DTU

DTU Mini Sector Development Project
April 2021

# Green fuels in 'Blue Denmark' (the Danish maritime sector): DTU suggestions for research needs

# Preface

Blue Denmark aims to be an international leader in climate-friendly shipping. However, the transition to more sustainable shipping is a major challenge. It will require significant investment in new technology, ships, and energy infrastructure, and a systemic approach to collaboration across sectors and possible green fuel buyers.

In this report, DTU presents the results of its work in mapping the research opportunities for green fuels in Blue Denmark. The work has identified the need for research across systems, and the entire value chain. The mapping was completed using knowledge from DTU researchers, and input from the sector and sector organizations. This report identifies challenges, research needs, and framework conditions that can help support the potential for green fuels in Blue Denmark. The report concludes with recommendations for research needs in selected areas, and education and test and demonstration projects. It is our hope that the report can help secure Blue Denmark a position at the very forefront of sustainable shipping for many years to come.

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# Contents





## Our approach

The main purpose of the mini sector development project is to identify the technological challenges companies face in relation to the transition to using green fuels in Blue Denmark, and assess what DTU research is needed in light of these technological challenges. In concrete terms, the project has developed new achievable and focused visions for research and innovation.

The mapping was carried out through interviews with key people in companies, public institutions, authorities and sector associations, and 'pressure tested' at a 'Visions for research and roadmap' workshop, attended by interviewees, and at three steering committee meetings, attended by the heads of the participating departments at DTU. In parallel with the interviews, workshops, and steering committee meetings, the insights obtained have been discussed at fortnightly working group meetings for the participating DTU researchers.

Researchers from the DTU Centre for Oil & Gas, DTU Compute, DTU Electrical Engineering, DTU Energy, DTU Physics, DTU Chemistry, DTU Chemical Engineering, DTU Management, DTU Mechanical Engineering, DTU Environment, DTU Space, and DTU Wind have participated in the project. DTU Maritime and the Office for Research, Advice, and Innovation at DTU have coordinated.

The recommendations in the report reflect the dialogue with actors from the sector and across the DTU departments involved. DTU is the report initiator and responsible for its content.

## Sector development

Sector development projects are one of the tools, DTU uses to collaborate with the business sector and authorities. The aim of the projects is to improve the competitiveness of technology-intensive sectors by creating an overview and action plans for the development and use of new technologies.

**The method involves:**

- Mapping and analysing the use of technology in the sector, via interviews and workshops
- Identifying bottlenecks and development needs – at companies, authorities, and DTU
- Developing recommendations for research and framework conditions

The sector development projects are created in a forum comprising representatives of companies, authorities and sector associations, in Denmark and abroad, and researchers from DTU.

# Introduction

Denmark is one of the world's leading maritime nations, and Blue Denmark is one of Denmark's strongest business sectors. Around 60,000 people are directly employed in Blue Denmark, and about 42,000 people are indirectly employed. Overall, this equates to 3.8 percent of employment in Denmark.[1] Blue Denmark generates 5 per cent of Denmark's GDP and 25 per cent (DKK 232 billion) of Denmark's total exports. Blue Denmark thus has great socio-economic significance in Denmark.[2]

Blue Denmark is part of a global industry. Over 90,000 commercial ships sail on the oceans of the world, and use about 250 million tonnes of fossil fuel per year. [3] More than 95 per cent of Danish shipping takes place outside Danish waters.[4]

Blue Denmark faces major challenges as it transitions to a more environment and climate-friendly mode of transport, and greater digitalization and new business models. Shipping accounts for 2-3 per cent of the world's total CO2 emissions, and transports just over 80 per cent of world trade[5]. Although shipping companies have significantly streamlined and reduced the fuel consumption of ships in recent years, there is a need to switch to new fuels and means of propulsion. The International Maritime Organization (IMO) has decided that shipping must reduce its emissions by at least 50 per cent by 2050.[6] Maersk has gone even further, and has announced that the company will be climate neutral by 2050.[7]

In 2018, Blue Denmark was responsible for the emission of 0.8 million tonnes of CO2 from shipping in Danish waters, amounting to just over 2 per cent of the total emissions from all 13 climate partnerships (35.9 million tonnes of CO2). Blue Denmark's CO2 emissions from shipping in international waters (including owned and chartered ships) amounted to 52.8 million tonnes of CO2. In other words, emissions were 47.1 per cent more than emissions from the 13 climate partnerships combined. So the challenge is considerable, and the solutions can contribute greatly to the green transition in Denmark.[8]

Although shipping companies have significantly streamlined and reduced the fuel consumption of ships in recent years, there is a need to switch to new fuels and means of propulsion. The "Climate Partnership for Blue Denmark" puts it as follows:

*"While continuous optimization using known measures has resulted in significant reductions in emissions, these reductions have been offset by growth in world trade. Ships have become more climate-friendly, but since global trade and the fleet size is growing, global greenhouse gas emissions from shipping have not decreased. This 'race' between efficiency improvements and rising trading volumes will only intensify in the coming decade. Shipping companies are expected to hit a technological ceiling and exhaust opportunities for further greenhouse gas reductions using current technology, while growth of 50-250 per cent is expected for world trade carried by sea by 2050.*[9]

In light of the above, green fuels are identified as the key element of the climate partnership's recommendations and initiatives:

*"We can and must take energy optimization measures as far as possible, but achieving our goal by 2050 will require completely new fuels. These are only now being developed and are thus not fully known. Alternative, CO2-neutral propellants and fuels are therefore at the heart of our recommendations and initiatives."*[10]

Alcohols, ammonia, biomethane, hydrogen, and batteries are just some of the relevant technologies, but they are not yet ready in any form or scale that can be used in commercial shipping. Long-term investments and the development of new technologies will be required. Reaching that point will require significant research, development, testing, and demonstration activities.

To evaluate whether an alternative fuel can support Blue Denmark in reducing emissions, we need to assess not only the use of alternative fuels on board, but the entire value chain. Using other feedstocks and fuels will only lead to real climate gains if there are no alternative forms of utilization that can contribute to greater climate gains. When assessing the environmental and climate footprint of shipping, all relevant emissions and resource consumption must be included. Both the direct and indirect environmental and climate impacts of using other fuels must be measured, which underlines that Blue Denmark will become an integral part of the energy system.

Alternative fuels are still a fledgling field, highlighting the need for more intensive research before it is clear which fuels will be the best to use. The market potential therefore depends on the right fuels – and their safety – being optimized by the research environments. Denmark is in a strong position, because of the research environments and because there is unique collaboration between sectors.[11]

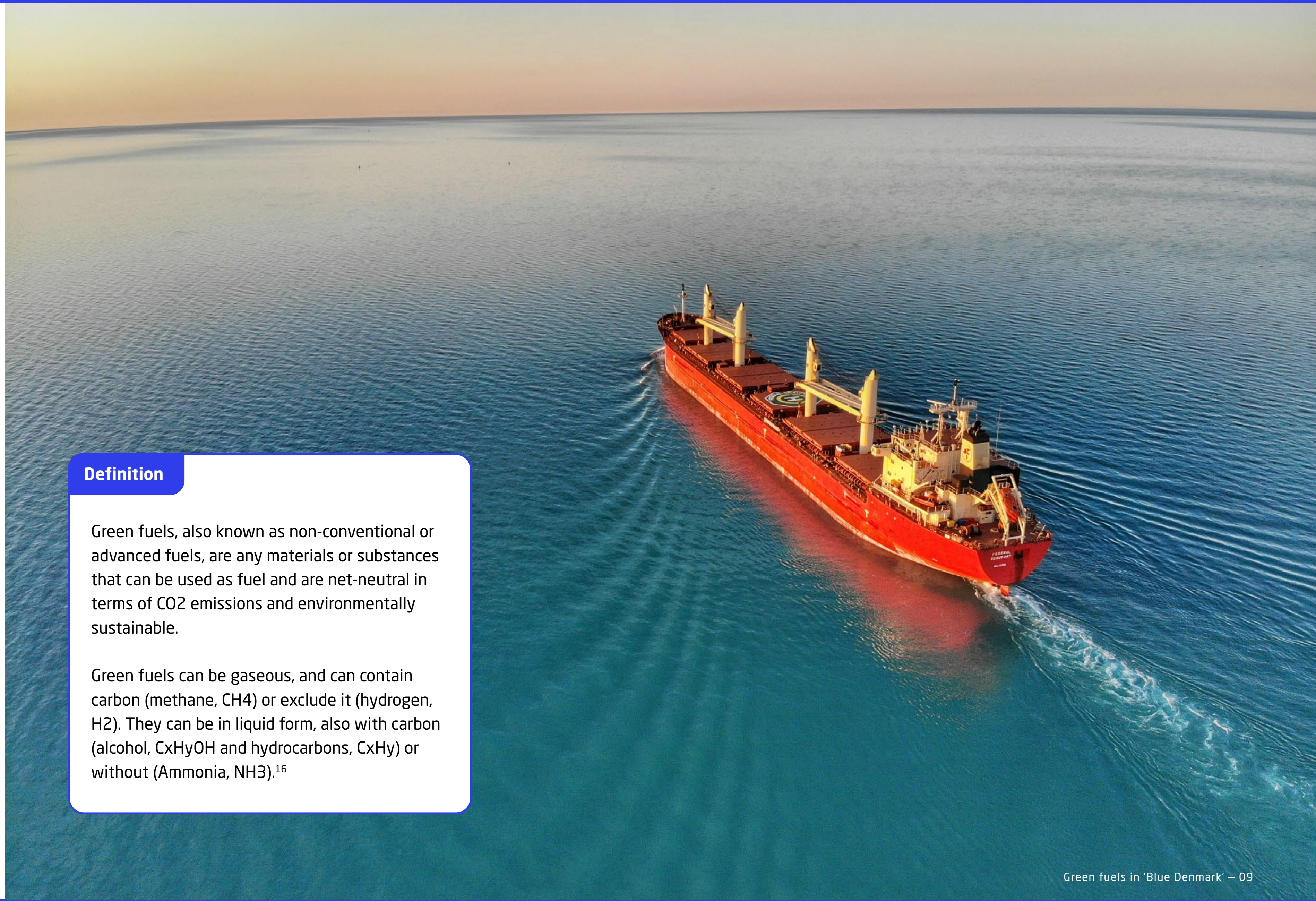
Technological maturity and price determine how quickly a new fuel will become available on the market. Any new energy system must provide the same or better service than the existing one. Fossil fuels are expected to remain part of the energy mix for many years. It is therefore also important to consider existing and future framework conditions, such as limiting SOx and NOx, and IMO strategies to reduce greenhouse gas emissions. Market-based mechanisms (such as carbon and bunker taxes) are also being explored, as making it more expensive to use carbon-based fuels could be one way to advance the use of technologies to reduce greenhouse gas emissions. [12]

Green partnerships are a new instrument in research and innovation policy. The partnerships aim to get all relevant actors from research, business, and authorities to perform long-term, strategic multi-year research and innovation activities, which will keep Danish researchers and companies at the forefront in the development of new solutions.[13] Such partnerships are supported by initiatives such as the newly established Maersk Mc-Kinney Moller Centre for Zero Carbon Shipping.[14]

The Danish Innovation Fund plays a key role in financing the green transition, as it helps to translate the political priorities into research and innovation that contribute to this transition.[15]

Based on the report from the mini sector development project on green fuels in Blue Denmark, DTU will explore European and international funding options. DTU will explore concrete application options in relation to green/alternative fuels in the EU framework programme for research and innovation, including the opportunities in the European Green Deal in 2020 and in the upcoming work programmes by Horizon Europe. Together with relevant European platforms and industry, DTU will also seek influence on future application opportunities in Horizon Europe by actively lobbying the European Commission.





**Definition**

Green fuels, also known as non-conventional or advanced fuels, are any materials or substances that can be used as fuel and are net-neutral in terms of CO2 emissions and environmentally sustainable.

Green fuels can be gaseous, and can contain carbon (methane, CH4) or exclude it (hydrogen, H2). They can be in liquid form, also with carbon (alcohol, CxHyOH and hydrocarbons, CxHy) or without (Ammonia, NH3).[16]

# Recommendations for research, education and test and demonstration projects

Green fuels have been identified as one of the primary ways of reducing CO2 emissions over the next decade. In Denmark, the aim is for green fuels to help reduce CO2 emissions in transport (specifically in heavy land transport, ocean-going ships and aircraft), and in energy-intensive industries (cement, steel and sugar production/refining).

The biggest challenge is to drive down the price of green fuels so that they are competitive with fossil fuels. This will be a process that requires the parallel development of supply and demand, regulation to promote this, industrialization/scaling, and testing and demonstration projects.

This also applies specifically in the context of green fuels in Blue Denmark.

### Recommendations for research

In the short term, the expectation is that some combinations of feedstocks, green fuels, and marine engines for ocean-going ships will be chosen which fulfil factors in relation to: (1) feedstock life cycle and substitution, (2) industrializing/scaling production, distribution, and storage of green fuels, (3) market development, (4) sector coupling/smart energy systems as a means of balancing the energy system and reducing costs, including through digitalization, AI and dynamic tariffs, (5) optimizing electrolysis and catalysis processes to reduce costs and develop new materials, (6) modelling, control, and optimization of Power-2-X production plants, (7) integration of distributed Power-2-X production plants into the electricity system, while ensuring the system remains balanced and robust, (8) feedstock security of supply, (9) ship engine factors and (10) safety conditions.

Choosing the combinations of feedstocks, green fuels, and ship engines is no easy task. Knowledge has to be developed within each of the areas listed above. But it is the combination of knowledge regarding each of the factors that can ultimately establish an informed basis for decisions. Establishing an enlightened basis on which to make these decisions will be no easy task.

The challenges and research needs for each of the listed factors are briefly described below.

# 01

## Research is required into the optimal use of feedstocks for green fuels in Blue Denmark, compared to in other downstream sectors, based on LCAs and substitution analyses

Access to feedstocks will be a key challenge in the future, as global energy demand increases in step with population growth and economic advances – and there is a focus on the green transition in several sectors. There will be greater demand for green energy in the fossil-free society, and demand for biomass and biofuels may lead to pressure on the available resources in Denmark and abroad for use in food, feed, materials, energy, etc. The supply of feedstocks is critical, and it is therefore important to ensure that each feedstock is used where it has the greatest effect. The environment and climate impacts associated with feedstocks are typically associated with the production phase, but distribution and storage can also lead to significant emissions. In particular, land use associated with feedstocks is of environmental and climate significance. The availability of feedstock is important for the environment and climate profile of a fuel. If feedstock, such as biomass, is already being used for other purposes, then the production of green fuels from the same biomass will cause indirect climate impacts.

Research is therefore needed into the (competing) needs for green fuels in the downstream sectors, and the development of consistent and proven models for life cycle assessment of resource systems. Research is needed into the optimal use of local renewable energy, biomass, and waste resources. Research is also needed into life cycle assessment across green fuels – with environment impacts other than climate change (land use and water, ecotoxicity, and particle pollution, etc.) – and the systematic identification of environment and climate impacts associated with the provision and storage of feedstock. Research is needed into life cycle assessments of fuel systems that focus on the entire fuel system and address the full value and process chain. Research is needed into environment and climate regulation and incentive structures to support the production of sustainable alternatives to traditional fossil fuels, and quantifying the environment and climate impacts of emissions, depending on geography, time horizon, and concentration levels.



# 02

## Research is needed into industrializing/scaling the production, distribution, and storage of green fuels

Just as market development will be essential in order to drive down the price of green fuels, industrializing/scaling the production, distribution, and storage of green fuels will also be essential.

Research is therefore needed into how the various combinations of feedstocks and green fuels relevant to Blue Denmark can be industrialized and scaled up.

Fundamental to industrialization is the requirement that feedstocks, fuels, production technology and process plants are developed in a coordinated manner. Cost-effective fuel and production technology scaling principles must first be identified, then a cohesive modular product and production architecture must be developed. This will allow the process to be gradually scaled, with greater technical efficiency and lower production costs. The same principles can be used to streamline logistics throughout the value chain, from factory to consumption.



# 03

## Research into market development is necessary in relation to various perspectives

It is important to research into the competitive use of various feedstocks to produce green fuels. In many cases, downstream sectors compete with each other for the same feedstock. It is likely that a number of other downstream sectors with higher profit margins will be able to pay a higher price for green fuels and the respective feedstocks than shipping companies. This will likely result in a market structure where just a few companies have pricing power. It may therefore be necessary to have appropriate regulation during the market organization stage, to maintain market competitiveness. It is therefore useful if companies in Blue Denmark can clarify which green fuels and associated feedstocks they will be able to pay a price for that can outbid competition from other downstream sectors.

Research is therefore needed into which combinations of feedstocks and green fuels shipping companies and other relevant companies in Blue Denmark should seek to utilize in the future, given the companies' ability to compete on the price of feedstocks and green fuels with other downstream sectors.

**Research is needed into the parallel development of supply and demand, and regulation to promote this.**

The biggest challenge is to reduce production costs and increase competition, leading to lower prices for green fuels. Market development will be essential for this. The markets for green fuels are evolving, supply chains are not fully developed and the learning curve may not have taken effect. They can be established with growing supply and demand. Subsidy schemes may be necessary during the entry phase for the market, as for other innovations. Research is needed into which subsidies and taxes, together with environmental legislation for fossil fuels, are most economically efficient in supporting the market development for green fuels. This knowledge will also provide a basis for choosing the relevant combinations of feedstocks that can reduce the cost of producing green fuels.

**Research is needed into market mechanisms and the impact of taxes on fossil and green fuels, price guarantees on green fuels, exclusive purchasing agreements, etc.**

At present and for the foreseeable future, prices of green fuels will be higher than fossil fuels. This is a critical factor in the conversion to green fuels. While ever there is not a sustainable business case for green fuels, the price remains a barrier to their use.

Research is needed into the economic, social, and regulatory barriers to greater use of green fuels in shipping, especially in ocean-going ships. Increased use will lead to learning effects and cost reductions, that can make green fuels available at a lower cost. In addition to economic barriers, there may be socio-political barriers that impede the market uptake of green fuels. Research is needed to find out if these barriers exist and how they can be lowered.

**Research is needed into sharing capital costs in production and distribution infrastructure across several producer and downstream sectors, to ensure return on investment.**

Some of the largest players in the fuel supply market base their choice of which combinations of feedstocks and green fuels to work to develop on the necessity of sharing capital costs in production equipment and infrastructure across several producer and downstream sectors. The aim is to ensure profitability and success with business development based on green fuels. Being responsible for all the investment costs is deemed to be too risky.

Shipping companies can also become consumers by directly investing in all or part of the green fuel supply chain, to increase security of supply. Alternatively, they can sign exclusive contracts with fuel suppliers.

Research is therefore needed into the extent to which actors in the producer and consumer sectors can actually share investment costs, in order to reduce the risk to individual companies and ensure profitability and business development.

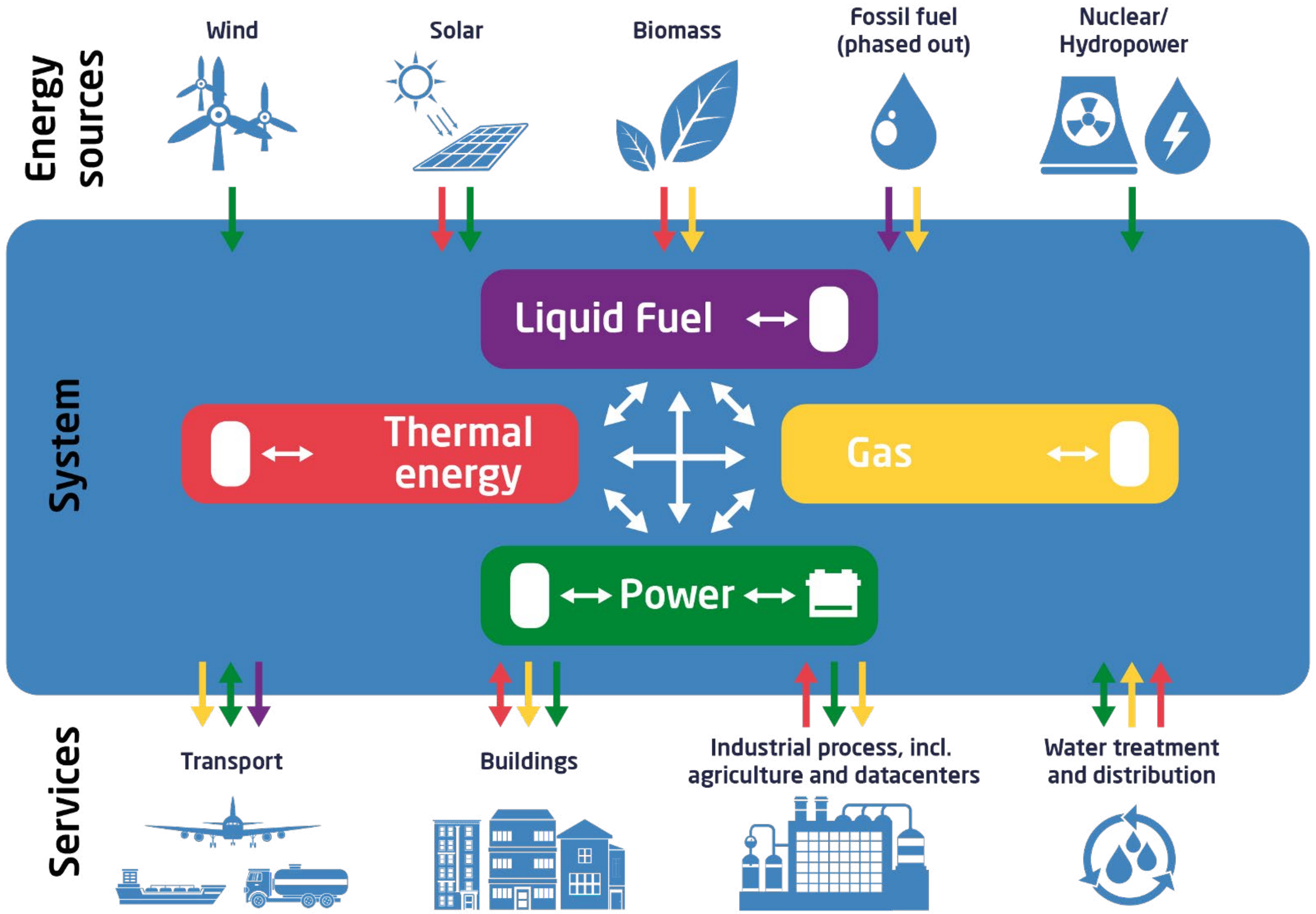
# 04

## Research is needed into sector coupling/smart energy systems as a way of reducing the price of green fuels, through digitalization, AI, dynamic tariffs, etc.

The biggest challenge identified by actors throughout the value chain is to drive down the price of green fuels so that they are competitive with fossil fuels. The price of green maritime fuels and the available resources will determine which fuels will primarily be used. One of the ways to do this is to integrate the production, storage, and distribution of green fuels with the energy system through sector coupling.

Research is therefore needed into where it would be cheapest to produce green fuels, globally, and which fuels can be produced and used in the short term and which need to be further developed. Research is needed into whether the use of renewable energy resources (especially wind) and energy infrastructure (electricity, district heating, and gas) can enable Denmark to supply green fuels to the maritime sector at competitive prices, and how digitalization, AI, and dynamic tariffs can support this. Research is also needed into what a cost-effective transition to green fuels in 2050 will look like, taking into account the gradual replacement of the existing shipping fleet, and robust investment scenarios, given the uncertainties in factors like future electricity and biomass prices.

DTU Sector coupling model.
Source: DTU (2020): Smarte Energisystemer er vejen frem. DTU Sektorudviklingsrapport.



# 05

## Research is needed into optimizing electrolysis and catalysis processes, to reduce costs and develop new materials

Converting the energy system to green fuels is no simple task. The challenges include scaling and improving the efficiency of core technologies, such as the electrolysis and catalytic processes that convert hydrogen into other fuels. There are several possibilities as to which green fuels ships can use in the future, and therefore also many challenges.

Roadmaps need to be prepared, showing how to develop sustainable green fuels that can be produced at competitive prices using scalable technology.

Green electricity can be used to extract nitrogen from the air and to produce hydrogen through electrolysis. Biomass could potentially be used to produce hydrogen, but it is not an ideal solution, as it makes more economic sense to use biomass for carbon-containing synthetic fuels.

Synthetic DME, methanol, and methane are typically produced at the same plant, with only the last synthesis steps being different. All types of biomass can, in principle, be used for the production of DME and methanol, via thermal gasification of biomass to form synthetic gas.

Pyrolysis of fibrous biomass is a cheap and robust option that is also scalable and can handle large feedstock variation. The addition of heat can be electrified using renewable electricity to maximize the oil yield. The bio oil can be used in existing refinery processes, where it is upgraded to various fuel grades in combination with green hydrogen. The light gases can also be upgraded to methane or methanol if the heating is electrified.

Biogas (primarily methane) is produced through the natural decomposition of perishable biomass, and can thus be considered a sustainable fuel. Biogas production can be accelerated by adding heat, enzymes and bacteria, and optimizing the composition of various perishable biomasses. The biogas yield can be almost doubled if the CO2 content is methanated using hydrogen from electrolysis.

Hydrogen can be produced using any hydrocarbon-containing feedstock. However, in relation to sustainable energy and the production of renewable fuels, only hydrogen production through electrolysis of water makes sense. If hydrogen is used as a feedstock for the production of carbon-containing fuels (e.g. based on CO2 or pyrolysis oil), greater energy density and less complicated storage and refuelling are achieved. This is attractive, but the conversion results in energy loss.

**Relevant areas to be clarified include:**

- How can the interplay between electrolysis systems and wind energy production be optimized?
- How can the design of wind turbines specifically be optimized for electrolysis plants (including the design of low wind turbines)?
- Can system design be optimized using new integrated design models that combine wind turbine and electrolysis systems?

In relation to ammonia, research is needed into the possibility of creating effective scalable air separation technologies, and new catalysts that allow the reaction to proceed at lower temperatures. Research is also needed into how ammonia can be produced most efficiently under variable loads from fluctuating renewable energy sources.

In relation to methanol and DME, research is needed into adding more electrical heat during biomass gasification, so that less electrolysis hydrogen is needed for the process. Research is also needed into increasing the addition of CO2 from point sources, in order to reuse the carbon for fuel production using electrolysis hydrogen and electric heat. In relation to methanol, research is basically needed into the same issues as apply to DME.

In relation to pyrolysis oil, research is needed into whether bio oil can be continuously upgraded to high value sustainable drop-in biofuel oil. Research is needed into how much bio oil needs to be upgraded in order to be used for ship and aviation fuel, and whether distribution and storage logistics can be developed for raw or partially processed bio oil.

Research is also needed into whether more efficient refrigeration systems can be developed, so that liquid biogas can be kept cold on ships and trucks, without evaporation or excessive energy consumption.

In relation to hydrogen, research is needed into the development of better electrolyte membranes and 3D electrodes, and extending the lifespan of the next generation. Research is also needed into reducing the use of animal/limited resource materials and lifespan. Research into more robust cells that do not degrade under high power load and cell stacks that can be larger without further losses in production is also important. Research is also needed into where and how solid oxide electrolysis cells can be utilized in the energy system to achieve the best possible efficiency and economy, and how to best operate coupled systems during dynamic operation from fluctuating renewable energy sources.

# 06

## Research is needed into modelling, control, and optimization of Power-2-X production plants

The number of Power-2-X production plants in the energy system in Denmark and other countries will increase over the next decade. The plants will become an important part of the energy systems, and the efficiency of the energy systems may face challenges for this reason. Modelling, control, and optimization of the plants will therefore have a major impact on the efficiency of the plants, and of the energy systems as a whole.

In light of this, research is needed into how hybridization, automation, modularization, and management and control systems can contribute to ensuring the highest possible plant efficiency.



# 07

## Research is needed into integration of distributed Power-2-X production plants into the electricity system, while ensuring the system remains balanced and robust

The growing number of Power-2-X production plants will also have an impact on the balancing and robustness of the energy system. The plants will challenge the continued balancing and robustness because they will be distributed, but will also make continued balancing and robustness possible by enabling the development and use of network services that can contribute to the fulfilment of these two factors.

Research is therefore needed into new market design principles and monetization/models for resource sharing and ensuring the robustness of energy systems.



# 08

## Research is needed into security of supply for feedstocks

High security of supply for feedstocks, to ensure a stable energy supply, is critical to the development of green fuels. Wind power, solar energy, biomass, and other renewable energy sources are already competitive – or close to it – in relation to fossil energy. However, both wind power and solar energy are weather dependent, and security of supply varies as the weather changes. Biomass is also often a decentralized resource. A switch to a renewable energy supply is therefore not without security of supply challenges. Carbon is also essential to the life we live today. Apart from biomass, $CO_2$ is the only source of carbon. Together with hydrogen, $CO_2$ is an essential part of the food chain for Power-2-X technologies for the production of fuels.

Research is therefore needed into various feedstocks and their availability. Research is needed into how to store renewable energy more compactly, and how to reduce variability, for example by combining several forms of energy. Research is needed into 'hybrid plants' (that combine solar with wind and storage), and plants that combine solar and wind energy with the production of hydrogen and $CO_2$, for use in Power-2-X products, and how these plants can be optimized. Research is needed into how to make cheaper wind turbines and farms, and turbine technology designed directly for Power-2-X, so that the interplay between electrolysis systems and wind energy production is optimized. In relation to biomass, research is needed into how to make the pelleting process more efficient, so it is less energy-intensive and more robust.

# 09

## Research is needed into ship engine factors relevant to the use of green fuels

Large marine engines are highly developed for fuel efficient and reliable ship propulsion. They are optimized for high efficiency and to utilize poor quality fuel, and have a long service life with long service intervals. Ship engine factors are important, as different types of green fuels have different effects on the ship engine. These can lead to different derived effects. As an alternative to internal combustion engines, fuel cells can be used.

Fuel cells are normally considered to be significantly more efficient than internal combustion engines, but the comparison is usually made on smaller drivelines of up to a few hundred kW (such as in buses and trucks). In the maritime setting, where engines are much larger and can therefore have significantly higher efficiency, the efficiency argument is not as strong. Research is needed into converting the existing fleet to use green fuels, and derived emissions when using fuel other than fossil fuels. This includes research into blending and the amount of green fuels (e.g. methanol) in the fuel oil, and the impacts on the fuel system, operation of the engine, and other emissions. Research is needed into whether SOFCs (solid oxide fuel cells) will be a cost-effective alternative to conventional marine engines, and whether sufficient reliability and lifespan can be achieved for SOFCs.

Green fuels in ship engines present various challenges, calling for new methods for modelling, forecasting, controlling, and optimizing. For ammonia, there are particular challenges with nitrous oxide, and foundational new models and methods are needed to minimize concentrations of nitrous oxide. It is important to develop new knowledge about the processes (such as the Otto process) so that the engines can tolerate different types of green fuels. Among our general focus areas is lambda control, but since a wide range of factors affect the lambda value, research is needed into new models and model-based optimization methods. Research is also needed into software sensors, which can be used when auto tuning the four-stroke engines of the future. There are also emissions requirements that raise the need for research into multivariate data-intelligent process control, with continuous feedback from emissions.



# 10

## Research is needed into safety factors relevant to the use of green fuels

Ship safety factors cover safety on board, including the safety of crew members. New fuels will introduce other areas such as toxicity, that need to be considered in relation to safety – both in terms of handling and storage. For example, ammonia places high demands on safety and crew training when used as a refrigerant. But experience shows that with good safety standards and a well-trained crew, the risk of accidents can be minimized.

Research is needed into safety in relation to a new value chain – in terms of safety on board, in the event of leakage and bunker systems. Research is needed into whether special consideration should be given to the engine fuel system in relation to various green fuel alternatives, as well as the need for alarm systems and training.



## Recommendations for training

Many of the challenges associated with green fuels have to be addressed by technologies that will require interdisciplinary research and innovation. This applies, for example, to the overlap between competencies necessary for the production of the various green fuels, based on the individual feedstocks.

And it applies to combining expertise on ship engine factors, safety, reduction in CO2 emissions and energy consumption, life cycle analyses, tax factors, sector coupling, and business, with the aim of developing a common basis for assessing the value of green fuels in relation to each other, and compared to fossil energy sources such as bunker oil. Against this background, a proposal for training and for continuing training have been made.

**It is recommended that interdisciplinary study programmes are developed that give students competences in a number of the interdisciplinary overlap areas that need to be mastered to meet the challenges.**

**It is recommended that continuing education courses are developed for all parties in the sector. Vertically, at each link in the value chain, and horizontally across the value chain for the production, distribution and storage of green fuels, and in relevant aspects of integrating these activities into the overall smart energy system.**



## Recommendations for test and demonstration projects

As already noted, the biggest challenge is to drive down the price of green fuels so that they are competitive with fossil fuels. Industrialization/scaling is a key means of achieving this. Testing green fuels in ship engines and the integration of Power-2-X production facilities into the overall energy system through sector coupling (smart energy systems) in test and demonstration projects will be crucial in this regard.

For example, hydrogen is very difficult to handle safely and efficiently on board and requires new cryogenic tanks. Ammonia is linked to new unanswered questions about the significance of slow combustion and potentially major CO2 emissions in post-processing systems.

These issues give rise to the following recommendation for test and demonstration projects related to green fuels in marine engines.

**It is recommended that green fuels are trialled in ship engines, in test and demonstration projects that test the bunkering process, storage in fuel tanks, fuel systems, combustion methods, engine technology, post-processing of exhaust gases and safety factors.**

In order for the integration of Power-2-X production plants into the overall energy system through sector coupling to help drive down the price of green fuels, changes in framework conditions in the form of dynamic tariffs and grid tariffs will be necessary. The changes to framework conditions must help ensure that smart energy systems create the necessary flexibility and work as efficiently as possible in terms of reducing CO2 emissions and costs.

For the future flexibility of smart energy systems, it is important to ensure that all types of consumers have an economic incentive to act flexibly or invest in technology and appliances that can ensure an automatic response. This means that fixed prices, fixed tariffs, and especially subscription schemes are highly unsuitable and should be avoided.

This gives rise to a recommendation on trialling dynamic tariffs in test and demonstration projects, that can help promote sector coupling and further development of smart energy systems.

**It is recommended that dynamic tariffs are researched and tested, based on real-world test regions with realistic conditions and diverse framework conditions, including alternative market designs and charges. It is important that these sandbox projects for testing framework conditions are both scalable and representative.**

## The approach of the world's largest ports to the production, storage, and distribution of green fuels and associated research strategies

"The largest ports in the world have launched an energy transition that is necessary in order to survive increasing international competition from other ports, and to comply with the IMO agreements on reducing CO2 and sulphur emissions."



### Singapore

With 5,000 maritime companies and 170,000 jobs, which combined generate 7 per cent of the country's GDP, the maritime sector is a priority in Singapore. That is why it has developed a roadmap for maritime transformation, with the vision of making Singapore a centre for excellence in energy and environmentally friendly solutions. The Port of Singapore must in the future be able to support a combination of green fuels. In the short term, this combination will include LNG, LPG, and biodiesel mixed with conventional fuels. In the longer term, the focus is on bio-LNG, third generation biodiesel feedstocks such as microalgae, biomethanol, and hydrogen fuel cells using hydrogen from renewable non-biological energy sources such as solar and wind power.[17]

In a report from Nanyang Technological University, which houses a research centre for maritime energy transition and sustainability, the development of third generation feedstock for the production of biodiesel and hydrogen fuel cells, and the expansion of biomethanol production were highlighted as future research areas. There is also a need for research into safe storage of green fuels, handling by-products, and how to maintain a reliable and sustainable supply of feedstock amidst competition from other sectors such as the aviation sector.[18] The Singapore authorities have also supported the development of an LNG-powered vessel that began operation in 2018.

## Rotterdam

Rotterdam is the largest and busiest port in Europe, a workplace for 200,000 people, and home to the largest petrochemical complex in Europe. The port also emits 20 per cent of the Netherlands' greenhouse gases. The vision is therefore to develop a carbon-neutral and circular port, where CO2 emissions are reduced by 49 per cent by 2030, and up to 90 per cent by 2050.

This is to be achieved, in part, by developing a smart energy system for the port's factories, where oil and gas will eventually be replaced with electricity and green hydrogen from solar panels and offshore wind turbines. Space has already been allocated for the new renewable energy sources in the port area. At the same time, fossil fuels for ships are to be replaced with biomass, recycled materials and green hydrogen.

Rotterdam houses Europe's largest cluster of factories producing bio-based fuels and chemical products from vegetable feedstocks such as corn. In connection with the energy transition, ships and port industry will have access to a combination of green and fossil fuels.[19]

There are also plans to capture CO2 from the port area, to be stored in pockets under the North Sea. The port of Rotterdam has also partnered with a number of companies to develop battery-powered container ships to operate on the country's many rivers and canals.[20] The energy transition is also underway across the border in the Belgian port city of Antwerp, which opened a bunkering station for hydrogen in 2019.[21]

## Shanghai

The city of Shanghai is centrally located in the vast Yangtze Delta, where the largest container port in China and the world connects one of the fastest growing economies globally with the rest of the world. China generally wants to achieve carbon neutrality by 2060, and is a signatory to the IMO agreement to halve greenhouse gas emissions from the global shipping sector by 2050. Chinese ports have particularly focused on reducing air pollution and sulphur emissions. In Shanghai and 10 other major port cities, special emission control areas have therefore been introduced. These require ships to use fuels containing less than 0.5 per cent sulphur. Chinese ports also offer cleaner energy sources in the port areas for docking ships.[22]

One of the green fuels in focus in China is methanol. The Chinese Ministry of Transport is working with the Methanol Institute global trade association and a number of the world's largest methanol producers to develop methanol as marine fuel, and a roadmap for its introduction.[23] China is the world's largest shipbuilder, and in 2017 it launched the world's first electric zero-emission ship, which can sail 80 km after two hours of charging.[24]

# Denmark as a location for test and demonstration projects



The Climate Partnership report on Blue Denmark formulates the aim of getting a zero-emission ship in operation by 2030.

For this to happen, excellent research and innovation will be needed. This is dependent on test and demonstration projects, which ideally encompass activities across the green fuel value chain.

It is therefore relevant to examine the quality of the activities in Denmark across the value chain for green fuels, and evaluate Denmark as a location for test and demonstration projects on this basis.

The value chain spans the following activities:

- Wind turbines (green electricity), agriculture (biomass), or industry ($CO_2$ from point sources or air)
- Ports and energy islands (storage and/or production and distribution)
- Electrolysis and catalysis, etc.
- Fuel cells
- Blue Denmark (ship engine developers, other maritime industries, and shipping companies)
- Research
- Proactive agenda-setting regulation on the green transition for Blue Denmark

The following is an attempt to summarize the quality of activities in Denmark across the value chain, based on Danish companies and public authorities.

## Wind turbines, agriculture, and industry

When Denmark prides itself on a position of international leadership in renewable energy, it is no empty claim. As a nation, we have done well over the last few decades. Compared to the 1990 level, which is the base year used in the annual international climate negotiations, Denmark is the country that has come furthest in switching from fossil fuels to renewable energy sources.[25]

This is due primarily to the development of wind turbine technology, and the fact that it has been possible to gradually drive down the price of wind turbine technology and increase the kW capacity. Denmark has an extremely strong position in this regard, as reflected in the fact that:

- In 2019, the Danish wind turbine sector generated revenue of DKK 142.6 billion. This was a drop of DKK 7.5 billion from 2018, but the industrial part of the wind turbine sector increased revenue by DKK 10 billion from 2018 to 2019.
- Exports of wind energy technology and services amounted to DKK 66.5 billion in 2019, making wind energy the single most important technology in Danish energy technology exports, which totalled DKK 122.6 billion in 2019.
- In 2019, the number of FTE (full-time equivalent) employees in the wind turbine industry was 33,159. This was a slight increase of 1 per cent compared to 2018, when 32,774 were employed in the wind turbine industry.[26]

Danish agriculture is very efficient and competitive when compared internationally. This also applies to biomass. However, 43 per cent of the biomass used in Denmark is imported. At the same time, the consumption of biomass per capita in Denmark is very high internationally.[27] This calls into question the security of supply for biomass, and hence the certainty that biomass can be included in sufficiently large quantities as a feedstock in the production of green fuels, which will increase over time.

Danish industry is also very efficient and competitive internationally, and already deeply integrated into the general energy system, both as an energy consumer and as a contributor to balancing the energy system when handling the fluctuations in the production of renewable energy. Particularly as a supplier of $CO_2$ as a feedstock from point sources, it can be assumed that Danish industry, under the right framework conditions, will be able to contribute to the production of green fuels.

**Ports and energy islands (storage and/or production and distribution)**
Danish port infrastructure is generally very well developed. The following ports appear to be particularly relevant to production, storage, and distribution: Aalborg, Esbjerg, Fredericia, Rønne, and Aarhus. The planned establishment of two energy islands – one in the North Sea and one on Bornholm – are interesting initiatives that have the potential to further improve the infrastructure for the production, storage, and distribution of green fuels, especially from the green electricity feedstock.[28]

**Electrolysis and catalysis**
In Denmark, electrolysis and catalysis are particularly represented by Haldor Topsøe. Based on leading expertise in how to reduce CO2 emissions using technology, the company has set a strategic goal of being a world leader in this business activity by 2024.[29]

**Fuel cells**
Development and production of fuel cells in Denmark is represented by IRD Fuel Cells.

**Blue Denmark (ship engine developers, other maritime industries, and shipping companies)**
Blue Denmark has been highlighted as one of the twelve strongest Danish business sectors by the Danish Board of Business Development, which is under the Danish Business Authority. According to the Danish Business Authority, a strong business sector is a business and technology area which, due to global specialization and competitiveness, can contribute more to Denmark's growth than other sectors.[30]

Denmark has all links in the maritime chain, from ship designers to shipyards and maritime suppliers, shipping companies, and shipping and service companies. Synergies in the blue sector have helped Denmark establish a global position of strength in the maritime field. Danish companies are leaders in many areas of the maritime ecosystem. Denmark is also a strong international player with activities in virtually all shipping segments, especially container freight, tankers, bulk cargo, and offshore activities, including offshore wind.[31]

The Danish maritime sector is at the forefront in the production of advanced and energy efficient solutions for Danish and foreign ships and maritime companies around the world. In everything from design to production and service, the sector has accumulated and exploited competences and know-how about the needs of the maritime world and the possibilities technology offers.[32] Denmark also has a number of the world's leading maritime equipment manufacturers, in relation to engines, coatings, safety equipment, green maritime technology, etc. Denmark has a number of specialized shipyards, which are very competitive in terms of design and quality.[33]

Finally, with MAN Energy Solutions, Denmark has a company that has developed 80 per cent of the ship engines installed in ocean-going ships, and with highly competitive shipping companies such as Maersk, Torm, Norden, DFDS, and Scandlines, there is extremely strong quality on the demand side for the development of ship engines that can use green fuels.

**Research**
Danish maritime research is very high quality compared to research from other traditional maritime nations. Results from previous analyses show that Danish maritime research publications have had a higher impact than publications from Germany, Norway, the Netherlands, and Greece. For example, the Maritime Logistics research at DTU is among the top three in the world.[34] Danish maritime research has great scientific impact, with a number of key strengths. This has given the Danish maritime sector a strong technological competitive advantage.[35]

Denmark also has a leading position in the research and development of energy technologies. Danish research institutions and technology companies have a strong foothold, especially in wind technology, biotechnology, and food and sound technology[36]. Denmark's strong position in biotechnology can therefore be brought even more into play in the green transition. There are a great many opportunities in the field of biotechnology, and some technologies will definitely have a greater impact on the green transition than others.



Most recently, Power-2-X technology has created completely new possibilities. Research into energy storage and conversion is one of the key disciplines here, and Danish research in general and research at DTU in particular is very strong in this field. Thirty six per cent of Denmark's scientific articles in the field are among the 10 per cent most cited articles in the world, and the quality of Danish research is well above the world average (2.7 times higher). The quality of research in energy storage and conversion at DTU is three times above the world average. By comparison, the figures for leading research nations such as USA and the UK are 2.4 and 2.3, respectively.[37]

Research is also currently being done at DTU in areas such as the ability of enzymes and microorganisms to not only bind CO2 from the air, but also convert CO2, with the help of the electrons generated from wind turbines or the like, into bio-based chemicals, feed, and perhaps even food.[38] The FCH (Fuel Cell and Hydrogen) Test Centre gives businesses working with fuel cell and hydrogen technologies access to advanced testing and demonstration of components and systems[39].

DTU is a world leader in life cycle analysis of the environmental impact of products[40] — a competence that is central to achieving the green transition for Blue Denmark.

Due to Denmark's early investment in wind energy, Danish companies and government researchers now possess unique knowledge about systems that can handle fluctuations in the production and consumption of energy.

According to several reports[41], Denmark is the EU country that has launched the most smart grid projects. The EU Commission's 'Smart Grid Projects in Europe' report put Denmark in first place, with 80 registered smart grid projects and a demonstration budget of at least EUR 1 million, while Germany was second on the list with around 40 projects.[42]

In 2014, the European Commission's Joint Research Centre identified DTU as the organization in Europe with the most R&D activities in the field. In 2017, Deloitte identified intelligent energy solutions as the energy technology field with the greatest market potential for Danish industry.[43] The Confederation of Danish Industries (DI), together with 24 companies, has launched a strategy development project that aims to result in a national strategy for sector development in the first quarter of 2021.[44] So Denmark is now well advanced in sector coupling. This is a great opportunity, given that sector coupling is one of the key means to drive down the price of production, storage, and distribution.

It is also an advantage that a number of test and demonstration projects are already underway in Denmark in the field of sector coupling. These include PowerLabDK — one of the world's leading test laboratories for energy systems. Companies, organizations, students, and researchers from Denmark and abroad can develop and test future large-scale electricity and energy technology solutions here[45]. The same applies to the Nordhavn[46] in Copenhagen and Bornholm energy island[47] projects, Center Danmark, Unil-lab.dk in the triangle region[48], and GreenLab in Skive.[49]

## Proactive agenda-setting regulation on the green transition in Blue Denmark

With the Danish Maritime Authority, the Danish Ministry of Industry, Business, and Financial Affairs has historically been agenda-setting for international regulation on the green transition in shipping. Over the last 10-20 years, for example, efforts have centred on ship paint and CO2 emissions from shipping. While the Danish Maritime Authority shares influence with similar agencies in other major maritime nations, the agency has clearly succeeded in maximizing its influence internationally, such as in the IMO and the EU. This possibility also exists in relation to regulation, and the promotion of green fuels.

The Danish Ministry of Climate, Energy, and Utilities has historically been instrumental and agenda-setting in reducing CO2 emissions. This is reflected in the fact that Denmark is the country that has been best in the world at converting from fossil fuels to renewable energy sources[50], and is the most energy technology export-specialized EU country. The latter represents a clear competitive advantage. Most recently, with the Danish Government's Energy Agreement from June 2019 and the launch of the 14 climate partnerships, the Ministry has added even more to its efforts. The Government and a broad majority in the Folketing have reached an agreement on the future of the North Sea, which includes an end date in 2050, after which oil and gas can no longer be extracted, and a final cancellation of the eighth round of tenders. This is an agenda-setting political decision that will advance the transition to green fuels.[51] Finally, with its research strategy and the designation of green fuels in the transport and industrial sectors and carbon capture and storage as two of four missions, the Government has signalled that green fuels are high on the agenda this decade.

# **Appendix 1:** Members of the steering committee, working group, and interviewees/workshop participants

### Members of the project steering committee

Morten Willaing Jeppesen, Centre Director, DTU Centre for Oil & Gas

Per B. Brockhoff, Head of Department, DTU Compute

Søren Linderoth, Head of Department, DTU Energy

Jane Hvolbæk, Head of Department, DTU Physics

Erling Halfdan Stenby, Head of Department, DTU Chemistry

Kim Dam-Johansen, Head of Department, DTU Chemical Engineering

Mette Wier, Head of Department, DTU Management

Hans Nørgaard Hansen, Head of Department, DTU Mechanical Engineering

Claus Helix-Nielsen, Head of Department, DTU Environment

Henning Skriver, Acting Head of Department, DTU Space

Peter Hauge Madsen, Head of Department, DTU Wind

Director for Innovation and Entrepreneurship, Senior Vice President Marianne Thellersen, DTU (chairman)

### Members of the working group

Senior Researcher Karen Louise Feilberg and Senior Researcher and Advisor Simon Ivar Andersen, DTU Centre for Oil & Gas

Professor Henrik Madsen, DTU Compute

Professor Jacob Østergaard and senior researcher Shi-You, DTU Electrical Engineering

Senior Researcher Henrik Lund Frandsen and Professor Jens Oluf Jensen, DTU Energy

Associate Professor Jakob Kibsgaard, DTU Physics

Professor Anders Riisager, DTU Chemistry

Professor Anker Degn Jensen and Senior Researcher Jesper Ahrenfeldt, DTU Chemical Engineering

Professor Harilaos N. Psaraftis, Professor Marie Münster and PhD student Nicolas Jean Bernard Campion, DTU Management

Professor Anders Christiansen Erlandsson and Associate Professor Anders Ivarsson, DTU Mechanical Engineering

Professor Thomas Fruergaard Astrup, DTU Environment

Senior Researcher Jens Olaf Pepke Pedersen and Professor Ole Baltazar Andersen, DTU Space

Hans E. Jørgensen, Head of Section, DTU Wind

Kasper Dam Schultz, Special Consultant, DTU APR

Senior Executive Officer Lars Brückner and Senior Officer Louise Nolle, DTU AFRI

Mette Sanne Hansen, Head of Centre, DTU Maritime/Management (Lead Professor)

Mads H. Odgaard, Senior Executive Officer, DTU AFRI (Project Manager)



### Interviewees/workshop participants – in companies and public institutions:

Jesper Raakjær, Development and HR Manager, Aalborg Harbour

Valdemar Ehlers, Technical Director, Danish Maritime

Bo Larsen, Senior Executive Officer, Danish Shipping

Per Winther Christensen, Head of Technical Affairs, Danish Shipping

Director Frank Rosager, Danish Biogas

Pat A Han, R&D Director, Haldor Topsøe

Poul Georg Moses, Senior Director of R&D, Haldor Topsøe

Tore Sylvester Jeppesen, Senior Director of Business Development, Haldor Topsøe

Jacob Sterling, Head of Technical Innovation, Maersk

Ole Graa Jakobsen, Vice President, Maersk

Dorthe Marie Sveistrup Jacobsen, Head of Emission Reduction Department, MAN Energy Solutions

Michael F. Pedersen, Senior Manager, MAN Energy Solutions

Stefan Meyer, Head of Engine Process Research, MAN Energy Solutions

Tue Johannessen, Head of Maritime Application and Viability, Maersk Mc-Kinney Moller Centre for Zero Carbon Shipping

Henrik Røjel, Head of Fuel Efficiency & Decarbonization, Nordic

Lars Villadsgaard Toft, Bioeconomy Manager, SEGES/Danish Agriculture & Food Council

Hans Otto Kristensen, self-employed

Palle Kristensen, Senior Executive Officer, Danish Maritime Authority

Thomas Blomgren-Hansen, Senior Executive Officer, Danish Maritime Authority

Anne Zachariassen, Technical Operating Officer, Port of Aarhus

Mads Søgaard, Sustainability Engineer, Port of Aarhus

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