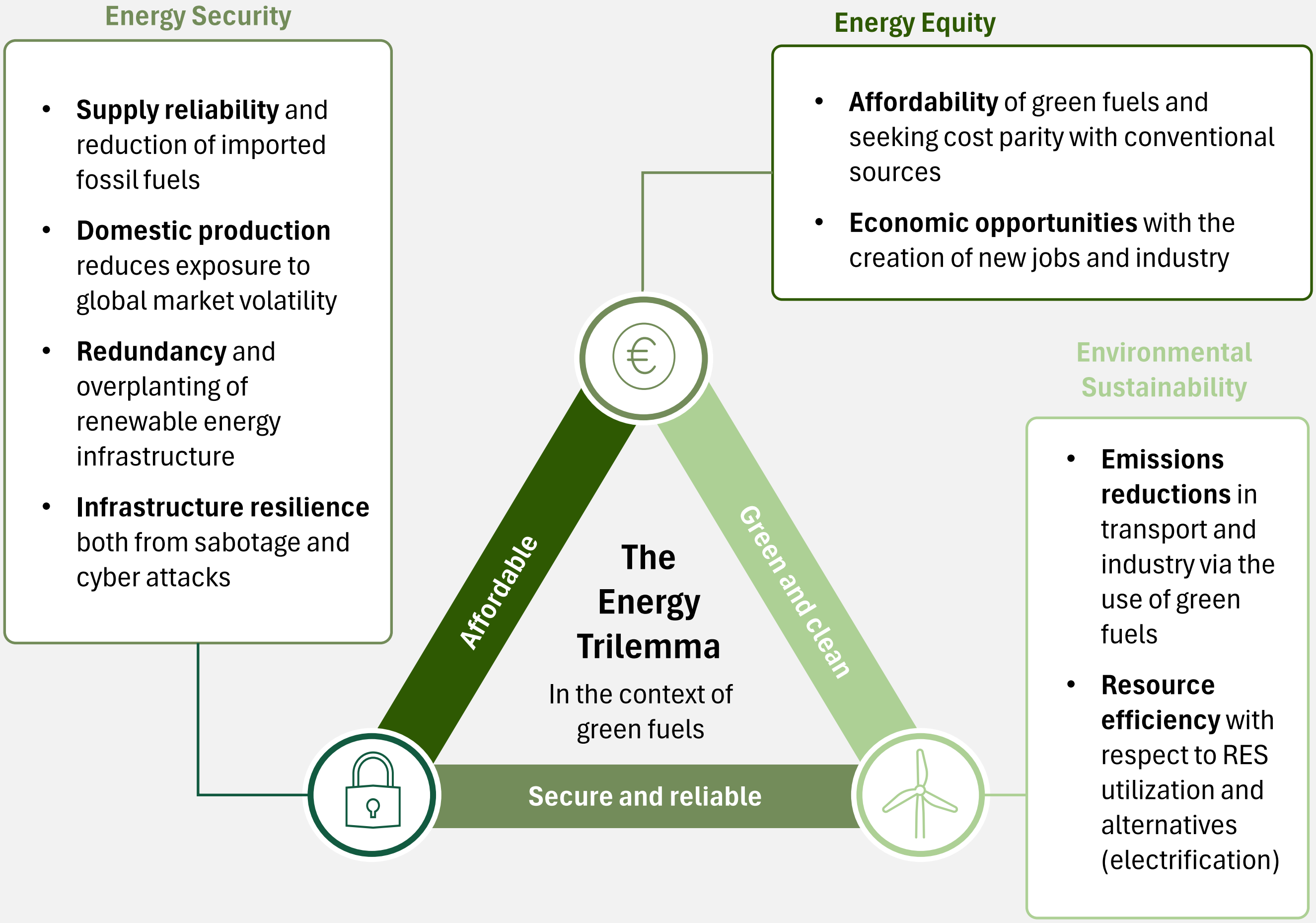
However, green fuels currently lack affordability. Initial production costs are higher compared to conventional fossil fuels, mainly due to feedstock costs, the nascent stage of technologies and infrastructure development, and relative cheapness of fossil fuels. Despite this, technological advancements and economies of scale are expected to reduce costs over time, making green fuels more economically competitive. If, or when, parity is met depends on various factors. Currently, green fuels are poised to meet two out of the three pillars of the energy trilemma—energy security and sustainability—but affordability remains a challenge that will likely be addressed with continued innovation and supportive policies. Achieving affordability will be imperative to accelerate market uptake of green fuels and will be a key focus in the coming chapters.

The security of supply angle

The adoption of green fuels enhances Denmark's energy security by providing an alternative to imported fossil fuels, thus reducing vulnerability to geopolitical risks. The Russian war against Ukraine has highlighted the importance of energy independence, as European countries seek to decrease their reliance on Russian natural gas. Denmark's strategy, in alignment with the EU's REPowerEU plan, focuses on increasing biomethane production and expanding renewable energy sources, aiming to replace imported energy supplies with domestically produced, sustainable alternatives.[6]

Additionally, by enabling the storage and conversion of renewable energy into storable and transportable fuels as gases and liquids, green hydrogen provides a flexible energy reserve that can be tapped into during periods of low renewable energy production.

Figure 1.2: The Energy Trilemma



Energy Security

- **Supply reliability** and reduction of imported fossil fuels
- **Domestic production** reduces exposure to global market volatility
- **Redundancy** and overplanting of renewable energy infrastructure
- **Infrastructure resilience** both from sabotage and cyber attacks

Energy Equity

- **Affordability** of green fuels and seeking cost parity with conventional sources
- **Economic opportunities** with the creation of new jobs and industry

Environmental Sustainability

- **Emissions reductions** in transport and industry via the use of green fuels
- **Resource efficiency** with respect to RES utilization and alternatives (electrification)

This flexibility helps to stabilize the grid and ensure a consistent energy supply, even when wind and solar outputs fluctuate. Curtailment and grid surplus (high generation but low consumption) issues can be addressed by allowing electrolyzers to provide flexible offtake solution for green power produced. The ramp rate and dynamics of the electrolyzer are important considerations here.

The integration of green hydrogen into the national grid also supports the continuous build-out of renewable energy infrastructure when the grid cannot handle the added generation capacities, one of the identified bottlenecks of mass build out of renewables, This is covered more in Chapter 4: Systems Integration.

Cost Elements

Green fuels are more expensive that conventional fuels and will be so until production costs come down or conventional fuels are penalized (e.g. pollution costs are internalized). Green fuel production can be considered a conversion process whereas fossil fuel production is an extraction process – wherein the conversion has already taken place geologically over millions of years of pressure and heat. These dynamics make it inherently more challenging for green fuels to compete on cost. The production of green fuels involves multiple energy-intensive steps. These include the generation of renewable energy (e.g., wind, solar), the conversion of that energy into a usable form (e.g., electrolysis for hydrogen), and further processing or refinement to produce efuels. Each of these steps introduces inefficiencies, cost, and complexity. Moreover, the infrastructure required for the production, distribution, and storage of green fuels is still underdeveloped and requires significant capital investment. In contrast, the existing infrastructure for fossil fuels is well-established, further compounding the cost and disadvantage for green fuels.

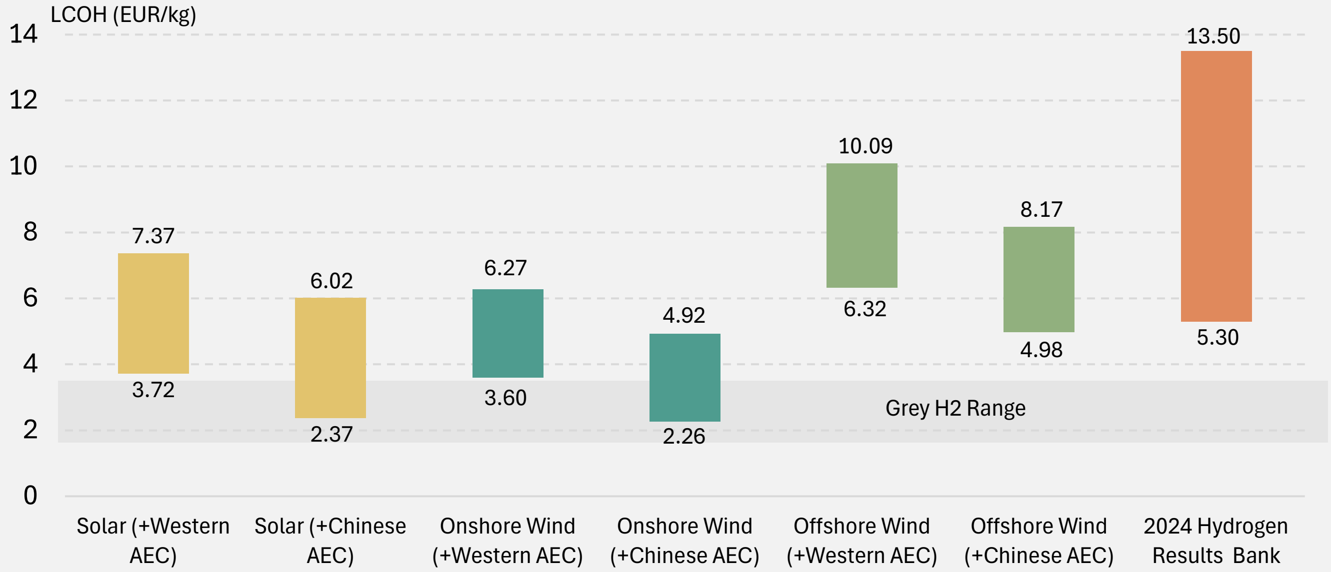
Hydrogen costs

The main price element for most hydrogen is electricity cost which can make up 50-80% of the levelized cost of hydrogen (LCOH). Therefore, the cost of energy (e.g. solar vs wind) is extremely important for cost competitive hydrogen (and derivatives) production. Cheaper electricity means cheaper hydrogen which means cheaper efuels. Cost reductions, particularly offshore wind, will be critical for Denmark to compete on hydrogen price. Electrolyzer plant capex is also important. Currently, alkaline electrolyzers plants (includes stack, EPC, BOP) range in the costs of ~800-1000EUR/kW in the west and about a third of that cost in China.[9] CAPEX costs for electrolyzer plant typically make up around 30% of the cost of hydrogen.

Many analyst predict that cheap electricity + cheaper electrolyzers can make hydrogen cost competitive with grey hydrogen in the near-future (e.g. 2-3EUR/kg hydrogen). China is already producing at 2.50/EUR.[11]

Figure 1.3: Levelized Cost of Hydrogen (LCOH) Estimates, 2023

Different renewable technologies shown with Western and Chinese Alkaline Electrolyzers (AEC)



Notes: Low end and high end LCOE estimates for solar (utility scale), onshore, and offshore wind from Lazard LCOE+
Western alkaline electrolyzers assumed capex of 850EUR/kW. Chinese Alkaline assumed capex of 270EUR/kW
Other assumptions: 7% discount rate, 30-year lifetime, 55kWh/ kg H2, 4000 FLH, LCOH does not include sale of heat or O2
Source: Lazard LCOE+ June 2024[7], Agora Energiewende LCOH Calculator[8], BloombergNEF[9], EC H2 Bank Results[10], Ramboll Analysis

Ongoing biogas/biofuels projects:

There are over 150 operational biogas upgrading facilities in DK of which livestock waste (slurry, manure) constitutes around 75 pct. of the biomass input.[12] Many of these sites are biomethane upgrading facilities that can inject methane into the national grid. Within Denmark, the company Emmelev A/S produces 1st generation biodiesel using rapeseed oil while the company Daka ecoMotion A/S FAME biodiesel using animal fat and other residual products. Overall, domestic production of liquid biofuels is limited.

Ongoing PtX projects in DK

Currently, there are over 40 active PtX projects in Denmark, the majority of them located in Western Jylland.[13] Most of the planned gigawatt scale sites are pure hydrogen production (feed-to-pipeline), but there are several examples of PtX plans to include production of derivatives including:

Ammonia:

- ● Skovgaard Energy REDDAP: "Renewable Dynamic Distributed Ammonia Plant, Lemvig (operational)
- Bornholm Bunker Hub, Rønne (concept)
- CIP Høst, Esbjerg (Hydrogen and Ammonia). (FEED)

Methanol:

- ● European Energy, Kassø facility (construction)
- Green2X , Vordingborg Biofuel (under approval)
- Greengo energy, Megaton Phase 1 (concept)

Sustainable Aviation Fuels:

- ● Arcadia efuels, Vordingborg (under approval)
- MeSAF, Aalborg to be integrated with existing Power2Met facility (feasibility study completed)
- CIP Fjord PtX, Aalborg (concept)

E-methane:

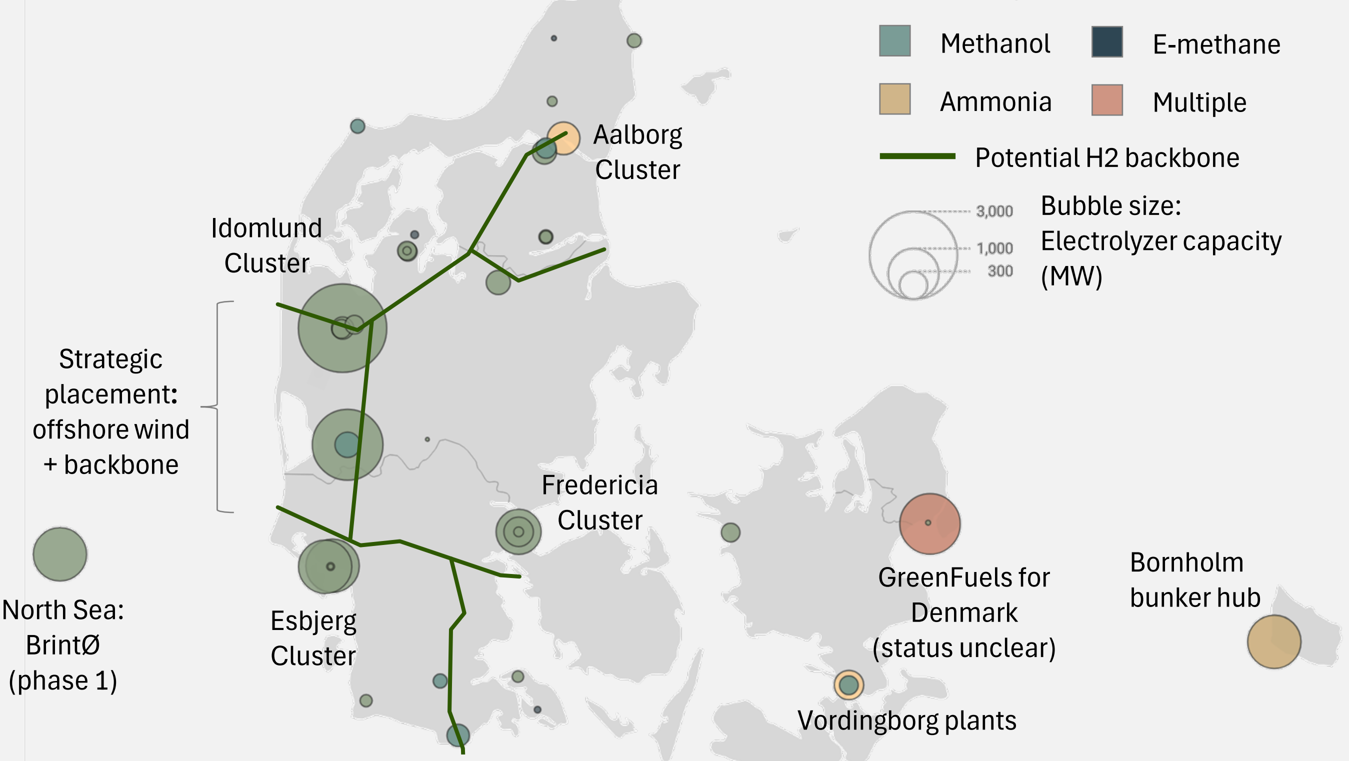
- ● Andel and Nature Energy (Shell) Biogas +PtX Glansager (operational)
- Electrochaea P2G-Biocat, Roslev (under approval)

● = First of a kind in DK (operational or soon-to-be)

Note: the above lists are not exhaustive

Figure 1.4 PtX projects in Denmark

All projects shown including concept and feasibility stages



Source: Brintbranchen "Brint i Tal"[13], Rystad Energy, Guidehouse European Hydrogen Backbone[14], Ramboll Analysis

Planned infrastructure: hydrogen backbone

Much of the ongoing discussion related to hydrogen in Denmark surrounds the development of the hydrogen backbone to Germany. The pipeline, likely to be built in phases, would stretch from the southern border, and up through Western Jylland, where it eventually would connect to a hydrogen storage facility in Lille Torup. The first section of the backbone would consist of a repurposed natural gas pipeline. The final routing and connections points are still being studied and will be influenced by current knowledge of hydrogen projects and expectations about the landing of offshore wind power connected to the ongoing North Sea offshore wind auctions.

Energinet has entered a cooperation agreement with German Gasunie, who is responsible for developing the German part of the backbone (“hyperlink 3”).[15] Such a pipeline would allow for hydrogen produced in Denmark, to be delivered to Germany, where it would be used in the German industrial and transport sector (substantially more existing demand than Denmark).

The pipeline is still undergoing user studies, route selection studies, FEED studies with additional clarity expected in end of 2024. Final investment decision (FID) is expected in Q1 2025 based on the latest information.[16] The concrete investment decision for establishing the hydrogen infrastructure is made by Energinet who requires approval from the Ministry of Climate, Energy, and Utilities, which depends on demonstrating sufficient demand and positive socio-economic benefit. If FID is made, tendering, environmental studies, and further engineering work would commence in 2025. Construction would take place in 2027-2028 with the first gas exports to Germany ready in 2028. Storage in the North to Lille Torup would be connected in 2030.

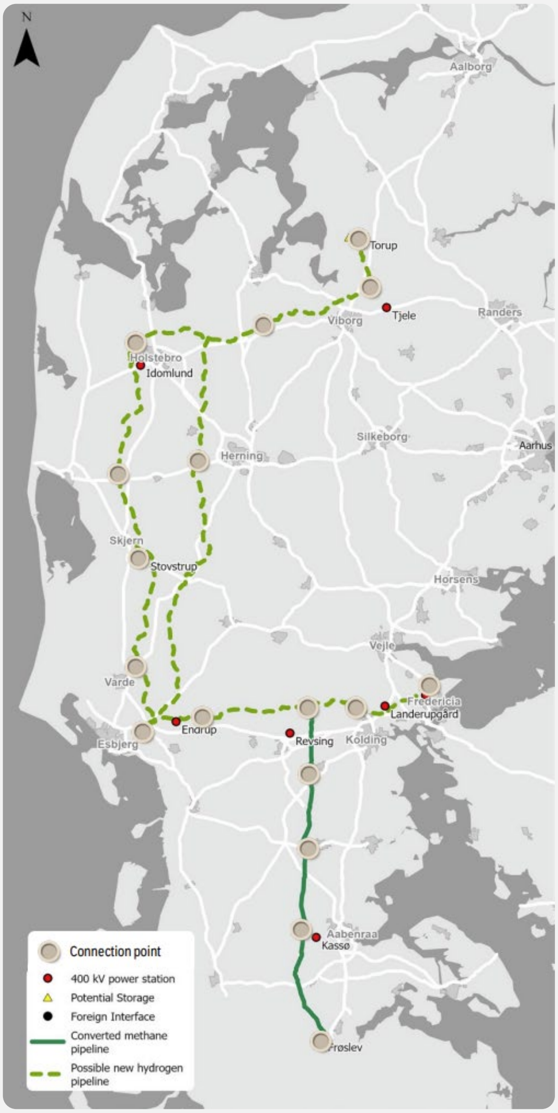
Outside of the main backbone, hydrogen pipeline branching infrastructure will also be needed. This includes connections between small scale producers and users of hydrogen, not directly connected to the main backbone. Evida is responsible for developing this part of the Danish hydrogen network.

Many proponents of the backbone point to the following benefits:

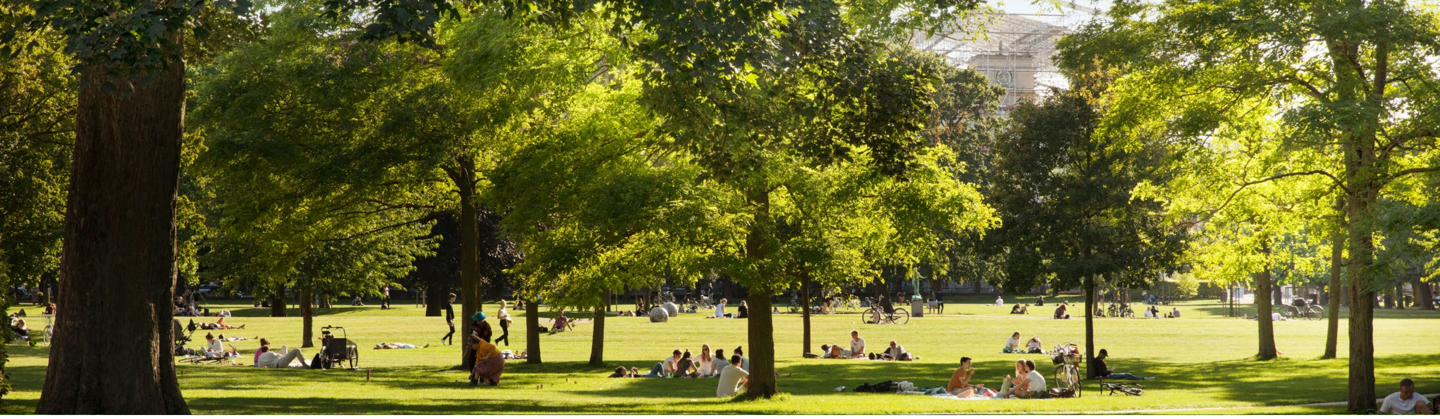
- Increased load factors for PtX plants significantly improving the business case for producers
- Socioeconomic benefits of 30-75 billion DKK by 2060 compared to a BAU scenario (highly dependent on assumed price levels of offtake)[17]
- Infrastructure provides incentives to invest in PtX capacity (and offshore wind overplanting capacity) and gives a route-to-market for producers
- Increases demand for Danish hydrogen and helps Denmark become a net exporter of green energy.

When commercial market participants were surveyed by Energinet, they found that 96% of respondents stated the need for hydrogen infrastructure and 97% of production from H2-only producers is expected to be destined partly or wholly for export.[17] This underscores the crucial need for hydrogen infrastructure to the overall PtX project landscape. Without it, most large-scale hydrogen plants will undoubtedly never move out of the concept and feasibility stages and reach FID. Transporting those volumes of hydrogen via truck would be impractical and uneconomical.

Figure 1.5: Proposed backbone routing



Source: Energinet, Information package June 2024[16]



2. Danish Potential

Danish climate goals

Denmark aims to reduce its carbon emissions by 70% by 2030 and achieve climate neutrality by 2050. The latest KF24 analysis places Denmark's current emissions at 41.4 MtCO2e.[18] The 2030 goal, over 1990 levels is 23.5 MtCO2e, meaning that around 18.2Mt will have to be reduced in the next six years. The main reductions are projected to come from electricity and heating, transport, CCS, and manufacturing, respectively. The expected reductions between now and 2030 are shown in Figure 2.1.

Danish Energy Agency assessment of PtX potential

In 2021, the DEA assessed the "robust potential" of PtX and efuels to contribute to climate reduction targets for 2030 and 2050.[19] Robust potentials is defined as areas of application where direct electrification is not possible or expected to be more expensive than adopting PtX fuels. For some applications, there is an "indeterminate extent" or "uncertain potential" for the effectiveness of PtX and efuels for sectors or applications which include significant adoption of electrification as being the most practical or cost-effective solution. Some transitional solutions, like blending methanol or efuels into gasoline and diesel are deemed possible in the short term but likely not long-term cost-effective solutions. The expectation is that they will not be competitive compared to 2nd or 3rd generation biofuels in the long run. Overall, the DEA estimates PtX can contribute 1.3 - 5.1 MtCO2e of which 0.5 - 1.9 MtCO2e would contribute to the domestic 70% target for 2030. For 2050, the estimate is a potential of 4.1 – 8.2 MtCO2e of which 1.1 – 3.5 MtCO2e would contribute to national targets. The majority of reductions would come from shipping and aviation or other "hard to abate" sectors. See Table 2.1 for a breakdown of PtX reduction estimates.

Figure 2.1: Danish GHG reduction measures 2022-2030, Mt CO2e

Source: Danish Energy Agency KF24[18]

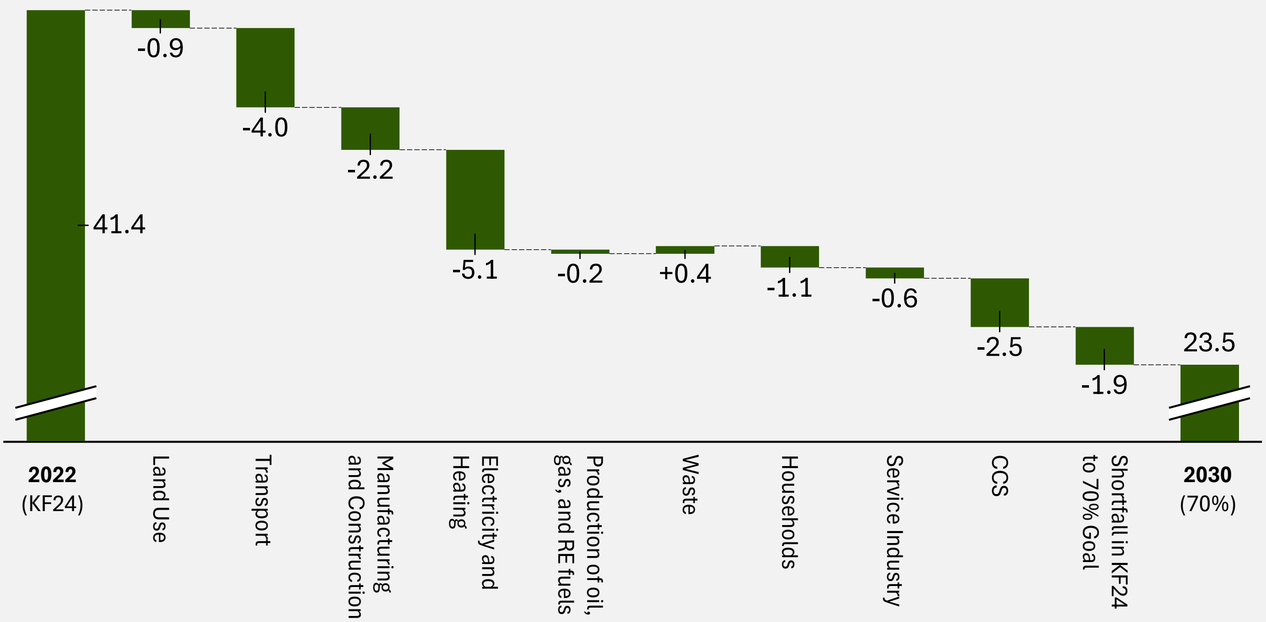


Table 2.1: DEA estimates for the use of PtX fuels in emissions reduction, Mt CO2e

Source: Danish Energy Agency "Demand for Power-to-X products", 2021[19]

	2030	2050
Robust potentials		
PtX to maritime	0.6 - 1.2	1.9 - 2.6
-of which domestic maritime	0.1 - 0.4	0.4 - 0.7
PtX for aviation	0.3 - 2.5	1.5 - 3.0
-of which domestic aviation	0.02 - 0.13	0.08 - 0.15
Robust potentials of indeterminate extent		
H2 to road transport (vans, trucks, and buses)	0.02 - 0.5	0.4 - 1.6
H2 to industry, direct use	0.0 - 0.1	0.0 - 0.5
H2 or e-diesel to industry, internal transport	0.0 - 0.2	0.2 - 0.5
Efuels for defence/military (aircraft, ships, vehicles)	unknown	unknown
H2 to biogas production (refineries)	unknown	unknown
Production of chemicals (fertilizers, plastics)	unknown	unknown
Uncertain potential for transitional solutions that are not deemed cost-effective		
Methanol blended into gasoline	0.03 - 0.05	0.00 - 0.01
Efuels blended into diesel/gasoline	0.3 - 0.5	0.0 - 0.1
Total estimated potential	**1.3 - 5.1**	**4.1 - 8.2**
Of which contributes to the 70 percent target	**0.5 - 1.9**	**1.1 - 3.5**

Danish PtX Strategy

On March 15th, 2022, the Danish government entered into a political agreement ("The PtX Agreement")[20] on the development and promotion of hydrogen and other green fuels. Building on the earlier 2021 PtX strategy which envisioned 4-6GW of electrolyzer capacity, the new PtX Agreement also dedicated funding to support production of PtX in Denmark and dedicated PtX taskforce, among other overarching measures shown in Table 2.2. The agreement aims to position Denmark as a leading force in Northern Europe for the production and export of green energy and fuels, while also establishing the country as a frontrunner in the development of PtX technology.

The agreement outlines several key initiatives, including the establishment of national hydrogen infrastructure, which will enable the production, storage, and distribution of green hydrogen across the country. Furthermore, the agreement emphasizes the importance of international collaboration, particularly with neighbouring countries like Germany, to create a robust market for green hydrogen. This collaboration is seen as vital for securing long-term offtake agreements and ensuring that Denmark can maintain its competitive edge

A PtX taskforce[21] was appointed that will run through 2026. The main goals are coordination between state and municipal authorities focusing on approval and permitting processes for PtX projects as well as identifying barriers to sector development. Additional focus themes for the committee include infrastructure, permitting, water supply, grid flexibility, use of excess heat, and location siting for PtX projects.

Table 2.2: Danish PtX strategy measures

Source: KEFM, 2022

Measure	Status
Denmark to target 4-6 GW of electrolysis capacity in 2030	○
Dedicate 1.25 billion DKK to support production of PtX in Denmark	●
Enable direct lines, geographically differentiated tariffs, and local collective tariff structures	○
Enable the build-out of infrastructure for hydrogen in Denmark	○
Appoint of PtX task force to support developing a market for hydrogen and infrastructure for hydrogen in Denmark	●

● Complete ○ In progress

Danish Green Gas Strategy

The Danish Green Gas Strategy[22], published in 2021, aims to transition Denmark's gas system to fully green by 2035, aligning with the broader goal of reducing greenhouse gas emissions by 70% by 2030. The strategy envisions a complete phase-out of natural gas, replacing it with biogas and other green gases like hydrogen and e-methane, with biogas expected to make up 70% of gas consumption by 2030. By 2035, the goal is to achieve 100% green gas consumption. The Green Gas Strategy presents nine interlinked objectives that represent the green gas while remaining competitive. The main strategic objectives for the strategy are listed below in Table 2.3.

The gas strategy outlines several hurdles to overcome. A significant challenge is modifying the existing gas infrastructure to handle an increasing share of biogas and new green gases like hydrogen, which requires substantial upgrades and potential repurposing of pipelines. Integrating PtX technologies into the gas system (hydrogen, e-methane, etc) also demands careful planning as ensuring the compatibility of various green gases within the current system, including managing different gas qualities and compositions. Developing reliable and scalable storage solutions for green gases to manage supply and demand fluctuations is additionally key for the strategy's success.

Success of biogas

The Danish gas strategy seems to be well on track. In 2023, biogas in the form of upgraded biomethane already made up nearly 40% of the domestic supply.[23] The latest AF23 projections[24] expect biogas to supply 100% of domestic demand by as early as 2030. This is driven partly by lowered gas usage, specifically for households, and the further integration of biogas upgrading plants connected to the gas grid. Domestic supply may even outpace demand, meaning there could be a potential export market for biomethane (depending on the gas quality requirements for neighbouring countries).

Figure 2.2: Danish Biogas (GJ) 1990-2030

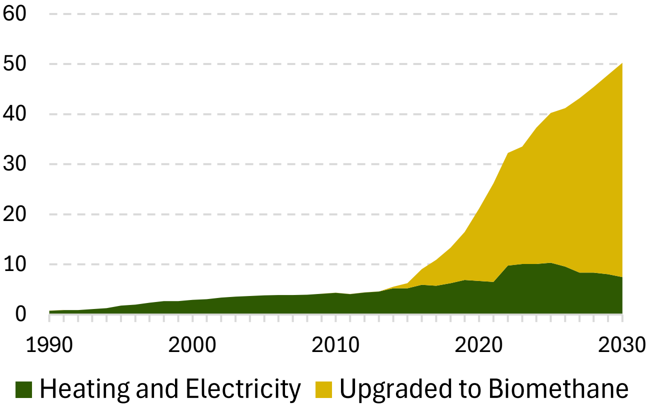


Table 2.3: Danish Green Gas Strategy objectives

1	Green gases must supplement electrification and be used where it has the greatest value
2	Green gas in industry must support jobs in Denmark and provide economic growth and employment opportunities
3	The transition to green gas must occur with consideration for competitive tariffs and on commercial terms
4	Green gas must eventually be able to compete on market terms
5	Green gases must be produced sustainably
6	The development of green gas production and gas infrastructure must include a high level of public involvement and take into account biodiversity and the environment
7	The gas system must support and be used for the green gases of the future
8	The gas system needs to be adapted to efficiently support Denmark's future energy system, contributing flexibility and security of supply
9	Denmark must help further the development of a well-functioning European market for green gases

● Consumption ● Production ● Future System

Figure 2.3: EU-level hydrogen strategies

Plan	By 2024		By 2030		
EU Hydrogen Strategy	Install 6GW of H2 electrolyzers	Produce up to 1 million tonnes of renewable H2	Install 40GW of H2 electrolyzers	Produce up to 10 million tonnes of renewable H2	
REPowerEU plan			Produce 10 million tonnes renewable H2	Import 10 million tonnes renewable H2	Biomethane production to 35 bcm[i] by 2030

i. bcm = billion cubic meters. 2022 EU production was 4.2 bcm of biomethane

Denmark within a European context

Denmark's green fuels goals sit within a greater overarching EU strategy regarding hydrogen and renewable fuels. In July 2020, the European Commission (EC) published a communication outlining the EU Hydrogen Strategy, setting the course for renewable hydrogen in the EU.[25] The strategy focuses on obtaining, distributing, and scaling up the use of renewable hydrogen, with non-binding quantifiable targets for the EU's production. It also acknowledges the need for support for low-carbon hydrogen during a transitional phase. In 2022, following Russia's war against Ukraine, the EC issued its REPowerEU communication, which included more ambitious production targets than those in the Hydrogen Strategy and set import targets for the first time.[6] The two main strategies are shown in Figure 2.3.

On a per capita basis, Denmark's PtX plans are by far the most ambitious. The goal of 4-6GW of electrolyzer capacity amounts to 0.68 to 1.02 GW of electrolyzer capacity per million inhabitants, which is over three times the Dutch amount and over five times the amount Germany targets per person.

An export driven strategy

Estimates place the electrolyzer capacity required to serve domestic needs (for 2030 measures) at around 1.8 to 2.7 GW.[26] Achieving the 4-6 GW target means that the residual capacity will go to exports in neighbouring markets. This approach is core to the Danish PtX strategy wherein Danish production would meet potential supply gaps in export markets and gain revenues from the sale of hydrogen, or other hydrogen based efuels.

Table 2.4: Country level hydrogen strategy comparison

Country	2030 goal for electrolysis (GW)	Govt. allocated funds (mio. EUR)	Electrolysis goal (GW/mio. People)
Denmark	4 – 6	167	0.68 - 1.02
France	6.5	4,000	0.10
Germany	10	4,600	0.12
Spain	4	900	0.09
Netherlands	3 – 4	7,500	0.17 – 0.23
Portugal	2 – 2.5	140	0.20 – 0.25
UK	5	480	0.08

Figure 2.4: Denmark's strengths in green fuels

Access to green energy

- High penetration of RES. Planned build out of 6+ GW offshore wind by 2030
- Grid projected to hit >90% renewable by 2027

First movers (end-use)

- Global companies willing to take risks and innovate on new technologies (e.g. Maersk, MAN, etc)

Supply of biogenic CO2

- High amount of biomass CHP and biomethane upgrading with potential capture points
- Import strategy and creating CO2 infrastructure

Equipment manufacturing

- Home base to world-class electrolyzer OEMs and auxiliary equipment manufacturers
- Innovators in 2nd gen electrolyzers (SOEC)

Advanced infrastructure integration

- Resilient electricity grid with EU leading TSO
- District heating network offers integration with PtX and possible revenue streams
- Testbed for sector-coupling / integration tech.

Geographic placement

- German market access with future connection to backbone for cross-border H2 exports
- Closer to German offtake compared to Scandinavian neighbors

Strong innovation ecosystem

- World leading technology and engineering companies, industry organizations, and universities
- Strong history of industry partnerships

Government support

- Strong government commitment to the green transition with proactive policy measures
- Financial funding (PtX tender) and innovation fund targeting new clean technologies

Danish strengths

Denmark is a leader in energy technologies and benefits from strong government support and world-class technology companies. The country's established reputation in renewable energy, particularly wind power, provides a solid foundation for expanding into hydrogen and PtX technologies. Denmark's innovation ecosystem, with leading universities and research institutions, drives cutting-edge research and benefits from collaboration between academia, industry, and government. Collaborative projects between research institutions and industry players are accelerating the commercialization of PtX technologies, positioning Denmark as a global innovation hub within green fuels. The key strengths are shown above in Figure 2.4.

Key limitations and hurdles

Denmark's strategy heavily relies on access to large amounts of renewable electricity, particularly from offshore wind. Any delays or shortfalls in renewable energy expansion could constrain hydrogen production capacity and hamstring ongoing PtX projects in the concept and feasibility stage. Limited renewable feedstock in the near-term will make green hydrogen less competitive (both relative to conventional fuels, and other producer nations), potentially causing investments to move to countries with cheaper input costs (e.g. Southern Europe, or hydropower countries).

Lack of domestic demand is another near-term hurdle. Unlike Germany, Denmark does not currently have many industrial processes that could offtake hydrogen and use it to decarbonize. There are no steel plants, no existing grey ammonia fertilizer plants, no large-scale chemical plants where an easy switch can be made. Existing Danish demand is 96% concentrated in refining use.[27] Germany has over 68x the existing hydrogen demand of Denmark (0.025Mt versus 1.74 Mt) with ongoing plans to stimulate demand in its Kraftwerksstrategie[28] via subsidization of the roll-out of a wave of hydrogen-fired power plants.

The assumption that there will be future demand for hydrogen, particularly in transport sectors such as long-haul aviation and shipping, but the timeline and scale of this transition are uncertain. Additionally, the market for green fuels, especially in new applications like transport, is still nascent, creating uncertainty about future demand and fuel cost.

There are limited immediate use cases and the impact for PtX on the 2030 targets is relatively limited compared to other government priorities in electrification, energy efficiency, and carbon capture and storage, which could be seen as more impactful (with regards to national emissions accounting) in the near-term with a business case featuring less risk.

A further challenge is the extensive infrastructure development required to support large-scale hydrogen production, storage, and distribution. Denmark's existing infrastructure is not fully equipped for the widespread use of hydrogen, necessitating significant investments in pipelines, storage facilities, and end-use infrastructure such as fuelling stations. Convincing policymakers and the public of the socioeconomic benefits of this investment may be difficult, particularly when considering the "bang-for-buck" in terms of near-term decarbonization impact. Prioritizing which projects to fund—whether immediate, high-impact decarbonization initiatives (e.g. 2030 goals) or long-term strategic PtX infrastructure—will be a complex decision-making process for Danish policymakers and investors.

International developments:

Since the last roadmap was developed in 2021, there have been significant global developments in the green fuels space. This is largely driven by government climate legislation, supply aspects related to energy security and geopolitical leverage, and strategies that emphasize the importance of securing a leading position in energy technology manufacturing (jobs, exports, etc).

In the US, the Inflation Reduction Act (IRA) and the CHIPS and Science Act were passed in 2022 and are the two cornerstone pieces of legislation of the Biden administration's climate and economic plan. The IRA includes provisions for tax credits, grants, and other financial incentives aimed at accelerating the development of hydrogen production, infrastructure, and associated technologies.[29] The Chips Act will invest billions into accelerating zero-emissions technologies such as energy storage, hydrogen, and CCUS technologies. It also includes funding for bolstering STEM education and workforce development within high-tech and green jobs.[30]

China has also made strides in the green fuel sector, focusing heavily on scaling up its hydrogen production capabilities. The Chinese government has outlined ambitious targets for hydrogen development in its latest Five-Year Plan, emphasizing the role of hydrogen in decarbonizing its vast industrial sector and reducing reliance on imported fossil fuels. Additionally, China is subsidizing and investing heavily in electrolyzer manufacturing, positioning itself as a key supplier in the global hydrogen supply chain. A similar strategy that has been utilized in PV solar manufacturing.

Outside of the U.S. and China, other countries are also making significant moves in the green hydrogen space. For example, Saudi Arabia is developing one of the world's largest green hydrogen projects as part of its NEOM megacity, aiming to become a global hub for hydrogen production and export. Additionally, Australia is rapidly advancing its hydrogen industry, with a focus on exporting green hydrogen to energy-hungry regions such as Japan and South Korea.

These developments indicate a rapidly evolving global landscape where nations are competing to secure leadership positions in hydrogen and other renewable energy technologies.

Tariffs and potential implications

The EU followed the US's lead and recently introduced 17 to 38 % import duties[31] on Chinese manufactured EV's in response to concerns over unfair competition.

These tariffs, designed to protect the European automotive industry from what is perceived as subsidized, below-cost competition from Chinese manufacturers, underscore the growing tensions between major economic blocs over control of the emerging green economy. As EVs are a critical component of the transition to decarbonized transport, the imposition of tariffs may have cascading effects on related technologies and industries (e.g. electrolyzers, fuel cells, critical materials).

Denmark, as part of the EU, will need to navigate these challenges carefully. The country's leadership in green hydrogen and renewable energy could be bolstered by the EU's protectionist measures, provided they are coupled with strong domestic policies that encourage innovation and investment. However, Denmark must also be wary of the potential for increased costs and reduced access to critical technologies if global trade tensions continue to rise.

Competition for funding

Competing with other nations that are also investing heavily in green fuels technologies could impact Denmark's ability to secure necessary resources, such as EU-level financing and private investments, and maintain its position in the global market.

Denmark's ambition to be a leader is challenged by the sheer scale of investments and subsidies being rolled out by other countries, particularly China and the United States. The aggressive expansion of electrolyzer manufacturing in China, backed by substantial investments, puts pressure on Danish manufacturers to remain competitive. Moreover, the U.S. has implemented the Inflation Reduction Act and other policies that provide substantial financial incentives to local industries, potentially attracting investments that might otherwise have flowed to Europe, including Denmark. Denmark's ability to attract private investments will be crucial, requiring a clear strategy that highlights the country's strengths in renewable energy and leadership in clean energy technologies

Danish trajectory – where should the ambition lie?

Denmark's trajectory in green fuels is at a critical juncture. Given the nation's established strengths in renewable energy, particularly wind power, and the increasing global competition in green hydrogen and PtX technologies, Denmark must carefully consider its next steps. The key question is: where should Denmark's ambition lie?

On one hand, Denmark could choose to maintain its current level of ambition, leveraging its existing expertise in renewable energy to solidify its position in the emerging green hydrogen market. However, simply maintaining the status quo might not be enough in an increasingly competitive global landscape where other nations are scaling up and investing more heavily in their efforts.

Alternatively, Denmark could scale down its ambitions, focusing on niche areas within the green fuels sector where it has the strongest competitive advantage. This approach might reduce risk but could also limit Denmark's potential to lead in a rapidly growing global market.

The most ambitious path would be to double-down on the focus on green fuels and PtX technologies, aiming to make PtX the next "wind adventure". This would involve significant investment in innovation, infrastructure, and partnerships, both within the EU and globally. By doing so, Denmark could not only sustain its leadership in renewable energy but also become a pioneer in the next generation of green technologies, securing long-term economic and environmental benefits.

One critical question is whether Denmark can produce offshore wind energy at a cost low enough to make its hydrogen production globally competitive. The ability to generate hydrogen economically will be crucial in establishing Denmark as producer and exporter of hydrogen and other efuels. Continued advancements and cost reductions in offshore wind are crucial, especially in the face of rising inflation and material costs.

Another concern is whether delays in renewable capacity additions (potentially unbankable wind projects at current support levels[32], prolonged permitting and approval processes, etc) could hinder the near-term scalability of PtX projects. The scalability of PtX technologies is directly linked to the availability of abundant, cheap renewable energy. If the expansion of offshore wind or other renewable resources lags, it could significantly impact the viability and timing of PtX projects, potentially causing Denmark to miss critical market opportunities. Projects could sit for years in the concept phase before decisions are made whether to proceed.

Furthermore, A key consideration is whether there will be a sufficiently robust offtake market in neighbouring countries, particularly Germany, that is willing to pay a premium for imported green hydrogen. Germany's energy transition strategy places a significant emphasis on hydrogen, but the extent to which it will rely on domestic production versus potentially more cost-effective imports versus Danish imports will directly influence Denmark's export prospects. Securing and understanding this offtake market is essential for the long-term viability of Denmark's green hydrogen strategy, as the success of both countries in meeting their climate targets is closely intertwined. Germany's demand could serve as a critical driver for Denmark's hydrogen economy, but only if pricing, supply stability, and strategic alignment are effectively managed.

What the market thinks

Ramboll conducted surveys in 2022 and 2023 with over 100 key developers and investors in PtX and green fuels to assess Denmark's role in producing and exporting green fuels.[33,34] The key conclusions from these surveys are summarized below:

- The majority (62%) believe Denmark should both produce and export green hydrogen and green fuels. Meanwhile, 18% prefer a focus solely on hydrogen, 11% on green fuels alone, and 9% suggested other priorities.
- The two biggest barriers identified were the availability of sufficient competitively priced green electricity and the development of necessary infrastructure for export and transport. These are seen as both the greatest challenges and the most crucial prerequisites for establishing a robust market for green fuels.
- The industry sees Denmark's trajectory as that of a green fuel producer and exporter but stresses the need for improved regulatory conditions. Ensuring this is primarily the responsibility of Danish and EU policymakers.
- Politicians can support companies by simplifying and accelerating regulatory approvals, setting CO2 reduction requirements in the transport sector (such as green fuel blending mandates), and providing funding for essential infrastructure like port facilities and hydrogen refuelling stations.

3. Innovation Ecosystem

Research and development underpin all aspects of green fuels development, and the ecosystem that allow ideas to evolve into demonstrations projects and eventually to large-scale commercialization is crucial to highlight. One of Denmark's main strengths, relative to its small size, is its high innovation output. Denmark consistently ranks among the top countries in global innovation rankings[35], demonstrating its leadership in clean energy technology. The government understands the importance of funding innovation in energy technologies, not only from a climate perspective, but from a national welfare and jobs perspective. This leadership is often said to have formed Denmark's success in wind and other energy technologies, that are now exported globally.

However, it is essential to recreate and sustain this innovative environment for green fuels to ensure Denmark remains competitive. By building an ecosystem that includes government support, funding entities, universities, small firms, start-ups, large firms, and industry associations, Denmark can and will continue to lead in the energy transition. Ensuring continued collaboration and investment in research and development will be key to maintaining Denmark's position at the forefront of green fuel technologies and the broader clean energy sector.

The ecosystem for green fuel development is a dynamic network of stakeholders including research institutions, private companies, industry associations, and policymakers. Together, these entities drive technological advancements, policy frameworks, and market mechanisms to accelerate the development of green fuels. Linking these entities are uni or bi-directional flows of funding, knowledge sharing, intellectual property, and trained people that culminate in new innovations that can reach commercialization and contribute to the development of a green fuels industry domestically, and exports of Danish technology abroad. This ultimately results in national socioeconomic benefit and welfare. The figure below shows a simplified way of how various stakeholders interface with each other.

Figure 3.1: Innovation ecosystem

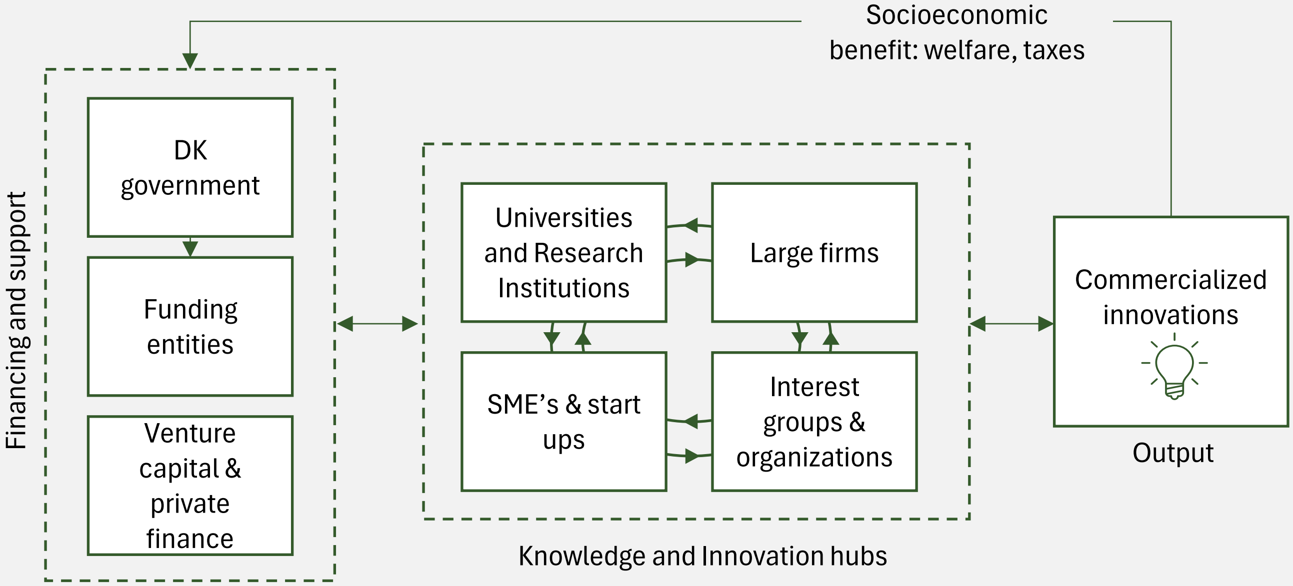


Table 3.1: Innovation ecosystem for green fuels development

Entity	Role in innovation ecosystem	Examples of pro-innovation measures for green fuels	Main levers
Government	Designs regulatory frameworks, sets policies, and funding support levels. Creates incentives and sets long-term goals for green transition and climate targets.	• Creation of energy parks (zones) for fast-track permitting • World's first Power-to-X tender awarding 1.25 billion DKK • Danish-German joint declaration on H2 infrastructure	• Legislation and mandates • Funding and support • International agreements
Public funding entities	Entities such as the Innovation Fund, EIFO, etc. distribute funds to research projects, missions, and startups. Supports early-stage development of green fuel technologies.	• Funding of Innomissions such as MissionGreenFuels • Green accelerator programmes for innovative ideas • Funding of "lighthouses" for Danish municipalities[37]	• Grants • Strategic funding • Knowledge hubs
Universities & research institutions	Conducts fundamental and applied research. Bridges gap between theoretical and practical applications of green fuels. Facilitates knowledge transfer to industry and a trained workforce.	• DTU "Risø Gateway" project to create test facilities for PtX and green fuels • DTU/AAU CAPeX – PtX laboratory for advanced materials research • AAU's collaboration project with Port of Aalborg	• Education and knowledge transfer • Strategic research areas
Private capital	Provides investment needed for scaling up technologies. Engages in venture capital and private equity funding for innovative projects.	• CIP's Energy Transition Fund and Advanced Bioenergy fund allocating over 3 billion EUR • ESG aligned investment funds by banks, pension funds	• Investment funds • Venture capital • Private equity
Large companies	Implements and scales up innovative technologies. Invests in R&D and collaborates with research institutions.	• Company backing of pilot projects such as Green Fuels for Denmark, Green Hydrogen Hub • Innovation and industrialization of new electrolyzer technology	• R&D funding • Partnerships • Corporate investment
Small and medium enterprises	Innovate rapidly and adapt new technologies. Acts as a key player in early-stage development and niche markets.	• Arcadia efuels SAF facility in Vordingborg (first in DK) • Electrochaea's biocatalyst technology for synthetic methane production	• Collab. with universities • Niche focus and risk-taking ability
Industry groups	Advocates for policy direction and industry standards. Facilitates collaboration among companies and with government agencies.	• Green Power Denmark publications for policymakers regarding H2 infrastructure • Brintbranchen's "hydrogen Academy" to disseminate industry knowledge	• Advocacy • Standards • networking events • lobbying
MISSION GREEN FUELS	Supports the development and market introduction of green fuels technologies via the funding of research and innovation projects	• Support for more than 20 projects (~280 million DKK) for green fuels research and technology development	• Strategic funding • Stakeholder coordination • Roadmaps

4. Systems Integration

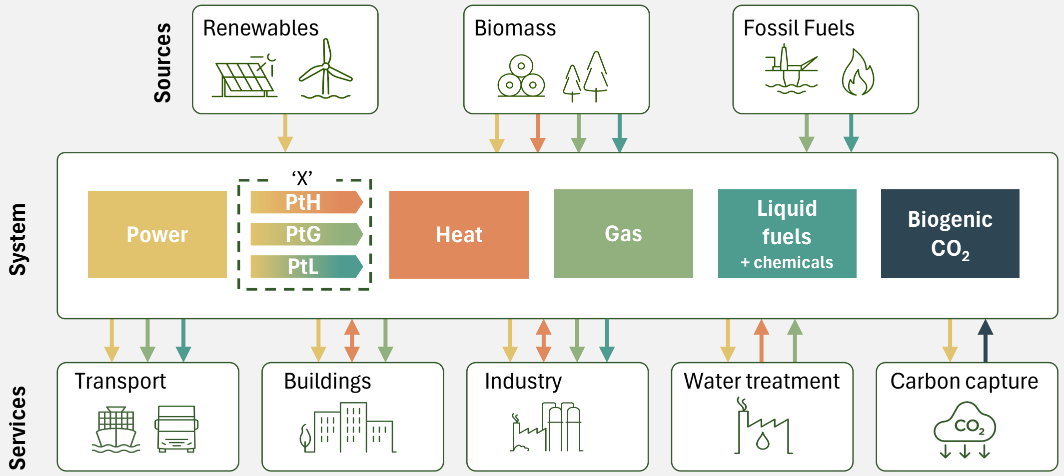
At its core, PtX is a sector coupling technology that builds bridges between different energy systems; converting green electrons into various sustainable gases and fuels. Large scale electrolyser plants will need considerable integration with new or existing infrastructure. This includes electricity generation infrastructure, district heating networks, water and wastewater infrastructure, as well as future CO2 infrastructure. PtX plants consume substantial power to produce hydrogen, generating significant surplus heat and oxygen in the process. Additionally, the electrical interfaces of gigawatt scale PtX have considerable impacts on grid capacity, flexibility, and planned build out. This chapter explores how the production of green fuels will integrate with current and future energy systems.

Integration with electricity net

Gigawatt scale PtX plants and the associated wind and solar build-out have significant implications on the energy system. As such, their integration with the collective grid must be considered carefully. Various connection models for large scale PtX can be considered depending on the scale of the electrolyzer plant, geography, local grid capacity, tariff design, and profit model. Green electrons can flow from RES either through the grid to the PtX facility, or directly to the electrolyzer plant, or a combination of both, where optimization and price hedging can occur.

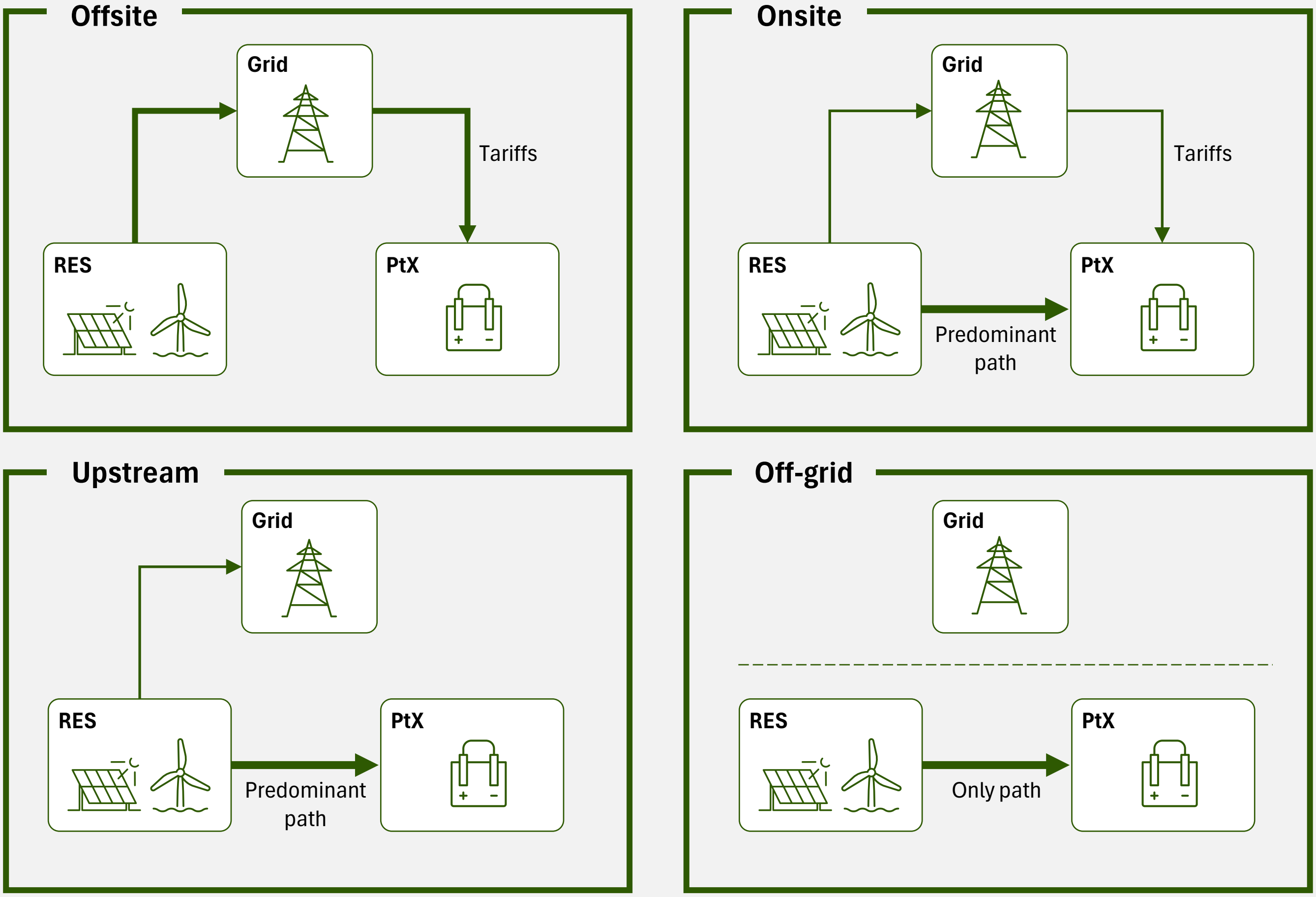
In 2023 a draft bill allowing “direct lines” where a high voltage lines directly connect production and consumptions points is to be implemented in the Danish Electricity Supply Act.[36] Direct lines allow for the coupling of large-scale offshore wind projects in the gigawatt+ scale allowing for offtake of green electrons without overloading the grid with excessive power influx. This could potentially mean less upgrades are needed to the existing electricity grid and less curtailment of offshore wind power, when supply exceeds demand. The changes allow for A) establishment of a direct line with approval from the Danish Energy Agency B) direct lines both onshore and offshore C) up to four different consumptions plants (PtX sites) D) electricity supplied to be subjected to taxes and duties. This is an important development for the viability of large scale PtX due to reduced transmission bottlenecks and grid stability. It may also improve the economic viability of projects, depending on the tariff model and grid connection fees.

Figure 4.1: Sector coupling



Source: Adaption from DTU’s Sector Development Report,[37] 2020

Figure 4.2: PtX connection models



Source: Adaption from Energinet's "Potential for PtX in Denmark in the near term from a systems perspective" 2019.[38]

Connection Models

The four main connection models for PtX are shown in Figure 4.2 above. Each model comes with its own set of advantages and disadvantages.

The offsite connection model has no direct connection to the electrolyzer plant and all power generator from renewables passes through the collective grid. This is an option if the renewable sources and PtX plant are located geographically distant. In theory, this is the most macroeconomic efficient connection model and may be the desired long-term end state once the grid is sufficiently renewable.

The onsite and upstream models are systems that are in connected to the grid and to the PtX facility and offer greater flexibility and potentially higher revenue streams, in the case of high electricity prices where sell-to-grid would offer the highest price. In addition, having the electrolyzer connected to the grid allows for potential supplementation of grid-sourced electricity during periods of lower renewables production, making it easier to produce hydrogen at a steady rate and avoiding major system ramping. However, this may introduce complication in green certification if the grid mix is not 90% or greater renewable.

Off-grid production is relevant for a decentralized of remote models such as energy islands where connection to a grid is not technically or economically feasible or where hydrogen itself will be the energy carrier onshore. For such models, the owner may experience additional costs from overplanting of RES or needing to supplement the system with energy storage during periods of low power output.

Ancillary Services

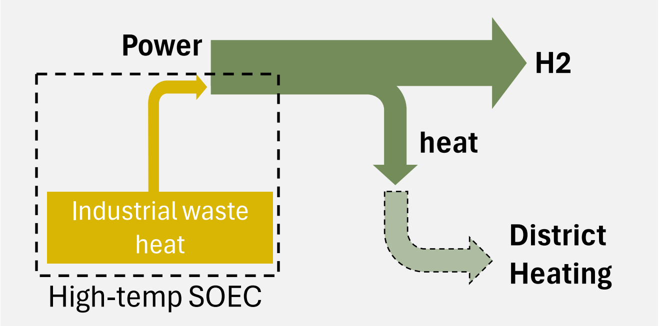
Power-to-X can also offer ancillary services to the grid in the form of frequency response (FCR). During periods of excess electricity supply, electrolyzers can increase their power consumption to absorb surplus energy, thus helping to balance the grid frequency. The speed of this ramping depends on the type of electrolyzer and plant design. Conversely, they can reduce their consumption or temporarily shut down during power shortages, aiding in demand response effort. This flexibility in operation allows electrolyzers to offer valuable balancing services.

In theory, hydrogen can provide a form of grid services via combustion in a hydrogen peaker plant or used in a hydrogen fuel cell power plant to provide for peak load periods. This would allow hydrogen to be used as a grid stabilizing energy source during periods of low intermittent power if the hydrogen is taken from a storage facility or via line packing (storing compressed H2 in a pipeline network) to be later used for power applications. However, this suffers from low round trip efficiency and would likely be better suited for large scale battery energy storage or another form of storage.

Integration with heating systems

A by-product of low-temperature electrolysis is heat, typically ranging between 50 and 80 °C, which can be recovered and utilized in district heating networks. For Alkaline Electrolysis Cells (AEC), approximately 27% of the energy input can be recovered as heat, while Proton Exchange Membrane (PEM) electrolysis has an estimated heat recovery potential of 33%.[40] The amount of recoverable heat depends on several factors, including the efficiency of the electrolysis process, operating parameters, current density, and stack design.

In contrast, high-temperature Solid Oxide Electrolysis Cells (SOEC) use heat as an input, with around 20% of the energy required for electrolysis supplied by high-temperature steam, reaching up to 600 °C. This characteristic makes SOECs particularly suitable for integration with industrial waste heat sources, maximizing cost efficiency. Sector coupling in this scenario occurs at the front-end of the system, where the placement of SOEC plants adjacent to high-temperature heat sources, such as those found in industrial processes, facilitates industrial symbiosis and enhances overall system efficiency.



According to COWI and Dansk Fjernvarme analysis[42], selling heat for district heating uses can improve revenues by 5 to 15%, based on the operating hours of the PtX plant. This could provide a competitive advantage to hydrogen produced in Denmark, making the LCOH more competitive compared to PtX not integrated with district heating systems. However, If PtX plants were to be placed offshore or geographically remote, the benefits of system coupling with heat would be lost. However, there could be potential uses for some of the heat in optimizing the auxiliary processes connected to the system.

On a Danish level, analyses estimate that a build out of 6 GW of PtX could potentially provide enough heat to meet 20% of district heating needs.[42]

Integration with gas infrastructure

Utilizing existing infrastructure will be critical to lower to overall socioeconomic costs of transitioning to sustainable fuels. Re-using existing infrastructure, such as gas pipeline distribution networks, will be important and potentially preferred from a cost and carbon standpoint. Transmission system operators assume the costs for retrofitting to be at around 10-15% of new construction.[43] Upgraded biomethane can easily be injected into the existing gas grid and is done so extensively already.

Hydrogen can be blended into the existing gas grid at varying levels, but typically no more than 20% without major retrofitting, hazards, or compatibility issues with end-uses (e.g. gas appliances, furnaces). However, hydrogen carries only about one-third as much energy per unit of volume as does methane, which means that a 20 percent blend of hydrogen will only reduce the emissions impact of its use by 6 to 7 percent.[44] As such, pipeline blending of H2 at high levels is not likely to be a viable path forward or a significant contributor to emissions reduction. Retrofitting existing gas networks to be 100% hydrogen and used in the planned European hydrogen backbones is a likelier scenario.

In a ten-year testing period, FORCE Technologies tested hydrogen in steel and plastic pipes[45] (the same used in the existing gas grid) to investigate whether the existing gas transmission network can distribute hydrogen without fatigue-induced cracking or degradation. The results showed that long-term exposure to hydrogen had “no impact on the steel or plastic pipes” meaning that it is expected that the existing Danish gas system would be able to handle a full transition to hydrogen gas without major issues. However, upgrades may be needed for seals, valves, and compressors to handle the different properties of hydrogen, including its higher diffusivity and lower energy density compared to natural gas.

Integration with carbon supply

Effective integration of PtX plants with carbon supply is needed for producing efuels. PtX plants can utilize CO2 captured from industrial processes, power plants, or direct air capture technologies. Integrating carbon capture infrastructure with PtX facilities allows for a steady supply of CO2, essential for synthesizing fuels like e-methanol, e-methane, and other e-hydrocarbons. Additionally, transporting CO2 via pipelines to PtX plants or situating PtX plants near CO2 sources can minimize transportation costs and logistical challenges. Biogenic CO2 or syngas produced from processes such as anaerobic digestion or gasification can be used for efuel production. Co-locating "bio-e" generation infrastructure can be done strategically to optimize the various feedstock and waste streams and maximize cost-effectiveness.

Integration of biorefineries

Integration of biorefineries into existing energy systems supports the circular economy by utilizing waste and by-products from agriculture, forestry, and keeping waste food out of landfills. Similar to PtX, biorefineries can enhance energy system resilience and flexibility. Bio feedstocks can be stored and processed as needed. By producing biodiesel, biogas, or other bio derivatives, biorefineries provide fuels that can be blended with or substitute conventional fuels. This integration is facilitated by existing fuel infrastructure, such as pipelines and refineries, which can often accommodate biofuels with minimal modifications.

Upstream, effective integration of biorefineries with feedstock systems and waste sorting is vital. Incorporating agricultural residues and the organic fraction of municipal solid waste (OFMSW) with biorefineries requires coordinated efforts across multiple sectors. This includes developing infrastructure for collecting, transporting, and processing diverse feedstocks, as well as creating supportive policies and incentives to encourage participation from farmers, municipalities, and industries.

For the agricultural sector and biogas plants, the collection area, or geographic radius from which the plant collects is feedstock is an important factor for successful integration. The radius of the collection area typically ranges from 20 to 50 kilometers, depending on the plant's capacity and local infrastructure.[46] A smaller radius minimizes transportation costs and associated greenhouse gas emissions, enhancing the overall environmental benefits of the biogas plant. However, a larger radius may be necessary in sparsely populated or rural areas to gather sufficient feedstock.

For urban environments, the integration of OFMSW collection programs with biorefineries supports urban sustainability goals by closing the loop on waste and energy cycles. Copenhagen has a goal of recycling 70% of residents' waste by 2024 and has engaged in an ambitious marketing and awareness campaign to encourage residents to place biowaste into the appropriate collection bins.[47] In Copenhagen, food waste is taken to a biogas plant in Solrød, where it is upgraded to' biomethane and used in the gas network.

Integration with water systems

Producing large amounts of hydrogen requires significant volumes of water. Denmark's water infrastructure must ensure adequate water availability, treatment, and recycling systems to support the increased demand from PtX plants while maintaining the balance and sustainability of water resources. The ideal location for a PtX facility is where there is a reliable excess water supply that is not subject to competitive use from households and agricultural activities.

PtX plants can potentially utilize treated wastewater or greywater for their processes. This approach not only conserves freshwater resources but also aligns with Denmark's goals for sustainable water management. Collaborations with municipal water treatment facilities will be essential to establish pipelines and infrastructure capable of delivering treated wastewater to PtX plants.

MISSION GREEN FUELS

Systems integration and sector coupling are a key focus of MissionGreenFuels' strategic initiatives. Ongoing projects include:

- **PtX Sector Coupling and LCA:** This project involves evaluating optimal plant locations by considering grid capabilities, market forecasts, and resource availability. It also explores sector coupling and co-optimizing gas, electricity, hydrogen, and district heating.
- **PtX Infrastructure:** Focused on assessing hydrogen and CO2 infrastructure needs for a future integrated energy system, this project aims to shift from siloed approaches to holistic energy systems.
- **HyFueling HD:** This project validates hydrogen refuelling technologies linked to the HySynergy production site, including multi-ton storage buffers for use in heavy-duty fuel cell vehicles.

5. Social and Sustainability

Sustainability

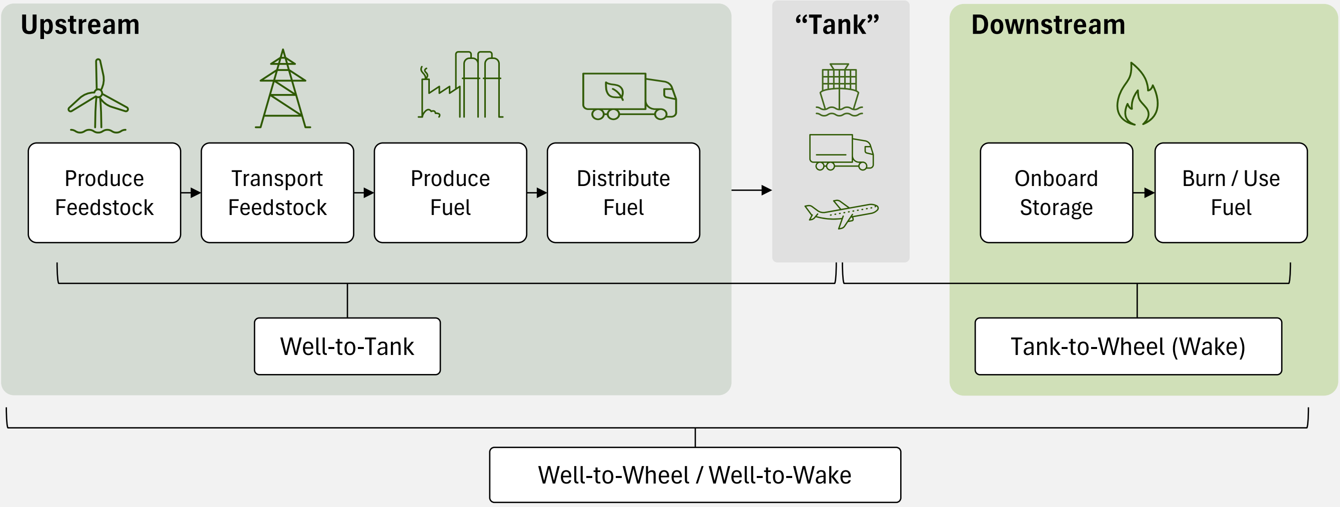
Sustainability issues surrounding green fuel production involve environmental, economic, and social dimensions. Environmentally, the production of green fuels, necessitates careful consideration of resource use and ecological impacts. Land use change, water consumption, and biodiversity loss (in regard to the mass build-out of wind and solar parks) are critical concerns, especially for biofuels, which can lead to indirect land-use change and habitat destruction if not managed responsibly. Furthermore, the production processes themselves must minimize emissions and waste to truly contribute to sustainability goals.

As such, Life Cycle Assessment (LCA) should be used as a tool to evaluate the environmental performance of green fuels. LCA examines the entire life cycle of a fuel, from raw material extraction to production, distribution, use, and disposal. This approach ensures that all potential environmental impacts are accounted for, including greenhouse gas emissions, energy use, water use, and pollutants. By identifying hotspots and inefficiencies in the production chain, LCA helps in optimizing processes and guiding policy decisions towards more sustainable practices.

Within transport fuels, the production, transport, and distribution emissions are commonly referred to as Well-to-Tank (WTT) while operational emissions during fuel usage are referred to as Tank-to-Wheel or Tank-to-Wake (TTW) depending on the type of transport (road vs maritime or aviation). The sum of emissions from both stages is used to evaluate a fuel's carbon intensity, or emissions per unit of delivered energy (e.g. gCO2e/MJ). The full lifecycle emissions are referred to as Well-to-Wheel or Well-to-Wake (WTW) and can be compared across different transport fuels. The potential sources for WTW of emissions are shown below.

Emissions related to green fuel production are a significant focus of LCA. Different production pathways have varying emission profiles; for instance, biofuels can sequester carbon during feedstock growth but may also release methane (via leakage) and nitrous oxide during production. Synthetic fuels, made through CCU, can potentially close the carbon loop but require substantial energy inputs and are highly inefficient compared to direct electrification. These aspects should be accounted for when assessing green fuels.

Figure 5.1: Life cycle stages of a green fuel



The embodied carbon of building several GW of renewable energy to support the production of efuels must also be taken into account. Thus, LCA provides a framework to compare these pathways and identify the most sustainable options, ensuring that the pursuit of green fuels does not inadvertently lead to adverse or unforeseen environmental impacts.

Social and community aspects

Large-scale energy projects require wide social acceptance to be carried out. Lacking a “social license to operate”[48] puts clean energy projects at risk and in the past has led to costly disputes, additional surveying and impact studies, project pauses, regulatory restrictions and difficulties in obtaining legal permits. Social acceptance is therefore critical to the success of green fuel advancement and the associated build out of renewable energy. If stakeholders‘ interests and expectations are not aligned, formal procedures and issuance of permits can be significantly delayed, or not given. Therefore, the social acceptance by local communities is as important as the technical and economic feasibility of the project.

As such, early two-way community engagement is needed to communicate the local benefits of large scale PtX projects. There is a high risk that projects are rejected by local communities if the project benefits are not clear at the start of project development, The idea of benefit sharing recognizes that the placement of large-scale industrial energy projects leads to significant changes in the local landscape and community dynamics. Benefits for local communities, and ways to create trust and credibility to increase the “social license to operate”, are listed below in Table 5.1.

Table 5.1: Potential community impacts and benefits of green fuels development

Negative impact	Description of impact	Strategy to mitigate
Land use and visual impact	• Alters local landscapes • Large scale land-use for projects (e.g. solar farms, onshore wind)	• Strategic site selection to minimize aesthetic impacts • Visual impact simulations
Disturbance and noise	• Noise, increased traffic during construction and operation phase • Impact quality of life for neighbors	• Noise mitigation measures, construction schedules • Communication channels for complaints
Resource competition	• Increased demand for water, or other resources, potentially competing with local needs	• Measures not to compete with local water or energy needs by using treated wastewater and own power

Positive benefit	Description of benefit	Strategy to implement
Job creation	• Employment opportunities in construction, operation, maintenance • Local economy boost	• Source local labour (if possible) and highlight job postings
Economic development	• Local economic activities through project-related investments • local spending and business opportunities (hotels, restaurants, etc)	• Estimate economic impact via studies, communicate results • Estimate tax generation for municipalities
Infrastructure investment	• Upgrades and modernization in local infrastructure such as roads and utilities • Improvement in local facilities	• Communicate planned infrastructure improvements to local community

Strategies to increase social buy-in

During the planning and development phase of PtX projects, analysis should be undertaken to quantify benefits to local communities such as permanent job creation, the types of jobs, economic activity, and local procurement of services or materials.

Outside of direct economic impacts, other strategies can be used to incentivise local support and increase community buy-in.[49] These strategies are meant to foster co-ownership and community involvement into the projects and have been used for onshore wind and solar development projects in Denmark in the past.

- **Co-ownership model:** Allowing communities to purchase shares in part of the project (e.g. 20% of the installed capacity) to take a financial stake in the success of the project. This has been successful for onshore wind.
- **Green pool / green fund schemes:** Project developers pay local municipalities a one-time sum of money per MW of capacity built which is then earmarked for community improvement projects such as bike lanes, playgrounds, parks, or infrastructure improvements.
- **Proximity bonus:** local community members within a certain radius of a project site, and the ones most likely impacted by disturbance, are given a pay-out-based production of site.
- **Property value guarantee:** financial compensation mechanisms to protect property owners from value loss due to siting of facility.

Implementing these strategies not only helps in gaining social acceptance but also ensures that the local communities see tangible (financial and non-financial) benefits from the projects.

However, there are many challenges associated with community engagement that must be overcome including limited municipal resources and skills for effective engagement (e.g. surplus of renewable energy projects and limited resources to effectively administer civic engagements), civic meetings that are often one-directional with limited or under-representative stakeholder engagement, or low levels of public awareness of understanding of green fuel technologies leading to misunderstanding.

Research into the most effective and democratic ways of civic engagement should be conducted to ensure that concerns are properly addresses and green fuel infrastructure is built in an equitable and fair way for local communities. Innovative community buy-in methods, such as the ones used historically in Danish wind development, should be studies for PtX and other green fuel infrastructure projects.

Safety aspects:

One of the main community concerns around PtX surrounds safety aspects with fuels such as hydrogen which is explosive and ammonia and methanol which are toxic at varying levels. The concerns around an accidental spill or explosion in local communities should be addressed early in the development of a project and communicated clearly. This could include descriptions of leak detection and monitoring systems, fire and explosion protection, safety distances used during project siting, emergency response plans, and so on. It is important for project developers to communicate transparently about the safety measures in place, emergency response plans, and the statistical likelihood of incidents, to alleviate public fears.

Future workforce needs

Skilling the future workforce or reskilling the existing workforce for the energy transition is one of the most critical needs identified by MissionGreenFuels stakeholders. There will be no energy transition if there are no workers to carry it out. Developing green fuels and the associated renewable energy feedstock will take an enormous amount of technical know-how, skilled labour, technicians, and other support roles. The list below lists strategies and examples of how to approach skills development for the green fuels sector:

Skilling the future workforce

Young people approaching higher education today should be targeted with STEM programmes that feature curriculums in green fuels, electrochemistry, energy storage and conversion, etc. Similarly, persons entering potential vocational education programmes (VET) should be encouraged to apply for programmes relevant for the energy transition: automation, electrical work, welding, controls, among others. See Table 5.2 for more occupational profiles and the relevant skills needed for green jobs.

Strategies: Embed green fuels and PtX education into standard engineering coursework across chemical, mechanical, and electrical disciplines. Expand the programmes offering tangible skills in green fuels technologies. VET jobs in automation, electrician should feature hands-on training with PtX technologies. Encourage apprenticeships during construction and operation phases of PtX facilities to skill the entering workforce with real-world experience.

Examples:

- DTU offers over 25 courses specifically relevant for green fuels and PtX in courses such as “Electrochemical energy technologies”, “Industrial Reaction Engineering”, and more. Other universities offer similar courses.[50]
- In June 2024, the Danish government allocated over 200 million DKK to vocational schools to invest in up-to-date equipment and training within the green transition and created frameworks to attract more young people to technical vocational educations, based on the expected shortage of skilled workers.[51]

Upskilling the existing workforce

The existing workforce in traditional engineering and trades fields (non-green fuels related) can be targeted via continuing education programmes (non-degree career training, professional continuing education, modules, etc).

Strategies: Offer topic specific training courses that build on existing competencies. For example, existing workers within shipping may need upskilling in the safety and handling procedures for ammonia, an area that builds on existing competencies for other fuels or materials handling.

Examples:

- Green Skills for Hydrogen Project (GreenSkillsforH2) has a core objective of addressing the hydrogen skills gap by providing training to industry. The alliance offers a suite of training material for competencies relevant for PtX.[52]
- Flexible Masters in Power-to-X offered by a collaboration between AAU, AU, DTU, and SDU that caters to working professionals.[53]

Reskilling the fossil fuel workforce

PtX plants (essentially chemical plants at their core), will share many crossover skills with traditional roles in the petrochemical industry. This includes workers with tangible skills in refinery operation, pipeline infrastructure, fuel-logistics, etc. Fossil fuel workers should be able to fill emerging green jobs with only minimal reskilling.

Strategies: Top-down corporate strategy to reskill parts of existing workforce to transition to green fuels. Offer compensation and re-qualification to existing workforce during fossil fuel phase-out.

Examples:

- RePowerEU strategy includes the Pact for skills partnership in which the EU aims to reskill several million workers for careers within the green jobs sector.[54]
- Danish companies phasing out or selling off oil and gas parts of their business and focusing on offshore wind and emerging green fuels sector.

Recruitment and integration of skilled foreign workers should also be considered to fill the projected skills gap.

In the box below, ongoing MissionGreenFuels projects that focus on social and sustainability aspects of green fuels are listed.

MISSION GREEN FUELS

Focus areas and projects within social & sustainability

MGF is strategically positioned to drive innovation within social and sustainability topic area related to green fuels, particularly within:

- Developing frameworks for effective citizen engagement and social buy-in
- LCA and sustainability assessments of green fuels feedstocks and production processes
- Disseminating safety guidelines to advance public acceptance

Examples of past of ongoing MGF projects include:

→ **Safer and Faster PtX**
  - Assessment of safety, risks, and mitigation in relation for social acceptance of PtX
  - A guideline to safer PtX will be developed

→ **COMON:** Engaging communities in the green fuels transition
  - Catalogue with best practices and promising venues for citizen engagement and acceptance
  - Scenarios and design guidelines for tackling barriers to development of green fuels

→ **DEEP:** Designing community collaboration for sustainable energy parks
  - Provide a platform for designing holistic energy parks, which includes both citizen needs and considerations for improving local nature and biodiversity.
  - Strategy for community collaboration, including principles and processes for involvement and dialogue

Table 5.2: Potential occupational profiles in the green fuels sector

Occupational profiles	Relevant educational development / skills
Engineers • Chemical engineers • Civil engineers • Electrical engineers • Mechanical engineers • Marine engineers • Power and grid engineers • Process engineers	• Deep understanding of electrochemical energy technologies (production, storage, use) • Understanding of energy systems integration, energy systems analysis, design, and optimization • Understanding of various fuel production methods (e.g., electrolysis, pyrolysis, biomass gasification). • Skills in data analysis, statistical modelling, and predictive analytics
Tradespersons and technicians • Process control technician • Automation technician • Electrical fitter • Electrician • Welder • Gas fitter	• Certifications in electrical safety, welding, or automation technologies • Hands-on experience with electrolyzers, synthesis equipment, and balance of plant equipment • Maintenance and troubleshooting skills for plant equipment and infrastructure
Safety and Quality Control • Health and safety officer • Quality assurance technician • Inspector • Emergency response coordinator	• Training in emergency response and hazardous materials handling .e.g. ammonia leakage • Skills in risk assessment, incident investigation, and reporting • Knowledge of safety standards and regulations specific to green fuel production and storage
Specialists • Plant operator • Water treatment plant operator • Integration specialist • Fuel cell and electrolyzer testing technician	• Specialized training in water treatment, electrolyzer technologies, or integration of renewable energy systems • Proficiency in laboratory techniques for testing fuel cells and electrolyzers • Experience in process optimization and systems integration for green fuels production
Logistics • Machinery operator • Heavy vehicle operator • Warehouse manager • Marine operator • Stevedore	• Understanding of regulations and safety requirements for transporting hydrogen and other green fuels • Knowledge of green fuel supply chain logistics, including transportation and storage • Skilling in the latest handling and safety requirements e.g. ammonia bunkering
Management • Operations manager • Maintenance manager • Planner and scheduler • R&D manager • Engineering manager	• Strategic planning and decision-making skills with a focus on sustainability and innovation • Leadership skills and experience in managing teams within the energy sector • Project management for complex infrastructure projects • Local stakeholder management (engagement)

Source: Adaption from PwC "Skills and Training to Support the Hydrogen Economy", 2022.[55]

6. Resource Potentials

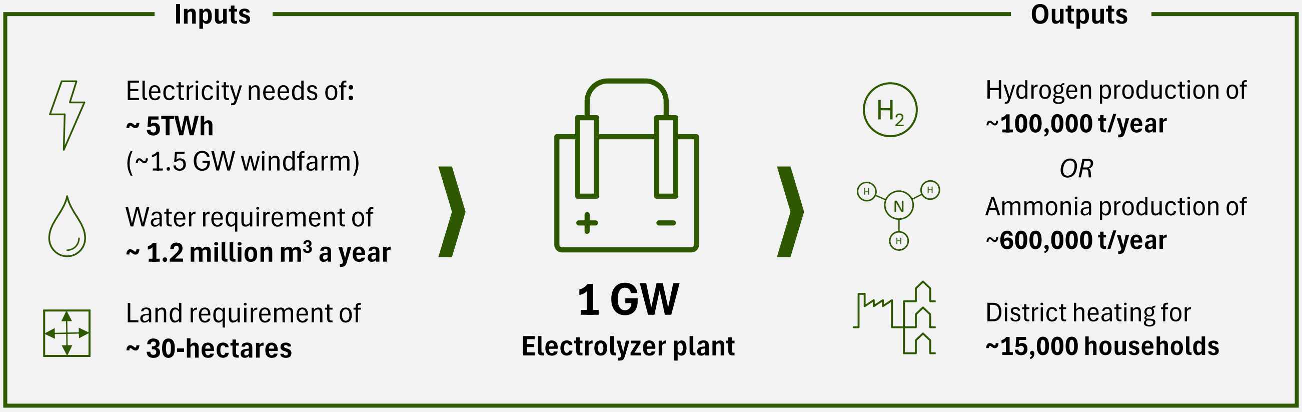
Production of green fuels will require a substantial amount of renewable energy, water, and biomass resources. This section describes the potential needs and availability of these feedstocks needed to produce green fuels.

Renewable electricity availability

To reach the government's target of 4-6 GW would require an estimated 20-30TWh of electricity, assuming 5,000 full load hours for the electrolyzer. For context, total Danish electricity consumption in 2023 was approximately 37 TWh, of which 30TWh was supplied by low carbon sources such as wind and solar. An additional 4-6GW would mean approximately 6-15 GW of additional renewable energy capacity would need to be dedicated to hydrogen production. The amount depends on the technology, its capacity factor, production profile, and the potential integration of energy storage. In essence, hitting the 4-6GW electrolyzer target would mean a doubling of Danish wind and solar by 2030, which stands at around 12GW in 2023.[56] To put the resource needs into context, the requirements for a generic 1GW electrolyzer plant is shown in Figure 6.1. As shown, A 1GW electrolyzer plant would need an equal or (likely) greater amount of additional renewable energy to power it, but this depends on the load profiles of both the RES source and the operational philosophy of the electrolyzer plant.

To meet this resource requirement, the Danish government is set to tender out large amounts of offshore wind capacity in the North and Baltic sea by 2030, amounting to a minimum of 9GW of capacity, with the potential for more via overplanting.[57] Energy islands in Bornholm and the North Sea are expected to provide 3GW and 10GW respectively are slated to come online in the mid 2030's.[58] Additionally, utility scale solar is expected to rise significantly, driven by the low levelized cost of power and the affordability of high efficiency panels. Most new additions will come from offshore wind and solar. Onshore wind will provide some marginal capacity addition in the near-term but is projected to remain fairly stable towards 2050, as shown in Figure 6.3.

Figure 6.1: Estimated needs of a generic 1 GW electrolysis plant



Assumptions

Electrolyzer running 5,000 hours a year at full-load with energy efficiency estimated at 64%

Windfarm operating at ~40% capacity factor

Land requirements, production outputs, district heating numbers are based on project HØST in Esbjerg.[59]

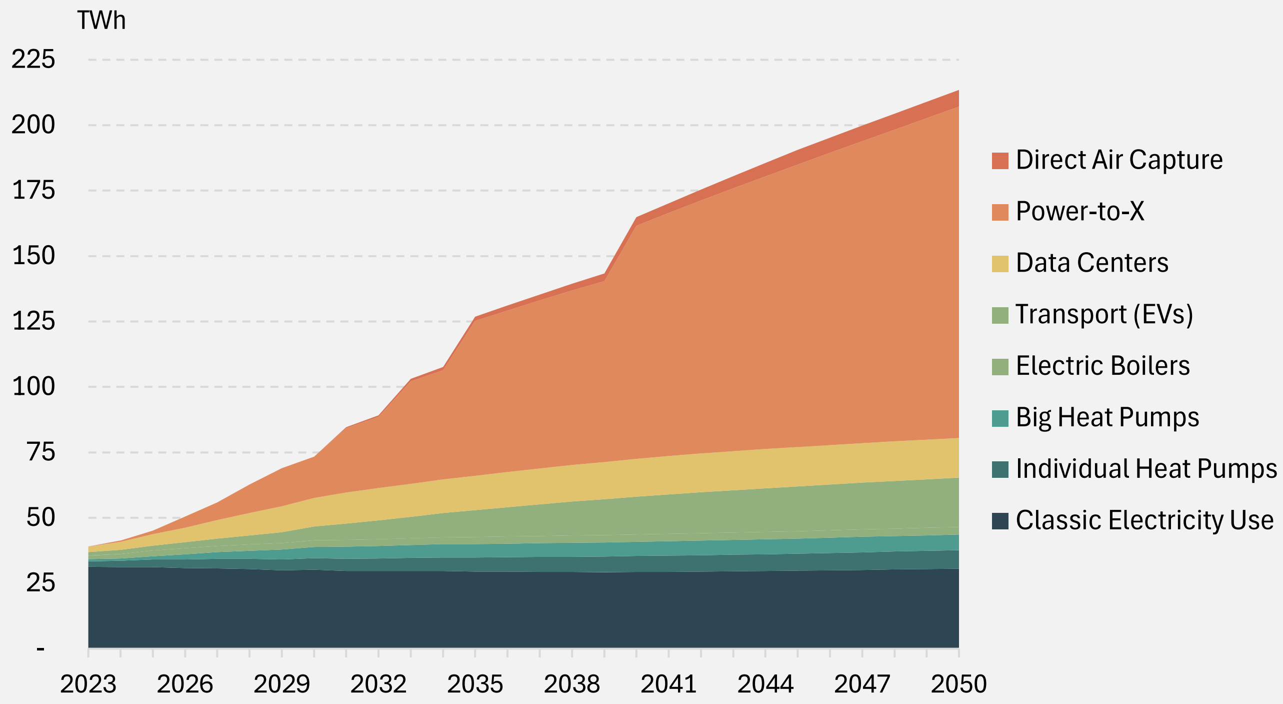
Massive electricity needs projected

When looking longer term, the latest AF23 analysis[24] projects that total Danish electricity use will reach 73TWh by 2030, of which more than 20% will be used for PtX. This is projected to reach 213TWh by 2050, of which almost 60% will be devoted to PtX and the production of green fuels. This energy consumption dwarfs the future needs of electrification technologies. Without PtX, total electricity consumption in 2050 would be projected to stand at 87 TWh, of which transport (EVs), heat pumps, and data centres drive most of the growth over baseline levels. The growth in electricity use is shown in Figure 6.2.

Data centres: a potential near-term competitor for renewable capacity additions

It is important to point out that data centres will also see a substantial rise in energy consumption from 2023-2030 going from 2 to 11TWH of demand (417% increase) in less than 10 years. This is mainly driven by the extensive power needs needed for AI compared to traditional computing needs. In the near-term, this could create an interesting dynamic and scarcity of renewable energy supply[60] as AI could potentially compete against PtX for new RES capacity, if the captured willingness to pay is higher in datacentres, or if PPA's with data centre operators lock-in the upcoming near-term supply.

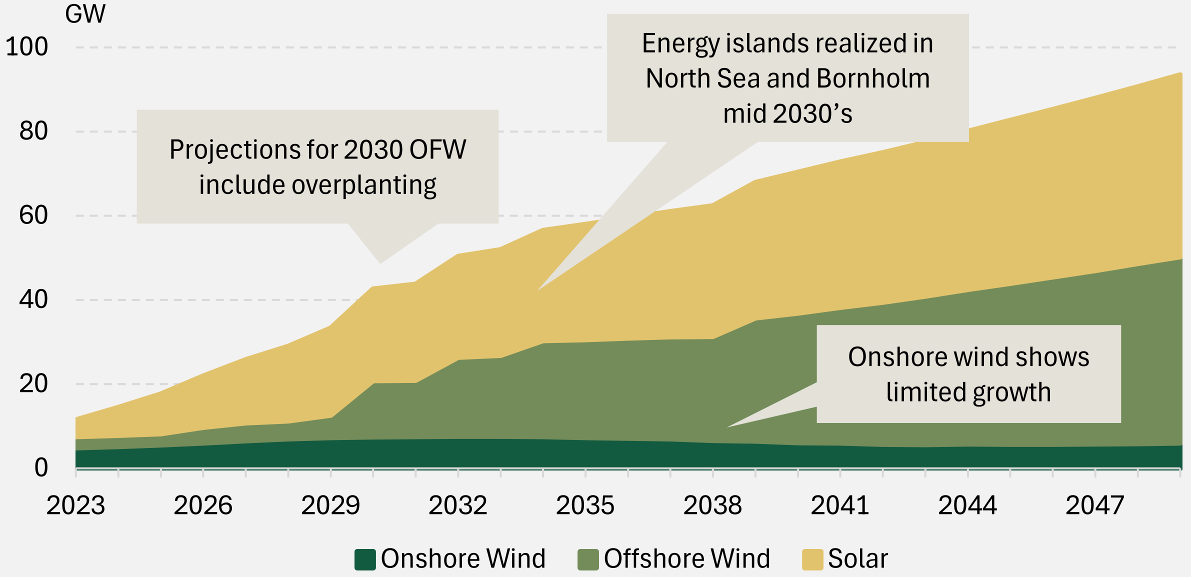
Figure 6.2: Electricity use projections 2023-2050



	2023	2030	2050
Total Use (TWh)	39.05	73.37	213.50
PtX Use (TWh)	0.025	15.82	126.65
PtX (%)	<0.1%	21.6%	59.3%

Source: Danish Energy Agency AF23: Analysis prerequisites for Energinet, 2023.[24]

Figure 6.3: Renewable capacity additions 2023-2050 (projected)



Projections for 2030 OFW include overplanting

Energy islands realized in North Sea and Bornholm mid 2030's

Onshore wind shows limited growth

Source: Danish Energy Agency AF23: Analysis prerequisites for Energinet, 2023.[24]

Water availability and sourcing in Denmark

Denmark is generally rich in water resources. The country's average annual rainfall is approximately 800 millimeters, providing a substantial replenishment of these resources. Water abstraction (taking water from a natural resource such as a lake or groundwater) in 2022 was 935 million cubic meters of which was dominated by agricultural use, followed by industrial and domestic use.[61] To minimize local water stress and improve sustainability, Denmark has implemented smart water management practices to ensure conservation of water resources.

The water demand for producing green hydrogen through electrolysis is modest relative to Denmark's total water availability. Producing one kilogram of hydrogen requires about 9 litres of water, with an additional 10-20 litres needed for associated processes like cooling and purification.[62] To achieve its target of 4-6 GW of electrolysis capacity, Denmark would require an estimated 4.8 to 7.2 million cubic meters of water, which represents less than 1% of the country's total water consumption.

While the overall water demand for hydrogen production is minimal compared to other uses, such as irrigation and cooling in thermal power plants, regional constraints could arise. Industrial-scale PtX projects may face challenges related to local water availability and infrastructure capacity. Therefore, intentional siting of PtX facilities is essential, with permitting processes that assess local and downstream water availability, competing uses, and rights

Denmark's water management policies, which emphasize sustainable use and efficient allocation, are well-positioned to support the integration of hydrogen production into existing frameworks without compromising other critical needs. Additionally, the potential for water recycling and reuse in hydrogen production through the use of wastewater, or desalinated water, could further reduce the reliance on freshwater resources.[63]

Bio-resources

Denmark's bioresource potential is characterized by significant opportunities across agricultural, forestry, and potentially marine sectors. For a land area covering approximately 43,000 km^2: 61% is used for agriculture, 13% for forestry, 14% for urban development, while natural areas, including lakes and streams, make up 12%.[64] Previous studies indicate that around 20 million tonnes of dry biomass are produced annually from cultivated land, with approximately 18 million tonnes being harvested. Strategies suggest this can be increased by an additional 10 million tonnes through improvements in agricultural practices, utilization of perennial crops, and enhanced forestry management.

A minimal portion of Denmark's agricultural land is allocated for dedicated energy production, with approximately 8,500 hectares planted with willow and poplar for wood chip production. Currently, large-scale cultivation of energy crops in Denmark is not feasible without impacting food and feed production. Due to the potential competition for land between energy crops and food/feed crops, the current emphasis in Denmark is on utilizing agricultural and forestry residues, along with organic waste, for energy production.[65]

Importantly, as straw-based or wood-chip combined heat and power (CHP) plants transitions heat production to electricity-based heat pumps, the demand for straw in CHP production is expected to decrease, potentially freeing up large quantities of biomass for other uses such as green fuels production.[66]

In terms of fats, oils, and greases (FOG) Denmark has a limited availability which can be used for biofuel production including HVO Hydrotreated Vegetable Oil (HVO) and biodiesel. The primary sources of these FOGs in Denmark include used cooking oil from the food service industry, animal fats from the rendering industry, and grease trap waste. However, due to the country's relatively small size and population, the domestic supply of these materials is limited. An estimate places the total energetic potential of FOG at ~0.3PJ/year which is much less than the potentials seen in agricultural residues, manure, etc.[67] Therefore, technology advancement is sought in lignocellulosic biomass conversion to produce bio-oils which can be later converted to HVO via hydroprocessing, etc.

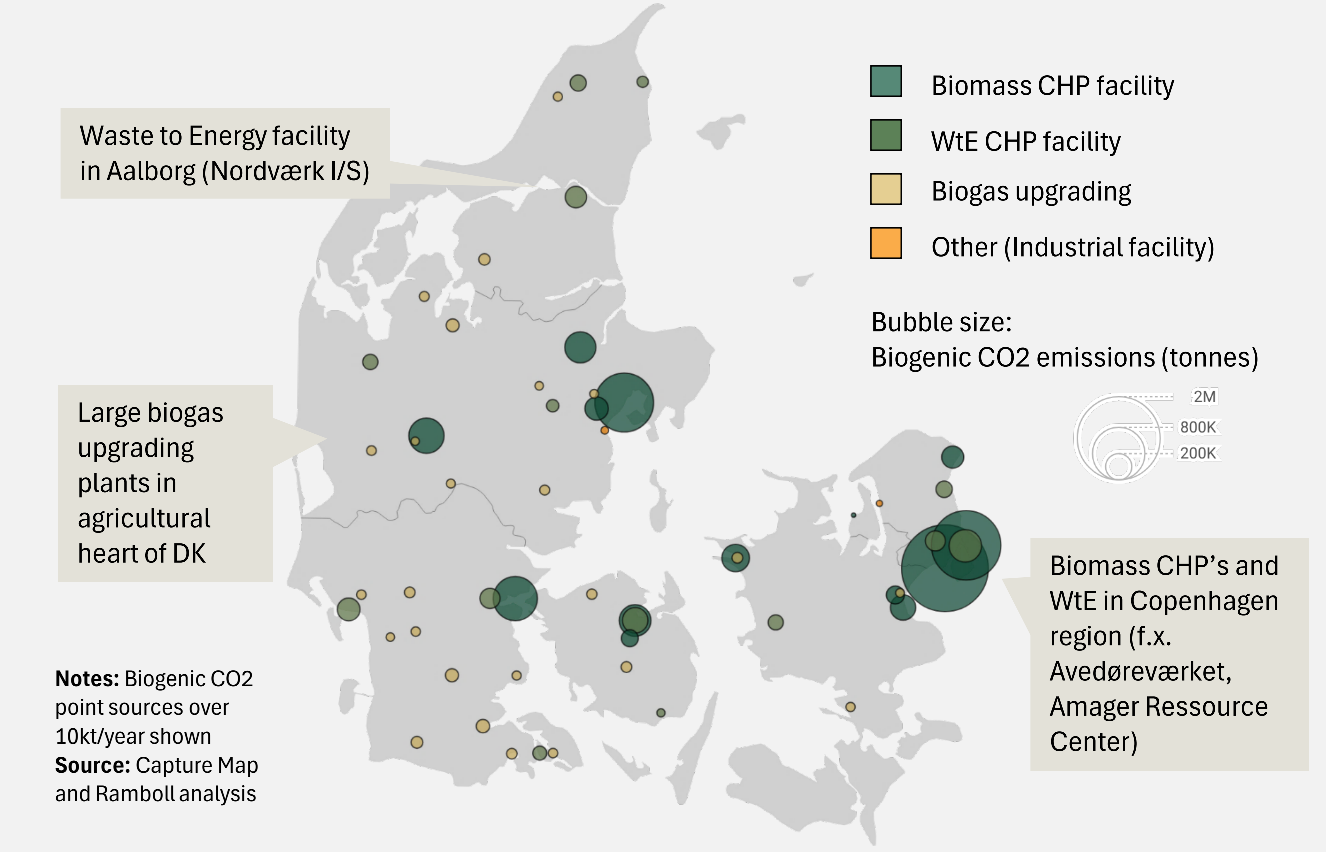
Studies on Danish biomass potentials theorize several ways to sustainably increase bio-resources available for biogas and biofuels production via:

- Increasing the recovery of agricultural residues such as straw and shifting to crops with higher biomass yields can provide additional raw feedstock.
- Cultivating perennial energy crops like willow, poplar, and Miscanthus on marginal lands can provide a steady source of biomass without impacting food production.
- Increasing the usage of forestry residues and improving forest management practices can boost the availability of woody biomass.
- Leveraging Denmark's marine resources by cultivating sugar kelp, sea lettuce, etc.
- Improving biorefinery technologies to convert biomass more efficiently, improving yield.

Biogenic CO2

Biogenic CO2 is carbon dioxide released from natural processes like the decomposition of organic matter or the combustion of biomass. It is considered carbon-neutral because the CO2 released is roughly equal to what the biomass absorbed during its growth, making it part of a closed carbon loop. This is why biogenic CO2 is often targeted in sustainability efforts, as its capture and utilization can contribute to reducing overall atmospheric CO2 levels when managed properly.

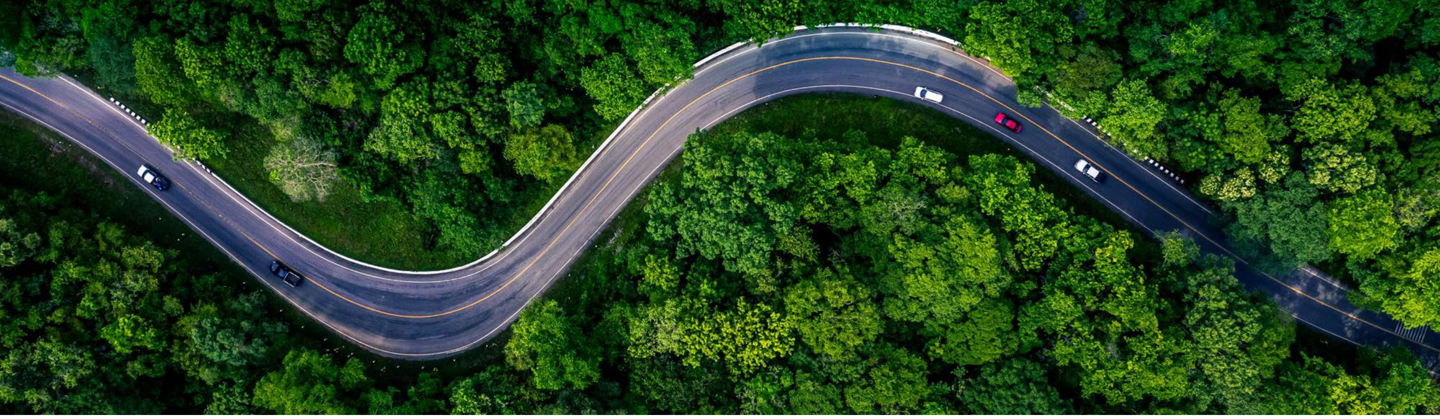
Figure 6.4: Biogenic CO2 point sources >10kt/year in Denmark



Notes: Biogenic CO2 point sources over 10kt/year shown
Source: Capture Map and Ramboll analysis

The technical potential for point-source capture of biogenic CO2 in Denmark is estimated to reach approximately 7 Mtpa by 2030 (INNO-CCUS).[68] Key sources include large-scale biomass combined heat and power (CHP) plants, Waste-to-Energy facilities (which emit both biogenic and non-biogenic CO2 due to their heterogeneous feedstock), and biogas upgrading plants. The total capturable biogenic CO2 will depend on the capture technology used, its efficiency, and the biogenic content of the feedstock. While Denmark may have sufficient biogenic CO2 available in the near-term, economic factors could limit the viability of capturing, transporting, and integrating it into PtX processes.

Biogenic CO2 will be driven by market dynamics including emissions trading schemes and incentives, influencing how biogenic CO2 is valued and utilized in the market. The CO2 market in Denmark is primarily driven by the demand for capturing and storing both biogenic and fossil CO2 emissions, a focus strongly supported by government policies.[69] There will also be a growing demand for biogenic CO2 in the green fuels sector, particularly for carbon-based efuels. However, in the short term, most of the CO2 captured in Denmark is earmarked for storage rather than utilization. Additionally, the availability of biogenic CO2 from biomass CHP plants may decline over time as the adoption of other technologies, such as renewables and heat pumps, changes their operational patterns.



7. Sector Pathways

This section outlines key sectors within industry and transport and their associated energy transition end-use pathways to meet the Danish climate targets. Data for these sections are taken from the Danish Ministry of Climate, Energy, and Utilities KF23 and KF24 reports which provide the latest overview of current and projected energy use, CO2 emissions, and sectoral trends for industry, transport, shipping, and aviation.[56] This is supported by the latest AF projections produced by the DEA for Energinet.[24] Total Danish emissions are shown in Figure 7.1.

The sectors pathways considered include the following:

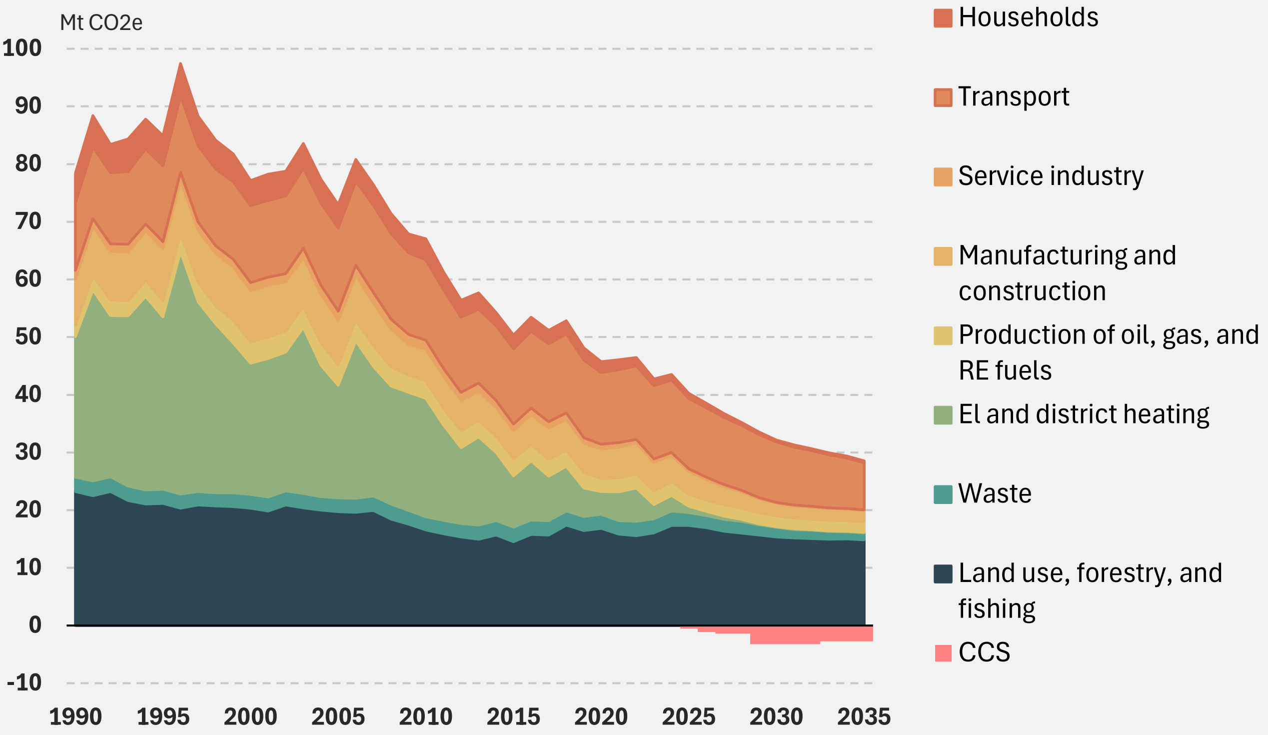
Industry: Manufacturing and energy intensive industry

Road transport: Heavy and light toad transport

Maritime: Domestic and international shipping

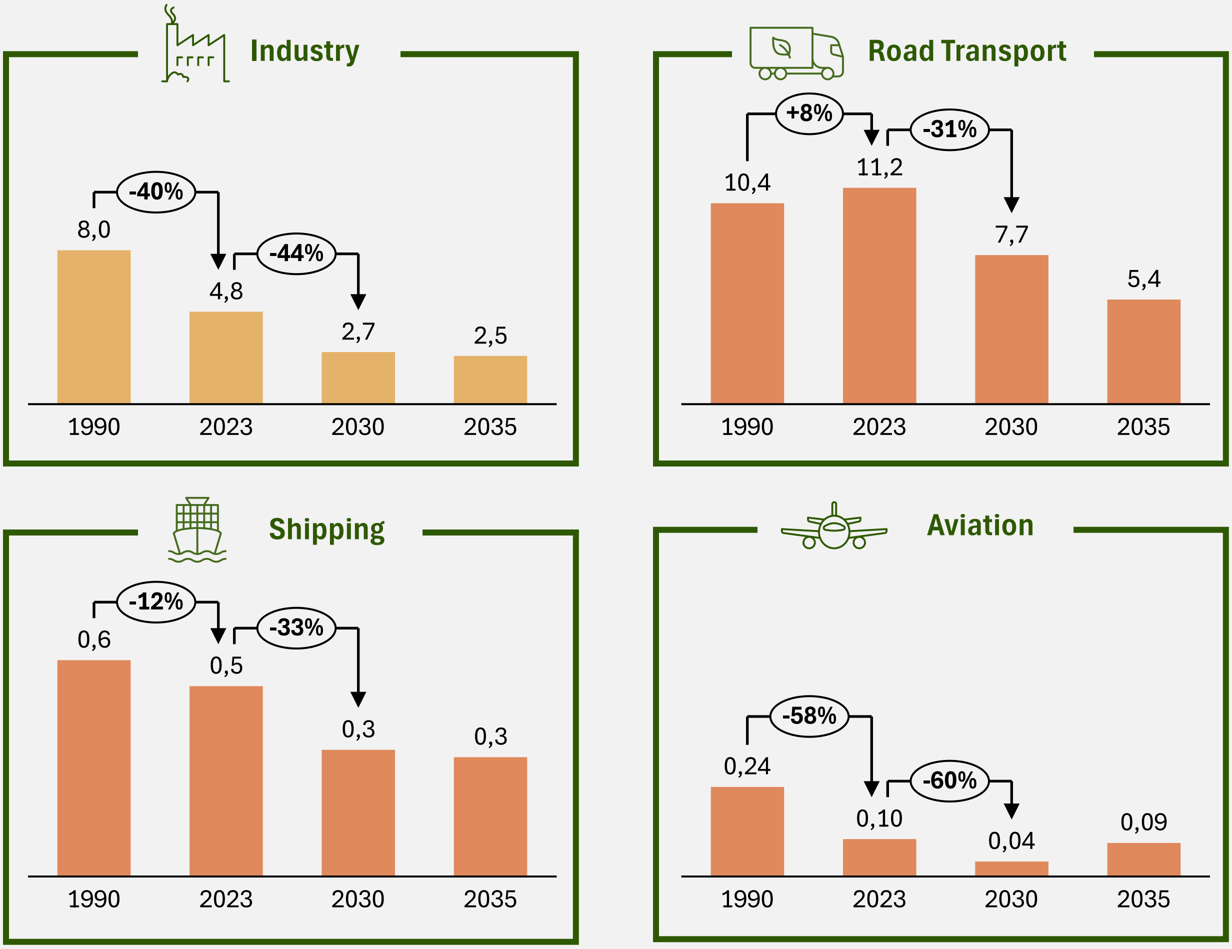
Aviation: Domestic and international air travel

Figure 7.1: Combined emissions (1990-2035) from KF23



Notes: Projections include negative emissions from CCS
Source: Danish Energy Agency KF23: Klimastatus og Fremskrivning, 2023.[56]

Figure 7.2: Sectoral emissions in industry and transport (Mt CO2$_e$)



Source: Danish Energy Agency KF23: Klimastatus og Fremskrivning, 2023.[56]

7.1 Industry

Current emissions profile

The industrial sector, which includes manufacturing and construction, is fundamental to the Danish economy accounting for over 20% of GDP.[70] This sector encompasses a wide range of activities from producing consumer goods, high-value manufactured goods for export, to building infrastructure and dwellings. While it has reduced its emissions by 40% since 1990, primarily through fuel switching from coal and energy efficiency, the sector in 2023 still accounts for 4.8 Mt CO2e annually, amounting to 12.6% of total Danish emissions. Other greenhouse gas emissions, from methane leakage, f-gases, or nitrous oxide are minimal and will not be covered in this pathway.

Of these 4.8 Mt CO2e, over half result from emissions from energy use in heavy industry. Cement production which still uses coal and petroleum coke as fuel or feedstock is a significant industrial emitter. Cement production, of which Aalborg Portland is the biggest player, is the largest emitter in Denmark and responsible for more than 5% of national emissions in 2022 (1.98 Mt CO2e).[71]

Decarbonization trajectory

Decarbonization of industry will primarily come from greening the energy used for industrial processes and then cleaning up emissions associated with cement production. For electrical energy users as motors, compressors, lighting, etc., carbon emissions will inherently decline as additional renewable energy capacity is added with a lower carbon intensity. Energy efficiency will make processes less energy hungry while electrification using heat pumps will be applied to low and medium temperature industrial heating needs. For high temperature applications, natural gas or biomethane can be used to create steam. As more biogas plants come online the share of biomethane in the grid is expected to increase and this the carbon intensity of blended natural gas will reduce.

For the cement industry, biomass (e.g. wood or agriculture residues) and waste can replace coal and petroleum coke for use in kilns. Enhancements in process efficiency, including the reduction of the clinker content in cement, are key. Clinker production is the most CO2-intensive part of cement manufacturing, and reducing its proportion in the final product, via biomass or industrial by-products such as fly ash can significantly lower emissions. For hard-to-abate emissions, CCS could also be an option for cement, being able to capture point source emissions and store them geologically.

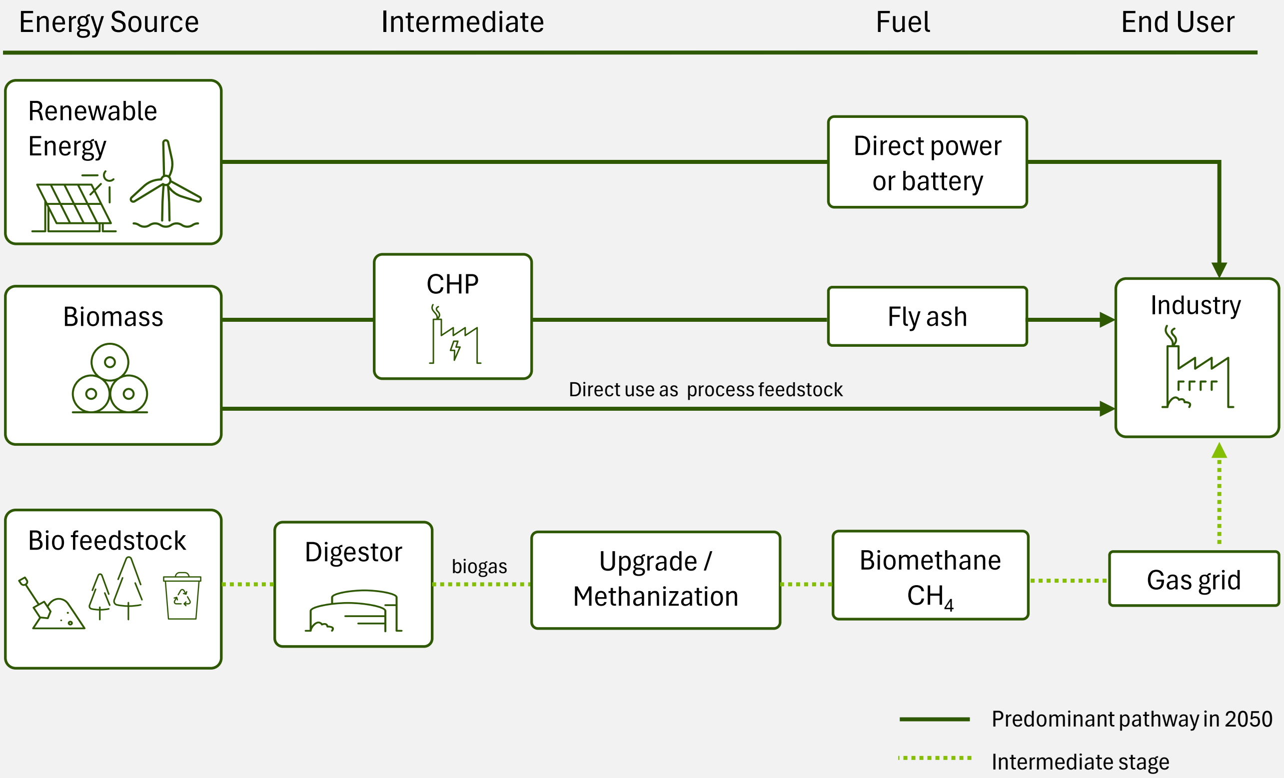
Policy drivers

Policy drivers to enact decarbonization along the industrial pathway include the Green Tax Reform Agreement of 2022 which aims to incentive industries to reduce their emissions via financial penalties. The implementation of a CO2 tax will drive significant emission reductions. In addition to the CO2 tax, the Agreement on the Allocation of Transition Support from the Green Tax Reform for Industry from March 19, 2024, allocates approximately 2 billion DKK for transition support targeted at companies that have the most difficulty transitioning.

Role of green fuels

In the near-term, the use of green hydrogen (or any other hydrogen derivative) is not foreseen, as direct electrification is considered a more economically attractive path than green hydrogen. An exception would be if hydrogen is blended into the natural gas grid, used to improve biomethane yields, or if e-methane becomes economically competitive with biomethane. Otherwise, hydrogen's use will be limited. However, it is important to note that the door should not shut on green hydrogen's use in industry; there is a possibility that cheap and abundant green hydrogen could attract heavy industry to Denmark in the longer term. This includes industries that use hydrogen as a feedstock, including fertilizer production, steel production, and certain manufacturing and chemical processes.

Figure 7.3: Fuel Pathway - Industry



Industry

Key points

① **Energy efficiency** and **electrification** are the key pathways to reduction in the industry with **biomethane** (or high-temp heat pumps) replacing natural gas for **high-temp processes**

② The **adoption of biomass and waste** (fly ash) to replace coal and petcoke in **cement production** is expected to reduce energy-related emissions

③ The CO2 tax introduced in the **Green Tax Reform Agreement** of June 2022 is a key driver of emission reductions (e.g. cement)

Emissions (Mt CO2$_e$)

1990	2023	2030	2035
8.0	4.8	2.7	2.5

Relevant technologies

Electrification

Green gases (biomethane)

Biomass

Long term-outlook (2035+)

- Limited use of green fuels outside of biomethane or biomass
- Existing natural gas infrastructure can be utilized with biomethane
- Heavy-industries wherein H2 can be used, limited in DK (steel, fertilizers, etc.)
- Possibility of attracting industry to DK with cheap green hydrogen
- Possible use of green H2 to improve biomethane yields or for e-methane production

7.2 Road Transport

Current emissions profile

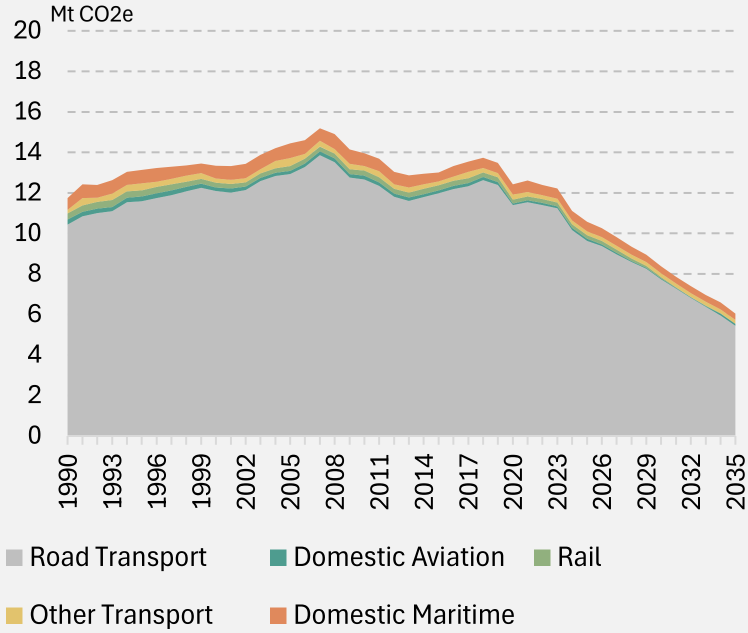
Of the four sectors covered in this roadmap, the emissions from road transport are the highest, when considering domestic emissions. In fact, emissions rose 8% between 1990 and 2023 levels amounting to 11.3 million tonnes in 2023. To hit the 2030 target, emissions must drop more than 30% by 2030. Of the road transport emissions in 2023, 60% originated with light or personal cars, 33% from goods and cargo trucks, and 7% from busses, motorcycles, or other forms of road transport. Historical emissions since 1990 are shown below in Figure 7.4.

Decarbonization trajectory

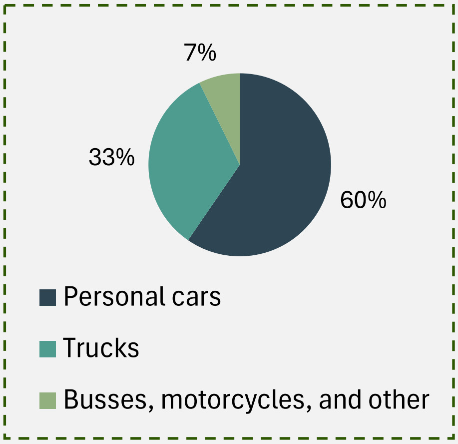
For light road transport, including personal mobility, the reduction in emissions will come from a shift from conventional internal combustion engines (ICE) vehicles to electric vehicles (EVs), plug-in hybrids, and improved engine efficiency (mileage). The success in adoption rates in EVs will come from the availability of charging networks, improved battery technologies lifespan and charging time, and overall cost reductions in the total cost of ownership for these vehicles. Hydrogen or e-fuels are not expected to be competitive as a fuel type for light road transport.

Carbon reduction will also come from blending renewable energy (RE) fuels into conventional fuels. Denmark is subject to the EU's Fuel Quality Directive, which requires EU Member States to reduce cradle-to-grave emissions of greenhouse gases in transport fuel by 6% per energy unit in 2020 relative to 2010.[73] Fuel specifications aim to ensure compatibility with engines and exhaust after-treatment systems, such as catalytic converters. Consequently, blending certain biofuels is limited due to incompatibility with some engines.

Figure 7.4: Transport emissions shown by source (Mt $CO2_e$)



Road transport by mode (2023)



The majority of road related emissions come from personal vehicles for mobility (60%)

In diesel, biodiesel (FAME) content is typically capped at 7%, while ethanol content in petrol is restricted to 10%. To accommodate higher blends of bioethanol, engines require upgrades to fuel system components with corrosion-resistant materials, recalibrated engine control units for optimization, and enhanced cold start systems. This is a barrier to increased biofuels.

Engines that can run on Methanol and DME are also an option but require engine modifications or special flex fuel vehicle (FFV) kits. Additionally, engines that are E85 (meaning 85% ethanol) are also a possibility. However, this may not be realistic based on the current trajectory of electric vehicles and the cost/limited availability of sustainably sourced biofuels. Corn ethanol, for example, does not meet the criteria for advanced biofuels. E85 is also limited by the number of fuelling stations offering this type of fuel as there are none in Denmark.

Other biofuels such as Hydrotreated vegetable oil (HVO), FAME, or methanol are also potential options in the intermediary stage due to ability to be "drop-in" or utilized in engines with minimal engine modifications. These fuels are compared in Table 7.1. Benefits of using biofuels in the near-term include the ability for easy transport and use in existing infrastructure and the ability to be further synthesized into sustainable aviation fuel when existing vehicle packages become electrified or run on hydrogen. This is shown on the intermediate fuels pathway in Figure 7.7.

Fuel Blending

- Since 2010, biofuels such as biodiesel or bioethanol have been blended into conventional fuels to lower their emissions intensity
- In 2023, bioethanol made up 6.8% of the energy content of conventional gasoline and biodiesel 5.5% of diesel fuels
- These numbers are driven by blending obligation minimums (DK and EU level)

Table 7.1: Comparison of intermediary biofuels for road applications

Criteria	FAME	HVO	Bio-methanol (MeOH)	Bio-Ethanol (EtOH)
Feedstock	Vegetable oils, animal fats, and waste oils	Vegetable oils and animal fats	Natural gas, biomass	Biomass such as corn, sugarcane, and cellulose
Production process	Transesterification	Hydrogenation	Biomass conversion or syngas reforming	Fermentation
Energy density	Moderate (about 37 MJ/kg)	High (about 44 MJ/kg)	Lower (about 20 MJ/kg)	Lower (about 27 MJ/kg)
Engine compatibility	May require modifications to engine and fuel systems	Drop-in fuel; compatible with existing diesel engines and infrastructure	Requires modifications for corrosion resistance	May require modifications for higher blends; corrosive to some materials
Infrastructure	Existing diesel infrastructure with minor modifications	Can use existing diesel infrastructure	Requires dedicated storage and handling infrastructure	Requires modifications to storage and distribution systems
Cost	Affected by feedstocks prices and availability. May be impacted by seasonality and certification of sustainable or "advanced" feedstocks			
Environmental impact	Reduces GHG emissions; could lead to land-use change (ILUC)	Reduces GHG emissions; promotes waste recycling	Reduces GHG emissions; can produce toxic by-products	Reduces GHG emissions; Controversial: food vs fuel debate[i]

i. If not sustainably sourced (e.g. corn ethanol). It is possible to create ethanol from waste products and lignocellulose that meet Annex IX criteria for sustainability: "Advanced Biofuels"

Heavy Road

For heavy road-transport, electrification and hydrogen will be relevant. Despite the higher efficiency of electric engines, the weight, space, and fuelling behaviour of large trucks may make the electric option less attractive. However, improvements in battery density, charging times, or battery-swapping technologies may change this dynamic over time. Hydrogen is an option and can be used in fuel cell electric vehicles (FCEVs). It is attractive for heavy trucking because it offers a high energy density, allowing for longer driving ranges and shorter refuelling times compared to battery electric trucks, which is crucial for the logistics in the transportation industry. The decision of whether to go with an electric of hydrogen trucks depends on the requirements for the vehicle, the status of charging or refuelling infrastructure, and the total cost of ownership between the options. A comparison of electric and hydrogen trucks are shown in Table 7.2.

The adoption rate of electric vehicles is an important factor to consider when aiming to reduce carbon emissions in transport. KF projects that electric truck vehicle sales will start to accelerate in 2027-2028 as the technology sees maturity and commercialization. By 2029, over half of new truck sales are expected to be electric. In the models, hydrogen trucks start seeing sales from 2030 onward but are projected to make up only 6% of new truck sales by 2035, while electric trucks will make up 62% of the total sales. The projections in truck sales in shown in Figure 7.5.

Table 7.2: Comparison of electric versus hydrogen fuel cell trucks

Criteria	Electric Trucks	Hydrogen Trucks
Energy density	Lower energy density; suitable for shorter routes and urban deliveries	Higher energy density; ideal for long-haul routes
Efficiency	Higher energy efficiency (~70%); electric drivetrains convert more stored energy into movement	Lower overall energy efficiency (~30%); hydrogen production, compression, and conversion result in energy losses
Refueling time	Longer charging times (30 minutes to several hours) depending on battery capacity and charger type	Short refuelling times (typically 10-20 minutes)
Infrastructure	Requires widespread charging infrastructure; currently limited but growing	Requires hydrogen refuelling stations; infrastructure is currently less developed but expanding
Operational range	Typically shorter ranges (160-480 km per charge)	Longer ranges (480-800 km or more per tank)
Cost	High initial cost; operational costs are lower due to cheaper electricity and fewer maintenance needs	High initial cost; operational costs higher due to hydrogen price and additional fuel cell maintenance
Weight	Heavier due to large battery packs, potentially reducing payload capacity	Lighter than electric trucks for similar energy storage capacity, potentially allowing higher payload
Maintenance	Fewer moving parts; lower maintenance requirements and costs	Requires maintenance of fuel cells and hydrogen tanks; more complex
Technological maturity	More mature with a broader range of models	Emerging technology; fewer models currently available but rapidly developing

Energy Mixes

When considering total energy use in road transport, gasoline and diesel are still projected to lead the energy mix through 2030 and 2035. This dominance is attributed to the existing vehicle fleets and the time required for a significant transition to low-emission vehicles and the necessary infrastructure build-out.

However, starting in the mid-2020s, biofuels, electricity, and hydrogen are expected to make notable inroads into the total energy use. This shift is driven by advancements in technology, supportive policies, and increasing market adoption of alternative fuel vehicles. Long-term, electricity, hydrogen, and a mix of green fuels are expected to overtake diesel and gasoline.

Figure 7.5: Projected sale of heavy-trucks (2019-2035), number of trucks

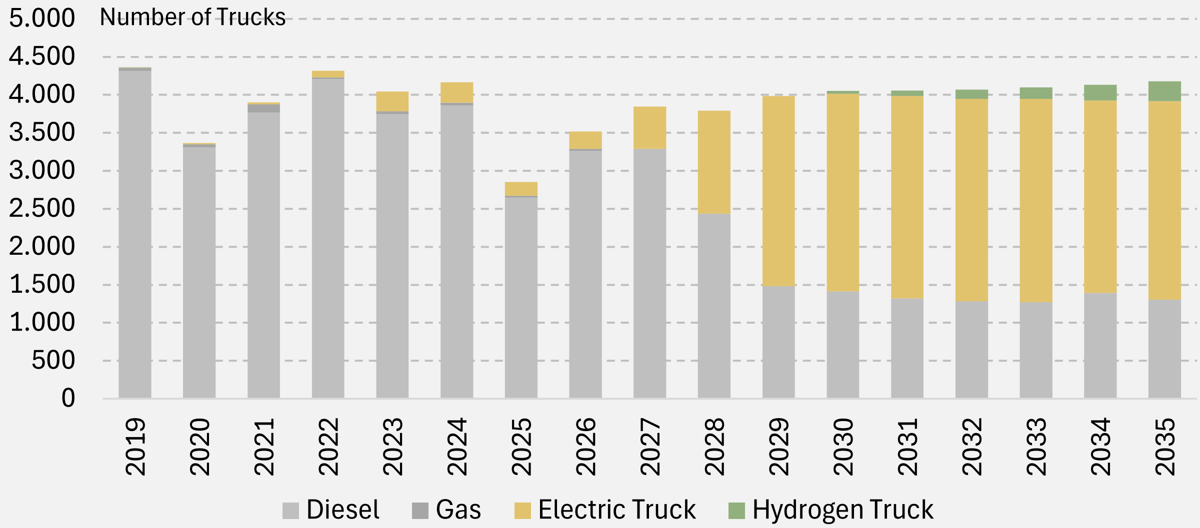


Figure 7.6: Energy use developments in road transport (1990-2035), PJ

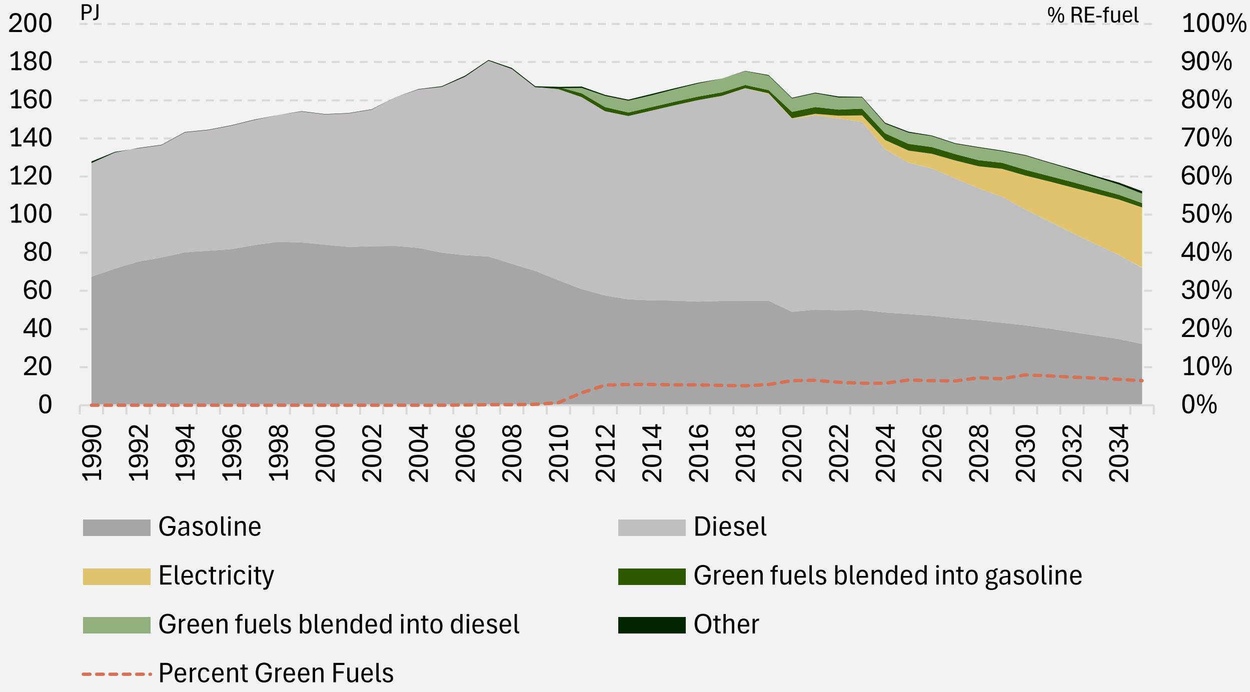


Figure 7.7: Fuel Pathway – Light road transport

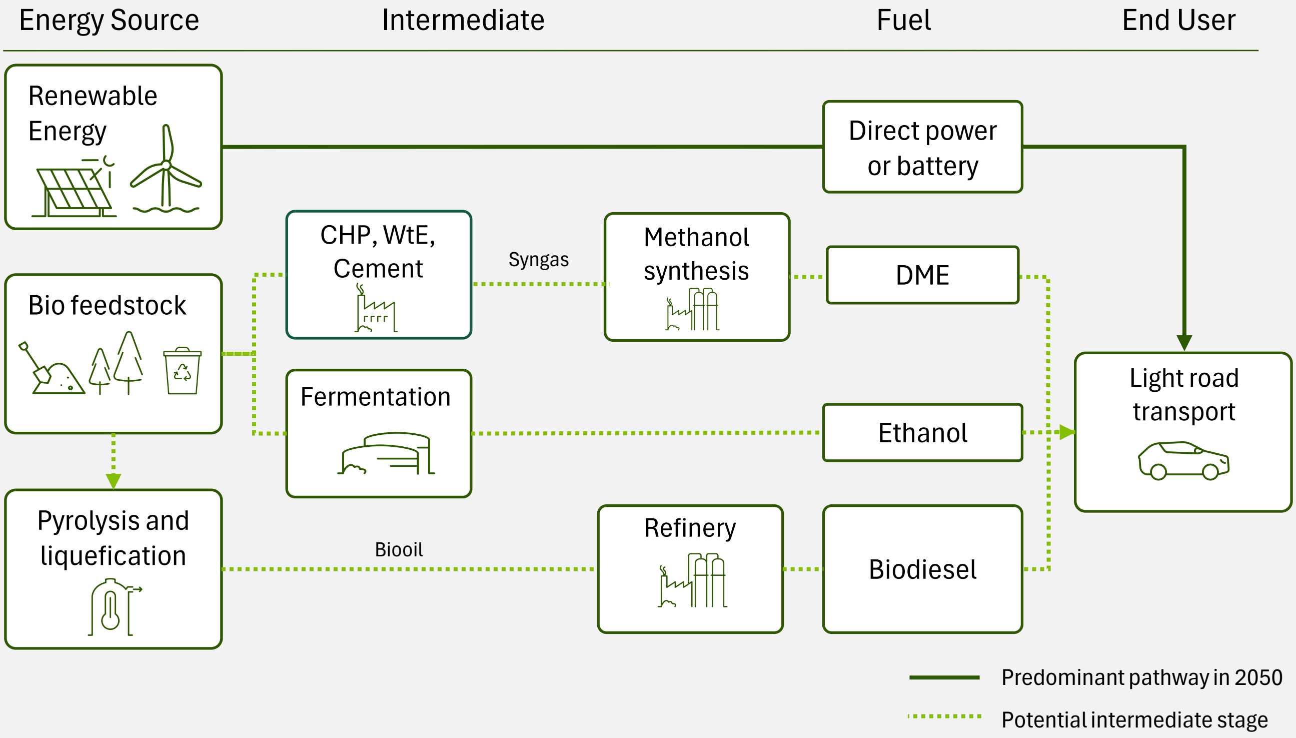
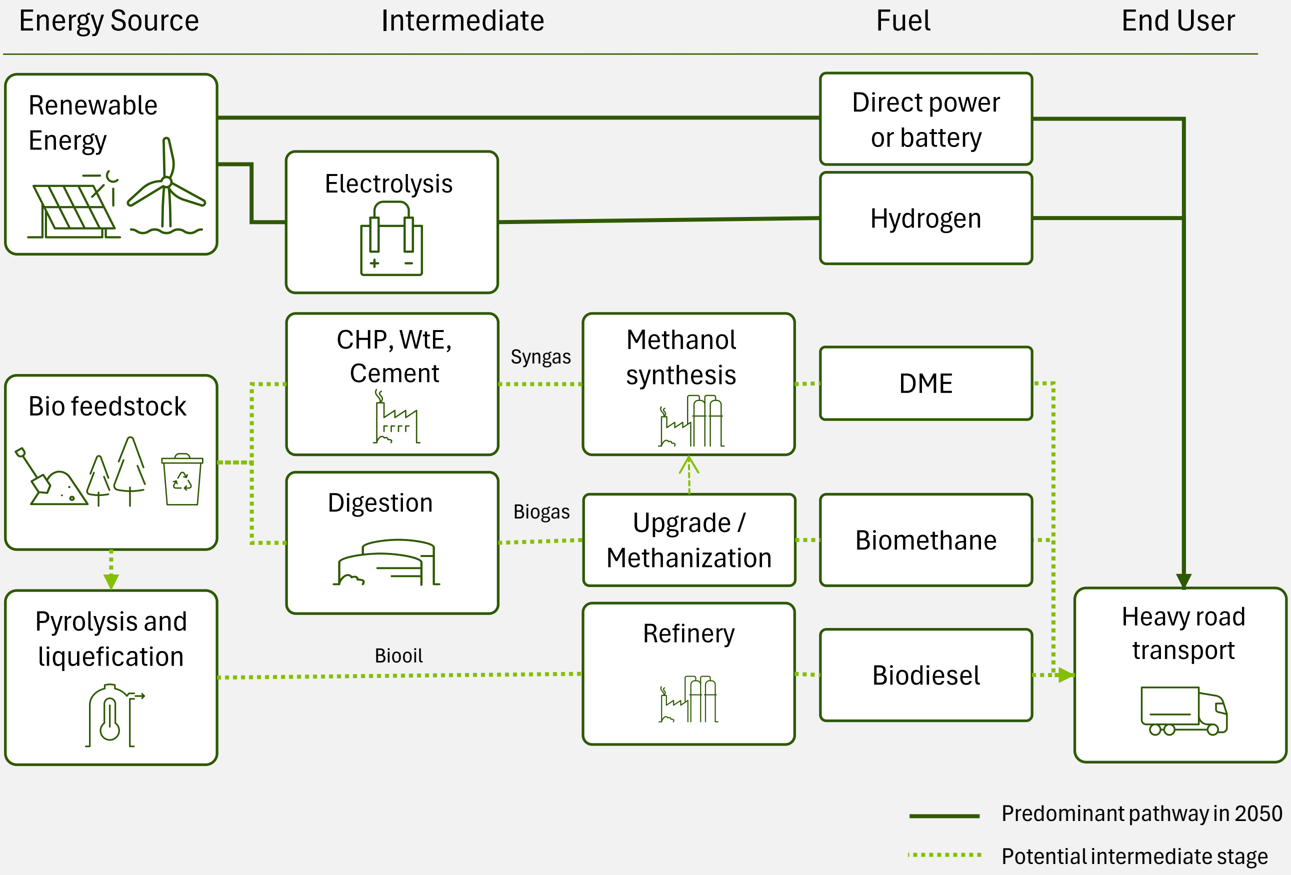


Figure 7.8: Fuel Pathway – Heavy road transport



Road Transport

Key points

① Light road and personal vehicles will be electrified.

② Intermediate fuels (HVO, FAME, MeOH, EtOH) can be considered in the transitional phase to electric and H2 as drop in fuels.

③ Heavy-road expected to be a combination of electrification, blended green-fuels, and hydrogen fuel cells. Use-case dependent.

Emissions (Mt $CO2_e$)

1990	2023	2030	2035
10.4	11.2	7.7	5.4

Relevant technologies

- Electric Vehicles
- H2 Fuel cell vehicles
- Biofuels

Long term-outlook (2035+)

- Electrification of trucks likely as battery technologies improve
- Use cases for hydrogen fuel cells exist in heavy transport where batteries are not practical
- Intermediate fuels can be considered to lower emissions in the transitional phase to electric and H2

7.3 Maritime

Current emissions profile

In 2023, the domestic shipping and maritime sector accounted for 4.1% (0.52 Mt CO2e) of total transport emissions which equates to ~1% of total national emissions. Like domestic aviation, maritime activity within Denmark is a small piece of the national emissions inventory when zooming out and considering the 70% goal. The primary sources for domestic maritime emissions include domestic ferry routes and goods transport (including to and from Greenland and the Faroe Islands) that rely primarily on diesel fuel. The sectoral emissions are shown in Figure 7.9.

International shipping

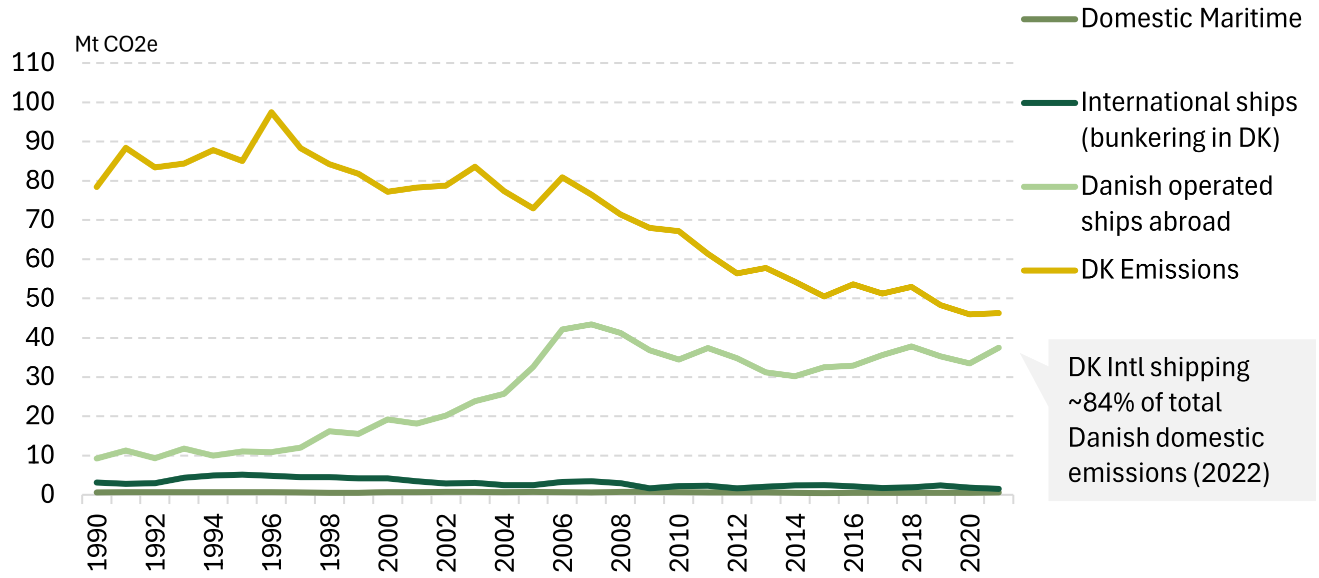
On an aggregate level, 95% of Danish shipping activities take place outside of Denmark and international shipping is a significant source of carbon emissions. In fact, Danish operated ships abroad and international ships bunkering in Denmark accounted for a substantial 39 million tonnes of CO2e.[74]

Emissions from these two sources have risen more than 200% since 1990. The major contributors to carbon emissions from Danish-operated ships include international logistics giants such as Maersk, DFDS, and more. They are significant contributors to the todays globalized economy. When compared, these emissions are more than 80% of Danish emissions (compared to domestic inventory) and represents perhaps the greatest opportunity for decarbonization via green fuels and the most impactful on a global stage, where Danish innovation and strategic positioning can have the greatest outsized influence.

Fuel usage today

Currently, most vessels are fuelled by conventional fuels: marine diesel oil (MDO), heavy fuel oil (HFO). Other names or derivations of these bunker fuels include Low sulphur fuel oils (LSFO), or marine Gas Oil (MGO). Their usage will vary based on application and particulate and sulphur content and regulated by different emissions requirements.

Figure 7.9: Emissions in the domestic and international maritime sector



DK Intl shipping ~84% of total Danish domestic emissions (2022)

LNG and LPG

Recently liquified natural gas (LNG) and liquefied petroleum gas(LPG) have made some advances in replacing heavy fuels, but their usage remains limited and is not technically a long-term green solution considering carbon intensity and methane leakage. Nonetheless, their usage as fuels will likely see use as a bridging technology. More than 40% on new ships on order are LNG/LPG vessels, while 8% are methanol, according to DNV.[75] There could be some "lock-in" effects here, but this could present an interesting entry point for liquified biomethane or synthetic natural gas in the near to medium term.

Green fuels

Green fuels proposed for the maritime sector include biofuels (HVO/advanced biodiesel, bio-oils), methanol, ammonia, and hydrogen. Their usage and potential are constrained by feedstock availability, retrofit ability of existing ship fleets, production volumes of the fuels, and health and safety considerations, among others. Their main characteristics compared to conventional fuels are shown in Table 7.3. The assessment of parameter ratings of the different fuels is generic and may change on a case-by-case basis. The table is meant to give an overview of the main fuel types and some of the barriers to overcome for proposed fuel alternatives.

Table 7.3: Evaluation of maritime fuel options across key parameters

🟩 Favourable / Mature 🟨 Neutral / Minor challenges 🟥 Unfavourable / Major challenges

Fuel Type	LSFO / HFO	LNG	LPG	HVO / biodiesel	Bio-oil	Bio-LNG / SNG	Methanol	Ammonia	Hydrogen[vi]	Electric Battery
Energy density (volumetric)[i]	🟩	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟥	🟥
GHG emissions[ii]	🟥	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩
NOx, SOx, PM emissions[iii]	🟥	🟨	🟨	🟥	🟨	🟨	🟩	🟨	🟩	🟩
Flammability	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟩
Toxicity	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟩	🟩
Engine compatibility[iv]	🟩	🟥	🟥	🟩	🟩	🟥	🟨	🟥	🟥	🟥
Storage convenience	🟩	🟥	🟥	🟩	🟩	🟥	🟨	🟥	🟥	🟨
Bunkering availability	🟩	🟨	🟨	🟨	🟥	🟥	🟨	🟥	🟥	🟨
Commercial readiness[v]	🟩	🟩	🟨	🟩	🟥	🟨	🟨	🟥	🟥	🟨
Regulations and guidelines	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟥	🟥	🟨

Notes: i. Compared to that of HFO. The energy density tells you how much storage volume is needed on the ship to obtain the energy required to propel a vessel. Can be a limiting factor for long-range applications. ii. Highly dependent on well-to-tank production process, renewable sourcing of feedstock, and the calculation methodology for methane slippage. Modelling lifecycle fuel emissions highly depending on case-by-case basis. iii. Emissions of sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM) from ships. Highly dependent on the engine/energy conversion process and scrubber technologies employed on the vessel. iv. Capability of fuel to be used in existing engine stock with little to no modifications. Fuels that are unfavorable require significant retrofits or completely new engines to be able to be utilized. v. Considering availability of fuel, and current technology readiness levels. vi. Renewable hydrogen used in a fuel cell considered.

Sources: DNV Comparison of Alternative Marine Fuels[76], Challenges and opportunities for alternative fuels in the maritime sector – Foretich et. al.[77], Fuel Pathway Maturity Map – Mærsk Mckinney Møller Center for Zero Carbon shipping.[78]

Cruising range

Another critical factor for fuel types are the typical bunkering intervals, cruising time, or the amount of time which a vessel can operate without refuelling. This metric indicates the amount of energy that can be stored onboard. The length of route and the type of vessel (bulk carrier, container, ferry, tankers, passenger ferries, etc) will dictate what fuels will be relevant. There are other factors at pay including vessel cruising speed, weight, etc. A simplified table, based on analysis from DNV is shown below in Table 7.4.

For the Danish domestic maritime sector, routes will be on the shorter end and the amount of cargo limited when compared to large international cargo ships. This allows for lower onboard storage needs and operation profiles that align more with hydrogen and electric batteries. Notably, there exists already four electric ferry routes in Denmark with an additional 14 proposed routes.[79] Many of these routes are short and connect the various islands south of Fyn and Sjælland. For domestic maritime, the DEA expects limited to no usage of green fuels for decarbonization by 2035 in the latest climate status and projection (KF) analysis. However, long-term there may be local usage of methanol, ammonia, biofuels, etc for coastal routes within Danish waters.

For international shipping, the pathways are more limited and must rely on energy dense fuels to cross international bodies of water with vessels often carrying thousands of containers on major import/export routes such as Aarhus to New York (25 days) or Fredericia to Yantian, China (37 days). Electric batteries and compressed hydrogen will likely not be feasible for these applications without great leaps forward in their respective technologies. A mix of biofuels, methanol, and ammonia (emerging in that order) will be the likely candidates for international shipping in the long-term. Nuclear propulsion could also be a dark horse and warrant a second look.

Fuel Costs

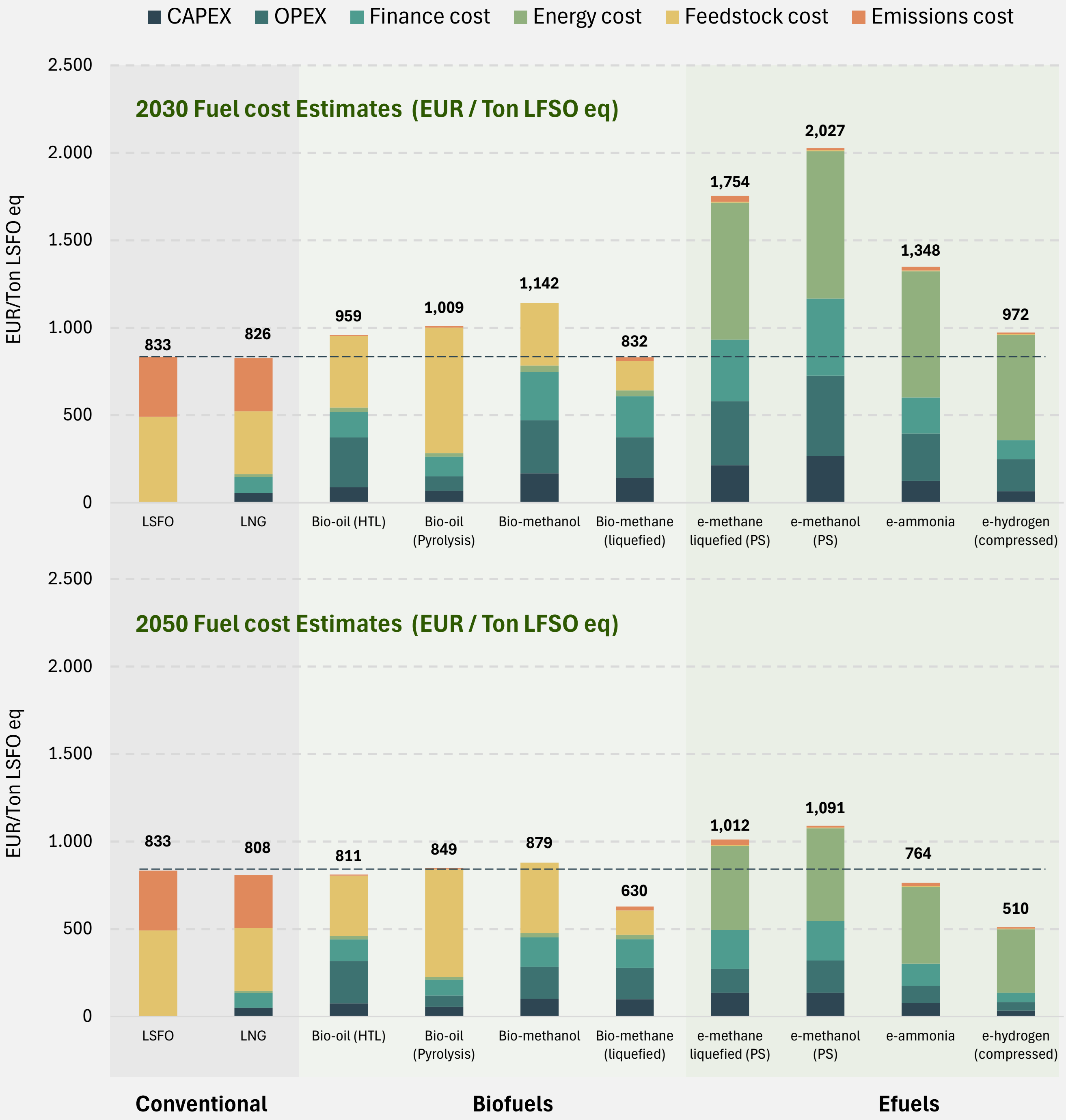
For fuel costs, efuels such as methanol and ammonia will be considerably more expensive than conventional fuels in the short to medium term. The main cost components are the energy costs and opex for producing these fuels (low conversion efficiency from RES input). In 2030, methanol and ammonia are estimated to be 2x-3x the cost of HFO/LSFO ammonia. However, costs are expected to come down and reach closer cost parity by 2050, albeit being more expensive simply due to the inherent nature producing efuels and the amount of conversion steps needed. Cost parity depends strongly on the carbon pricing dynamics of the future, which are difficult to predict. Biofuels are more cost competitive in the near-term, being slightly costlier than conventional fuels in 2030. By 2050, they are expected to be on the same level as conventional LSFO and LNG – assuming ample availability of feedstock. Long-term, two of the cheapest fuel types to produce are expected to be biomethane and compressed hydrogen. However, handling and compression costs are excluded which may add additional costs to using these fuels on a vessel. Cost estimates for 2030 and 2050 are shown in Figure 7.10 and are produced using Maersk fuel cost calculator.[80]

Table 7.4: Typical bunkering intervals by fuel type

	LSFO / HFO	HVO / biodiesel	Bio-oil	LNG	LPG	Methanol	Ammonia	Liquid H2	Compressed H2	Electric Battery
Vessel cruising range[i]	Months	Months	Months	Weeks	Weeks	Weeks	Weeks	Days	Hours-Days	Hours
Typical vessel type[ii]	Large cargo ships	Large cargo ships	Large cargo ships	Medium cargo ships	Medium cargo ships	Medium cargo ships	Medium cargo ships	Small cargo ships	Small cargo ships	Short range ferries
Applicability	International							Domestic / regional		

Notes: i. Endurance will depend on ship operations, speed, and onboard storage capacity. ii. Large cargo = vessels designed for long-haul routes and can carry massive amounts of cargo, including bulk commodities, containers, and oil (e.g. ultra-large or very large crude carriers). Medium cargo = Most common shipping vessels - bulk and container carriers (e.g. ships designed to fit through Panama or Suez canals). Small cargo = vessels used for short-haul routes, feeder services, and specialized cargo operations.
Source: Adapted from DNV Comparison of Alternative Marine Fuels-[76]

Figure 7.10: Marine fuel cost estimates in 2030 and 2050



Notes: LSFO: Low Sulfur Fuel Oil, HTL: hydrothermal liquefaction, PS: point source carbon capture, e-methane also referred to as synthetic natural gas (SNG). Bio-oils shown for different conversion technologies HTL and pyrolysis (share similar technical characteristics to HVO)
Ton LSFO eq ~42 GJ of energy.
Emissions considered on well-to-wake (WTW) with an applied cost of 100 USD per ton CO2e and held static for 2030 and 2050.
Conversion rate USD to EUR = 0.92
Source: Adapted from Maersk Fuel Cost Calculator v0.9.2 (public).[80]

No single winner

It is important to note that most analyses that assess the roadmaps for sustainable maritime fuels highlight significant uncertainties do not crown a single “winner”; the overall conclusion is that a number of fuels will likely be required . Intermediary fuels (LNG/LPG) will be needed to bridge existing fleets to lower emissions fuels and the projected long-term mix of methanol, ammonia, biomethane, synthetic, methane, etc will depend on several factors including biomass availability, renewable energy build out, technological advancement, and regulations. Analyses from DNV project that by 2050, green fuels uptake will accelerate in the mid 2030’s, culminating to an estimated ~14,000 PJ/year in 2050.[75] The estimated fuel mix for the maritime sector is shown in Figure 7.11.

Pathways

Based on what is currently known, the pathways for the maritime sector are theorized below:

Short-term pathways (before 2030)

Short-term emission reduction levers include the electrification of short-distance ferry and goods transport routes, implementation of energy efficiency measures (such as hull design, propulsion efficiency, hybrid systems, route optimization), and the reduction of carbon intensity in fuels through blending with green fuels. In parallel, demonstration projects and technology development for methanol-powered ships (e.g. Laura Maersk), ammonia engines, and the planning of infrastructure and "green shipping corridors" for green fuels will advance. The emergence of dual-fuel engines, which can run on both diesel and methanol, will be instrumental during this transitional period as production capacities of green fuels will be limited in the scale up period. Additionally, the use of HVO and biofuels as drop-in replacements for conventional engines will be prevalent in the short to medium term. This will be complemented by the introduction of new vessels, advancement of technology readiness levels (TRLs) for ammonia engines, and the development of necessary bunkering infrastructure.

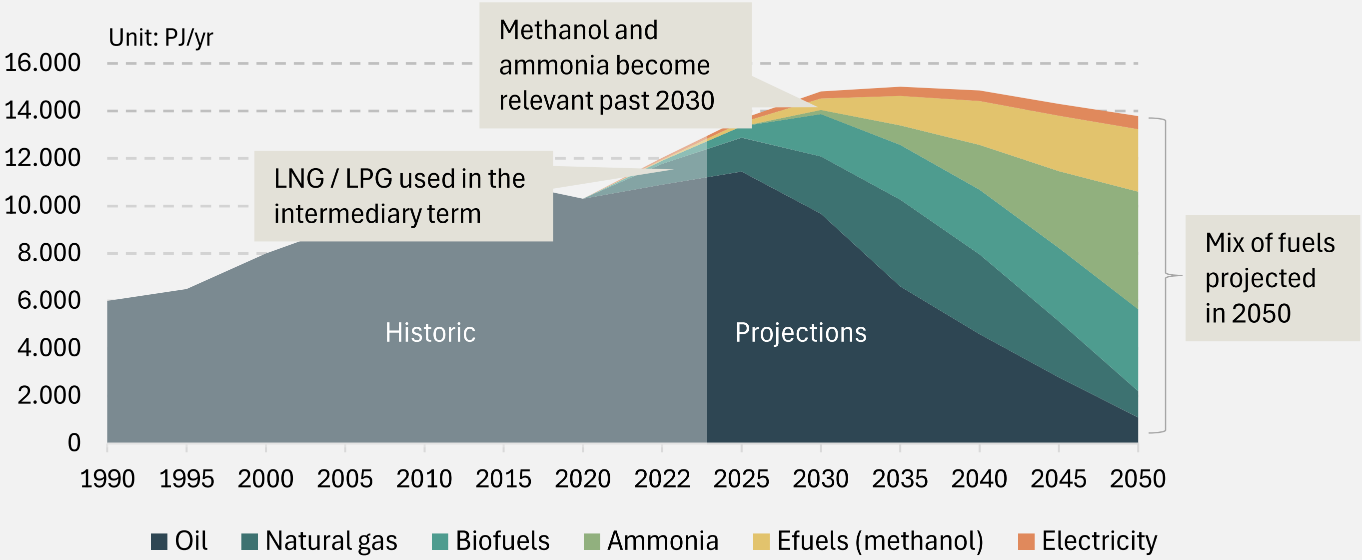
Medium-term pathways (2030-2040)

In the medium term, the maritime industry will see a significant shift towards the widespread introduction of green fuels, such as green hydrogen, methanol, and ammonia, as technological advancements and infrastructure development mature. The deployment of zero-emission vessels will be accelerated, supported by the establishment of comprehensive bunkering infrastructure, green shipping corridors, and global regulatory frameworks. Policy and emissions pricing are expected to incentive this shift as well as voluntary corporate sustainability goals. Dual-fuel engines will continue to play a crucial role, gradually transitioning to pure green fuel operations (e.g. diesel to methanol). Continued research and development will enhance the combustion efficiency and safety of these fuels, while strategic investments in renewable energy production and supply chains will improve their economic viability. Bridging technologies such as LNG ships could see a shift towards biomethane or synthetic natural gas as the fuel, given their availabilities.

Long-term pathways (2040+)

The long-term pathway for decarbonizing the maritime industry envisions the full-scale adoption of efuels, such as ammonia and methanol. By 2050, these fuels will be readily available on the marine fuel market, facilitated by an expansive global bunkering infrastructure capable of supporting large-scale distribution and storage. Vessels will be equipped with advanced propulsion systems, including high-efficiency fuel cells and next-generation internal combustion engines specifically designed for these green fuels. Comprehensive international regulations will mandate the use of zero-emission fuels, enforced by organizations such as the International Maritime Organization (IMO), aiming for net-zero emissions with intermediate targets of 20% reduction by 2030 and 70% by 2040.[81] The high initial costs of transitioning to alternative fuels could be mitigated by financial incentive mechanisms and carbon pricing. Significant investments in infrastructure, including the establishment of green shipping corridors, will support the widespread use of alternative fuels. Achieving these decarbonization goals will require a lifecycle approach to evaluating fuel sustainability, ensuring that well-to-wake emissions are minimized.

Figure 7.11: World maritime energy demand projections by fuel type



Methanol and ammonia become relevant past 2030

LNG / LPG used in the intermediary term

Mix of fuels projected in 2050

Source: Adapted from DNV Energy Transition Outlook 2023 report.[75] Historic data from IEA word Energy Balance 2022.[82]

Maritime

Key points

① **International shipping** emissions are substantial, with Danish-operated ships emitting ~39 million tonnes of CO2e/yr, presenting a **major decarbonization opportunity**.

② The majority of vessels currently use conventional fuels like marine diesel oil (MDO) and heavy fuel oil (HFO), with some adoption of **LNG and LPG as interim solutions.**

③ Proposed green fuels for shipping include **biofuels, methanol, ammonia, and hydrogen**, though they face challenges related to feedstock availability, retrofitting existing fleets, production volumes, cost, and safety considerations

④ No clear winner: a **mix of green fuels (and batteries)** is expected to be utilized in the maritime sector in 2050

Emissions (Mt $CO2_e$)

	1990	2023	2030	2035
Domestic	0.58	0.52	0.49	0.49
Intl.[iii]	12.4	39.0	35.4	24.3

Relevant technologies

Biofuels

Natural gas[i]

Bunkering infra.

Methanol

Ammonia

Propulsion tech[ii]

Outlooks

Short-term (before 2030)

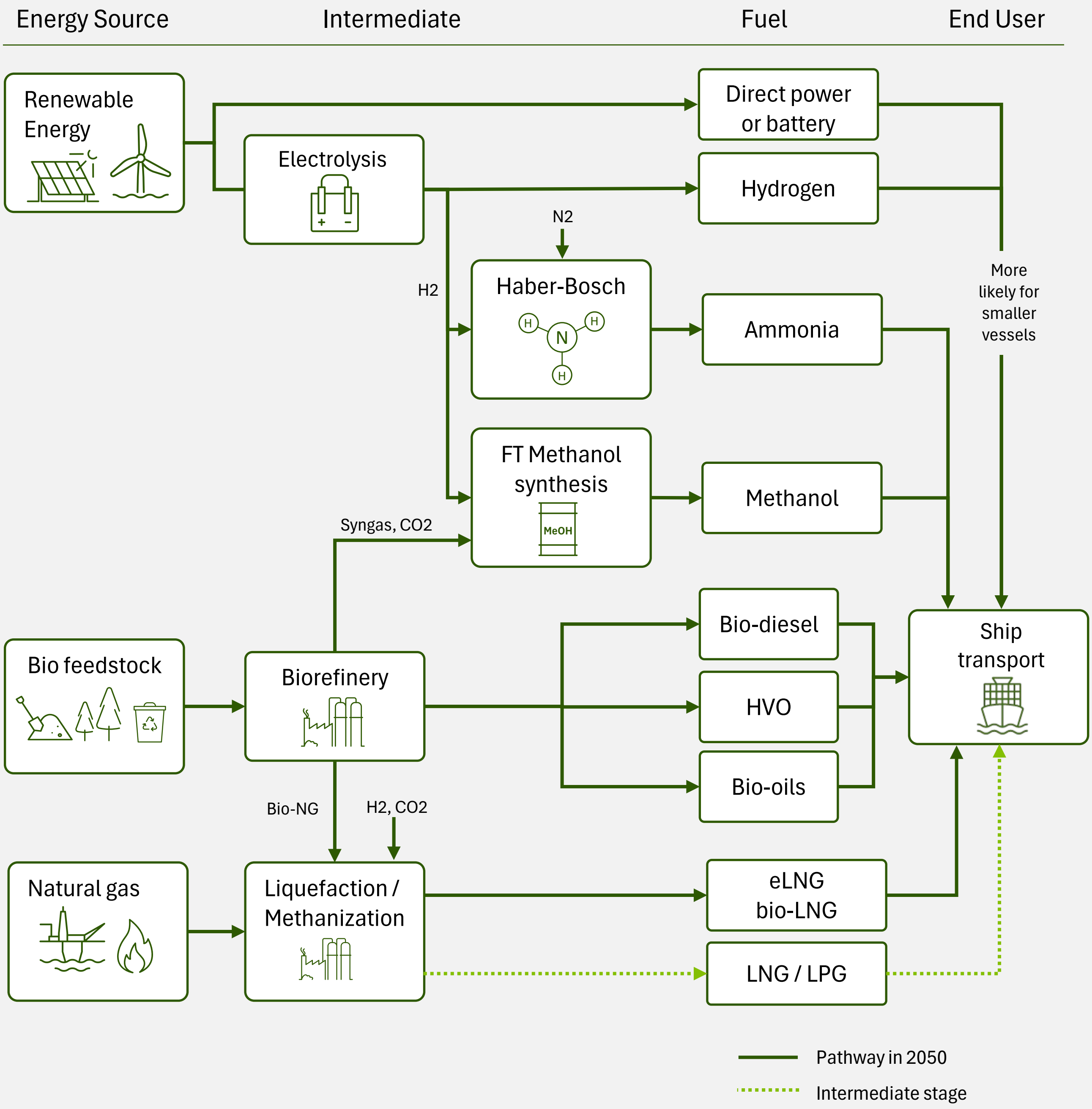
- Use of intermediary fuels (biofuels, LNG/LPG), or electrification of small vessels
- Emissions intensity reductions via fuel blending any efficiency improvements
- Technology maturity of efuel technologies and associated propulsion/handling tech

Long-term (after 2030)

- Conversion of existing maritime fleets to green fuel compatibility (retrofit or new)
- Scale up of methanol, ammonia, hydrogen fuel types and widespread usage

i. Includes LNG, LPG, SNG, of bio-LNG
ii. Propulsion tech includes battery-electric propulsion, methanol and ammonia engines, and ammonia/H2 fuel cell technologies
iii. For international shipping, projections to 2030 and 2035 use IMOs targets for 20% and 70% reduction by 2030 and 2040 (over 2008 levels) to project a conceivable emissions profile in those years

Figure 7.12: Fuel Pathway – Maritime



7.4 Aviation

Current emissions profile

Domestic aviation emitted 0.12Mt CO2e in 2023 accounting for 1% of total domestic transport sectors emissions. When compared to the 70% GHG reduction target by 2030, domestic aviation is almost negligible, with the total sector emission only accounting for 0.26% of total Danish emissions. However, for international or cross-border (long-haul) aviation, aviation emissions peaked at ~6Mt CO2e in 2019 (pre-covid) and have now sit at 4.2 Mt CO2e for 2022. For international aviation, passenger flights constitute most of the aviation activities and, consequently, the majority of greenhouse gas emissions from the sector. Domestic and International emissions are shown comparatively below.

A hard-to-decarbonize sector

The aviation sector has limited pathways to decarbonize due to aircraft range/weight constraints as well as limitations imposed by existing airport infrastructure and operating models. Sustainable aviation fuel (SAF), produced through bio-based or synthetic (power-to-liquid or PtL) technologies, provides a "drop-in" replacement that can be blended up to 50% in existing aircraft.[83] Other technologies that have been theorized to decarbonize the aviation sector include novel propulsion technologies in the form of hydrogen and battery-electric aircraft. Each have their own set of unique barriers and challenges that are listed in Table 7.5 on the following page.

Figure 7.13: Emissions in domestic and international aviation sector (2009-2022)

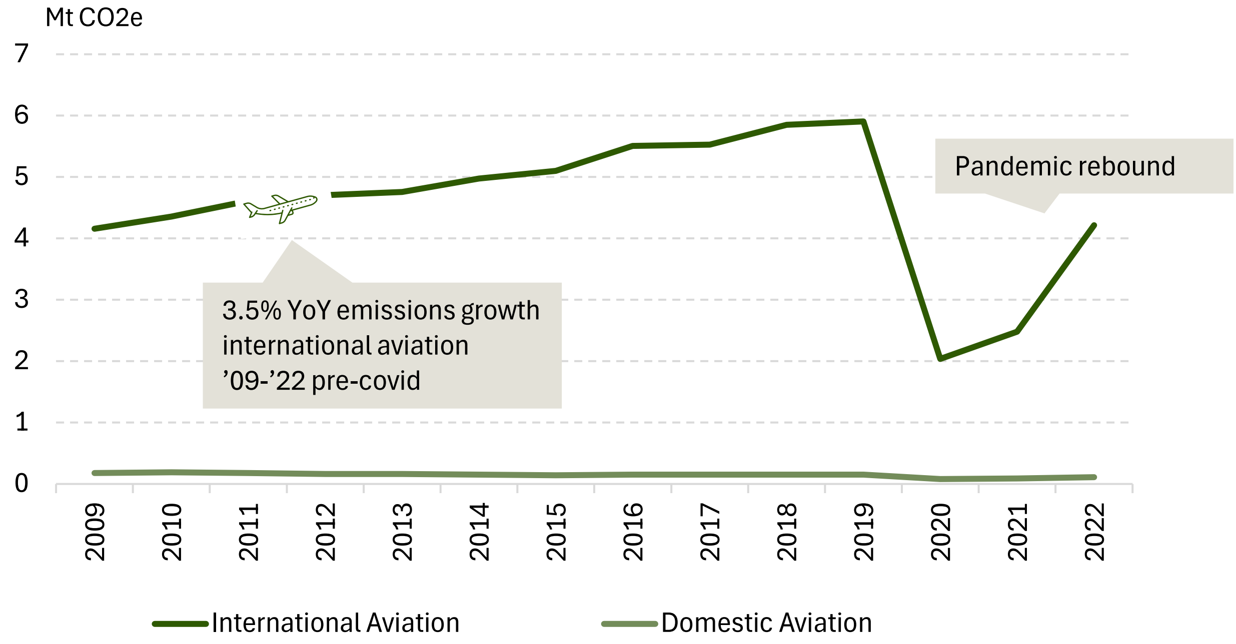


Table 7.5: Comparison of aviation fuels

Comparison vs traditional jetfuel	SAF (bio + e)	Battery-Electric	H2 Fuel Cell	H2 Turbine
Aircraft design	🟩 Used with existing fleet	🟥 New aircraft design		
Airport infrastructure	🟩 Existing fueling infrastructure	🟥 Battery exchange of fast-charging needed	🟥 Liquified H2 distribution and storage needed	
Aircraft operations	🟩 No change	🟨 Longer; depending on technology	🟨 1-2x longer fueling time	🟨 2-3x longer fueling time
Climate impact[i]	🟨 30- 60% reduction	🟩 100% reduction	🟩 75-90% reduction	🟨 50-75% reduction
Efficiency of propulsion system[ii]	🟥 ~15-20%	🟩 ~60-75%+	🟨 25-45%	🟨 ~30%
Expected market entry	🟩 Before 2030	🟨 Estimated 2035-2040		

🟩 Clear advantage 🟨 Minor obstacle or drawback 🟥 Major obstacle or drawback

Notes: i. Climate impact assumes 100% RES. Includes CO2, NOx, and water vapour contrails for combustion (SAF + turbines)
ii. Well-to-wake efficiency estimates – highly dependent on well-to-tank efficiency and upstream losses
Sources: Mission Possible Partnership[84], Clean Aviation EU[85]

Sustainable Aviation Fuels (SAF)

Overall, SAF has the clear advantage pre-2030 based on the ease to integrate SAF into existing aircraft and airport operations. Based on the immaturity of battery-electric and hydrogen and the need for aircraft redesign, and associated development costs and regulatory hurdles associated with novel technologies, SAF will be the primary pathway focused on in this roadmap. It is expected that bio-based SAF will be the most relevant in the short-term before e-SAF (power-to-liquid) technologies scale. However, the other technologies come into play in the medium and long term and may play a role in domestic aviation decarbonization, especially with shorter domestic routes (e.g. Copenhagen to Aalborg ~240kms).

SAF Properties

Like Jet fuel, SAF consists of various hydrocarbons and is defined by performance specifications rather than a specific chemical composition, with kerosene-type fuels having carbon numbers between 8 and 16 (Jet-A) and naphtha-type fuels between 5 and 15 (Jet-B). The composition varies based on the petroleum (or other feedstock) source and can be optimized during the production process for specific requirements like freezing and smoke points. For SAF, there are four pathways that are the most likely candidates to scale and attract attention: bio-oils such as HVO or hydroprocessed esters and fatty acids (HEFA); alcohol-to-jet (AtJ); gasification/Fischer-Tropsch (gas/FT); and power-to-liquid (PtL) efuels. These production pathways are compared in Table 7.6

Table 7.6: Comparison of SAF pathways (bio and eSAF)

Category	**Bio-based SAF**			**eSAF (PtX)[i]**
Name	**Bio-oils (HVO/HEFA)**	**Alcohol-to-jet (AtJ)**	**Gasification + Fischer-Tropsch**	**Power-to-liquid (PtL)**
Feedstock	Vegetable oils, animal fats, and waste oils, lipids	Any bio feedstock that can produce alcohols (forestry residues, wood waste and agricultural residues), MSW		Green electricity + CO2 (biogenic or point source)
Production process	Hydrotreatment commonly used at petroleum refineries	Fermentation followed by catalytic upgrading	Gasification followed by Fischer-Tropsch synthesis	H2 electrolysis, combined with CO2 to produce hydrocarbons
Technology maturity	Mature TRL = 9	Emerging TRL ~7	Emerging TRL~7	Pilot/Prototype TRL ~5-6
GHG reduction %[ii]	73-85%	85-94%	85-94%	99-100%
Timing for scale up	Now : Proven and scalable technology	<2030: Significant near-term potential however techno-economic issues to overcome		After 2030: PtX , RES, and CO2 infra build-out needed
Limitations / barriers	Inherent limitations on waste oil feedstock	High production costs, fragmented feedstock availability, technical complexity		High energy requirements, cost, biogenic CO2 availability
Sustainability considerations	Potential competition with food crops, deforestation risks	Land use, potential competition with food production	Water, air pollution, ash, and by-product disposal	Requires significant renewable electricity supply

Notes: i. Synergies with hydrogen utilization in (G/FT) process to optimize syngas/H2 ratios for SAF production (bio-e-SAF)
ii. Compared to fossil kerosene. LCA values from CORSIA
Sources:, Mission Possible Partnership[84],Clean Aviation EU[85], World Economic Forum[86], ICAO[87], SDU (2019)[88]

SAF Timing

Based on maturity and technical feasibility the pathway for SAF will likely be: A) production of HVO/HEFA based biofuels in the short-term until feedstock is tapped B) production of alcohols upgraded to jet and gasification/FT based biofuels in the short and medium term, and finally C) the emergence of PtL liquids post 2030 when the technology is mature and there is ample RES to produce vast quantities of efuels. If production of HVO/HEFA is uneconomical in DK, jump to points B or C and rely on imports for HEFA based SAF in the near-term. These SAF pathways, alongside battery/H2 technologies, are described in the next sections.

Short-term pathways (before 2030)

Due to infancy of SAF and limited production quantities, immediate near-term CO2 reduction in the aviation sector will come in the form of demand reduction (via taxation, consumer behaviour shift) or alternative transportation modes becoming more attractive. Additionally, enhancing fuel efficiency, optimizing flight operations, and increasing the use of SAF via blending mandates will help reduce CO2. SAF based on HVO/HEFA will be the first to see widespread traction and typically blended with conventional jet fuels of ratios of 50%. In the short-term, this will likely be imported. Technological maturity of gasification/FT, and Alcohol-to-Jet will take place and demo plants scaled up.

Medium-term pathways (2030-2040)

Between 2030 and 2040, the mass-scale up of bio-based SAF refineries including gasification-FT plants, Alcohol-to-jet plants, and the required feedstock collection infrastructure will be needed. The emerging technologies will mature and see widespread adoption. E-SAF based on electrolysis will start to mature as additional gigawatt scale electrolysis plants start entering operation. On a parallel pathway, the focus may shift towards the introduction of novel propulsion technologies, such as hydrogen and battery-electric aircraft. Hydrogen combustion and fuel cell technologies offer significant potential for reducing CO2 emissions but may only be relevant for short and medium-haul flights. However, the deployment of these technologies requires overcoming substantial technical and infrastructural hurdles, including the development of new aircraft designs and airport refuelling infrastructure. SAF is likely the most realistic solution in the short and medium term due to existing fleets and the infrastructure and supply chain around fuel bunkering and the needs for an energy-dense drop-in fuel that can replace conventional jet kerosene. During the medium term, electric and hydrogen planes may see some niche applications and demo routes as R&D projects from major and novel aircraft manufactures come to fruition.

Long-term pathways (2040-2050)

By 2040 and beyond, the sector aims to achieve near-total decarbonization through scaled up e-SAF production and the commercial adoption of hydrogen and electric propulsion for medium to long flight ranges. Methanol/ethanol plants that have been producing road fuels can be converted to upgrade to SAF (as that sector will become electrified). The scale needed will be enormous: globally, hundreds of SAF production plants will be needed.[86]

Production synergies with other green fuels

It is important to note that the production of SAF there are also synergies with the production of sustainable road fuels or chemicals. Synthesis processes such as AtJ, gasification/FT, and PtL yield other products than SAF such as biodiesel, naphtha, and other light hydrocarbons. For example, a typical gasification/FT process with a 20% conversion rate will yield ~60% kerosene (SAF), with 22% of road fuels (biodiesel), and 18% light hydrocarbons gases and liquids such as LPG and naphtha. These ratios can be optimized depending on the amount of introduced hydrogen feedstock and the plant operating parameters.

Aviation

Key points

① In Denmark, **domestic aviation is a minor piece** of overall transport emissions and the use of green fuels to make significant climate impact on the 2030 70% goal is limited

② **International aviation and potential exports** of DK based SAF is **more consequential** to the Danish green fuels industry

③ Policy drivers include **ReFuelEU targets** and DK national level goals, and voluntary targets

④ Based on inherent **bio feedstock constraints**, PtL e-SAF will become a long-term solution. Intermediate fuel production from other pathways (road, shipping) should eventually be **converted to SAF**

Emissions (Mt $CO2_e$)[iii]

	1990	2023	2030	2035
Domestic	0.24	0.12	0.14	0.14
Intl.	2.3	4.2	5.3	5.3

Relevant technologies

Bio-SAF tech	Power-to-liquid (PtL) efuels	Novel propulsion

Outlooks

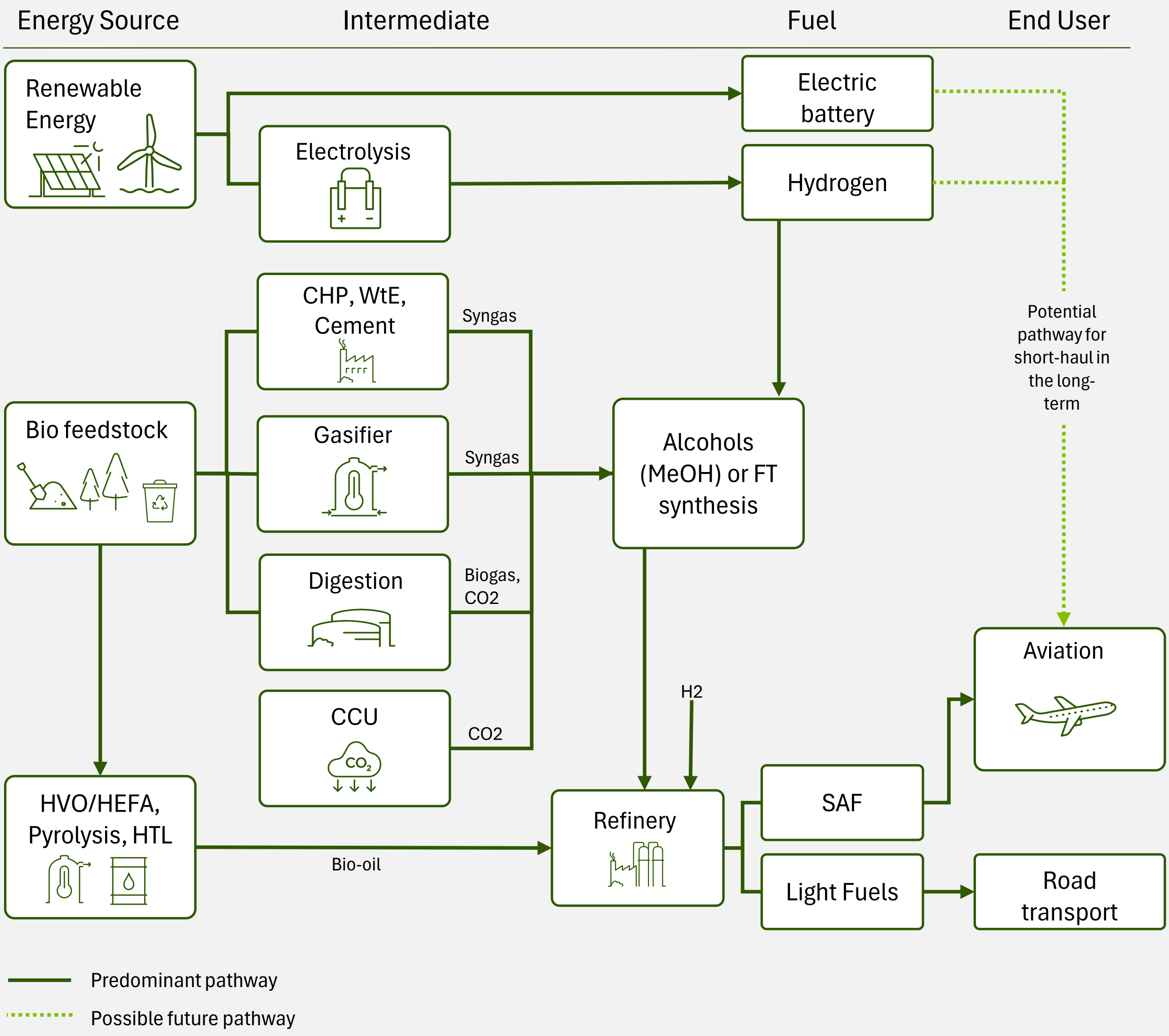
Short-term (before 2030)

- Bio-SAF in the form of HEFA/HVO the most relevant and proven. Potentially imported
- Continued technological maturity of gasification/FT, alcohol-to-jet, HTL, PtL synthesis via first-of-a-kind plants in DK

Long-term (after 2030)

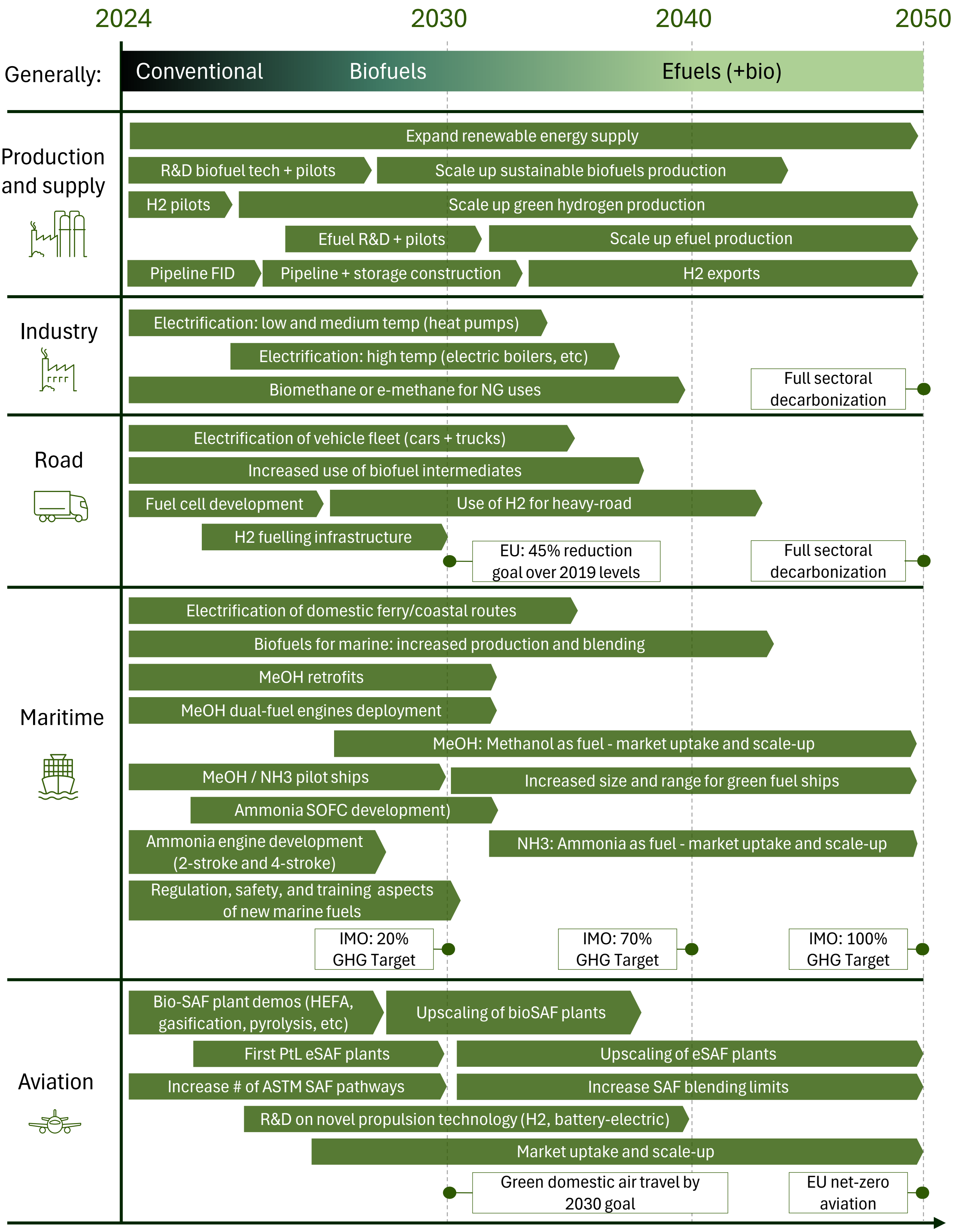
- Continued scale up of bio-SAF, mass scale up and adoption of PtL
- Conversion of MeOH plants to AtJ plants
- Novel propulsion systems (electric / H2 fuel cell or turbine) may become relevant

Figure 7.14: Fuel Pathway – Aviation



7.5 Sector Timing

The below figure estimates timing on the path towards 2050 for various segments in the green fuels sector. Overall, the figure shows a phased approach to scaling from pilots to industrial-scale operations, supported by infrastructure build-out, technology development of both supply and offtake, and market adoption in various industrial and transport sectors. Policy targets in 2030, 2040, 2050 are shown alongside the developments.



2024 2030 2040 2050

Generally: Conventional, Biofuels, Efuels (+bio)

Production and supply

- Expand renewable energy supply
- R&D biofuel tech + pilots
- Scale up sustainable biofuels production
- H2 pilots
- Scale up green hydrogen production
- Efuel R&D + pilots
- Scale up efuel production
- Pipeline FID
- Pipeline + storage construction
- H2 exports

Industry

- Electrification: low and medium temp (heat pumps)
- Electrification: high temp (electric boilers, etc)
- Biomethane or e-methane for NG uses
- Full sectoral decarbonization

Road

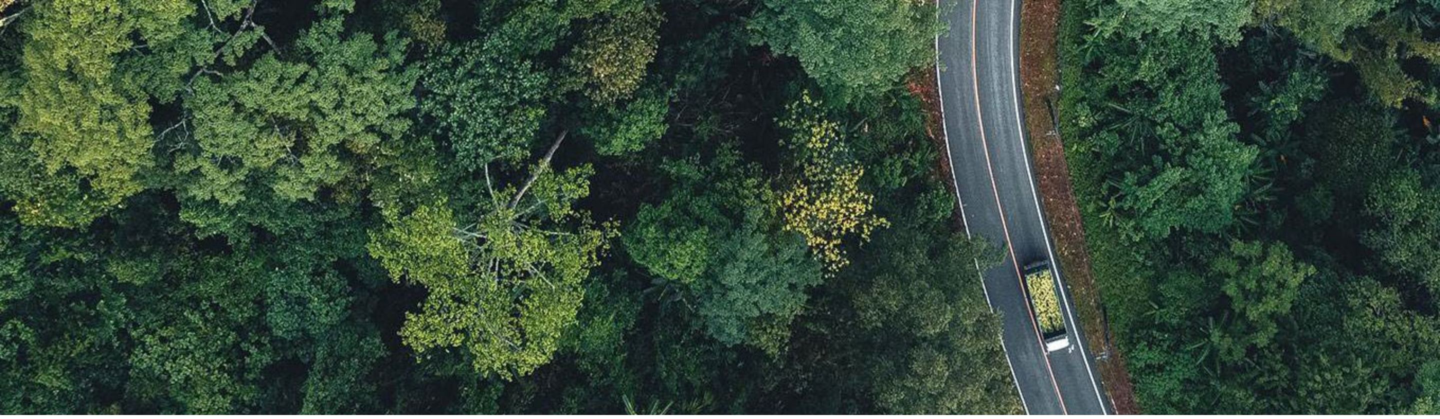
- Electrification of vehicle fleet (cars + trucks)
- Increased use of biofuel intermediates
- Fuel cell development
- Use of H2 for heavy-road
- H2 fuelling infrastructure
- EU: 45% reduction goal over 2019 levels
- Full sectoral decarbonization

Maritime

- Electrification of domestic ferry/coastal routes
- Biofuels for marine: increased production and blending
- MeOH retrofits
- MeOH dual-fuel engines deployment
- MeOH: Methanol as fuel - market uptake and scale-up
- MeOH / NH3 pilot ships
- Increased size and range for green fuel ships
- Ammonia SOFC development)
- Ammonia engine development (2-stroke and 4-stroke)
- NH3: Ammonia as fuel - market uptake and scale-up
- Regulation, safety, and training aspects of new marine fuels
- IMO: 20% GHG Target
- IMO: 70% GHG Target
- IMO: 100% GHG Target

Aviation

- Bio-SAF plant demos (HEFA, gasification, pyrolysis, etc)
- Upscaling of bioSAF plants
- First PtL eSAF plants
- Upscaling of eSAF plants
- Increase # of ASTM SAF pathways
- Increase SAF blending limits
- R&D on novel propulsion technology (H2, battery-electric)
- Market uptake and scale-up
- Green domestic air travel by 2030 goal
- EU net-zero aviation



8. Green Fuel Roadmaps

Methodology

The following sections present the insights from MissionGreenFuels stakeholders along the various fuel types: green hydrogen, intermediary fuels, maritime fuels, and aviation fuels. Key activities, potential challenges, and opportunities in the scale-up of these fuels are informed by **expert interviews, stakeholder surveys, and workshops** held during the data and insights collection phase of the roadmap updating process.

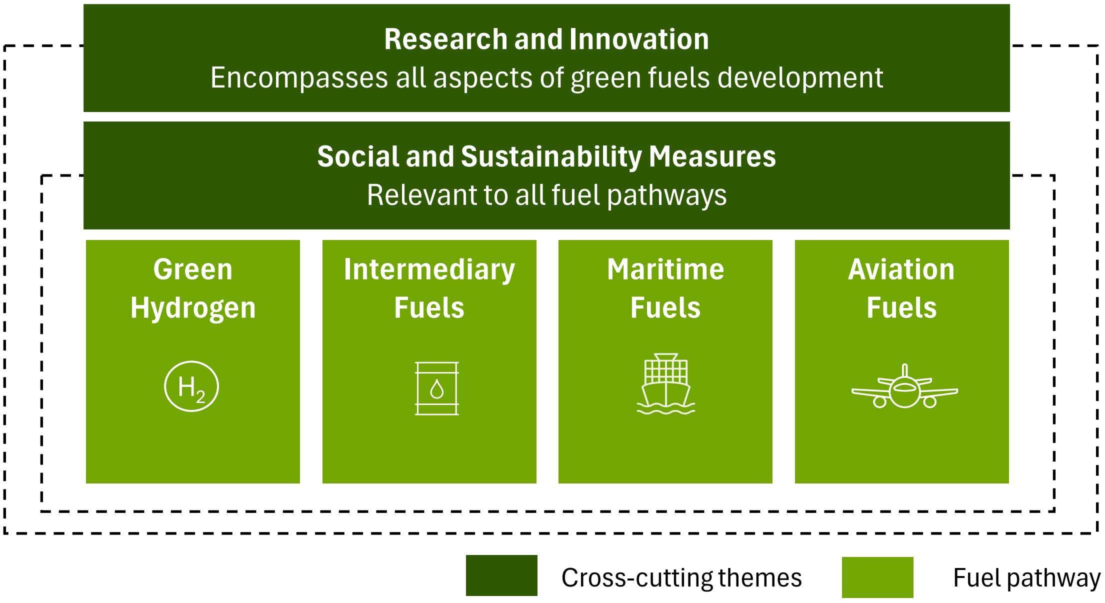
The **key activities in the short-and-long term are identified** by stakeholders and presented across various themes including technical, commercial, regulatory, and financial, and social elements. Timing of when activities will happen is informed by the latest developments in industry and policy, however longer-term activities are uncertain and estimates of when developments will likely happen instead of will surely happen. Ramboll insights and interviews were used as complementary information sources. Extensive public sources such as academic papers, industry reports, and grey literature were consulted and can be found in the references section. It is important to note that MGF supports new and low-TRL technologies not mentioned in the roadmap.

Cross-cutting themes: social Sustainability and Innovation

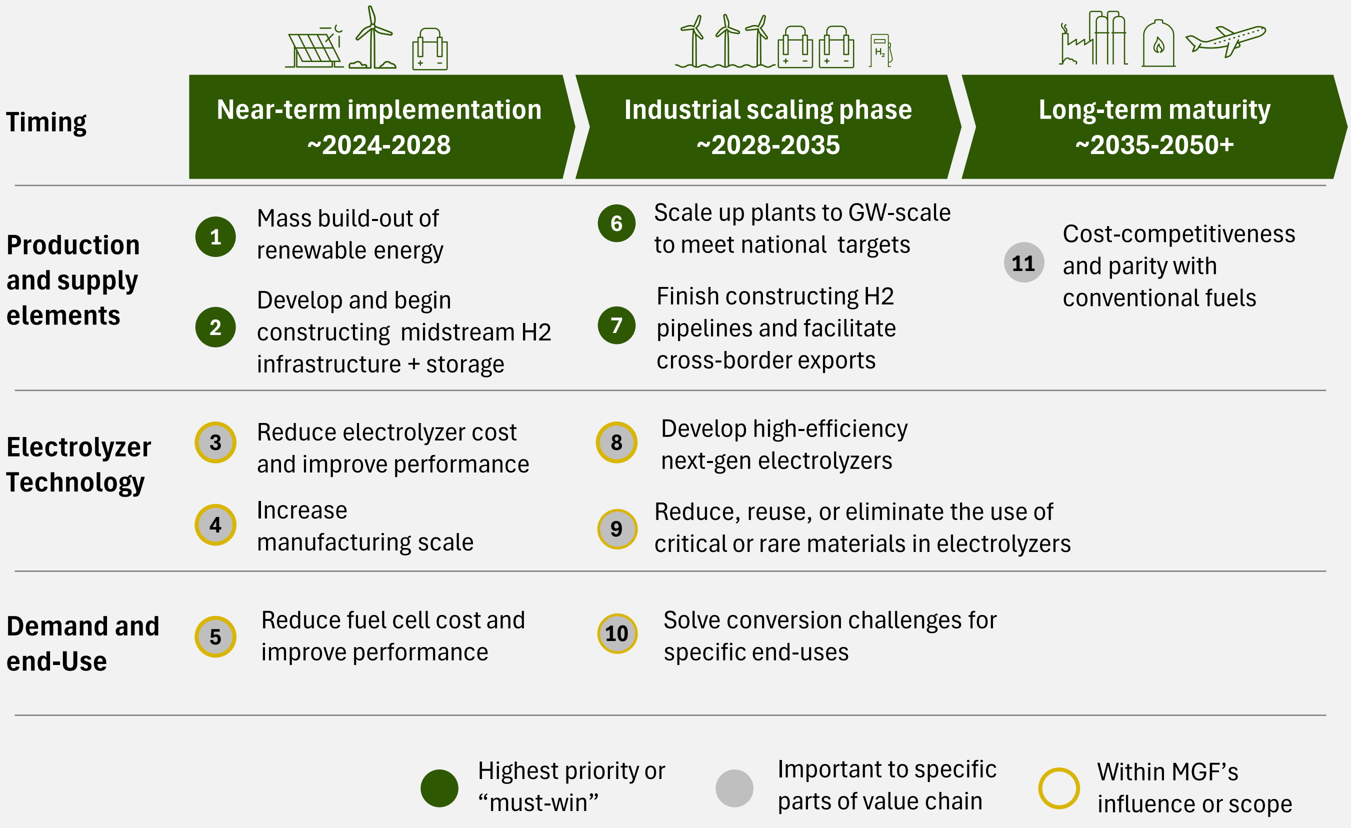
It is important to note that the roadmaps presented in chapter 10 are technically focused, however **social and sustainability issues are cross-cutting** and can be found in Chapter 5. Similarly, commercial, regulatory and financial needs can be found in in Chapters 9 and 10, respectively.

While the roadmaps pinpoint specific R&D measures along each fuel pathway, **innovation is relevant for all fuel pathways**. This includes research in citizen engagement, sustainability, and the development of frameworks for measuring the environmental and social impacts of green fuel projects.

Figure 8.1: Innovation underpins all aspects of green fuel development



8.1 Key activities in the green hydrogen roadmap



Timing	Near-term implementation ~2024-2028	Industrial scaling phase ~2028-2035	Long-term maturity ~2035-2050+
Production and supply elements	1 Mass build-out of renewable energy 2 Develop and begin constructing midstream H2 infrastructure + storage	6 Scale up plants to GW-scale to meet national targets 7 Finish constructing H2 pipelines and facilitate cross-border exports	11 Cost-competitiveness and parity with conventional fuels
Electrolyzer Technology	3 Reduce electrolyzer cost and improve performance 4 Increase manufacturing scale	8 Develop high-efficiency next-gen electrolyzers 9 Reduce, reuse, or eliminate the use of critical or rare materials in electrolyzers	
Demand and end-Use	5 Reduce fuel cell cost and improve performance	10 Solve conversion challenges for specific end-uses	

● Highest priority or "must-win"

● Important to specific parts of value chain

○ Within MGF's influence or scope

① Mass build-out of renewable energy

Significantly more wind, solar, and grid infrastructure will be required to feed energy intensive hydrogen and efuel production. As shown in the Chapter 4 , Denmark would need an additional 30+GW and 80+GW by 2030 and 2050 respectively to power PtX and other electrification technologies. To achieve this, extensive investments and streamlined permitting processes in wind farms, particularly offshore wind, and solar power installations are key.

Overcoming barriers includes addressing grid integration challenges, regulatory hurdles, and land/resource acquisition issues. Denmark must enhance its grid infrastructure to handle increasing amounts of intermittency and invest in short- and long-term energy storage solutions. Collaboration and dialogue between government and private sectors for tendering and creating attractive investment frameworks as well as developing robust supply chains and a skilled workforce, will be essential.

Continuous technological advancements and cost reductions are also needed to improve bankability of projects, particularly offshore wind.

Recommendations to increase the speed and success of renewables deployment has been extensively outlined in the 2023 report "More sun and wind on land" by NEKST (DK's national energy crisis team) and should be referred to for concrete recommendations.[89]

② Develop and begin constructing midstream H2 infrastructure and storage

Infrastructure will be needed to offtake green hydrogen production and to transport it to relevant markets and end-users. Deciding to fund and construct this pipeline is neither cheap nor without risk. However, without a viable offtake, many of the current projects in the concept and feasibility stage projects will fail to culminate. For many projects, this offtake is industrial centers in Germany (chemical, steel manufacturing) which need cross-border H2 pipelines to facilitate the transfer of green molecules. For the proposed Jutland backbone West, final investment decision (FID), by Energinet with approval by the Danish Ministry of Climate, Energy and Utilities, is expected to occur in Q1 2025, after Energinet has conducted market dialogue and due diligence on potential users of the pipeline.

After a decision is made, a phased build out of the main pipeline is expected to occur (south to North) from 2027-2030 with an eventual connection to storage facilities in Lille Torup around 2030.

③ Reduce electrolyzer cost and improve performance

Improved electrolyzer performance means less RES input for the same amount of H2 output and an improved production cost as electricity costs can typically represent in excess of 50% of the levelized cost of green hydrogen. At scale, even small efficiency improvements will be important. The difference between a 60% (typical for AEC electrolyzer system - LHV) to a 70% efficient system for a 1GW electrolyzer plant running at 5000 full load hours results in an avoided use of 0.5TWh of electricity, around the consumption of annual of 90,000 Danish citizens. Less energy consumption also means less RES build-out and less environmental impact on land and offshore resources. The importance of electrolyzer efficiency in the success of hydrogen cannot be understated.

④ Increase the scale of electrolyzer manufacturing

Denmark aims to lead in green technology manufacturing, necessitating the development of large-scale production facilities. Domestic manufacturing of AEC, PEM, and SOEC technologies will need to be scaled up to provide the technologies domestically but also to export abroad. Scaling up SOEC manufacturing is currently being done, with Topsoe expected to finish construction of a 500MW/yr factory in 2025 in Herning.[90] This will be coupled with an announced sister factory in USA (with a capacity of 1GW/yr), expanding the geographic reach of manufacturing with Danish technology.

Competition from China may prove challenging. It is unlikely that Danish OEMS can match the cheap cost of Chinese electrolyzers in the near-term. The recent European Hydrogen Bank auction results reveal that Chinese electrolyzers are two to five times cheaper to buy than western equipment. Instead, performance, efficiency, and reliability should be the selling points. Additionally, there are proposed regulatory measures in the Net-Zero Industry Act that safeguard European OEMs from unfair competition (dumping) wherein at least 40% of the annual deployment needs for net-zero technologies manufactured in the EU by 2030.[91] Net-zero technologies include electrolyzers.

Nonetheless, increasing production volumes in Europe can help drive down cost via economies of scale and improved manufacturing processes to help the EU compete with cheaper produced electrolyzers from abroad while simultaneously creating local benefits.

⑤ Reduce fuel cell cost and improve performance

On the application side, fuel cells that consume less hydrogen for the same amount of output will be important for end-use. Improved fuel cell technologies could result in longer vehicle ranges, reduced weight, and enhanced viability for transport applications. Overcoming barriers such as the high costs of rare metals and durability issues is crucial. Developing alternative catalysts and improving fuel cell designs to increase efficiency and longevity should be a priority for innovation and research activities in the near and medium term.

⑥ Scale up plants to GW-scale to meet national targets

Many Danish gigawatt-scale concept plants are currently slated to be built in phases, such as a 50-100 MW phase-1 plant followed by later enlargement to 1 GW or more. The second or third phases are typically contingent on securing access to renewable energy sources (e.g., large-scale offshore wind connected to the upcoming auctions), viable offtake via H2 pipelines, and a positive business case. Strategic planning and phased implementation that align with infrastructure build-out and demand growth will be essential to managing risks and ensuring project viability.

⑦ Complete the construction of the H2 backbone and necessary branching infrastructure

In relation to the development of a hydrogen backbone, prioritizing key routes and leveraging existing infrastructure (e.g., repurposed gas lines) where possible will facilitate progress on creating a hydrogen network that connects supply to demand. Overcoming regulatory approvals, environmental impact assessments, and land acquisition challenges are crucial steps. Engaging stakeholders early in the planning process can help mitigate opposition and streamline approvals.

⑧ Develop high-efficiency next generation electrolyzers

Denmark's vision of producing cost-effective green hydrogen requires the development of high-efficiency next-generation electrolyzers. These include, but not limited to, high temperature SOEC and AEM electrolyzers. Challenges include expenses and limited availability of precious materials used in high-performance catalysts. Focused R&D programs and collaboration with academic and industry partners are necessary to overcome these technical hurdles via new materials and designs can enhance efficiency and durability or reduce the need for rare materials. Scaling up production processes will reduce costs and ensure that Denmark remains at the forefront of next gen electrolyzer technologies.

9 Reduce or eliminate the use of critical or rare materials in electrolyzers

Eliminating the use of critical metals is important for the long-term sustainability and security of supply in electrolyzer manufacturing. Prioritizing materials that are readily available, recyclable, and sourced from regions with low geopolitical risk can mitigate supply chain vulnerabilities. R&D and innovation in catalysts, such as developing alternatives to platinum-group metals and other rare earth elements, should be a priority. This includes researching non-precious metal catalysts or advanced ceramic materials that can deliver similar performance with a lower environmental and economic footprint. The transition to these alternatives will enhance the scalability of electrolyzer production and make hydrogen more economically viable and sustainable in the long term.

10 Solve challenges for specific end uses

For end-uses that will use hydrogen directly the necessary downstream fuelling infrastructure will be needed. For heavy-duty fuel cell vehicles to be adopted, the fuelling infrastructure must be in place and the trucks must be both demonstrated and made widely available at a reasonable cost. Achieving this requires advancements in vehicle fuel cell technology, including reducing capital expenditure and increasing availability of fuelling ports. These areas present significant opportunities for further research and development.

11 Cost-competitiveness and parity with conventional fuels

Achieving cost-competitiveness with conventional fuels and making hydrogen a mainstream energy source is an ultimate long-term goal for green hydrogen. A two-pronged approach of lowering H2 production costs and penalizing fossil fuel usage should be taken in parallel. However, this must be done in a balanced manner—too much penalization risks making industries uncompetitive, inflationary pressures, and cost pass-through to consumers, while excessive incentivization risks creating market distortions and inefficiencies.

MISSION GREEN FUELS

Focus areas and projects within green hydrogen

The partnership's focus on fostering collaboration between universities and private companies aligns with the need to enhance green hydrogen production efficiency and integration into the wider energy system. MGF is strategically positioned to drive innovation and R&D, particularly in the following topics:

- Improving electrolyzer stack performance and reducing costs
- Innovation in electrodes, membranes, catalysts
- Optimizing manufacturing processes,
- Advancing next-generation electrolysis technologies
- Materials sustainability
- PtX sector coupling modelling
- LCA tools and methodologies

Examples of past or ongoing MGF funded projects that address the needs identified for green hydrogen:

→ **ComElCo:** Competitive Electrolyzer Converters
  - Focuses on enhancing the efficiency and reducing the cost of electrolyzers through innovative converter technologies.

→ **H2-SAF:** Low-Cost hydrogen as green fuel enabler
  - Aims to make H2 production more economically viable by developing low-cost production methods and infrastructure solutions.

→ **GREMEOH:** Green H2 cost leadership and scalability (in manufacturing)
  - Analyse and develop optimal automation processes for the assembly of speed- and quality-critical electrolyser components

8.2 Key activities in the intermediary fuels roadmap

Timing	Near-term implementation ~2024-2028	Industrial scaling phase ~2028-2035	Long-term maturity ~2035-2050+
Production and supply elements	1 Scale up feedstock collection and pre-treatment processes 2 Assess sustainability of feedstocks via LCA	6 Industrial scale deployment and scaling of biorefineries 7 Integration of carbon capture for later efuel production	10 Adoption and utilization of organic waste streams: Aqueous HTL, Dairy waste, wastewater
Technology Development	3 Demonstration of technologies: HTL, pyrolysis, gasification, etc. 4 Identify synergies between HTL, pyrolysis, thermal gasification, and end-products	8 R&D and advancement of fuels made from 2nd and 3rd generation feedstocks	11 Fully integrated bio-e-refineries optimized for green fuel production
Demand, End-use, Markets	5 Identify and understand the end-demands for different types of intermediary green fuels	9 Develop and implement standards for fuel quality and blending requirements	

● Highest priority or "must-win"
● Important to specific parts of value chain
○ Within MGF's influence or scope

1 Scale up feedstock collection and pre-treatment processes

Scaling up feedstock collection and pre-treatment processes requires the development of sophisticated logistics and supply chain models to efficiently source diverse feedstocks, including agricultural residues, manure, municipal solid waste, and other sustainable materials sourced both domestically and internationally. This involves optimizing the collection, transportation, and storage of these feedstocks, ensuring a steady and reliable supply chain. Advanced pre-treatment technologies are critical to improving feedstock quality, ensuring uniformity, and reducing contaminants, all of which are essential for maximizing conversion efficiency in subsequent processing stages.

Pre-treatment methods such as torrefaction, drying, and size reduction must be engineered to handle large volumes of feedstock while improving homogeneity and minimizing the presence of impurities. Torrefaction, for example, thermally decomposes organic material at lower temperatures to produce a more energy-dense and dry feedstock, which is easier to handle, store, and convert. Drying is crucial to reduce moisture content, which enhances the calorific value and also improves the efficiency of subsequent conversion processes such as pyrolysis or gasification. Strategically locating pre-treatment facilities close to feedstock sources can significantly reduce transportation costs and logistical complexities, ensuring a more consistent and efficient supply chain.

Innovation in feedstock sourcing and pre-treatment could include the deployment of digital tools for real-time monitoring of feedstock availability and quality, allowing for dynamic adjustments in sourcing and processing. Automation can further improve the efficiency of pre-treatment operations, ultimately leading to better conversion yields and more sustainable biofuel production.[92]

2 Assess sustainability of feedstocks via LCA

To ensure the sustainability of feedstocks used in green fuel production, comprehensive LCAs must be developed and tailored to specific feedstocks and production pathways. This includes evaluating the environmental impacts associated with the entire lifecycle of feedstocks, from cultivation or collection to conversion and end-use. LCAs should consider factors such as GHG emissions, land use changes (direct or indirect), water and energy consumption, and waste generation.

Comparative LCAs can identify the most sustainable feedstocks, guiding industry stakeholders in selecting optimal bio resources for green fuel production. Furthermore, integrating LCA findings with economic and social impact assessments provides a rounded view of sustainability, balancing environmental benefits with cost and societal impact. Standardizing LCA methodologies and creating accessible databases will ensure consistency and transparency across the industry.

③ Demonstration of technologies: HTL, pyrolysis, gasification, biomethanisation

Demonstrating the technical feasibility and economic viability of advanced conversion technologies such as Hydrothermal Liquefaction (HTL), pyrolysis, biomethanisation, and FT/gasification is critical for future the large-scale production of green fuels that uses 2nd or 3rd generation bio-feedstocks. Pilot and demonstration projects should be designed to validate these technologies under real-world conditions, assessing performance metrics such as conversion efficiency, product yield, and process stability. Collaboration with academic institutions and industry partners can advance the development of these technologies, leveraging cross-sector expertise and resources. Field trials must address the variability in feedstock characteristics and operational environments to ensure robustness and scalability. Securing funding from government programs and private investors is essential to accelerate these demos, providing the necessary support to move from pilot projects to full-scale commercial operations.

④ Identify and exploit synergies between HTL, pyrolysis, gasification, and their end-products

Identifying and exploiting synergies between HTL, pyrolysis, and gasification processes can enhance the efficiency and output of biorefineries. Research should focus on the potential integration points where intermediates from one process can be used as inputs or supplements in another, thereby maximizing resource utilization and reducing waste. For instance, the bio-oil produced from pyrolysis could be further upgraded through gasification or HTL to produce higher-value fuels or chemicals. Similarly, syngas from pyrolysis and gasification can be directly used for hydrogen production, thereby reducing the need for external hydrogen production facilities using electrolysis. Analysing the compatibility of these intermediates with downstream refining and conversion technologies is crucial for ensuring integration and optimizing process flows. Co-processing opportunities should be explored to utilize diverse feedstocks effectively and improve overall biorefinery economics. Techno-economic models can help identify the most cost-effective pathways for integrating these technologies, providing a framework for designing and operating fully integrated biorefineries.

⑤ Identify and understand the end-demands for different types of intermediary green fuels

Avoid putting the cart before the horse by fully understanding the market demands for intermediary green fuels. Conduct comprehensive market research and stakeholder engagement to provide insights into which sectors are likely to adopt these fuels and under what conditions (e.g. willingness to pay, substitutability, offtaker terms, etc). Analysing the technical specifications and quality requirements of these end-use applications ensures that the fuels produced will be compatible with existing infrastructure and technologies.

Additionally, developing flexible synthesis plants that can adapt to evolving demands is important for maintaining competitiveness. This includes the capability to switch or upgrade to other fuel types if market conditions change. The demand for certain green fuels may shift, requiring producers to adjust their output or transition to different fuel products that align with new market realities. This adaptability ensures that green fuels can continue to meet the specific needs of different end-use markets, even as technological and market landscapes evolve.

⑥ Industrial scale deployment and scaling of biorefineries

Construct and deploy biorefineries at an industrial scale after pilot and demo projects are validated. Ensure the plants are optimized for large-scale production, including securing reliable quantities of feedstock supply and ensuring integration with existing infrastructure (utilities and logistics networks). Additionally, securing funding is crucial, often involving a combination of public and private investment, grants, and incentives designed to accelerate and de-risk the deployment of these plants.

⑦ Integration of carbon capture for later efuel production

Integrate carbon capture technologies within biorefineries to produce biogenic CO2 for later utilization in efuel production. For example, during the upgrading process of biogas to biomethane, biogas is split into CH4 and CO2 wherein this CO2 can be captured at relatively low cost due to its high purity.[93]

This CO2 can then be used for the production of carbon-based efuels. Research should focus on developing carbon capture systems that are compatible with biorefinery processes, ensuring integration without compromising efficiency. High capture rates with low energy penalties are desired to enhance the overall economics. Please refer to the INNO-CCUS roadmap for the latest look at carbon capture technologies.[68]

⑧ R&D and advancement of fuels made from 2nd and 3rd generation feedstocks

R&D should be conducted to advance the production of fuels from 2nd and 3rd generation feedstocks, with a focus on improving long-term sustainability and increasing production yields. Second-generation feedstocks include agricultural residues, forestry waste or lignocellulosic non-food biomass such as Miscanthus, while third-generation feedstocks primarily involve high-yield, fast-growing sources like algae.[94] Research should prioritize improving cultivation techniques and leveraging genetic engineering to boost feedstock quality and growth efficiency as well as improving pretreatment steps for handling these feedstocks. Collaborating with academic institutions and industry partners is crucial to accelerate these advancements.

⑨ Develop and implement standards for fuel quality and blending requirements

Establishing and implementing standards for fuel quality and blending requirements is key for ensuring the reliability and performance of green fuels in various applications. Research into the effects of increasing blending ratios (above the 7% for FAME and 10% on ethanol in the EU Fuel Quality Directive[73]) on engine performance, emissions, and overall fuel efficiency is necessary to inform these standards and ensure they are both practical and effective. Ensure fuel quality standards are harmonized across EU member states to allow transfer of liquids and gases cross-border with no differences in performance for the end-use applications.

⑩ Adoption and utilization of organic waste streams: aqueous HTL, dairy waste, wastewater

Utilizing organic waste streams like HTL by-products, dairy waste, and wastewater offers significant potential for green fuel production. HTL converts wet biomass into bio-crude oil, with the aqueous by-products containing organics that can be processed into biogas or hydrocarbons. Dairy waste, rich in organic matter, can be used for bioethanol or biogas production. Wastewater, also high in organics, can be treated to produce biomethane or biomass for biofuels. Integrating these waste streams into biorefineries enhances resource recovery and minimizes environmental impact.

⑪ Fully integrated bio-e-refineries optimized for green fuel production

Related to points 4 and 7, the end-goal will be developing fully integrated bio-e-refineries optimized for green fuel production with systems that combine multiple conversion technologies, such as HTL, pyrolysis, and gasification, with carbon capture and e-fuel production. This integration must be optimized to achieve maximum efficiency and output while minimizing waste and emissions. These projects should focus on optimizing process flows, energy integration, and waste management to enhance overall performance.

Focus areas and projects within intermediary fuels

MGF is strategically positioned to drive innovation and R&D, particularly in the following topics for intermediary fuels:

- LCA of biomass production processes and assessment of feedstock sustainability
- R&D in low-TRL bio technologies
- Developing fuel blending improvements and qualities
- Quantifying Danish biomass potentials cross 1st, 2nd, and 3rd generation feedstocks
- Optimizing process and energy flows

Examples of past or ongoing MGF funded projects that address the needs identified:

→ **CARMA-Green Fuels:** Cross Mission Carbon Management
  - Explores potentials for sustainable biomass production in DK, with scenario development

→ **STAB3: Stability Improvement of Biooil-Bunker-Blends**
  - Aims to assess the stability of bio-oils when blended with conventional oils and formulate ways to enhance blend stability

8.3 Key activities in the maritime fuels roadmap

Timing	Near-term implementation ~2024-2028	Industrial scaling phase ~2028-2035	Long-term maturity ~2035-2050+
Production and supply elements	1 Expansion of biofuel production (HVO, bio-oil) 2 Deployment of first ammonia, methanol plants	6 Establish regional production hubs for ammonia and methanol 7 Infrastructure modernization at ports	10 Large scale production of bio and efuels for maritime uses 11 Global availability of green fuels in ports worldwide
Technology Development	3 Expand dual-fuel engine and retrofit technologies 4 Advance ammonia engine and SOFC tech.	8 Advance TRL of mid and downstream equipment: bunkering, storage, scrubbing, leak detection	
Demand, End-use, Markets	5 Advance safety procedures, crew training programmes	9 Establish first green shipping lanes between production hubs	

● Highest priority or “must-win”

● Important to specific parts of value chain

○ Within MGF’s influence or scope

1 Expansion of biofuel production and feedstock collection

Scale up domestic biorefinery capacity and sustainable sourced biomass supply chains to significantly increase production. This is relevant for all transport sectors that will rely on biofuels in the near-term. This includes necessary upstream pieces such as feedstock collection, processing, and pre-treatment to ensure sufficient raw material availability. Exploring new feedstocks and developing the technologies to convert them will be important to ensuring that sufficient raw materials are available.

2 Deployment of first ammonia and methanol plants

Finish construction on the first methanol and ammonia plants within Denmark. Planned sites in Denmark include European Energy’s e-methanol Kassø facility with 52MW of electrolysis to produce an estimated 42,000 tonnes of methanol annually.[95] This is equivalent to the annual volume of three to four of Maersk’s first green container ships, the Laura Maersk with a capacity of 2,100 TEU. Construction is expected completion in 2024. For ammonia, the REDDAP (Renewable Dynamic Distributed Ammonia Plant) PtX facility in Northern Jutland will be Denmark’s first, producing 5,000 tons per year of ammonia.[96] The project is a collaboration between Skovgaard Energy, Topsoe, and Vestas and is expected to enter operation in 2024. These plants will provide practical experience in building and operating PtX facilities in Denmark and will strengthen industry collaboration and technological expertise in green fuel production. The knowledge gained will be critical for refining future projects and scaling up sustainable fuel production.

3 Expand dual-fuel engines and engine retrofit technologies

Dual-fuel engines with the ability to run on conventional fuels but also methanol will be needed in the near-term. This flexibility is crucial as the global supply chains for low-carbon fuels are still developing, and availability may be inconsistent in the short term. Dual-fuel engines mitigate the risk associated with the limited availability of these fuels by allowing ships to switch back to traditional fuels if necessary. For ships ordered today, dual-fuel engines would future proof them (from carbon intensity requirements and emissions compliance) as the average container vessel has a lifetime of 25-30 years.

MAN Energy solutions offers "methanol ready" four stroke engines and Alfa Laval methanol fuel supply systems, among other technologies for green fuel enablement for vessels. Both are seeing real-world usage and commercialization. However, dual-fuel engines are more complex than single-fuel engines, requiring advanced fuel management systems and additional safety measures to handle different types of fuels. This complexity often leads to higher upfront costs and potentially higher maintenance requirements. Retrofits of existing engines is also an increasingly viable solution for ship owners looking to transition to cleaner fuels without the need for new vessel construction. This typically involves modifying the fuel injection and ignition system and upgrading engine components and gaskets with methanol resistant materials. While retrofitting is generally more cost-effective than building new methanol-capable vessels, it still represents a significant investment.

4 Advance ammonia engine and ammonia SOFC technologies

For ammonia engines, ammonia is combusted generating thermal energy which is converted into mechanical work to drive an engine's pistons. Marine engine developers have been making recent advancements in ammonia engine technologies. In 2023 Wärtsilä launched the world's first four-stroke engine based on ammonia which is now available on an engine platform suited for small to medium bulk carriers and tankers. Additionally, MAN is working on deploying the world's first two-stroke ammonia engine with an expected operation onboard a commercial vessel in 2026.[97] Successful demonstration of an ammonia engine will be a critical milestone for green fuels.

On the fuel cell side, ammonia solid oxide fuel cells (SOFC) directly convert chemical energy into electrical energy without the intermediate step of combustion. The primary emissions are water vapour, with no NOx emissions (unlike ammonia combustion). Typical efficiency is 60% and this can be optimised to 85% with heat recovery. However very high operating temperatures (500-1000 °C) are needed. Ammonia SOFC technology is still in the development phase (TRL 4-5) but will be seeing piloted use on real-world ships in the coming years.[98] For SOFC, applications will likely target small to medium sized vessels.

5 Advance safety procedures and crew training programmes

Due to the more complicated nature of new engine technologies, the use of new green fuels, and potential safety risks associated with ammonia (toxic) and hydrogen (explosive), specialized crew training programmes should be established. This includes for on ship operations, fuel bunkering, and storage. Multiple Danish stakeholders are working on advancing this topic. DBI's "SafeSBU" project (with partners FORCE Technology, Complete Solutions, DFDS, Port of Rønne and Aalborg University) is working to produce comprehensive guidelines for safety, as well as training courses for workers involved in the storage, bunkering, and usage of hydrogen, ammonia, and methanol in the maritime industry.[99] Similarly, companies such as DNV, Danish Technological Institute, and more and offering theory and training on green fuel safety and handling.[100] A well-prepared workforce is essential for reducing the likelihood of safety incidents and for advancing the integration of green fuels in the sector.

6 Establish regional production hubs for ammonia and methanol

State-designated "energy parks" or industrial energy zones will help speed up the deployment of green fuels facilities. Currently there are over 18 areas for energy parks undergoing dialogue and development with local municipalities.[101] These designated energy parks will have streamlined planning and approval processes, allowing for exceptions to certain regulations to facilitate the development of renewable energy projects (wind, solar, PtX) and associated infrastructure. They are also likely to be located in strategic locations in relation to onshore substations or future infrastructure (e.g. H2 backbone), reducing distances for power lines or branching pipelines. Establishing multiple production facilities in one regional hub will leverage shared infrastructure, driving synergies and reducing costs.

7 Infrastructure modernization at ports

Danish port infrastructure is generally very well developed, with key ports such as Aalborg, Esbjerg, Fredericia, Rønne, Hanstholm, Hirtshals, Frederikshavn, Aabenraa, and Aarhus being particularly well-suited for green fuels due to their locations to existing or future renewable energy build-out (e.g. North Sea or energy islands) or strategic positioning on key cargo routes. Upgrading port infrastructure to handle ammonia and methanol involves developing specialized storage and bunkering facilities, implementing rigorous safety and environmental controls, and integrating these operations smoothly with existing port activities. Current innovation projects, such as the multi-stakeholder Marco Polo project in Northern Jutland investigates how green fuels can be integrated at ports to accommodate future volumes of methanol.[102] Safety, and technical challenges as well as community buy-in and social aspect are looked at in detail.

8 Advance TRL and manufacturing of auxiliary components

Scaling up the manufacturing of auxiliary components is crucial to support green fuels value chains. Producing green fuels at scale requires more than just the core production technologies like electrolyzers. It also involves the development and manufacturing of hundreds of other pieces of equipment such as specialized storage tanks, valves, and containment systems, as well as bunkering infrastructure necessary for safe and efficient fuel distribution across the mid and downstream part of the supply chain.

Technologies that are already commercially available but essential to green fuel operations need to be manufactured at scale to avoid bottlenecks in the supply chain. This includes sometimes overlooked equipment, such as electrical components like switchgears, substations, and BOP equipment like gas separators, scrubbers, heat exchangers, and valves. For midstream storage and handling infrastructure, this could involve the development of storage tanks and containment systems designed to handle the sometimes corrosive or toxic properties of green fuels. For downstream applications on ships, it includes the manufacture of onboard storage tanks, fuel supply systems, safety and monitoring equipment, and emissions control equipment.

9 Establish first green shipping lanes between production hubs

In step with port infrastructure modernization, strategic green shipping corridors should be established, connecting green fuel bunkering locations. This could include coastal routes within DK but also cross-border partnerships and agreements with ports in other first-mover countries such as The Netherlands, Norway, Sweden, or the UK and with partners in important trading ports in Asia. These lanes would connect major production nodes, ensuring a reliable supply of green fuels for vessels operating on these routes. This would not only demonstrate the feasibility of zero-emissions shipping but also create a reference for expanding green shipping corridors globally. Challenges include decisiveness on fuel pathways (whether to adopt a mono or multi-fuel strategy) and the need for explore innovative commercial, business, and financial arrangements for stakeholders taking the first-mover risks.

10 Large scale production of bio and efuels for maritime uses

To meet the expected demand for green fuels in the maritime sector, Denmark must focus on scaling up biofuel and efuel production to levels that can support both its own domestic needs and the bunkering demands of international ships arriving in Danish ports. This involves significantly expanding existing production facilities and constructing new plants designed to operate at industrial scales.

11 Global availability of green fuels in ports worldwide

Long-term end goal for green fuels industry. This will take an enormous amount of global investment and coordination. Establishing a global trade network for green fuels is crucial to ensure consistent supply availability for the maritime industry. This involves creating standardized trading frameworks, developing robust logistics and distribution networks, and fostering international partnerships to secure long-term supply agreements.

MISSION GREEN FUELS

Focus areas and projects within maritime fuels

MGF is strategically positioned to drive innovation and R&D, particularly in the following topics for maritime fuels:

- Support for pilot and demo plants for ammonia and methanol production
- R&D in low TRL technologies (bio and efuel)
- TRL advancement of equipment such as sensors, fuel injection, bunkering equipment, etc
- Safety and handling aspects for green fuels
- Guidebooks, training guides, and implementation roadmaps for ports and port workers

Examples of past or ongoing MGF funded projects:

→ **SafeSBU:** Safe storage, bunkering, and usage of green fuels
  - safety design processes, use cases, and approval processes to support fast and safe implementation among mid- and downstream stakeholders in ports.

→ **COMPAS:** competitiveness on ammonia production through flexible ammonia plants
  - Improvement in ammonia tech. Focuses on the techno-economic assessments of technology upgrades on the flexible ammonia plants

8.4 Key activities in the aviation fuels roadmap

Timing	Near-term implementation ~2024-2028	Industrial scaling phase ~2028-2035	Long-term maturity ~2035-2050+
Production and supply elements	1 Pilot biofuel based SAF production 2 Deployment of first PtL plants	6 Scale up SAF production and required infrastructure	9 Establish global SAF production networks
Technology Development	3 Advance TRL of alcohol-to-jet and gasification for bioSAF 4 Advance TRL of PtL fuel synthesis for eSAF	7 Advance new propulsion technologies for hydrogen planes (turbines, fuel cells)	
Demand, End-use, Markets	5 Assessment and certification of new SAF Pathways	8 Global standardization for SAF quality and blending rules	

● Highest priority or "must-win"

◍ Important to specific parts of value chain

○ Within MGF's influence or scope

① Pilot biofuel-based SAF production

Increase production of biofuels relevant for aviation such as HEFA and HVO and other bio-oils which can be upgraded to SAF. Currently there is no domestic production of HEFA/HVO bioSAF in Denmark and these fuels are imported from countries such as Finland or France which have established production facilities.[103] Denmark could develop existing bioSAF production pathways such as HEFA based on used cooking oils or explore new bio-oil production pathways such as HTL based on agricultural residues or pyrolysis based on lignocellulosic biomass of waste plastics. Similarly, biomass-based methanol/ethanol could be upgraded to alcohol-to-jet.

② Deployment of first PtL SAF plants

The near-term will see the construction and piloting of several PtL eSAF plants, many based on public-private partnerships. These include:

- **MeSAF in Aalborg:** builds on an existing e-methanol pilot project, Power2Met aiming to advance eSAF production from pilot to commercial scale of 10,000 tonnes SAF annually. Partners include European Energy, Vertimass, Kosan Gas, AAU Energy, Aalborg Airport, Port of Aalborg, and Hydrogen Valley.[104]

- **FrontFuel project in Viborg:** The project will pilot Fischer-Tropsch (CO2 + hydrogen) to synthetic crude further refined to SAF. Project partners include Topsoe, Aarhus University, and Sasol.[105]

- **Padborg SAF facility:** Partnership between European Energy and Swiss Metafuels AG to construct eSAF facility next to European Energy's future Padborg PtX facility in Southern Denmark.[106]

- **Arcadia efuels Vordingborg:** First planned commercial eSAF plant in Denmark based on Fischer-Tropsch. Slated for completion in 2026 and aims to produce 100 million liters of efuels per year (both eSAF and eNaptha). Technology providers include Topsoe and Sasol with intended offtake with DCC & Shell Aviation.[107]

③ Advance TRL of alcohol-to-jet, gasification, and other bioSAF pathways

Currently, alcohol-to-jet (AtJ) technology sits at TRL 7-8, biomass gasification + Fischer-Tropsch is at TRL 7-8, HTL with upgrading at TRL 4, while other pathways such as direct sugars to hydrocarbons from lignocellulosic biomass sits at 5. There are other low TRL and emerging technologies that could increase the total addressable biomass potential for the use in SAF and other green fuels. Please see the table in Appendix 1 for the list of TRL's associated with bioSAF production. Engage in research and development of these technologies to advance them to TRL 9. Benefits of advancing these technologies include the ability to use 2nd and 3rd generation bio feedstocks at larger volumes, increase circularity of feedstocks, and improved efficiencies.

④ Advance TRL of PtL fuel synthesis for eSAF

The Fischer-Tropsch pathway and is fully commercial (TRL 9) and has been used for decades based on the gasification of coal and producing syngas to create hydrocarbons. However, other steps of the PtL process are at lower TRLs, particularly the Reverse Water Gas Shift Reaction (RWGS) which is only at TRL 5-6. The RWGS or "CO2 reduction" process converts captured CO2 into CO to produce syngas. This limits the overall TRL of the integrated Fischer-Tropsch based e-SAF process. The e-methanol pathway to produce e-SAF does not require the RWGS reaction but requires many subsequent processes such as olefin synthesis, oligomerisation, and hydrotreating. The TRL of this process sits at 7-8.[83]

In addition, the CO2 source (point source, DAC, etc) will have varying levels of readiness . The availability of biogenic / point source CO2 could become a bottleneck for the production of eSAF based on availability or competition from other forms of CCU or CCS. The need for TRL advancement in CCU technologies such as DAC will likely be needed in the long-term.[68]

⑤ Assessment and certification of new SAF pathways

Currently there are 9 approved SAF production pathways from ASTM international with varying blending limits up to 50%. The feedstocks of these fuels vary from fats and oils, energy crops, lignocellulosic biomass, to algae. Some will not meet the EU's sustainability criteria for advanced biofuels if for example produced via energy crops. These list of approved ASTM pathways are shown in Table 8.1.

Table 8.1: ASTM approved SAF production pathways

Pathway	Certification Name[i]	Blending Limit	Feedstocks	Year Approved	Estimated TRL[ii]
Hydroprocessed Esters and Fatty Acids (HEFA)	HEFA-SPK	50%	Vegetable and animal fat	2011	9
Biomass Gasification + Fischer Tropsch (Gas + FT)	FT-SPK	50%	Crops, lignocellulosic biomass, solid waste	2009	7-8
Biomass Gasification + FT with Aromatics	FT-SPK/A	50%	Crops, lignocellulosic biomass, solid waste	2015	6-7
Alcohols to Jet (AtJ)	ATJ-SPK	50%	Sugar, starches lignocellulosic biomass	2016	7-8
Catalytic Hydrothermolysis Jet (CHJ) (Also known as HTL)	CHJ of CH-SK	50%	Vegetable and animal fat	2020	6
Direct Sugars to Hydrocarbons (DSHC)	HFS-SIP	10%	Sugars, lignocellulosic sugars	2014	7-8, or 5[iii]
HEFA from Algae	HC-HEFA-SPK	10%	Microalgae oils	2020	5
FOG Co-processing	FOG	5%	Fats, oils, and grease	2018	-
FT Co-processing	FT	5%	FT biocrude	2020	-

i. ASTM-approved pathway to SAF. The specific production pathway, may not necessarily meet certain regulations (e.g. ReFuelEU Aviation) based on the sustainability of the feedstock.
ii. TRL's from " Drop-in SAF production pathways" by European Union Aviation Safety Agency.[83]
iii. TRL 5 for lignocellulosic feedstock. TRL 7-8 for conventional sugar feedstock.

There are 11 new SAF pathways that are currently under evaluation including biomass pyrolysis, non-recyclable plastic pyrolysis, among others. New SAF pathways should meet sustainability criteria as set out by Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[87] and have LCAs performed to quantify life cycle emissions and validate the reductions potential of the pathway.

6 Scale up of SAF production and required infrastructure

Production should be scaled up significantly to meet national and international GHG emissions reductions targets. Estimates for GHG scenarios conclude that 300-400 SAF plants could be needed globally to produce 40-50Mt SAF by 2030 (13%–15% of total jet fuel demand), the majority of these being HEFA plants.[86] A mass scale up of SAF production plants must take place between now and 2050 to meet net zero goals in the aviation sector. Some estimates place to total capital investment between now and 2050 in the $5.1 trillion range which includes upstream inputs to fuel production, and the SAF production plants themselves. Massive investment is needed.

7 Advance new propulsion technologies

In parallel with the development of drop-in SAFs for existing aircraft engines, there should be a focused effort on R&D for novel propulsion technologies using batteries or hydrogen. Innovation in these areas is expected to initially emerge from smaller aircraft but has the potential to scale up to larger planes. Benefits of these technologies include more efficient energy conversion processes, improved LCA performance, and reduced reliance on bio-feedstocks. Innovation in this space will likely be driven by established aerospace companies and new startups collaborating to overcome technical challenges and bring these technologies to market. This effort will also require regulatory support and infrastructure development to ensure successful adoption and integration into the aviation sector.

8 Global standardization for SAF quality and increase of blending limits

Global standards for SAF quality exist, primarily governed by ASTM D7566, which currently allows a maximum blending limit of 50% with conventional jet fuel. However, blending limits are lower (10% or 5%) for certain SAF pathways that are less advanced or have different chemical compositions. Increasing these blending limits will require research to ensure compatibility with existing aircraft engines and fuel systems, as well as rigorous safety testing and certification.

9 Establish global SAF production networks

To ensure global availability of SAF, it is crucial to establish a robust production network that leverages regional advantages. Certain geographies offer favourable production conditions, such as access to cheap renewable energy, abundant sustainable biomass, and proximity to major ports or aviation hubs. By identifying and investing in these strategic locations, a globally integrated SAF supply chain can be developed, facilitating the widespread adoption of SAF and supporting the aviation industry's transition to sustainable fuels.

MISSION GREEN FUELS

Focus areas and projects within aviation fuels

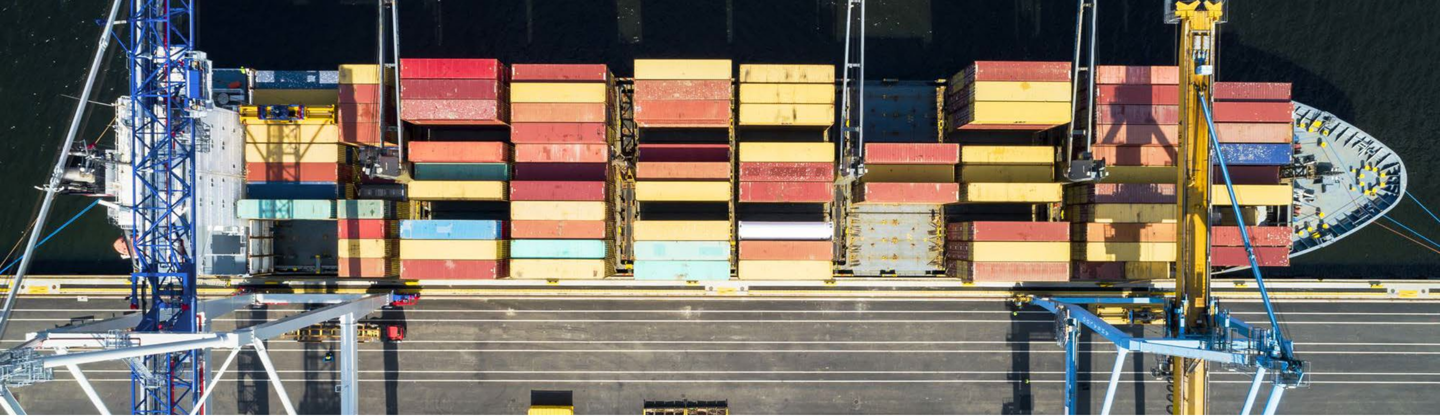
MGF is strategically positioned to drive innovation and R&D, particularly in the following topics for aviation fuels:

- Support for pilot and demo plants for bioSAF and eSAF demonstration
- Assessment and validation of SAF production pathways from a techno-economic perspective
- Support for R&D in low TRL technologies (bio and efuel)
- LCA methodologies for SAF pathways
- Guidebooks and implementation roadmaps for airports

Examples of past or ongoing MGF funded projects:

→ **Methanol-to-Jet:** Fuel Process Development
- Create a strategy for and commence ASTM certification of the Methanol-to-jet pathway for use of the fuel in commercial aviation. Integration of process into energy systems

→ **MTHiO:** Methanol to higher olefins
- The first step in methanol conversion to SAF.
- Conduct pilot-scale experiments to investigate and demonstrate the MTO process in large scale for future industrial up-scaling and commercialization



9. Commercial Activities

Market-based measures to accelerate the deployment of green fuels are described more closely in this section. These measures are meant to increase the build out of green fuel supply and stimulate demand. For PtX specifically, stakeholders often describe a chicken-and-the egg paradox where supply and demand are mutually dependent but neither can develop independently. Breaking this paradox requires commercial mechanisms to de-risk and create certainty in the market for green fuels. The paradox, main barriers, and potential solutions are shown in Figure 9.1. The potential solutions to break the paradox widely relate to lowering costs, reducing uncertainty, and enabling predictability in the market.

Figure 9.1: The green fuels paradox with potential solutions

Theme	Main barriers	Potential solutions
Green fuel competitiveness requires	• Higher costs compared to conventional fuels • Limited economies of scale • Limited RES, CO2, or bio feedstock	• R&D to improve production efficiency and reduce costs • Subsidies to encourage investment • Penalize fossil fuels to make alternatives attractive
Increased production requires	• Lack of large-scale production facilities • Insufficient supply chains • Regulatory hurdles slowing down new plant development	• Provide financial support to de-risk construction of large-scale production facilities • Streamline regulatory processes to expedite project approval
Demand and use-cases requires	• Technological maturity varies across sectors, limiting immediate applicability • Limited market demand due to higher costs and lack of awareness	• Implement mandates and blending quotas to create market demand • Support demo projects to demonstrate use-case viability
Offtakers willing to commit requires	• Uncertainty in the long-term supply and pricing of green fuels • First mover disadvantage – expensive now, cheaper later • Risk aversion among buyers	• Risk-sharing mechanisms • Secure offtake agreements through long-term contracts with price guarantees • Strong partnerships

Additional commercial needs identified by MissionGreenFuels stakeholders emphasize the need to advance infrastructure, develop robust supply chains, and implement market strategies that drive demand and ensure economic viability. By establishing strong supply chains and promoting cross-sector integration, the green fuel industry can overcome significant barriers to market entry and scale-up. These actions are critical to enabling the widespread adoption and impact of advanced technologies, which might otherwise struggle to reach commercial maturity and instead end up in the innovation "valley of death". Below are description of the top commercial activities, as identified by stakeholders necessary to support the growth of the green fuels sector:

Commercial activities within green fuels

As expressed by MGF stakeholders

1. Expand green fuel infrastructure
2. Develop robust supply chains
3. Stimulate market uptake of green fuels
4. Establish project references
5. Foster cross-sector integration
6. Public-private collaboration
7. Align with international developments

● Commercial Activity

○ Within MGF's influence or scope

1 Expand green fuel infrastructure

Expanding green fuel infrastructure is needed to connect supply and demand centres. Producers of green fuels need efficient distribution pathways to be able to offtake their product as well as storage solutions to be able of to balance supply-demand fluctuations. The development of midstream and downstream infrastructure such as pipelines, fuelling stations, storages, bunkering facilities, as well as upstream feedstock infrastructure such CO2 pipelines is important. The most critical piece of infrastructure in the near-term is arguably the hydrogen pipeline to Germany. Building this will provide an offtake and the ability to scale domestic green hydrogen production. Outside of the actual FID and construction of the pipeline, implementing early connection models or pipeline tariffs, such as competitive pricing and incentives for early adopters, will further lower barriers. and stimulate demand. Collaborative planning with key markets, like Germany, and a focus on long-term storage solutions will create a connected green fuel network, laying a strong foundation for future expansion.

2 Develop robust supply chains

A single unreliable (or uneconomic) link within various green fuel supply chain can jeopardize the entire system, underscoring the need for a fully developed and economically viable value chain from producer, to distributor, to user. On the production side, strategies to ensure robustness could include diversification of feedstock sources (e.g. multi-feedstock capability for biofuel production or leveraging multiple renewable energy sources). For equipment, this could include diversification of OEMs, standardization of components, supply chain risk management practices. Additionally, collaboration and forming partnerships with stakeholders across different sectors, such as energy producers, transportation providers, and component manufacturers, can strengthen the supply chain. Collaboration can lead to shared resources, joint investments in infrastructure, and coordinated planning.

3 Stimulate market uptake of green fuels on the demand side

To stimulate demand and encourage market uptake of green fuels, there is a need for ambitious, yet realistic policy mandates for the use of green fuels is various end-uses. These could include blending requirements and mandates for a minimum share of green fuels in energy mixes, which would create a baseline level of demand and predictability in green fuels uses by sector. These mandates should be coupled with a financial incentive to comply. Business models that leverage GHG emissions savings via usage of green fuels are also essential, as they provide a financial rationale for adoption and making the switch from conventional fuels. Outside of financial or policy tools, running public awareness campaigns and educating the public and businesses about the environmental benefits and long-term cost savings of green fuels can drive further adoption.

4 Establish project references: demonstrate commercial viability of investments

Demonstrating the commercial viability of green fuel investments is vital for securing stakeholder confidence and increasing additional investments into the sector. Establishing credibility through successful projects and project references is important as these provide tangible proof of the technical and economic viability.

⑤ Foster cross-sector integration

Integration is necessary to maximize the efficiency and impact of green fuel technologies. Ensuring practical and reliable technology integration across different sectors can unlock new synergies as well as revenue streams (via stacking), such as using surplus heat from electrolysis processes in other industrial applications or using hydrogen production as a way to balance the grid in times of excess renewables generation. Denmark can demonstrate technology leadership and aim to showcase successful integration of large-scale PtX projects.

⑥ Public-Private collaboration

Public-private collaboration is fundamental to advancing green fuel initiatives in Denmark. Success depends on the cooperative efforts of government entities, private companies, and research institutions to align strategies, share resources, and drive innovation. Examples of effective collaboration include joint ventures in R&D, co-investment in infrastructure, and the development of regulatory frameworks that support innovation. Establishing clear governance structures and communication channels within these collaborations will ensure alignment of goals and efficient use of resources.

⑦ Align with international developments

The global landscape for green fuels is quickly evolving. Denmark's commercial success in green fuels will depend on making technologies cost-effective to compete globally, especially as it pursues a green fuel export strategy aimed at supplying regional industry and transport needs. Production costs must be competitive with those in other leading markets, such as Norway, Sweden, and Spain, while the cost and performance of electrolyzers should match those produced in Germany, France, and the USA. To achieve this, Denmark should prioritize international collaborations, R&D, and knowledge sharing, ensuring its technologies align with global trends and maintain a competitive edge in the global energy market.

MISSION GREEN FUELS

Focus areas within green fuels markets

MGF is positioned to drive innovation and R&D, particularly in the following commercial topics:

- Models for market development of green hydrogen and other fuels
- Demand sizing for various fuel types
- Quantifying commercial benefits of sector integration + coupling
- Establishing project references via support of pilot and demo projects for upcoming technologies
- Research into energy systems models that combine market forecast and future demands

Examples of past or ongoing MGF funded projects:

→ **PtX Markets:** Markets, Policies, and Business Models for Green Fuels:
  - Assessment of green fuel markets and policies for demand uptake, business models, trading, and control strategy
  - Dataset on green fuel demand estimation

→ **PtX Sector Coupling and LCA :** Further development of energy system models
  - Analysis on the optimal locations of new plants based on grid capabilities, market forecasts, biomass, carbon availability , and integration opportunities
  - Co-optimisation of gas, electricity, hydrogen and district heating

10. Regulatory and Policy activities

Activities that fall under the regulatory framework for green fuels include setting emissions targets, creating certification schemes for fuel sustainability, implementing carbon pricing mechanisms, establishing clear guidelines for lifecycle emissions analysis, and developing supportive policies. These regulations can be national, on the EU level, or global.

National policy frameworks

Among the national-level regulations and policies in Denmark that drive the adoption of green fuels, the ones that set binding targets are:

→ **Danish Climate Act:** The Danish Climate Act sets a legally binding target of reducing greenhouse gas (GHG) emissions by 70% by 2030 compared to 1990 levels, with a goal of achieving climate neutrality by 2050. This binding target underpins many of the other policies and strategies, pushing for the adoption of green fuels as part of the broader decarbonization effort.[108]

→ **Renewable Energy Act:** While the Renewable Energy Act promotes the use of renewable energy sources, including green fuels, it also includes binding targets for the share of renewable energy in Denmark's overall energy mix. This indirectly drives the adoption of green fuels as part of achieving these renewable energy targets.[109]

The other policies and strategies, such as the Power-to-X Strategy, Green Gas Strategy, and Sustainable Aviation Strategy, provide important guidance and support for the transition to green fuels but do not set binding targets. These policies are more focused on providing support and facilitating the conditions necessary to meet the binding targets set by the Climate Act and Renewable Energy Act.

European level policy frameworks and targets

There are numerous EU level policies related to green fuels production, infrastructure, certification, as well as target setting for various transport sectors. These are listed on the next page in Table 10.1.

Global level policy and targets

On a global level, organizations such as the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO) have set targets that aim to increase the adoption of green fuels for the aviation and maritime sectors:

→ **IMO Strategy on Reduction of GHG Emissions from Ships (2023):** The IMO has set a target to reduce the carbon intensity of international shipping by at least 40% by 2030, 70% by 2040, and to reach net-zero GHG emissions by or around, i.e. close to, 2050. Reduction levels are to be compared to 2008 and account must use LCA guidelines to quantify the well-to-wake GHG emissions of marine fuels.[81]

→ **Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA):** The ICAO's global market-based aimed at stabilizing CO2 emissions from international aviation at 2020 levels. Airlines are required to offset any emissions above this baseline by purchasing carbon credits, thereby incentivizing the adoption of sustainable aviation fuels (SAFs) and other green technologies to reduce emissions. The ICAO also promotes the use SAF via the new ICAO Global Framework for Sustainable Aviation Fuels (SAF), Lower Carbon Aviation Fuels (LCAF), and other Cleaner Aviation Energies represents a commitment by ICAO and its Member States to collectively pursue the goal of reducing CO2 emissions from international aviation by 5% by 2030.[87]

Table 10.1: EU-level policies and frameworks for green fuels

RENEWABLE ENERGY DIRECTIVE (REDIII)

Renewable Energy Directive EU/2023/2413; amendment of 2023.[110]

- Sets a binding target for renewable energy in the EU's overall energy consumption to reach 42.5% by 2030, with a specific sub-target for RFNBOs in transport
- Defines RFNBOs and sets sustainability criteria, including the need for hydrogen to be produced using renewable electricity

DELEGATED ACT – RULES FOR RENEWABLE HYDROGEN

Commission Delegated Regulation (EU) 2023/1184.[111]

- Establishes specific criteria for renewable hydrogen production, certification schemes and GHG reduction thresholds (70%), rules on traceability and verification of RFNBOs
- ***Additionality:*** Ensuring that the renewable electricity used for hydrogen production is additional to what would have otherwise been generated, often implying new projects.
- ***Temporal Correlation:*** Ensuring that the renewable electricity used for hydrogen production corresponds to the time period during which the hydrogen is being produced

GAS PACKAGE

Directive (EU) 2024/1788.[112]

- Regulation establishes common internal market rules for renewable and natural gases and hydrogen seeking to facilitate the entry and integration of renewable and low carbon gases into the energy system
- Supports the creation of a European hydrogen backbone to transport H2 across member states

GREENHOUSE GAS EMISSIONS SAVINGS METHODOLOGY

Commission Delegated Regulation (EU) 2023/1185.[113]

- Defines a methodology for calculating greenhouse gas emission savings for RFNBOs
- Establishes a minimum threshold for greenhouse gas emission savings

ReFuelEU AVIATION

Regulation (EU) 2023/2405.[114]

- Mandates the incorporation of sustainable aviation fuels (SAF) into aviation fuel supplies.
- Fuel suppliers will have to incorporate 2% sustainable aviation fuels in 2025, 6% in 2030 and 70% in 2050. From 2030, 1.2% of fuels must also be RFNBOs, rising to 35% in 2050.

FuelEU MARITIME

Regulation (EU) 2023/1805.[115]

- Requires ships to progressively reduce their GHG emissions and carbon intensity by adopting alternative fuels, including hydrogen-based RFNBOs
- GHG intensity to gradually decrease over time, by 2% in 2025 to as much as 80% by 2050

TEN-E REGULATION

Trans-European Networks for Energy Regulation (EU) 2022/869.[116]

- Supports cross-border hydrogen projects to enhance energy security and integrate the hydrogen market within the EU. Provides funding and streamlined permitting processes for hydrogen infrastructure, promoting the large-scale deployment

NET ZERO INDUSTRY ACT

Regulation (EU) 2024/1735.[91]

- Boosts up the EU's manufacturing capacity of technologies that support the energy transition
- Increase competitiveness of EU industry, create quality jobs, and support the EU's efforts to become energy independent

Alongside these in-force regulations and policies, the activities for regulatory and framework activities identified by MGF stakeholders included an emphasis on the following topics:

① Regulatory and policy support:

- Implement funding mechanisms and subsidies to kickstart the PtX industry, with a focus on value chain projects that connect production and consumption nodes.
- Increase funding amounts. Danish PtX tender = 1.25 billion DKK, CCS tender = 28.3 billion DKK.[117]
- Policy backing of large-scale infrastructure projects such as the hydrogen backbone with the required branching infrastructure and storage possibilities.
- Streamlined permitting processes to ensure quick deployment of production facilities e.g. energy zones and preferential treatment.
- Support early-stage innovation and R&D efforts.

② Harmonized EU and International regulation

- Advocate for ambitious EU-wide regulations and international cooperation to standardize and certify green fuels production pathways and emissions reduction potentials.
- Develop cohesive standards and certification schemes for fuel quality to facilitate cross-border trading of green fuels within and beyond the EU.

③ Risk sharing frameworks

- Provide economic support to reduce the financial risks associated with early-stage investment.
- Utilize fixed premiums, Contracts for Difference (CfDs) or Carbon Contracts for Difference (CCfDs) to provide a guaranteed price for a green fuel to stabilize revenue streams and create predictability for producers.

④ Transparency and documentation:

- Standardized reporting frameworks, disclosure requirements, and fuel certifications processes for companies involved in green fuel production and usage to ensure sustainability.
- Comprehensive documentation of the environmental impact of green fuels from production to end-use via different feedstocks and production pathways, including low-TRL ones.

⑤ Effective citizen engagement frameworks

- Design effective citizen engagement and involvement frameworks working with local municipalities and stakeholders.
- Implement public awareness campaigns to educate citizens on the benefits of green fuels and involve them in the decision-making process.

⑥ Policy for education and workforce development

- Develop the education and training programs needed to equip the workforce with the necessary skills for the green transition. See Chapter 5: Social and Sustainability for the job profiles needed.
- Collaborate with academic institutions and industry stakeholders to align curricula with the evolving needs of the green energy sector, including courses in innovation.

● Regulatory Activity
○ Within MGF's influence or scope

MISSION GREEN FUELS

Focus areas within regulation and policy

For regulation and policy, MGF can help drive:

- Regulatory impact analysis to understand how current and proposed regulations affect green fuel markets and investment strategies
- Risk assessment frameworks for early-stage green fuel projects, identifying potential regulatory challenges, or opportunities
- Compliance frameworks for rules around low carbon hydrogen and RFNBOs

Examples of past or ongoing MGF funded projects:

→ **RIGHydro:** Regulatory innovation to incentivize green hydrogen:
  - Contribute to the planning of a green hydrogen infrastructure by tackling regulatory, implementation and institutional barriers,
  - Analysis of the latest regulatory developments

→ **PtX Markets:** Markets, Policies, and Business Models for Green Fuels:
  - Analysis of regulation for green fuels and market design, and the impacts on European PtX investment

11. Financial and funding activities

Funding estimates

Green fuels and the associated expansion of renewable energy infrastructure will require substantial investment. Achieving the national PtX target necessitates an estimated 20-30 billion DKK for 4-6 GW of electrolyzer capacity, based on 2023 CAPEX costs.[118] However, the investment required for the necessary renewable energy capacity—across wind and solar assets—is projected to be more than four times higher, amounting to 135-175 billion DKK.[119] Furthermore, significant investments in the billions of DKK will be needed for trucks, ships, and other downstream infrastructure. The Jutland hydrogen pipeline alone is expected to cost between 8-15 billion DKK.[120] However, more detailed capex and FEED studies are ongoing.[121] Aside from production and use element, investment must also be made into research, innovation, and the ecosystem that will support future technology advancements in the industry.

While these are large sums of money, the put it into perspective, the Danish state spent 120 billion DKK on COVID-19 related expenses[122] across 2020 and 2022 and will spend around 20 billion DKK on 27 F-35 fighter jets between 2021 and 2026.[123] Nonetheless, green fuels must also be compared to other decarbonization options that will be needed to meet the 2030 goals; there are a lot of things to spend money on, and it is essential that state money is spent wisely and act as a force-multiplier stimulating private investment into green projects.

Funding sources

Funding for technology and innovation at lower TRLs in PtX and green fuels technologies will predominantly come from public financial support, as these early-stage innovations require investment without immediate financial returns. However, there are also private foundations such as Villum and the Novo Nordisk Foundation that will fund R&D for lower TRL technologies. Higher TRL technologies, and their deployment in projects, will rely on a combination of private financing potentially assisted with public financing in the form of grants and incentives on a national or EU level. Below are possible sources of public financing for green fuels related technologies:

Table 11.1: National and EU-level funding opportunities

Project Stage	National-Level funding	EU-Level funding
Low TRL R&D – proof of concept	• Innovation Fund Denmark (MissionGreenFuels) • EUDP • Danish National Research Foundation • Various private foundations	• Horizon Europe • ERDF and cohesion fuds • Just Transition Fund • EIT Innoenergy
High TRL Scale-up and deployment	• Innovation Fund Denmark (MissionGreenFuels) • EUDP • Danish Green Fund • KIF – Danish climate investment fund • EIFO – Export and investment fund • Various private funds, pension funds	• ETS Innovation Fund (Hydrogen Bank) • Connect Europe (Energy and transport infrastructure) • Invest EU + LIFE • IPCEI • ERDF, Just Transition Fund

Since the last roadmap was published, new funding initiatives have emerged, including the Danish PtX tender and the European Hydrogen Bank, which are described below

Danish PtX tender

As announced in the government's 2022 PtX strategy, the first PtX tender in 2023 awarded 1.25 billion DKK (167 million EUR) to six sites totalling 280MW.[124] The support will be given as a fixed premium subsidy (DKK per GJ) price over a period of 10 years. However, the total bids submitted totalled over 4 billion DKK (675 MW) meaning that the auction was 2.4X oversubscribed signalling addition demand for state support. It is unclear when the next tender round will take place or what the support amount will be.

European Hydrogen Bank

On a European level, the winners of the first hydrogen bank auction were announced and awarded in 2024. The European Commission is awarding nearly 720 million EUR to seven hydrogen projects in Spain, Portugal, Norway, and Finland totalling a production capacity of 1.5 GW of electrolysis (1.58 million tonnes of green hydrogen).[10] The first auction received 132 bids from 17 European countries requesting over 15 times the available budget. Like the Danish auction, there is significant oversubscription to the available funds. Funding for the hydrogen bank comes from ETS Innovation Fund which itself is financed by revenues generated from the ETS, specifically from the auctioning of allowances. There are plans for a second round of the hydrogen bank auction to be launched by the end of 2024.[125]

Financial and funding Activities

Alongside the funding mechanisms, the activities for financing identified by MGF stakeholders included the following:

1. Financial support for value chain projects outside of production and supply elements

Support for value chain projects outside of production/supply elements is crucial for building an effective green fuels industry. Important linkages such as storage, logistics, fuelling infrastructure should not be overlooked when providing initial support to the industry. This support could even extend to things such as digital trading marketplaces and platforms that assist with the buying and selling of green fuels.

2. Fair tariff models for the first-users of the hydrogen backbone

To incentivize early adoption of hydrogen infrastructure, tariff models that balance initial costs with long-term benefits should be explored. A model that aims to prevent prohibitively high costs for first-users, which can be a barrier to early-stage investment, should be avoided. Possible approaches include staggered tariffs that decrease as more users connect to the hydrogen backbone, or offering other financial incentives to early adopters. This ensures that the economic burden of infrastructure development does not fall disproportionately on initial users and encourages early market participation.

3. Innovation in funding and support models.

PtX has high potential but also comes with high risk – investors may view PtX investments with caution due to uncertainties with infrastructure, renewable energy availability, and inherent risks in emerging low TRL technologies. Creating innovate financing models that attracts additional investment into the sector is important. On the demand side, this could be fuel purchase agreements with price hedging mechanisms or government backed guaranteed to mitigate long-term fuel price volatility. For example, a government backed "buyers club" with guarantees on price for the buyer to provide certainty in longer 10-15 year contracts. Such models would reduce investor risk and provide more stable and predictable demand, enabling more aggressive scaling of PtX technologies and infrastructure.

MISSION
GREEN FUELS

For funding, MGF can help drive:

- Direct funding of research, development, and innovation projects within the three main strategic workstreams of the mission:
    - Technologies
    - Infrastructure, PtX plants, Sector Coupling
    - Business and market development and acceptance
- Identify and prioritize key topics and areas for new research and innovation activities, while actively pursuing additional funding to support these initiatives

12. Key Performance Indicators

The following Key Performance Indicators (KPIs) are tools used to evaluate the progress of certain elements within Denmark's within green fuels sector. These KPIs are assessed using a system that provides a visual indication of how well the targets are being met. Each KPI is accompanied by comments that provide context and insights into the progress, challenges, and expected outcomes, along with references to the sources of the information.

KPI framework

KPI: Description of goal

Not meeting target

Target underway / Activity on track

Target met

Comments:

- Supporting comments and indicators for ranking

Green hydrogen KPIs

Progress metrics for Denmark's green hydrogen roadmap

KPI 1: Green hydrogen price

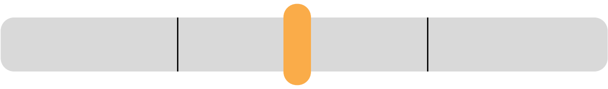
>10EUR/kg

4-10EUR/kg

<4EUR/kg

Comments:
The latest hydrogen bank results reveal an average production cost of 11.39 EUR/kg for Danish submitted bids
Individual projects not assessed.
Source: European Commission[10]

KPI 2: Hydrogen backbone



No political agreement – concept stage

Political and funding framework at advanced stage

FID reached – construction underway

Comments:
Market dialogue and user commitment process around pipeline underway by Energinet. Conditional investment decision likely to occur in Q1 2025
Source: Energinet June 2024 Information package[16]

KPI 3: Domestic Electrolyzer capacity (GW)

Unlikely to reach 4-6GW

Strong progress towards goals

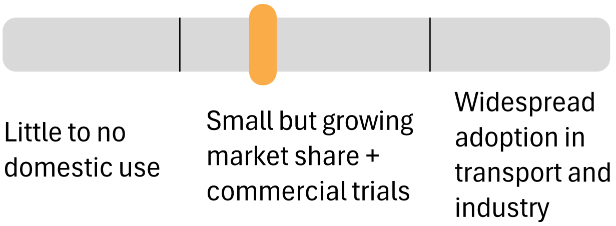
On track for 4-6 GW

Comments:

- Projects in concept/feasibility stage total 23+ GW
- Current FID: 0.4GW
- Multiple FIDs on large scale plants will likely be made in 2025

Source: Brintbranchen "brint i tal" August 2024[13]

KPI 4: Green hydrogen end-use (domestic)



Comments:

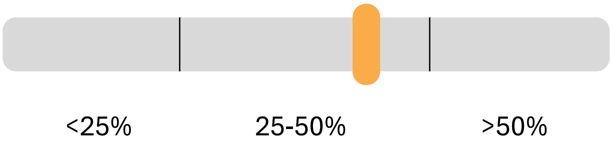
- Hysynergy project (Everfuel / Crossbridge) to use H2 in refining
- Concepts for DFDS ferry to Norway to use compressed H2
- Closure or repurposing of light-duty H2 filling stations serving passenger cars

Source: Project websites

Intermediary Fuels KPIs

Progress metrics for Denmark's biofuels and intermediary fuels roadmap

KPI 5: Biomethane usage (% of gas usage)



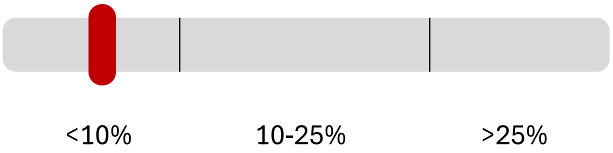
Comments:

In 2023, the percent share of biomethane in Danish gas consumption was ~40%

In Q1 2024 the share was 23%

Source: DEA Energistatistik May 2024[23]

KPI 6 Percent of green fuels in transport

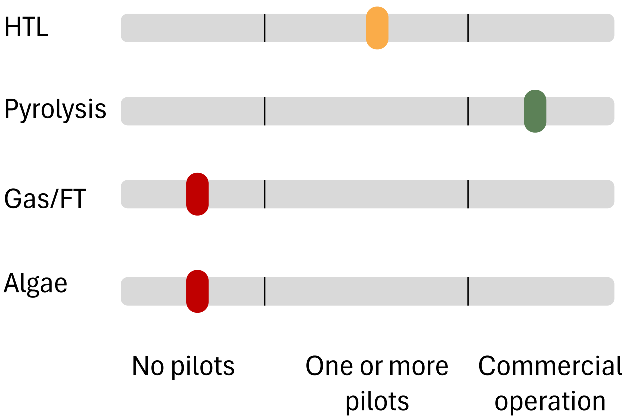


Comments:

Use of green fuels in transport reached levels of 6.5 % in 2022, mostly through fuel blending into diesel and gasoline

Source: KF23[56]

KPI 7: Next-gen biofuels technology plants



Comments:

HTL pilot: Aalborg University

Pyrolysis: SkyClean (agricultural waste), Quantafuel Skive (plastic), Elysium Nordic (tires)

Gasification/FT: No operating pilots identified

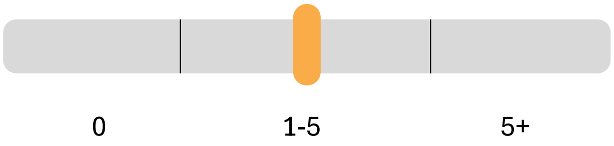
Algae: past research projects, no ongoing pilots for biofuels production

Source: Project websites

Maritime Fuels KPIs

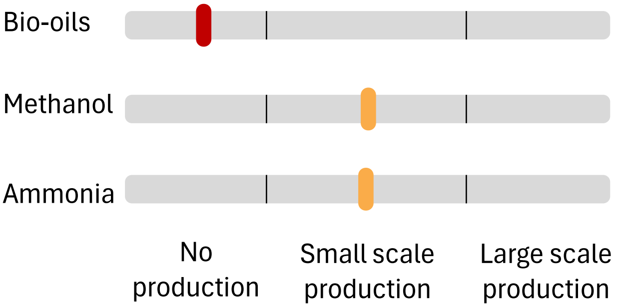
Progress metrics for maritime fuels and associated technologies

KPI 8: Number of green shipping corridors planned involving Danish ports



Comments:
DK-UK green shipping corridor in pre-feasibility study
Port of Rønne involved with European green corridor in Northern Europe and the Baltic Sea
Source: Mission Innovation – Green Shipping Corridors tracker[126]

KPI 9: Domestic production of green fuels for maritime uses

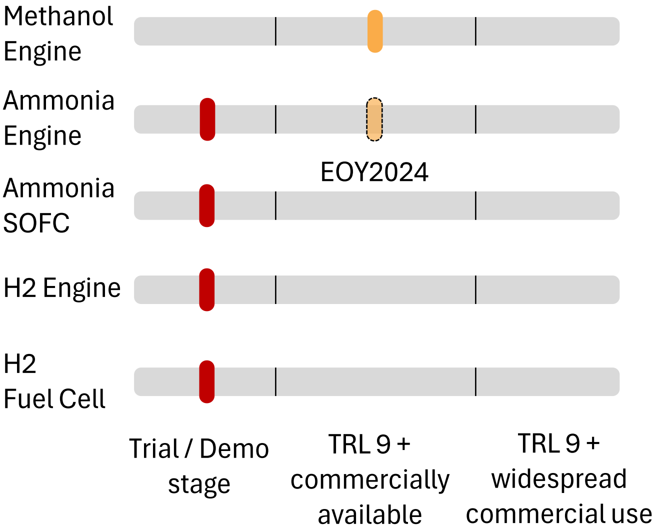


Comments:

- E-Methanol production planned at European Energy Kassø for 2024
- Ammonia production at Skovgaard Energy / REDDAP in Ramme slated for operation in 2024 (offtake for fertilizer of marine uses)
- CIP Høst to produce hydrogen and ammonia
- No current production of bio-oils for maritime use

Source: Project websites

KPI 10: Readiness of Engine / Fuel Cell technologies



Comments:

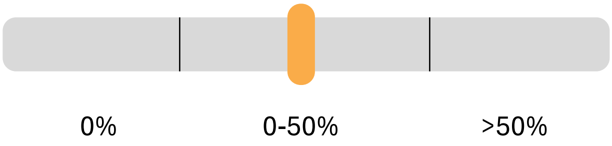
- Dual-fuel methanol engines seeing use on Maersk ships (three ships enabled as of Aug 2024)
- Multiple engine OEMs offering methanol engines / retrofits (Europe and Asia)
- MAN ammonia engine advancing quickly, projected TRL 9 and commercial use in late 2024/2025
- Ammonia SOFC is still at TRL4-5
- H2 combustion engine for ships TRL4-5
- H2 Fuel cell for maritime purposes is at TRL 6-8

Source: Project websites, ETP Clean technology guide[127]

Aviation Fuels KPIs

Progress metrics for aviation fuels and associated technologies

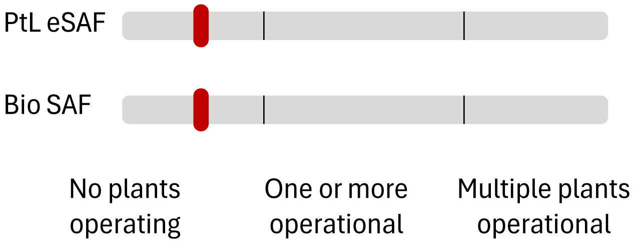
KPI 11: Share of Danish airports offering SAF[i]



Comments:
Four airports currently have incorporated SAF:
Sønderborg first to offer SAF in 2021
Billund began offering SAF in 2022
CPH began offering SAF in 2023
AAL airport first delivery in 2023 – part of the Norwegian Air AAL-CPH to
Most of the SAF is supplied by DCC and Shell aviation
Source: Projects websites, news announcements

i. Danish airports considered include CPH, BLL, AAL, AAR, RNN, EBJ, SGD, RKE, ODE. Count does not include smaller regional or recreational airports.

KPI 12: SAF production facilities in DK operational



Comments:
Multiple PtL SAF plants announced: MeSAF, FrontFuel, Arcadia efuels, European Energy Padborg
First commercial operation date slated for 2026 (Arcadia)
No current bioSAF plants (HEFA/HVO)
SAF used today in Danish airports is imported
Source: Project websites

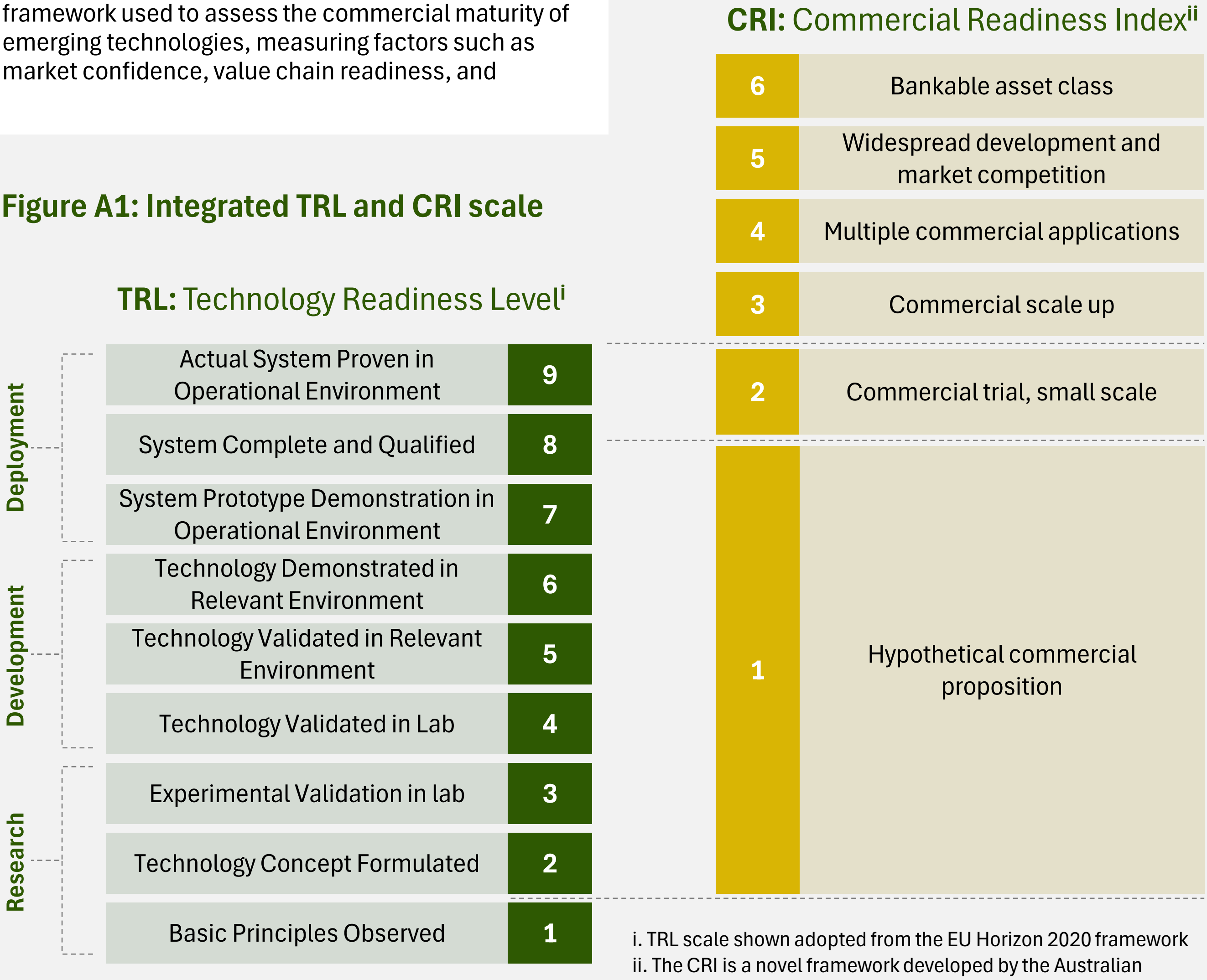
Appendix 1. Technology Readiness Levels

Technology Readiness Levels (TRLs) are a standardized metric used to assess the maturity of a technology, ranging from initial research stages (TRL 1) to full market deployment (TRL 9). Including TRLs allows stakeholders to gauge the current maturity of green fuels technologies, understand the remaining challenges, and prioritize investments in research and development across production, distribution and storage, and end-use parts of the value chain.

The **Commercial Readiness Index (CRI)** is a framework used to assess the commercial maturity of emerging technologies, measuring factors such as market confidence, value chain readiness, and regulatory environment. It helps stakeholders gauge how close a technology is to full-scale commercialization and widespread adoption

Using an **integrated TRL and CRI scale provides a comprehensive assessment** of both the technological maturity and the market readiness of established or emerging technologies within green fuels. TRL's are from IEA ETP guide[127], CRI's are from Ramboll assessment (best estimate of commercialization).

Figure A1: Integrated TRL and CRI scale



TRL: Technology Readiness Level[i]

Deployment	Actual System Proven in Operational Environment	9
	System Complete and Qualified	8
	System Prototype Demonstration in Operational Environment	7
Development	Technology Demonstrated in Relevant Environment	6
	Technology Validated in Relevant Environment	5
	Technology Validated in Lab	4
Research	Experimental Validation in lab	3
	Technology Concept Formulated	2
	Basic Principles Observed	1

CRI: Commercial Readiness Index[ii]

6	Bankable asset class
5	Widespread development and market competition
4	Multiple commercial applications
3	Commercial scale up
2	Commercial trial, small scale
1	Hypothetical commercial proposition

i. TRL scale shown adopted from the EU Horizon 2020 framework
ii. The CRI is a novel framework developed by the Australian Renewable Energy Agency (ARENA)

H2 Electrolyzer Technologies

Technology	TRL	CRI
Alkaline electrolyzer (AE)	9	3
Proton exchange membrane electrolyzer (PEM)	9	2
Anion exchange membrane electrolyzer (AEM)	6	1
Solid oxide electrolyzer cell (SOEC)	8	1

Other H2 Production technologies

Technology	TRL	CRI
Steam methane reforming + CCUS (blue H2)	9	3
Biomass waste gasification	5	1
Biomass waste pyrolysis (dry)	7-9	1
Biomass waste pyrolysis (wet)	4-6	1
Natural hydrogen extraction	5	1
Photocatalytic water splitting	5	1
Electric-powered steam reforming	4	1

Midstream hydrogen (storage and distribution) technologies

Technology		TRL	CRI
Storage	Hydrogen pressure vessel storage	9	4
	Liquid hydrogen storage tank	9	2
	Metal hybrids storage	4	1
	Aquifer storage	3	1
	Depleted gas fields storage	4	1
	Salt cavern storage	9	2
Processes	Hydrogen liquefaction	9	3
	Liquid organic hydrogen carriers (LOHC)	7	1
	Ammonia cracking	4	1
Distribution	Hydrogen Truck transport	9	5
	Liquid organic hydrogen (LOHC) carrier tanker	9	5
	Liquified hydrogen tanker	7	1
	Hydrogen blending into natural gas network	7	1
	New hydrogen pipelines	9	2
	Repurposed natural gas pipelines	8	1
	Hydrogen turbo compressors	6	1
	Hydrogen bunkering	4	1

Downstream hydrogen technologies (end-use)

Hydrogen Technologies

Technology		TRL	CRI
Industrial	Hydrogen low temperature heating	9	4
	Hydrogen high temperature heating	7	2
	Direct reduction of iron (DRI) based on 100% H2	6	2
	Direct reduction of iron (DRI) based on H2/NG blend	8	3
Road	Hydrogen fueling (low flow rate)	9	5
	Hydrogen fueling (high flow rate)	4	1
	Hydrogen tank (road vehicles)	9	3
	Hydrogen fuel cell electric vehicle (light)	9	4
	Hydrogen fuel cell bus	9	3
	Hydrogen fuel cell truck	8	2
	Hydrogen combustion (road) vehicles	6-7	2
Ship	Hydrogen fuel cell ship	6-8	1
	Hydrogen combustion engine (ship)	4-5	1
Aviation	Hydrogen storage tank (aircraft)	4	1
	Direct hydrogen combustion in jet engine	3-4	1
	Hybrid fuel cell propulsion system – jet engine	3-4	1
	Hydrogen fuel cell propulsion system	6-7	1

Biofuels production Technologies

Biofuels Technologies

Technology		TRL	CRI
Biogas/Biomethane	Anaerobic digestion (biomethane)	9	6
	Anaerobic digestion and biological methanation with H2 (biomethane)	7	1
	Anaerobic digestion and catalytic methanation with H2 (biomethane)	8	2
	Biomass gasification - small scale (biomethane) (dry)	9	2
	Biomass gasification - small scale (biomethane) (wet)	4-6	1
	Biomass gasification and catalytic methanation (biomethane)	7	2
	Biomethanisation of syngas	3-5	1
Biodiesel/Bio-oils	Alcohol-to-jet	7-8	2
	FAME production	9	4
	Gasification with Fischer-Tropsch (FT)	7-8	2
	Gasification and hydrogen enhancement and Fischer-Tropsch (FT)	5	1
	HVO / HEFA production	9	6
	Hydrothermal liquefaction (HTL) and upgrading (biodiesel)	4	1
	Pyrolysis and upgrading (biodiesel)	7	2
	Bio-oils from NCS (Non-Conventional Species) or halophytes	3-5	1

Biofuels Technologies

Downstream biofuels technologies (End-use)

Technology		TRL	CRI
Biofuels/other	Synthetic Iso-Paraffins “sugars to hydrocarbons” route	7	1
	Hydrothermal liquefaction (HTL) and upgrading of micro-algae	3-4	1
	Micro-algae hydrotreating (bio-oils)	4	1
	Enzymatic fermentation (lignocellulosic bioethanol)	8	3
	Production of Biomass-Derived Light Olefins	3-5	1

Downstream biofuels technologies (End-use)

Technology	TRL	CRI
Compressed biomethane truck transport	9	3-4
Liquified biomethane truck transport	9	3-4
Ethanol/Methanol-fueled diesel engine	9	3-4
Biomethane fueled ship engine	9	3-4

Efuels technologies

Efuels production technologies

Technology	TRL	CRI
Chemical methanation via catalyst (e-methane)	8-9	2
Methanol synthesis via catalytic hydrogenation	8	2
Fischer-Tropsch using CO2 reduction via reverse water gas shift (RWGS) reaction	6	2
Ammonia synthesis through Haber Bosch process	9	6
CO2 + Hydrogen to CH4 to syngas to Fischer-Tropsch	4-7	1

Midstream efuel (storage and distribution) technologies

Technology	TRL	CRI
Ammonia storage	9	6
Ammonia bunkering	9	6
Ammonia cracking	4	2
Methanol storage	9	6
Methanol bunkering	9	6

Downstream efuel technologies maritime and aviation

Technology	TRL	CRI
Ammonia fueled ship engine	6	1
Ammonia solid oxide fuel cell	4-5	1
Methanol fueled ship engine	9	3
Methanol fuel cell electric ships	6	1
E-kerosene for use as SAF in jet engine	9	4-5

Links to other Innomissions and partnerships

MissionGreenFuels

Advancing green fuels to meet the national climate goals is one of four Danish Innomissions and should not be viewed standalone as green fuel production intersects with several key topics such as land use and sustainable agriculture, the use of CO2 in the production of efuels, and using waste plastics for the production of oils via chemical recycling, among others. These overlaps highlight the necessity of a coordinated approach across multiple missions to effectively drive progress towards Denmark's climate objectives.

Innomission	**Focus area**	**Overlapping topics**
INNO-CCUS	Carbon capture, utilization, and storage technologies	• Biogenic CO2 utilization • CO2 transport and storage infrastructure for efuels production • Advancement of DAC technology for eventual efuel usage
AgriFoodTure	Sustainable agriculture and food production	• Use of agricultural waste for biofuel production • Sustainable land use and bio feedstock management
Trace	Circular economy initiatives, focusing on plastics and textiles	• Chemical and biological recycling for oil recovery (e.g. pyrolysis, HTL) for plastic waste

References (1/5)

Chapter 1:

1. DNV (2022) Hydrogen Forecast to 2050, Energy Transition Outlook 2022, https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050

2. Schreyer, Felix, et al. (2024) “Distinct roles of direct and indirect electrification in pathways to a renewables-dominated European Energy System.” One Earth, vol. 7, no. 2, Feb. 2024, pp. 226–241, https://doi.org/10.1016/j.oneear.2024.01.015

3. IRENA (2022), Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward, International Renewable Energy Agency. Available At: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf

4. Dansk Energi (2020) Recommendations for a Danish Strategy for Power-to-X. https://greenpowerdenmark.dk/files/media/danskenergi.dk/dokumenter/2020-11/Anbefalinger-til-en-dansk-strategi-for-Power-to-X.pdf

5. Klima- Energi og Forsyningsministeriet (2021). The Government’s strategy for Power-to-X. https://ens.dk/sites/ens.dk/files/ptx/strategy_ptx.pdf

6. European Commission (2022), REPowerEU Plan, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

7. Lazard (2024) LCOE+ June 2024, https://www.lazard.com/media/xemfey0k/lazards-lcoeplus-june-2024-_vf.pdf

8. Agora Energiwende (2023) Levelized Cost of Hydrogen Calculator V1.0, https://www.agora-energiewende.org/data-tools/levelised-cost-of-hydrogen-calculator

9. BloombergNEF (2024), Electrolysis System Capex could drop 30% by 2025, https://www.pv-magazine.com/2024/03/21/electrolyzer-prices-what-to-expect/

10. European Commission (2024). European Hydrogen Bank auction provides €720 million for renewable hydrogen, https://ec.europa.eu/commission/presscorner/detail/en/IP_24_2333

11. Marco Polo (2023), Can China Make Hydrogen Electrolyzers Cheap as It Did for Solar? (Part I), https://macropolo.org/china-hydrogen-electrolyzers-cheap-solar

12. Danish Energy Agency (2024), Biogas in Denmark, https://ens.dk/en/our-responsibilities/bioenergy/biogas-denmark

13. Brintbranchen (2024), Brint I Tal - Overblik over PtX-projektudvikling i Danmark. https://brintital.dk/

14. Guidehouse (2022), European Hydrogen Backbone Map (April 2022), https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf

15. Energinet (2023), Energinet and Gasunie agree on next steps towards a cross-border green hydrogen infrastructure, https://en.energinet.dk/about-our-news/news/2023/11/16/energinet-and-gasunie-agree-on-next-steps-towards-a-cross-border-green-hydrogen-infrastructure/

16. Energinet (2024), Danish hydrogen Backbone Information Package 1 June 2024, https://energinet.dk/media/ckqhzouy/informationspakke-1-juni-2024.pdf

17. Energinet (2022) , Reporting of the feasibility study of Danish hydrogen infrastructure, https://en.energinet.dk/media/vggfrlgi/results-of-the-feasibility-study.pdf

Chapter 2:

18. Klima- Energi og Forsyningsministeriet (2024), Klimastatus og -fremskrivning 2024, https://www.kefm.dk/klima/klimastatus-og-fremskrivning/klimastatus-og-fremskrivning-2024

19. Danish Energy Agency (2021), Efterspørgsel efter Power-to-X-produkter, https://ens.dk/sites/ens.dk/files/ptx/efterspoergsel_efter_power-to-x-produkter.pdf

20. Klima- Energi og Forsyningsministeriet (2022), Aftale om udvikling og fremme af brint og grønne brændstoffer af 15. marts 2022, https://www.regeringen.dk/media/11146/aftale-om-udvikling-og-fremme-af-brint-og-groenne-braendstoffer.pdf

21. Danish Energy Agency (2023), Afrapportering til aftalekredsen om PtX-taskforce, https://ens.dk/sites/ens.dk/files/ptx/afrapportering_af_ptx-taskforce.pdf

22. Danish Energy Agency (2021), Green Gas Strategy, https://ens.dk/sites/ens.dk/files/OlieGas/green_gas_strategy.pdf

23. Biogas Danmark (2024), Fakta om biogas, https://www.biogas.dk/fakta/

24. Danish Energy Agency (2023), Analyseforudsætninger til Energinet 2023 (AF23), https://ens.dk/service/fremskrivninger-analyser-modeller/analyseforudsaetninger-til-energinet

25. European Commission (2020), A hydrogen strategy for a climate-neutral Europe, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

26. Kraka Advisory (2023), Power-to-X bidrager kun lidt til danske klimamål, https://kraka-economics.dk/news/power-x-bidrager-kun-lidt-til-danske-klimamal

27. European Hydrogen Observatory (2024), Annual hydrogen consumption per country in Europe, https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/end-use/hydrogen-demand

28. Die bundesregierung (2024), Power plant strategy for hydrogen-capable power plants, https://www.bundesregierung.de/breg-de/aktuelles/kraftwerksstrategie-2257868

References (2/5)

29. Department of Energy (2022), Financial Incentives for Hydrogen and Fuel Cell Projects, https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects

30. Bipartisan Policy Center (2022), CHIPS and Science Act Summary: Energy, Climate, and Science Provisions, https://bipartisanpolicy.org/blog/chips-science-act-summary/

31. European Commission (2024), Press Release, Commission imposes provisional countervailing duties on imports of battery EVs from China while discussions with China continue, https://ec.europa.eu/commission/presscorner/detail/en/ip_24_3630

32. PwC (2024), Analyse af investeringsklimaet for havvind i Danmark, https://www.pwc.dk/da/publikationer/2024/analyse-af-investeringsklimaet-for-havvind.html

33. Ramboll (2022), Power-to-X holdningsundersøgelse blandt de vigtigste aktører i Danmark September 2022, https://7520151.fs1.hubspotusercontent-na1.net/hubfs/7520151/Ramboll_PtX%20survey%202022_Resultater-1.pdf

34. Ramboll (2023), Power-to-X holdningsundersøgelse blandt devigtigste aktører i Danmark Oktober 2023, https://7520151.fs1.hubspotusercontent-na1.net/hubfs/7520151/REN/Ramboll_PtX%20survey%202023_Resultater.pdf

Chapter 3:

35. Danish Patent and Trademark Office (2024), Denmark in top 10 among the world's most innovative countries, https://www.dkpto.org/news/2024/feb/denmark-in-top-10-among-the-worlds-most-innovative-countries-

Chapter 4:

36. Danish Energy Agency (2023), Application Instructions for the establishment of Direct Lines, https://ens.dk/sites/ens.dk/files/El/ansoegningsvejledning_til_etablering_af_direkte_linjer.pdf

37. DTU (2020), DTU Sector Development Report – Smart Energy Systems are the Way Forward, https://www.dtu.dk/-/media/dtudk/samarbejde/virksomheder-og-erhverv/sektorudvikling/smarte_energisystemer/2020-06-19-dtu-sector-development-project-about-smart-energy-systems-uk-summary-of-report.pdf

38. Energinet (2019), PTX I Danmark Før 2030: Potentiale for PtX I Danmark på kortere sigt I et systemperspektiv, https://energinet.dk/media/ff5nnyvy/ptx-i-danmark-foer-2030.pdf

39. Danish Energy Agency (2019), Muligheder og udfordringer ved indpasning af storskala PtX i det danske elsystem, https://ens.dk/sites/ens.dk/files/ptx/muligheder_og_udfordringer_ved_indpasning_af_storskala_ptx_i_det_danske_elsystem.pdf

40. Hans Böhm, Simon Moser, Stefan Puschnigg, Andreas Zauner,Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials, International Journal of Hydrogen Energy, Volume 46, Issue 63, https://www.sciencedirect.com/science/article/pii/S0360319921025477

41. Yongming Zhao, Huaqing Xue, Xu Jin, Bo Xiong, Renhe Liu, Yong Peng, Luyang Jiang, Guohua Tian, System level heat integration and efficiency analysis of hydrogen production process based on solid oxide electrolysis cells, International Journal of Hydrogen Energy, Volume 46, Issue 77, 2021, https://www.sciencedirect.com/science/article/pii/S0360319921036077

42. Dansk Fjernvarme, COWI (2021), Power-to-X og Fjernvarme, https://danskfjernvarme.dk/media/2rmhckxj/ptx-og-fjernvarme_download.pdf

43. Gascade Gastransport (2020), Hydrogen Infrastructure – The practical conversion of long-distance gas networks to hydrogen operation, https://www.nowega.de/wp-content/uploads/200915-whitepaper-h2-infrastructure-EN.pdf

44. Bard, Jochen & Gerhardt, Norman & Selzam, Patrick & Beil, M. & Wiemer, Martin & Buddensiek, Maike. (2022). The Limitations of Hydrogen Blending in the European Gas Grid: A study on the use, limitations and cost of hydrogen blending in the European gas grid at the transport and distribution level. 10.13140/RG.2.2.30093.41448

45. FORCE Technology (2020), Danish gas pipelines are ideal for transporting hydrogen, https://forcetechnology.com/en/cases/hydrogen-transport-danish-gas-pipelines-ideal

46. World Biogas Association (2020), Case study 3: Nature Energy, https://www.worldbiogasassociation.org/8-case-study-3-nature-energy/

47. State of Green (2022), Biogas from Copenhageners' food waste can now replace imported natural gas, https://stateofgreen.com/en/news/biogas-from-copenhageners-food-waste-can-now-replace-imported-natural-gas/

Chapter 5

48. Jason Prno, D. Scott Slocombe, Exploring the origins of 'social license to operate' in the mining sector: Perspectives from governance and sustainability theories, Resources Policy, Volume 37, Issue 3, 2012, https://www.sciencedirect.com/science/article/pii/S0301420712000311

49. International PtX Hub (2024), Benefits for Local Communities in the Context of Power-to-X, https://ptx-hub.org/wp-content/uploads/2024/02/International-PtX-Hub_202402_Sustainability-Briefing-4_benefits-for-communities.pdf

50. DTU (2024), DTU Couse Base: "Green Fuels", https://kurser.dtu.dk/search?CourseCode=&SearchKeyword=fuels

51. Børne og Undervisningsministeriet (2024), Ny aftale ruster erhvervsuddannelserne til den grønne omstilling, https://www.uvm.dk/aktuelt/nyheder/uvm/2024/jun/240607-ny-aftale-ruster-erhvervsuddannelserne-til-den-groenne-omstilling

References (3/5)

52. Green Skills for Hydrogen Project, https://greenskillsforhydrogen.eu/

53. AAU, AU, DTU, SDU, Flexible Masters in Power-to-X https://daces.dk/efteruddannelse-i-energilagring/

54. EU Pact for Skills, https://pact-for-skills.ec.europa.eu/index_en

55. PwC (2022), Skills and Training to Support the Hydrogen Economy, https://h2council.com.au/wp-content/uploads/2022/12/PWC-Developing-Australias-hydrogen-workforce_Presentation_20-September-2022.pdf

Chapter 6

56. Danish Energy Agency (2024), KF24: Klimastatus og - fremskrivning 2024, https://ens.dk/service/fremskrivninger-analyser-modeller/klimastatus-og-fremskrivning

57. Klima- Energi og Forsyningsministeriet (2024), Danmarkshistoriens største havvindsudbud skudt i gang, https://www.kefm.dk/aktuelt/nyheder/2024/apr/havvindsudbud

58. Energinet (2024), Energy Islands in Denmark, https://energinet.dk/anlaegsprojekter/energioer/

59. Høst PtX Esbjerg (2024), FAQ: https://hoestptxesbjerg.dk/da/faq/

60. Ingeniøren (2024), We will need at least 350 additional giant wind turbines to power data centres in 11 years, https://ing.dk/artikel/we-will-need-least-350-additional-giant-wind-turbines-power-data-centres-11-years

61. Statistics Denmark (2022), Water and Wastewater – Water abstraction in Denmark, https://www.dst.dk/en/Statistik/emner/miljoe-og-energi/groent-nationalregnskab/vand-og-spildevand

62. RMI (2023), Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption, https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/

63. Iris Group (2024), Water Tech Research in Denmark, https://irisgroup.dk/wp-content/uploads/2024/01/Water-tech-research-in-Denmark.pdf

64. Gylling, Morten & Jørgensen, Uffe & Bentsen, Niclas & Kristensen, Inge & Dalgaard, T. & Felby, Claus & Johannsen, Vivian Kvist. (2013). The + 10 million tonnes study: increasing the sustainable production of biomass for biorefineries. 10.13140/2.1.3101.8563.

65. Gregg, J. S., Bolwig, S., Solér, O., Vejlgaard, L., Gundersen, S. H., Grohnheit, P. E., Herrmann, I. T. (Ed.), & Karlsson, K. B. (Ed.) (2014). Experiences with biomass in Denmark. DTU https://backend.orbit.dtu.dk/ws/portalfiles/portal/97912187/Experiences_with_biomass_in_Denmark.pdf

66. AAU DCA Report (2019), Potential Danish Biomass Production and Utilization in 2030, https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport219.pdf

67. CE Delft (2020), Used Cooking Oil (UCO) as a biofuel feedstock in the EU, https://cedelft.eu/wp-content/uploads/sites/2/2021/04/CE_Delft__200247_UCO_as_biofuel_feedstock_in_EU_FINAL-v5.pdf

68. INNO-CCUS (2024), Direction 2050: The Danish CCUS Roadmap, https://inno-ccus.dk/wp-content/uploads/2024/08/INNO-CCUS-Rapport-Digital59.pdf

69. Klima- Energi og Forsyningsministeriet (2023), Strategic efforts for deployment of carbon capture and storage, https://ens.dk/en/our-responsibilities/ccs-carbon-capture-and-storage/political-agreements-and-applicable-legislation

Chapter 7

70. Statistics Denmark (2023), National accounts by industry, https://www.dst.dk/en/Statistik/emner/oekonomi/nationalregnskab/branchefordelt-nationalregnskab

71. Aalborg Portland (2023), ESG Report (2022 ESG performance in numbers, https://www.aalborgportland.dk/wp-content/uploads/2024/04/ESG_Rapport2023.pdf

72. Green Tax Reform for Industry (2022), Aftale mellem regeringen og Venstre, Socialistisk Folkeparti, Radikale Venstre, Det Konservative Folkeparti https://fm.dk/media/26070/aftale-om-groen-skattereform-for-industri-mv-a.pdf

73. European Commission (2009), Fuel Quality Directive Amendment, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0030

74. Danish Energy Agency (2024) GA24: Global Afrapportering - Denmark's global climate impact, https://ens.dk/sites/ens.dk/files/Analyser/danmarks_globale_klimapaavirkning-_hovedrapport_2024.pdf

75. DNV (2023), Energy Transition Outlook 2023 – Maritime Forecast to 2050, https://www.dnv.com/maritime/publications/maritime-forecast-2023/

76. DNV (2019), Comparison of Alternative Marine Fuels, https://safety4sea.com/wp-content/uploads/2019/09/SEA-LNG-DNV-GL-Comparison-of-Alternative-Marine-Fuels-2019_09.pdf

77. Anthony Foretich, George G. Zaimes, Troy R. Hawkins, Emily Newes, Challenges and opportunities for alternative fuels in the maritime sector, Maritime Transport Research, Volume 2, 2021, https://www.sciencedirect.com/science/article/pii/S2666822X21000241

78. Mærsk McKinney Møller Center for Zero Carbon Shipping (2024), Fuel Pathway Maturity Map, https://www.zerocarbonshipping.com/fuel-pathways/

79. ZEM Ports NS (2023), 14 new electric ferry projects in Denmark, https://northsearegion.eu/zem-ports-ns/news/14-new-e-ferry-projects/

80. Mærsk McKinney Møller Center for Zero Carbon Shipping (2024), Fuel Cost Calculator v_1.0, https://cms.zerocarbonshipping.com/media/uploads/documents/fuel_cost_calculator_v1.0.xlsx

References (4/5)

81. International Maritime Organization (2023), Revised GHG reduction strategy for global shipping, https://www.imo.org/en/MediaCentre/PressBriefings/Pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx

82. International Energy Agency (2022), World Energy Balance, https://www.iea.org/data-and-statistics/data-product/world-energy-balances

83. European Union Aviation Safety Agency (2022), What are Sustainable Aviation Fuels?, https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/what-are-sustainable-aviation-fuels

84. Mission Possible Partnership (2022), Making Net-Zero Aviation Possible, https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Making-Net-Zero-Aviation-possible.pdf

85. Clean Sky 2 (2021), Clean Sky 2 Technology Evaluator – First Global Assessment 2020 – Technical Report, https://cleansky.paddlecms.net/sites/default/files/2021-10/TE-FGA-TR_en.pdf

86. World Economic Forum and McKinsey (2020), Clean Skies for Tomorrow – Sustainable Aviation Pathways Insight Report, https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf

87. ICAO (2022), Sustainable Aviation Fuel (SAF) , https://www.icao.int/environmental-protection/pages/SAF.aspx

88. Winther Mortensen, A., Wenzel, H., Dalgas Rasmussen, K., Sandermann Justesen, S., Wormslev, E., & Porsgaard, M. (2019). Nordic GTL: A pre-feasibility study on sustainable aviation fuel from biogas, hydrogen and CO2. SDU Livscykluscenter, https://findresearcher.sdu.dk/ws/portalfiles/portal/155625931/Nordic_aviation_fuel_production_28_10_2019_final.pdf

Chapter 8

89. NEKST (2024) , Afrapportering fra NEKST-arbejdsgruppen - Mere sol og vind på land, https://www.kefm.dk/klima/nekst-den-nationale-energikrisestab/nekst-arbejdsgruppe-mere-sol-og-vind-paa-land

90. TOPSOE, SOEC Fabrik i Herning, https://www.topsoe.com/da/herning

91. European Commission (2023), Net Zero Industry Act, https://single-market-economy.ec.europa.eu/publications/net-zero-industry-act_en

92. Awogbemi, Omojola & Kallon, Daramy. (2023). Application of machine learning technologies in biodiesel production process—A review. Frontiers in Energy Research. 11. 1122638. 10.3389/fenrg.2023.1122638.

93. European Biogas Association (2022), Biogenic CO2 from the Biogas Industry, https://www.europeanbiogas.eu/wp-content/uploads/2022/10/Biogenic-CO2-from-the-biogas-industry_Sept2022-1.pdf

94. Ögmundarson, Ólafur & Thesis, Phd. (2018). Life Cycle Assessment of chosen Biochemicals and Bio-based polymers. https://www.researchgate.net/publication/334194870_Life_Cycle_Assessment_of_chosen_Biochemicals_and_Bio-based_polymers

95. European Energy Kassø, https://dk.europeanenergy.com/2023/10/27/european-energy-vinder-power-to-x-udbud-og-paabegynder-naeste-generation-af-e-fuel-produktion/

96. Skovgaard Energy Ammonia facility (REDDAP), https://skovgaardenergy.dk/rejsegilde-paa-groent-ammoniak-anlaeg-i-nordvestjylland/

97. MAN Energy Solutions, Ammonia Engine Testing https://www.man-es.com/discover/ammonia-engine-testing

98. Veldhuizen, Berend & van Biert, Lindert & Aravind, P V & Visser, K.. (2023). Solid Oxide Fuel Cells for Marine Applications. International Journal of Energy Research. 2023. 10.1155/2023/5163448.

99. DBI, SafeSBU project, https://brandogsikring.dk/nyheder/2024/nyt-projekt-skal-bane-vejen-for-power-to-x-paa-havne/

100. DNV, Role of Ammonia in a hydrogen economy training course, safety, https://www.dnv.com/training/training-course-role-of-ammonia-in-a-hydrogen-economy-228224/

101. Danish Energy Agency (2024), Lov om statsligt udpegede energiparker, https://www.planinfo.dk/Media/638526588092874375/Orientering%20om%20lov%20om%20statsligt%20udpegede%20energiparker.pdf

102. Energy Cluster Denmark (2022), Marco Polo DK – Methanol Readiness Cost Operationality Port Logistics - Denmark, https://www.energycluster.dk/wp-content/uploads/2023/01/Marco-Polo-DK-Final-Report.pdf

103. Advanced Biofuels USA (2019), Biofuels Production and Consumption in Denmark: Status, Advances and Challenges, https://advancedbiofuelsusa.info/biofuels-production-and-consumption-in-denmark-status-advances-and-challenges

104. MeSAF Aalborg, Project Information, https://mesaf.energy/project/

105. FrontFuel, New demonstration facility for sustainable aviation fuel at AU Viborg is first of its kind, https://bce.au.dk/en/currently/news/show/artikel/new-demonstration-facility-for-sustainable-aviation-fuel-at-au-viborg-is-first-of-its-kind

106. European Energy Padborg, https://dk.europeanenergy.com/2023/10/27/european-energy-vinder-power-to-x-udbud-og-paabegynder-naeste-generation-af-e-fuel-produktion/

107. Arcadia eFuels Vordingborg, https://arcadiaefuels.com/first-commercial-efuels-for-aviation-plant-in-denmark-on-schedule-for-2026-arcadia-selects-topsoe-and-sasol-technology/

References (5/5)

Chapter 10

108. Klima-, Energi- og Forsyningsministeriet (2020), Lov om klima - LOV nr 965 af 26/06/2020, https://www.retsinformation.dk/eli/lta/2020/965

109. Klima-, Energi- og Forsyningsministeriet (2020),VE-loven Bekendtgørelse af lov om fremme af vedvarende energi - LBK nr 125 af 07/02/2020, https://www.retsinformation.dk/eli/lta/2020/125

110. European Parliament (2023), Renewable Energy Directive III, https://eur-lex.europa.eu/eli/dir/2023/2413/oj

111. European Commission (2023), Delegated Act - Methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin, http://data.europa.eu/eli/reg_del/2023/1184/oj

112. European Parliament (2024), Gas Package - Common rules for the internal markets for renewable gas, natural gas and hydrogen, http://data.europa.eu/eli/dir/2024/1788/oj

113. European Commission (2023), Greenhouse gas emissions savings methodology, http://data.europa.eu/eli/reg_del/2023/1185/oj

114. European Parliament (2023), ReFuel Aviation - ensuring a level playing field for sustainable air transport, http://data.europa.eu/eli/reg/2023/2405/oj

115. European Parliament (2023), FuelEU Maritime - on the use of renewable and low-carbon fuels in maritime transport, http://data.europa.eu/eli/reg/2023/1805/oj

116. European Parliament (2022), TEN-E Regulation - guidelines for trans-European energy infrastructure, http://data.europa.eu/eli/reg/2022/869/oj

117. Danish Energy Agency (2024), Draft tender material for the Danish CCS Fund, https://ens.dk/sites/ens.dk/files/CCS/presentation_the_danish_ccs_fund_final.pdf

Chapter 11

118. Danish Energy Agency (2024), Technology Data for Renewable Fuels (Updated February 2024), https://ens.dk/en/our-services/technology-catalogues/technology-data-renewable-fuels

119. The Danish Government's Climate Partnerships (2020), Powering Denmark's Green Transition, https://greenpowerdenmark.dk/files/media/danskenergi.dk/dokumenter/2020-07/Powering_Denmarks_Green_Transition_Climatepartnership.pdf

120. Deloitte og Evida (2022), Cost-benefit analyse af en Dansk brintinfrastruktur, https://evida.dk/media/adjgkjrs/deloitte-hydrogen-cba-report-dk-v6b.pdf

121. Børsen (2024), Undersøgelser af milliarddyrt brintrør skydes i gang, https://borsen.dk/nyheder/virksomheder/undersogelserne-af-milliarddyrt-brintror-er-skudt-i-gang

122. Statistics Denmark (2022), COVID-19 Direkte offentlige udgifter til og med 1. kvt. 2022, https://www.dst.dk/da/Statistik/nyheder-analyser-publ/Analyser/visanalyse?cid=49837

123. Ingeniøren (2023), F-35s need engine upgrades unaccounted for in the Danish budget, https://ing.dk/artikel/f-35s-need-engine-upgrades-unaccounted-danish-budget

124. Danish Energy Agency (2024), The first PtX tender in Denmark has been determined: Six projects will establish electrolysis capacity on more than 280 MW, https://ens.dk/en/press/first-ptx-tender-denmark-has-been-determined-six-projects-will-establish-electrolysis-capacity

125. European Commission (2024), European Hydrogen Bank, https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/european-hydrogen-bank_en

126. Mission Innovation (2024), Green Shipping Corridor Route Tracker, https://mission-innovation.net/missions/shipping/green-shipping-corridors/route-tracker/

127. International Energy Agency (2024), ETP Clean Energy Technology Guide, https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

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