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Final FutureGas report

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Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Münster, M., Morthorst, P. E., Stryg, M., Aryal, N., Kofoed, M. V. W., Jensen, T. K., Ahlgren, E., Buchholz, S., & Pisinger, D. (2020). *Final FutureGas report*.

Final FutureGas report

September 2020

Preface

The main purpose of the FutureGas project was to contribute to a green transition through interdisciplinary and coordinated research across the gas sector. The goal was to answer two main research questions:

- *What could the role of natural gas, renewable gas and the gas infrastructure be in a future climate-neutral Danish energy system?*
- *Which role could gas have in the sustainable energy transition towards a climate neutral energy system?*

The project included the major stakeholders of the Danish gas industry as well as Danish and international universities (see below). The project was supported by the Danish Innovation Fund.

The project analysed the gas chain from supply to regulation: efficient production and use of green gases including potential conditioning to natural gas quality, flexible use of gas also for transport, system integration, as well as the application of measures to ensure an economically efficient use of gas.

The authors of this report carry individual responsibility for their respective chapters. All reports from the project can be found on the homepage www.futuregas.dk. Scientific articles can be acquired by mail to the authors.

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Executive Summary

This report aims to illustrate some of the main findings from the Danish research project, FutureGas, which was carried out from 2016-2020

Major findings

Denmark has a long-term target of having an energy system which is climate neutral by 2050. To achieve this, energy production based on renewable and variable renewable energy sources need to be increased.

Natural gas is a key energy carrier in the Danish energy system today, accounting for 17% of the total primary energy consumption. However, given the Danish long-term energy policy targets, combined with declining prices of renewable energy technologies leading to increased electrification and reduced use of natural gas, the transition away from fossil fuels and towards a renewable-based energy system is essential to investigate.

The project has entailed detailed energy system modelling as well as supplementary analyses and tests in labs. The energy system analysis is described in the first part of the report, while technological deep dives in the second half illustrate some of the work and findings in the other parts of the project. The most important findings given the assumptions outlined in the FutureGas Background report are summarized here:

- It is still feasible to distribute a significant amount of gas through the current gas system in the future. Thus it is recommended that the overall gas grid is maintained.
- The most important sectors for gas supply will be industry, but also to a certain degree households as well as the power and district heating sectors.
- In individual heating, hybrid heat pumps combining an electric heat pump with a gas boiler show up to be an interesting option, however with a high sensitivity to costs.
- Carbon Capture and Storage (CCS) has potential to become an economically viable option in 2050 and paves the way for more use of natural gas, especially in the part of the industry, where electrification isn't feasible.
- Existing regulation should be reconsidered to bring the energy system more in accordance with the socio economic results. Current regulation may lead to a higher use of biomass and a lower use of especially wind power and natural gas than what is seen to be socio-economically viable.
- Support to renewable gas production should be technology neutral, with fair accounting of externalities including negative GHG emissions, but also fertilizing benefits etc.

Scenario analyses

In the project the potential future role of gas and, in particular, renewable gases is assessed through comprehensive scenario analyses from 2020-2050. We analyzed three different scenarios to reach the goal of being climate neutral in 2050: Early sprint, Marathon and Late sprint. The scenarios represent different climate ambitions during the transition period.

- *Late Sprint* is a scenario with low ambitions in a transition period and a budget of 708 Mton CO_2 from 2020 to 2050. The scenario does not adhere to the Danish 70% GHG reduction target in 2030 (compared to 1990 levels) nor the Paris agreement as interpreted by the Danish Climate Council but does achieve becoming climate neutral in 2050.
- The *Marathon* scenario is in the upper range of the CO_2 budget (435 Mton) in order to adhere to the Paris agreement, while also achieving the Danish climate policies of 70% GHG reductions by 2030 and being climate neutral in 2050.
- The *Early Sprint* scenario has the lowest emission levels (376 Mton CO_2), achieving the Danish policies and furthermore being in the middle range with regard to the Paris agreement CO_2 budget.

See more about the scenarios in the beginning of Chapter 2.

The Balmorel Model

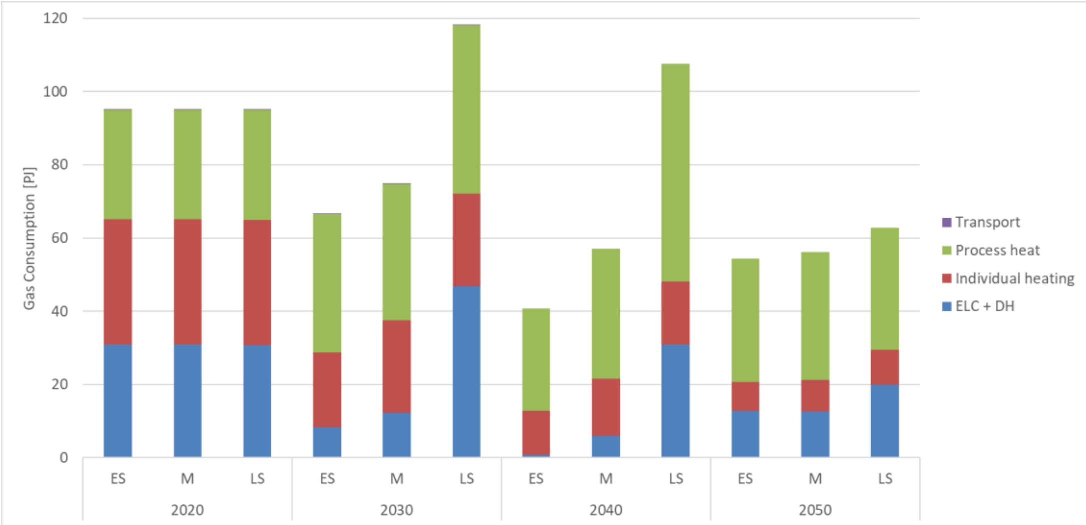
The scenarios are analyzed in the linear programming model, Balmorel, which represents the power and district heating system of Denmark and surrounding countries. For the FutureGas project the model was extended with improved representations of the individual heating and process heat sectors as well as renewable gas and liquid fuel production in Denmark. The remaining emissions from industry, domestic transport and agriculture are modelled in TIMES-DK. The Balmorel model represents the Nordic energy system (DK, SE, NO and DE) in this study, while TIMES-DK only represents Denmark. First step in the modelling was to use TIMES-DK to assess the CO_2 emissions available for the sectors represented in Balmorel (See Figure 2.1). For all scenarios, negative CO_2 caps for the Danish power and heating sectors in Balmorel are implemented in 2050, as, with the given assumptions, it is cheaper to implement CCS in the these sectors, than reduce all GHG emissions in the other sectors (agriculture, transport, direct fuel demand for industry). Further outputs from TIMES-DK include biogas and biomethane production levels and EV electricity demands.

The analyses in Balmorel show the potential role of gas in socio economic least-cost scenarios, where investment and operation of power transmission, storages and conversion units are optimized based on costs and efficiencies.

System analysis results

The main scenarios show possible pathways, where in particular the natural gas consumption levels vary in the transition period from 2020 to 2050, while ending at similar gas levels in 2050, at around half of the original demand. How gas is used in different sectors is shown in Figure 0.1, below.

Figure 0.1 Results on methane use by sector in different scenarios from 2020 to 2050



Key point: In 2050, gas is mainly used for process heat, but also for power and district heating as well as some for individual heating in the scenarios Early Sprint (ES), Marathon (M) and Late Sprint (LS)

In 2020, similar amounts of gas are used for 1) process heat, 2) individual heating and 3) power and district heating, as shown in Figure 0.1. Almost no gas is used directly for transport. In a transition period, the gas demands grow in the Late Sprint, while it decreases in the other two scenarios. The main difference is in power and district heating. All scenarios show net electricity import albeit at varying levels, unless self-sufficiency restrictions are imposed. This could change if more countries and transmission lines were included in the study e.g. connections to UK and NL. In all scenarios, the demand for gas slowly decreases in individual heating, where electrification takes place through electric and hybrid heat pumps, which combine an electric heat pump with a gas boiler.

A high sensitivity is however found both in terms of changes in costs and in terms of the individual consumers' willingness to shift heating technology. Regarding the use of gas for process heat, it increases slightly in all scenarios, due to a low degree of electrification and an assumed increase in demand. Under the given assumptions, direct use of methane for transport is not found to be competitive in any of the scenarios. Instead, electrification and liquid fuels are found to be cheaper alternatives.

For the three main scenarios, only domestic transport is included in TIMES-DK. Further aviation and shipping are included in sensitivity analyses. Similarly, no restrictions are imposed on import of biomass or biofuels in the main scenarios. Results of including these are shown in the FutureGas System Analysis Sensitivity Analysis Report Chapter 5. The results of the main scenarios show low levels of direct use of hydrogen, but in a situation where Denmark takes responsibility for producing green fuels for international transport bunkering in Denmark and if import of biomass or biofuels is discouraged, hydrogen is used as feedstock to produce liquid fuels (PtX) for the transport sector. More direct use of hydrogen may be seen depending on the future development of electric vs hydrogen vehicles (find further details in Chapter 3).

Substantial amounts of natural gas are still being used in 2050 due to the use of carbon capture and storage (CCS), the use of which is highest in the Early Sprint scenario in 2050. Reducing GHG emissions with the applied CCS technologies (in industry and power sectors) to achieve the goal of climate neutrality in 2050 is found to be cheaper than reducing emissions with other means in industry and transport. Emission reductions in agriculture are not optimized, which could be interesting further work. Application of CCS primarily allows for the use of natural gas in industry and for some fossil fuels in transport. As low cost differences are seen between a scenario with and without CCS the results are sensitive to changes in assumptions on costs and efficiencies of CCS technologies and competing GHG reduction options. (For more info see Chapter 1 in the FutureGas System Analysis Sensitivity Analysis Report and Technology costs in Appendix B in the FutureGas Background Report)

The gas demand in the different scenarios is mainly covered by natural gas and bio-methane. Biogas and bio-methane are used at the level corresponding to the installed capacities, which is projected by the Danish Energy Agency, until 2030. After that, bio-methane becomes feasible at a similar level to the production level in 2030, while biogas use is abandoned.

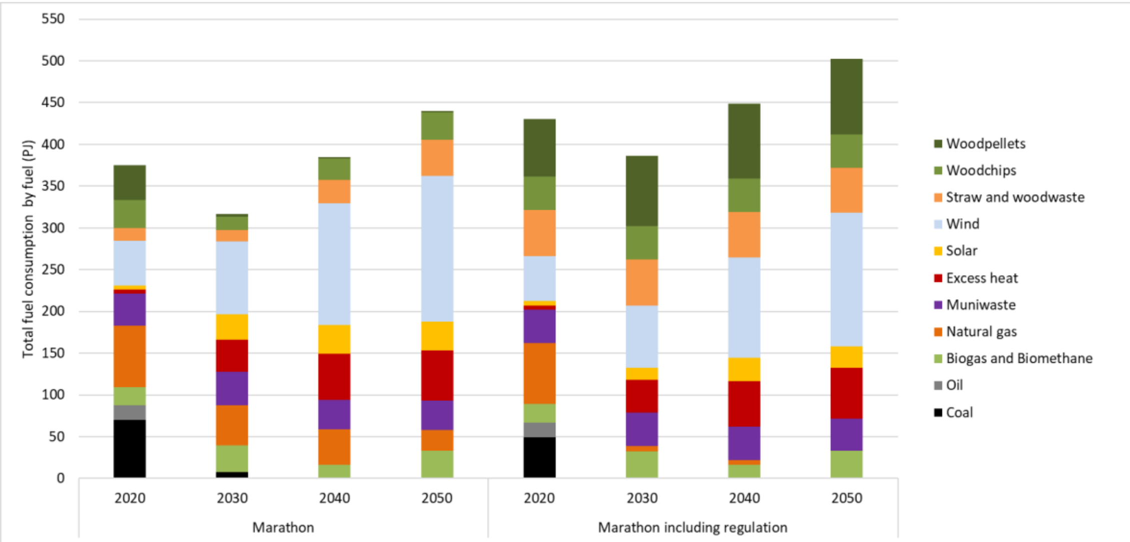
Biomethane levels differ between the scenarios, but ends at comparable levels in 2050. The highest level of above 30 PJ is found in the Marathon scenario in 2050. Lower levels are found in the Early Sprint scenario, mainly as more CCS is implemented. Biomethane consumption is however highly sensitive to the biomethane and natural gas prices. There is a clear tendency of lower bio-methane production prices leading to higher consumptions . Furthermore, a shift is seen from natural gas to bio-methane if natural gas prices increase. See Chapter 4 in the FutureGas Sensitivity Analysis Report.

Regulatory analyses

The socio economic analyses are supplemented with regulatory analyses, where existing taxes, tariffs and subsidies are included in the modelling. The level of taxes and tariffs are throughout the forecasting time period kept at the constant level of today while the level of subsidies are gradually reduced assuming an increasingly stronger competitiveness of especially renewable energy technologies.

The main results are shown in Figure 0.2, where the socio economic results are shown to the left (Marathon scenario) and the Regulatory base case is shown to the right. The figure illustrates a significant shift in the use of biomass (woodpellets, woodchips and straw) at the expense of especially natural gas and electricity (wind power) compared with the socio economic results. This is not surprising as in the current legislation no tax is levied on the use of biomass while this is the case for electricity and gas, thus implicitly favoring the use of biomass.

Figure 0.2 Fuel consumption in the Marathon scenario with and without regulation



Key point Use of biomass is higher in the Marathon scenario with current regulation than without

Summary of deep dives

The deep dive by Danish Energy Association in Chapter 3 shows ***hydrogen and Power-to-X (PtX)*** could be a dominant future green gas if prices of wind and solar power as well as electrolysis continue to drop significantly. Hydrogen and PtX products like e-ammonia, e-diesel, e-methanol and e-kerosene could play a large role in hard-to-abate sectors like chemical industry, aviation, shipping and heavy road transport. A breakthrough of electrolysis-based hydrogen in these sectors could lead to cost competitive prices in other sectors, hence reducing the role of natural gas and CCS. In conclusion, cheap hydrogen could significantly change the need for natural gas and CCS in the medium and long term compared to the results in the main scenario.

Another deep dive regarding ***production of renewable fuels and gases*** was made by DTU using the OptiFlow model. The results regarding renewable gas show that biomethane produced from anaerobic co-digestion of a mixed feedstock and upgraded via CO_2 removal would be the preferred option, however, in high gas demand scenarios, methanation is used. Results from the high spatial resolution energy system analysis, showed that biogas plants would be located in the countryside, since transport cost of manure is a determining factor. The results of different renewable liquid fuel production pathways in a 2050 climate neutral energy system show that electrofuels – in particular electrofuels using biomass and hydrogen – can play a prominent role in the future, to supply the transport sector. To produce these electrofuels, thermal gasification is used as a part of the process, which emphasises the need for developing and commercialising thermal gasification, as well as electrolysis. Furthermore, in a plausible scenario where Denmark produces fuels to supply aviation demands and do not import biomass or biofuels, the national biomass resources would be under high pressure. Consequently, to supply the liquid fuels in a sustainable way, there would be a need for hydrogen to boost the production, or carbon-free fuel production like ammonia, or more sustainable carbon e.g. potentially use carbon capture technologies or restructure the way of producing biomass for energy use. Moreover, the spatial-temporal energy systems analysis showed that production of renewable liquid fuels may occur near larger cities, with large district heating networks and demands. In this way, excess heat can be sold to the district heating network. The results show that excess heat from renewable gas and liquid production could supply a significant share of the Danish district heating demand. For more information see Chapter 3.

Finally, a deep dive into the potential for using ***methane in the Danish transport sector*** was made by Chalmers University. The results were that there are a number of different options towards a future cost-efficient transport sector in Denmark and various combinations of these will lead to the lowest system cost. The option with the lowest system cost depends on the assumed vehicle, infrastructure and fuel characteristics and rather small assumption differences changes the cost-efficient solutions chosen by the model. Electrification is important but not the only solution, natural gas could play a role as a cost-efficient transition fuel in some transport segments and up-graded biogas were in many scenarios included in the final year cost-efficient fuel mixes both in road transport and in the maritime sector, in the latter case as liquefied biogas. For the final FutureGas analyses, costs of electric vehicles were updated by DTU and as a result, more electrification was seen. For more information see Chapter 3.

It has further been examined in a deep dive by DGC how ***green gases such as biogas could be distributed cost efficient.*** It was found that grids for distribution of biogas to a larger number of costumers is not as cost effective compared to upgrade to methane quality. However, in some cases it might be relevant to supply larger industrial customers with biogas directly if the customer has a high constant gas consumption. (See more info in Chapter 3)

Another deep dive by DGC is about ***methane emissions***. Methane is a strong greenhouse gas and therefore it is crucial that methane emissions are are kept at a very low level in the whole chain from production, transport/distribution to utilization.

The climate impact of biomethane has been assessed. It was found that the biomethane production is more or less climate neutral, as negative impacts due to methane emissions, manure transport, and use of fossil based process electric power are balanced out by lower emissions from manure, which is degassed in a biogas plant.

Most of the existing installed stationary gas engines have relatively high methane emissions and dual fuel engines for transport has the same issue. New engine technology and after-treatment systems however exist, which allow gas engine operation with low methane emissions. It is assessed that 95 % of the climate impact (greenhouse gas effect) from end use is due to CO_2 from natural gas and 5 % is due to methane emissions. (See more info in Chapter 3).

The FutureGas project has entailed research on ***methanation technological development*** aiming at improving common understanding about efficient methanation, conditioning, and distribution of gas in future energy systems. The finding showed a biological system for methanation and gas conditioning is an emerging concept for high volumetric methane production combined with a conventional biogas plant and gasification technology where CO_2 is utilized as feedstock. The technological deep dives in laboratory-scale biomethanation reactor development in particular bioelectrochemical system and syngas biomethanation is described in Chapter 3. In the bioelectrochemical system, the CO_2 fraction from biogas is utilized by microbes, where the system could be powered from renewable sources to produce methane. Furthermore, up to 96% methane, production is possible by coupling biomass gasifier and syngas upgrading trickle bed bioreactor; however, exogenous hydrogen addition is essential to produce a methane-rich gas. This investigation developed promising syngas biomethanation trickle bed bioreactor as a future biological system; however, process optimization is crucial for scaling up the technology.

An important part of the project has been in terms of ***model development*** to ensure a good representation of the gas sector. This has resulted in improved representation of the gas sector in a number of energy system model with different foci:

- Gas consumption for individual heating and industrial process heat as well as CCS technologies in the Balmorel model
- Renewable gas and renewable fuel production in the network flow model, OptiFlow
- Gas network in the GasMo model
- Gas in transport in TIMES-DK

With regard to advanced mathematical modelling, the development during the project has shown that the choice of strategy for reducing the time domain may influence the quality of the results. With the optimal choice of aggregation strategy, high quality solutions can be found in much shorter time. These findings do not only ensure optimized quality in the results of the FutureGas project, but they have also been implemented in the analysis tool at Energinet to be used on a daily basis. Additionally, the results have led to the development of new solution approaches which either assist in finding optimal solutions of non-aggregated energy systems or in analyzing the robustness of the results and by that account for uncertainties in data and model assumptions. (See more info in Chapter 3).

The model development in the project is documented in a number of articles. Abstracts are available on the project homepage (www.futuregas.dk) and full articles can be obtained by contacting the authors.

Besides the regulatory energy system analyses the work package on ***regulation*** has addressed a number of more detailed regulatory issues, including

- The value-stacking method has been analysed especially in relation to the development of support schemes for the production and use of biogas. A major finding is that support for agricultural benefits of biogas production should be separated from the benefits found for the energy system, among other things easing an eventual cross-border trade of green gas.
- An analysis of the current EU renewable gas certificate market was undertaken. The analysis showed that a cross-border certificate system could open up for a larger market and demand. It would however be difficult to link the certificate to any support mechanisms unless the country specific RE-goals are linked to consumption of green energy – proved via certificates

For more details please refer to the project homepage www.futuregas.dk.

Conclusions and recommendations

At the offset of the project, two main research questions were formulated, which are answered below:

- *What could the role of natural gas, renewable gas and the gas infrastructure be in a future climate neutral Danish energy system?*

- Gas appears as a low cost solution mainly for industry, but also to some extent for individual households and for power and district heating as flexible backup capacity. With the given assumptions, gas is not seen as competitive in the transport sector due to cheaper alternatives.

- Gas consumption is decreased to around half of today's level by 2050 in all scenarios.

- The main renewable gas consumed is biomethane, which is mainly produced via upgrading of biogas via CO_2 removal.

- Hydrogen is mainly used for production of liquid biofuels and primarily when there is a high demand for transport fuels and limited availability of biomass.

- *Which role could gas have in the sustainable energy transition towards a climate neutral energy system?*

- Use of gas mainly differs between scenarios in the transition period due to different assumptions on allowed CO_2 emissions and costs of fuels. In the Late Sprint with late implementation of CO_2 reductions, natural gas consumption is increased in an intermediate period compared to today. The increase is mainly seen for power and district heating and depends on possibilities for import/export of power.

The conclusions and recommendations are based on the work presented in this report as well as findings from other parts of the project, which are documented in the articles and reports found on the project homepage www.futuregas.dk. In the following sections we summarize some of the main findings and make recommendations related to these.

Energy system analyses of gas consumption and gas distribution grid

The main findings of the system analyses of the FutureGas project show that given the assumptions outlined in the FutureGas Background report:

- There is still a need for - and it is economically viable - to distribute a significant amount of gas through the current natural gas system in the future.
- The most important sectors for gas supply will be industry, but also to a certain degree households as well as the power and district heating sectors.
- The direct use of gas for transport, is not found to be economically viable with the given assumptions. Other transport options including electrification and liquid bio-fuels are found to be more economic competitive.
- Carbon Capture and Storage (CCS) has potential to be an economically viable option in 2050, which paves the way for more use of natural gas, especially in the parts of the industry, where it is difficult to electrify.

Thus it is recommended that:

- The overall gas distribution grid in general is maintained. This will provide flexibility in terms of being able to provide gas for different types of consumers in the future and will provide storage capacity
- It is recommended to develop a strategy for development and implementation of CCS seen in a national perspective in connection with a potential delay in decarbonisation of difficult sectors

Although the overall gas distribution grid should be maintained, closing down of specific areas of the gas distribution could be relevant and should be analysed in further detail - especially with regard to industrial use of gas and the amount of gas used in households, both in relation to existence of specific alternatives to gas and the pace with which these alternatives can be implemented (willingness-to-shift). A long-term plan should be carried out for the future development of specific local gas grids, to facilitate a cost efficient transition for customers to green gas or other alternatives. A reduced use of gas might have severe consequences for gas tariffs and thus strong economic implications for gas customers might lead to a downward spiral with further reductions in gas demand.

Regulation

As biomass is not taxed, the current legislation implicitly gives a strong support to the use of biomass. Comparing the regulatory base case with the Marathon scenario we find, that because of biomass substitution, the use of natural gas and electricity is reduced significantly in the analyzed time period, although this is not socio-economically viable. Historically, biogas for CHP production has received substantial support in a Danish context, but future production and use of renewable gases may change.

Thus it is recommended that:

- Existing regulation should be reconsidered to bring the energy system more in accordance with shown socio economic results
- The future development of renewable gas production costs and uses are uncertain, therefore support to renewable gas production should be technology neutral, with fair accounting of externalities including negative GHG emissions, but also fertilizing benefits etc.

The characterisation of renewable gases and their differentiation based on the positive externalities need to be ensured in order to ensure a transparent market and price incentives for more sustainable products. It is therefore recommended that:

- A certificate system should be provided which guarantee the origin and degree of sustainability for the traded gas. The certificate could be national or international (targeting EU) and through regulation provide a demand and thereby a market e.g. through blending requirements or tax-benefits

New technologies

Low willingness to shift of individual consumers may lead to suboptimal choices seen from a socio economic perspective. Enhancing the willingness to shift is possible through increased information, ease of shifting and clear long term political targets as well as economic incentives. Thus it is recommended to:

- Provide information, ease of shifting and clear long-term political targets as well as economic incentives to motivate individual consumers to make socio economically feasible choices.
- Ensure that information on new technological solutions is available especially for private customers, e.g. on hybrid heat pumps, which currently constitute a low share of the market. Furthermore, operation and maintenance costs of hybrid heat pumps need to be investigated, as this has a high impact on the feasibility.
- The use of gas heat pumps for industrial purposes looks interesting from a socio economic perspective, however costs and efficiencies of both these and gas engine heat pumps deserve further attention.
- Biomethane and electrofuels might play a prominent role in the future. To produce electrofuels, thermal gasification appears to have a high potential, which emphasises the need for developing and commercialising thermal gasification, as well as electrolysis and biomethane production.

Methane emissions

Methane emissions are in Denmark very low regarding grids for gas transmission and distribution, they can however be substantial in gas production and in specific uses of gas. As methane slips have a high impact on greenhouse gas emissions the following should be considered:

- When assessing the climate impact of consuming gas, all GHG emissions from the full value chain should be taken into account, from production - in DK or abroad - over transmission and distribution to final consumption.
- Monitoring of gas production at all levels (including offshore, biogas/syngas plants and upgrading/ methanation) to ensure that methane emissions are kept at a constant low level.
- In general, gas appliances should be tested and certified for different gas qualities to avoid high GHG emission levels. In some engines, use of gas leads to significant emissions. As dual-fuels engines e.g. used in trucks or ships pose specific problems in terms of methane emissions, more research is required within this field and in the short term, the use of these engines should be regulated. Use of mixed gases may impact unburned gas emissions, so further analysis of implications on the appliance side of e.g. mixing hydrogen with methane should be investigated.

Related political goals

The national production of green gases and liquid fuels depends on whether a national target for decarbonisation of international transport exists and on the possibility to import biomass and biofuels. The development of the future Danish energy system opens for a number of possibilities that might lead to new business-opportunities for Danish companies, e.g. a production of green fuels for transport. However, to ensure investments, clear political signals will be needed. Thus it is recommended to develop strategies for:

- The potential inclusion of international transport in the national greenhouse gas emission target. This will probably be decisive for any Danish business engagement in future power-to-x and other green fuel projects.
- The future import of biomass and biofuels to the Danish energy system, including certification of sustainable biomass. High imports, as well as low green fuel production, may continue, if no policies are implemented.

Chapter 1. Introduction

This section provides an introduction to the FutureGas project and the background of the project.

Background

Marie Münster, DTU Management

Danish climate and gas policies

Denmark has set a target of becoming climate neutral by 2050. This target implies that the Danish energy system will experience a remarkable transformation in the future, heading towards more energy production based on renewable and variable renewable energy sources, and stronger couplings and interactions between energy sectors.

Today, gas is a key energy carrier in the Danish energy system, accounting for around 17% of the total primary energy supply. Given the Danish long-term energy policy targetsand limited natural gas resources in the North Sea, the transition away from fossil fuels and towards a renewable-based energy system is a promising, but challenging solution.

The FutureGas project

Natural gas, renewable gas, and the gas infrastructure can potentially play a key role in future energy systems. The FutureGas project has had the aim to address two main research questions emerging for the Danish gas sector, stakeholders and policymakers: 1) What is the role of natural gas, renewable gas and the gas infrastructure in a future climate neutral Danish energy system? 2) Which role will gas have in the sustainable energy transition towards a decarbonised energy system?

The long-term goals of the project were:

1. In an energy system context to facilitate the integration of the gas system with the power system, the district heating system and the transportation sector taking into account possible synergies
2. To facilitate a cost-efficient uptake of renewable gases, hereby in the longer term substituting natural gas and other fossil fuels

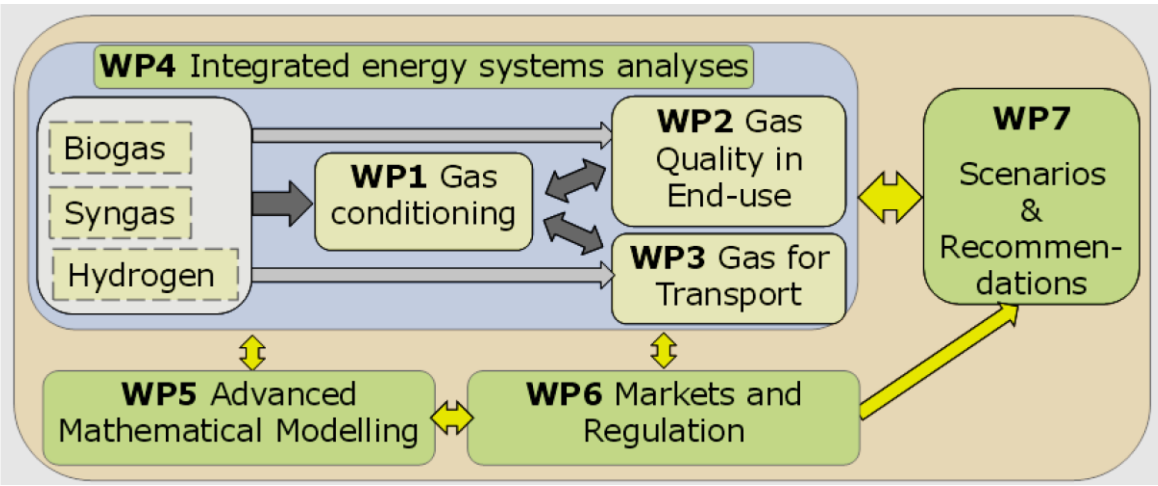
The project, which ran from 2016-2020, consisted of a wide range of partners from Danish and other European universities as well as from the Danish gas sector. During the project 27 scientific articles and 32 reports have been produced and a wide range of activities have been undertaken to reach out and engage with scientific peers and energy sector stakeholders. Info about partners and links to publications are available at the homepage www.futuregas.dk . The main deliverables from the project are summarized in Figure 1.1.

Figure 1.1 FutureGas deliverables

FutureGas deliverables	
Scientific Journal Papers published:	27 (11 more in pipeline)
Conference proceedings	14
Reports	32
White paper	1
FG Workshops	15
Conference presentations	33
Other FG presentations	47
PhD thesis	2 (1 more finishing)
Post docs	5
Master theses	7
PhD courses	5
Research awards	3

The project was organized in 7 workpackages covering the themes illustrated in Figure 1.2

Figure 1.2 Structure of the FutureGas project



This report aims to summarise the most important findings in each of the WP's with the first part focusing on the results from the integrated energy system analyses in WP4, WP6 and WP7, while the second part mainly illustrates highlights from the remaining WPs.

Chapter 2. System analysis results

This chapter first explains the main scenarios as well as the model framework of the system analysis, while the subsequent sections illustrates the results of first the socio economic analyses and secondly the regulatory analyses.

Scenarios and model framework

Marie Münster, DTU Management

This section provides an overview of the FutureGas scenario and model framework

The FutureGas scenarios were developed based on three main guiding frameworks:

1. The Paris agreement
2. Danish policies
3. ENTSOE/G scenarios

With regard to the Paris agreement, the Danish Climate Council has, based on population, assessed that Denmark should stay within a CO_2 budget of 325-425 Mt CO_2 budget for the total emissions over the period up to 2050 [1].

Recent goals of the Danish Government states that we should achieve a 70% reduction of greenhouse gases by 2030 (compared to the levels in 1990) as well as become climate neutral by 2050.

In 2018, the ENTSOE/G developed 3 common scenarios: Global Climate Action, Sustainable Transition and Distributed Generation. Global Climate Action assumes a high focus on climate ambitions, while Sustainable Transition allows for higher emissions.

Based on these frameworks three scenarios were developed illustrated in Figure 2.1, which all achieve climate neutrality in 2050, while differing in the path:

Early Sprint (ES): CO_2 budget 376 Mton (average of the range) (70% reduction in 2030) (inspired by Global Climate Action)

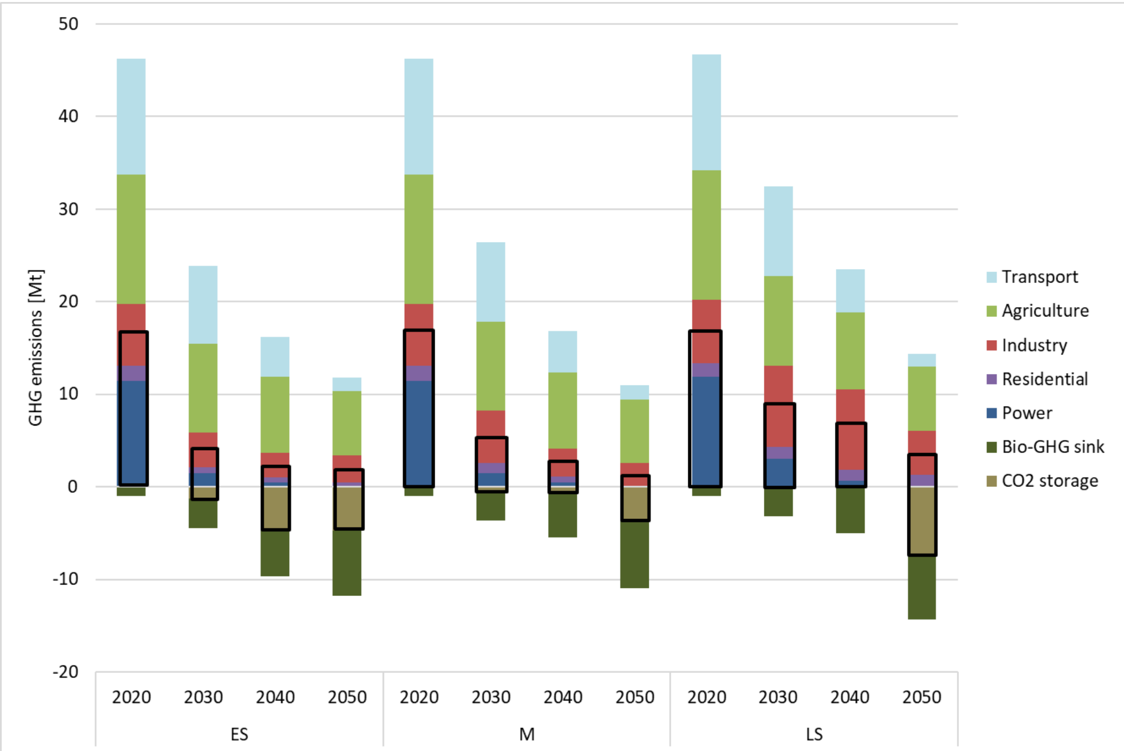
Marathon (M): CO_2 budget: 435 Mton CO_2 (high range) (70% reduction in 2030) (inspired by Global Climate Action)

Late Sprint (LS): CO_2 budget: 708 Mton CO_2 (BAU) (no reduction target in 2030) (inspired by Sustainable Transition)

Apart from the CO_2 budgets, the main difference between the scenarios is the assumptions on fossil fuel prices, which are based on the ENTSOE/G18 scenarios. The biggest difference is with natural gas, which is assumed to be 2-2.5 EUR/GJ cheaper in the LS scenario than in the other scenarios from 2030. (See Figure 7.2 in the Background report)

A more detailed description of the assumptions behind the scenarios, including energy demands, fuel prices, technology costs and efficiencies as well as renewable energy potentials can be found in the FutureGas System Analysis Background report. Apart from the main scenarios, a large number of alternative scenarios/ sensitivity analyses were analysed taking different framework conditions and different development of prices and technologies into account. The most interesting results are illustrated in the FutureGas Sensitivity Analysis report.

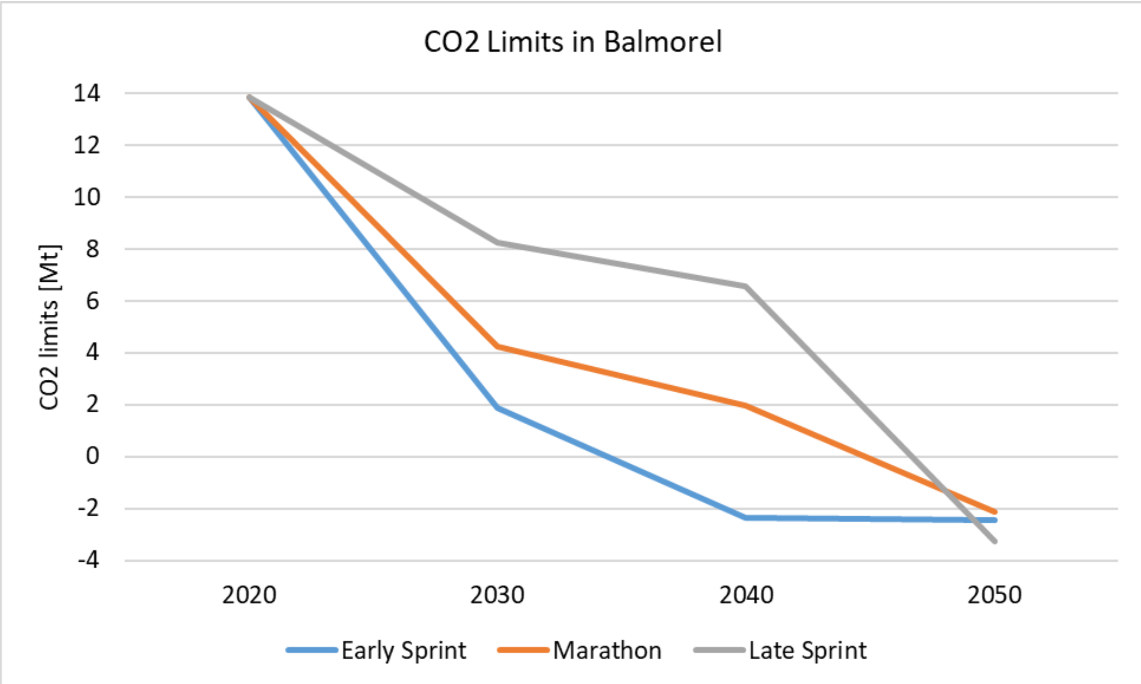
Figure 2.1 GHG emissions in the different scenarios. Black boxes illustrate the emission budgets handled in Balmorel



Key point Large GHG emissions in transport, agriculture and industry as well as power and heating

The total greenhouse gas emissions and the CO_2 budget for the power and heating sectors for each scenario were calculated in the TIMES-DK model as shown in Figure 2.1, where all energy and transport sectors are optimised to provide least cost solutions, given the required energy demands, emission reductions and costs and efficiencies of conversion technologies. Bio-GHG sinks consists of carbon sinks in forests and soils, including biochar, while CO_2 storage mainly consists of CO_2 captured from chimneys. The TIMES-DK model focuses on the Danish energy system and national travel demands with associated fuel production. The TIMES-DK model is coupled with a version of the Balmorel model, which covers the power and district heating sectors of Denmark, Norway, Sweden and Germany while including individual heat and process heat for Denmark. Both models include carbon capture and storage (CCS) options, while TIMES-DK also includes carbon capture and use (CCU) as well as carbon sequestration in forestry and farming. Outputs to the Balmorel model include biogas and bio-methane production levels, CO_2 budgets for the power and heating sectors, electricity demands for transport as well as excess heat capacities. The CO_2 limits implemented for each scenario in Balmorel is illustrated in Figure 2.2. For all scenarios, negative caps are implemented in 2050, as, with the given assumptions, it is cheaper to implement CCS in the power and heating sectors, than reduce all GHG emissions in the other sectors (agriculture, transport, direct fuel demand for industry). Due to a lower GHG budget in the Early Sprint scenario, negative caps are implemented already from 2040, while the highest reduction is required in the Late Sprint in 2050, as with the lower fossil fuels prices, it is less feasible to decrease emissions in the other sectors.

Figure 2.2 CO_2 limits for the Early Sprint, Marathon and Late Sprint scenarios implemented in the Danish power and heating sectors in the Balmorel model



Key point All scenarios reach negative levels by 2050 due to use of carbon capture and storage (CCS))

System Analysis Results

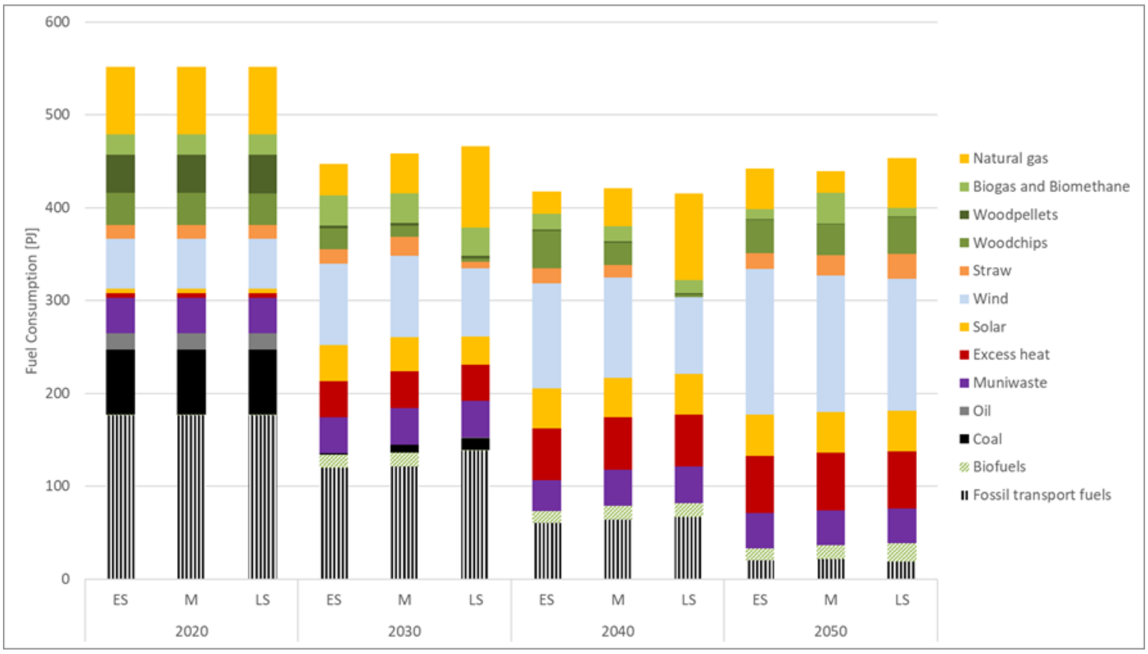
Marie Münster, DTU Management

This section shows the main results from the scenario analyses, focusing on the gas consumption.

Total gas consumption

Given the energy demands, fuel prices, technology costs and efficiencies as well as renewable energy potentials, the Balmorel model performs optimisation of Denmark and the surrounding countries, including investments and operation of transmission, storage and conversion units. The results illustrate potential least-cost pathways to obtain the given CO_2 caps. After 2020, the choice of fuels are set free and socio economic [2] investments are made for the next two years based on full foresight for only those years, investments are kept for the first year, and then the procedure is repeated for the next two years. As seen in Figure 2.3, this results in huge reductions in use of coal, woodpellets and light oil, which is substituted by increased use of wind power, straw, biomethane and excess heat in all scenarios. The main difference between the scenarios over the years are in the use of natural gas, wind power and woodchips. The increase in fuel consumption in 2050 compared to 2040 is due to less import of electricity.

Figure 2.3 Danish fuel consumption for power and heating sectors as well as domestic transport fuel demands from TIMES-DK

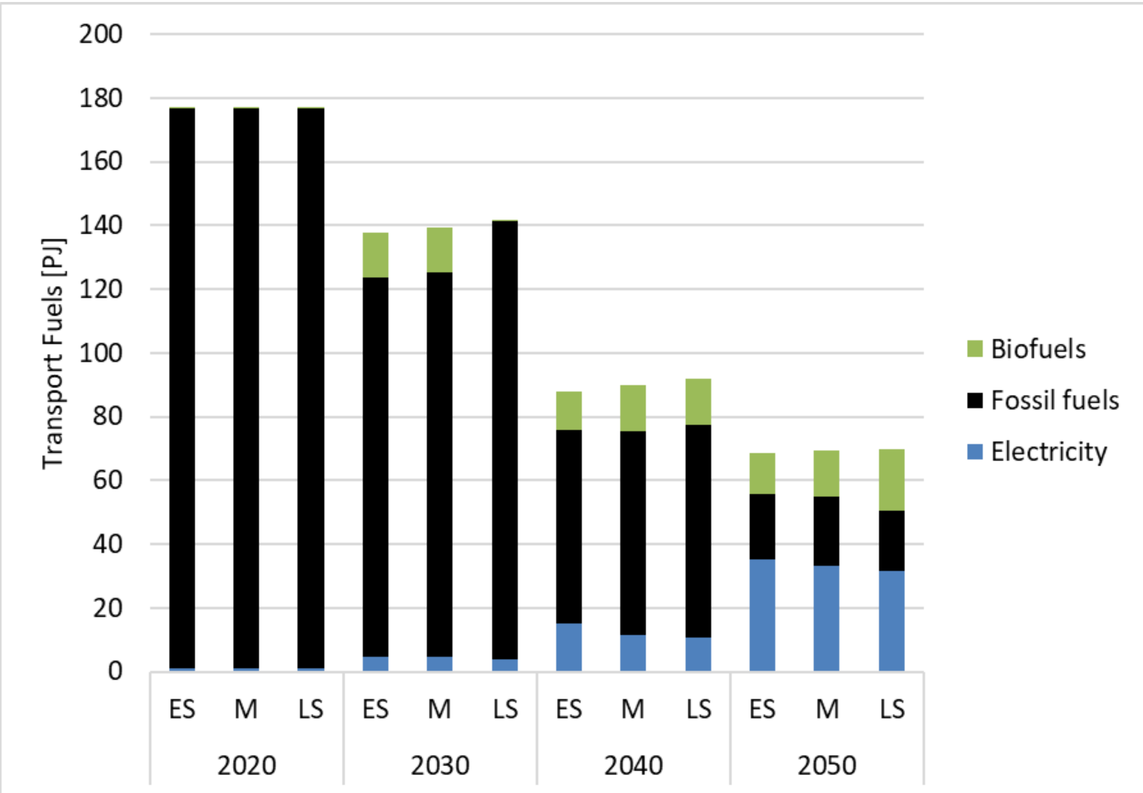


Key point: Fuel consumption decrease towards 2040, particularly in terms of transport fuels. The fuel consumption increases between 2040 and 2050 due to a lower import of electricity.

Figure 2.3 includes the fuel consumption for domestic transport. It can be seen that this is where the main fuel reduction takes place in all scenarios, as the domestic transport sector is electrified to a high degree, which reduces total fuel demand, although the increased electricity demand needs to be covered.

Figure 2.4 shows the TIMES-DK results on how the domestic transport sector is fuelled over the years in the different scenarios. The electrification seems moderate due to the high efficiency of the electric vehicles, but the results include 781000 electric/hybrid cars in Denmark in 2030 and 3087000 electric/hybrid cars in Denmark in 2050, of which most are hybrid in the beginning of the period and most pure electric in the end. Apart from fossil fuels and electricity, only a minor part is fuelled by biofuels. This changes, if the demands for international transport fuels are included, in which case the total fuel demand more than doubles and the share of biofuels increases to more than 50% in 2050. If biomass and biofuel imports are furthermore restricted, substantial amounts of electro-fuels enter in 2050 to constitute around 30% of the demand (for more info see the Sensitivity Analysis report).

Figure 2.4 Domestic transport fuel demands in Denmark in the different scenarios from 2020 to 2050 from TIMES-DK



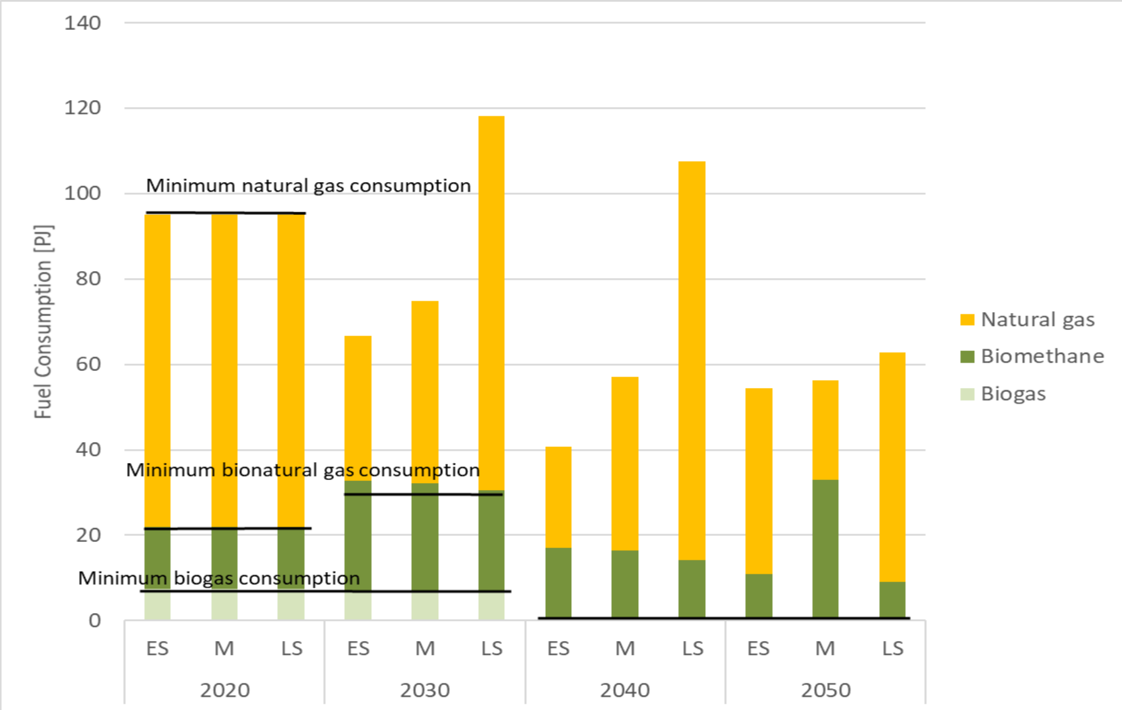
Key point Fuel demand for transport decreases due to efficient electrification

The differences in terms of total gas consumption for power, district heating, process heat and individual heating which were found using the Balmorel model can be seen in Figure 2.5. From 2020 to 2030, minimum consumptions levels for biogas and biomethane is implemented to reflect the existing and planned biogas and biomethane capacities. Biogas is furthermore limited to the current levels, as no further expansion of raw biogas networks is assumed. Already from 2030, the biomethane levels in Early Sprint and Marathon however exceeds the minimum. It is mainly found feasible to produce biomethane via upgrading of biogas (CO_2 removal). The main difference between the scenarios is the high natural gas consumption in the Late Sprint from 2030 to 2040 due to the lower natural gas costs and the higher CO_2 budgets. For all scenarios, however, the gas consumption has dropped to similar levels in 2050.

Biomethane levels differ between the scenarios, but ends at comparable levels in 2050. The highest level of above 30 PJ is found in the Marathon scenario in 2050. Lower levels are found in the Early Sprint scenario, mainly as more CCS is implemented. Biomethane consumption is however highly sensitive to the biomethane and natural gas prices. There is a clear tendency of lower bio-methane production prices leading to higher consumptions . Furthermore, a shift is seen from natural gas to bio-methane if natural gas prices increase. See Chapter 4 in the FutureGas Sensitivity Analysis Report.

In the study, the same level of socio economic tariffs have been applied. When consumption decreases, tariffs may however need to increase. This situation has not been analysed specifically, but the sensitivity analyses on gas prices indicate that this may lead to a downward spiral with less and less gas consumption.

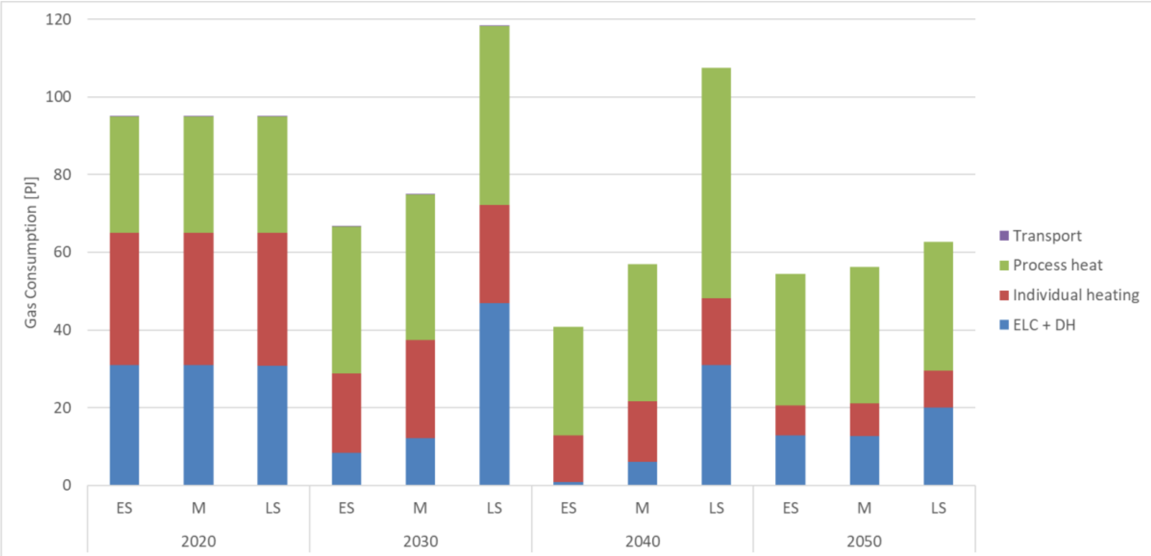
Figure 2.5 Consumption of natural gas, biomethane and biogas in the Early Sprint (ES), Marathon (M) and Late Sprint (LS) scenarios



Key point: Gas consumption varies considerably between the scenarios from 2030 to 2040. Black horizontal lines illustrates minimum consumption levels implemented in Balmorel due to existing demands and existing/ planned production capacities. For 2040-2050 no minimum levels are implemented.

The gas is used similarly in the three scenarios, with the main difference being for power and district heating, where the consumption is far higher in the Late Sprint scenario from 2030-2040, as shown in Figure 2.6. In general, the use of gas for individual heating decreases, while use for the industry sector increases slightly due to the increased demands assumed and a low degree of electrification. It is not found feasible to use gas directly for industry or transport when taking cheap electrification alternatives, infrastructure costs and methane slips from engines into account.

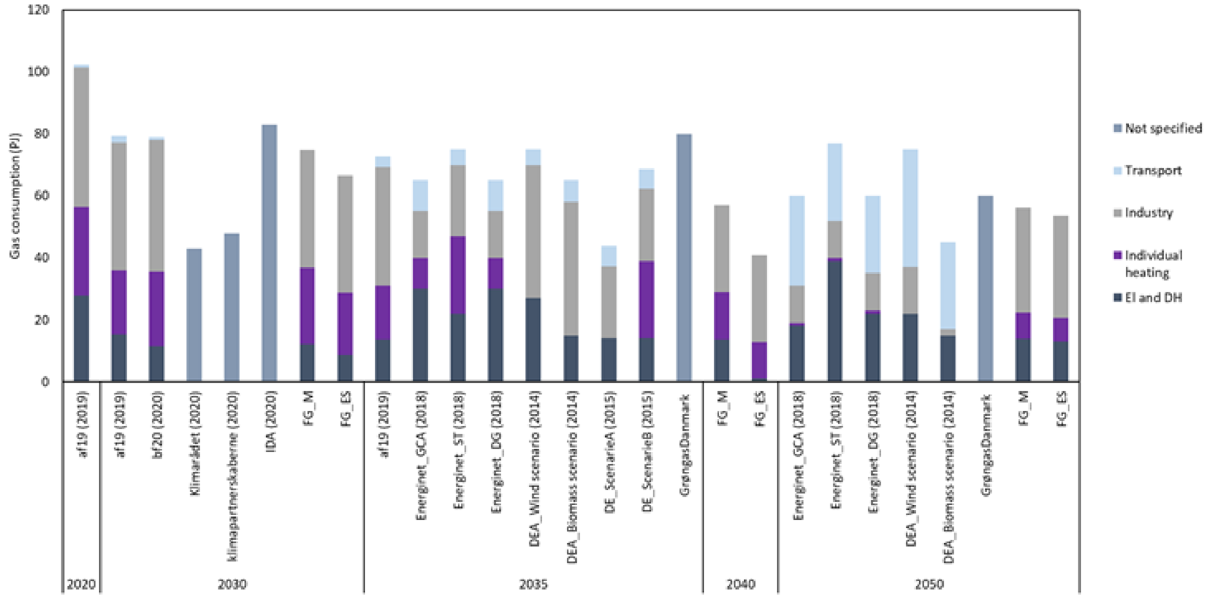
Figure 2.6 Gas consumption in different sectors and scenarios



Key point: Gas is mainly used for process heat in 2050, but also for power (ELC) and district heating (DH) as well as some for individual heating. Direct use of gas for domestic transport was not found feasible.

When comparing with other recent Danish energy system analyses, the total levels of consumption of the Early Sprint and Marathon scenarios are comparable to most of the studies, as seen in Figure 2.7. The gas consumption levels in the different sectors vary, and in particular regarding the future use of gas in the transport sector. While the other studies identify a significant gas demand in the transport sector by 2050, very limited use of gas in the transport sector are found in the Marathon and Early Sprint scenarios, under the defined scenario conditions. On the other hand, higher gas consumption levels are found in the industrial sector, which is primarily explained by a higher increase in process heat energy demands in the industrial sector in the FutureGas scenarios compared with the other studies. Figure 2.7 presents scenario results from different studies, which have applied different methodologies and hence not all gas demands are found based on optimization, as it is the case for the FutureGas scenario results.

Figure 2.7 Comparison of gas consumption in the Early Sprint and Marathon scenarios with other recent energy system analyses



Abbreviations: af19: Analyseforudsætninger 2019; bf20: Basisfremskrivning 2020; FG: FutureGas; ES: Early Sprint scenario; M: Marathon scenario; GCA: Global Climate Action scenario; ST: Sustainable Transition scenario; DG: Distributed Generation scenario; DEA: Danish Energy Agency; DE: Danish Energy Association

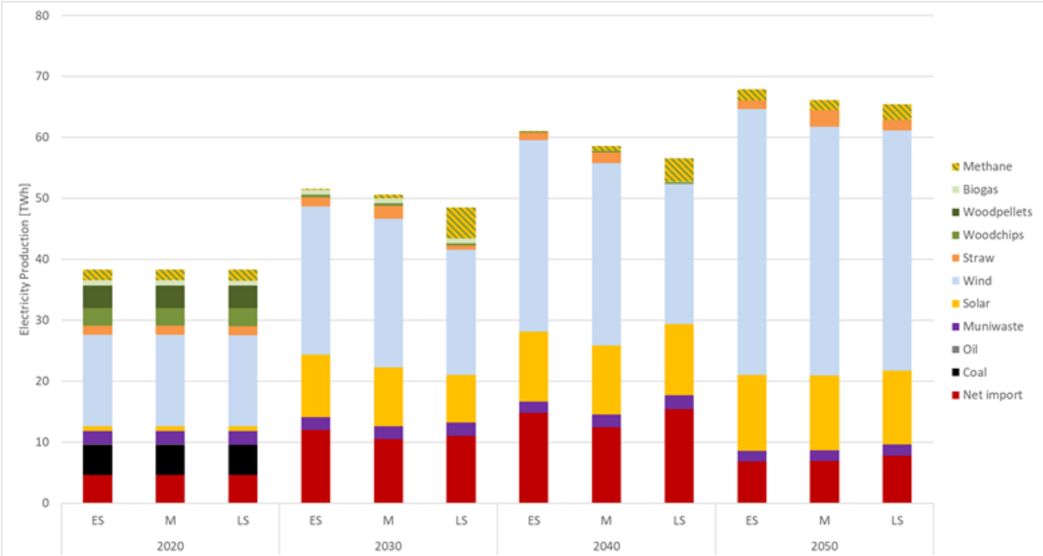
References:

af19 (2019): Analyseforudsætninger til Energinet 2019, Energistyrelsen;
bf20 (2020): Basisfremskrivning 2020, Energistyrelsen;
Klimarådet (2020): Kendte veje og nye spor til 70 procents reduktion;
Klimapartnerskaberne (2020): I mål med den grønne omstilling 2030;
IDA (2020): IDAs Klimasvar: Transport- og energiløsninger, iDA & AAU;
Energinet_GCA_ST_DG (2018): Systemperspektiv 2035;
DEA_Wind_Biomass (2014): Energiscenarier frem mod 2020, 2035 og 2050, Energistyrelsen;
DE_ScenarieA_B (2015): Gassystemets fremtid og udfasning af naturgas, Dansk Energi;
GrøngasDanmark: Data from Grøn Gas Danmark
FG_ES_M: Results from the FutureGas project

Key point The total gas demand in the Marathon scenario is comparable with similar recent studies, but the final uses differ

Focusing on electricity supply, the energy sources used to produce the required electricity amounts can be seen in Figure 2.8.

Figure 2.8 Electricity supply from different energy sources in the different scenarios.



Key point

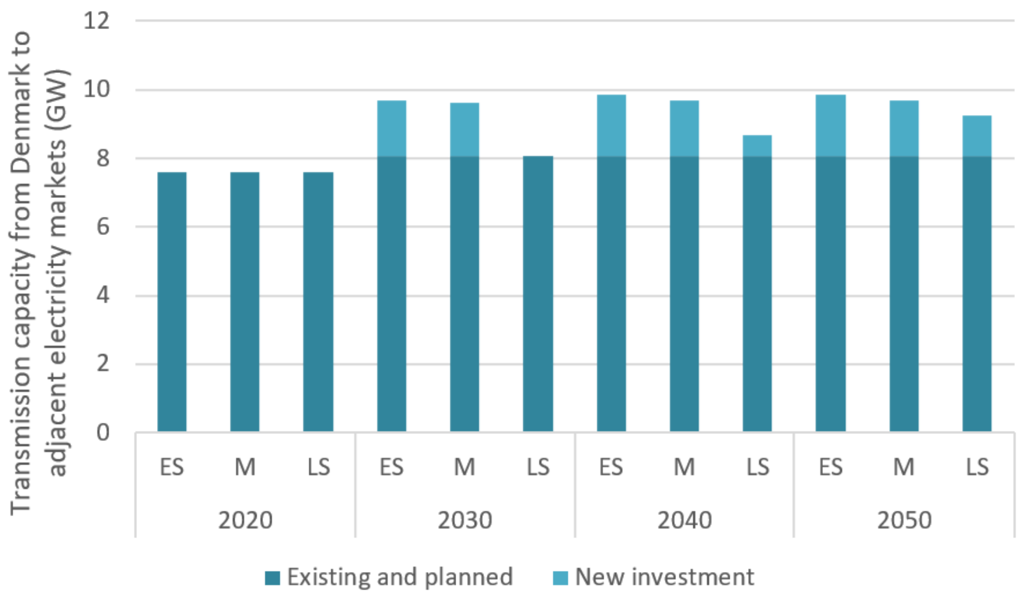
High shares of wind power in all scenarios as well as solar power from 2030. Natural gas and biomethane are shown together as methane, as the biomethane is upgraded to natural gas quality and distributed in the same grids as natural gas.

Note: Fuels used in combined heat and power plants to supply electricity demands are calculated based on electricity vs heat output ratios.

In all scenarios, wind power constitutes a major part of the power production, supplemented by high shares of solar power from photovoltaic cells (PV) from 2030. All scenarios furthermore rely on net import of power from the surrounding countries. If self-sufficiency is imposed, costs increase, while - particularly in Late Sprint - CO_2 emissions decrease. Change in fuel usage for surrounding countries when Denmark is self-sufficient shows a decrease solar PV, wind power and methane use up to 2050 (for more info see the Sensitivity Analysis Report). The different levels of electricity demand are due to different levels of electrification of transport and heating. The use of methane decreases from 2020 to 2040 for the Early Sprint and Marathon scenarios, while it after 2020 and stays high until 2050 in the Late Sprint scenario as natural gas is cheaper and the CO_2 budget higher. The limited number of countries covered in this analysis, might influence the results in the electricity generation mix, but it was chosen to prioritise a high level of detail on the Danish energy system instead. By 2050, almost a doubling is found in the generation capacity for plants using methane for all scenarios, although the electricity production decreases. This illustrates that the plants are mainly used for peak power production.

Transmission capacities between Denmark and neighbouring countries are illustrated in Figure 2.9. The level of capacities are similar, with least capacities in the Late Sprint Scenario, particularly in 2030 and 2040, due to more flexibility provided on the power production side. In general, only minor new investments are made by the model, compared to existing and planned capacities.

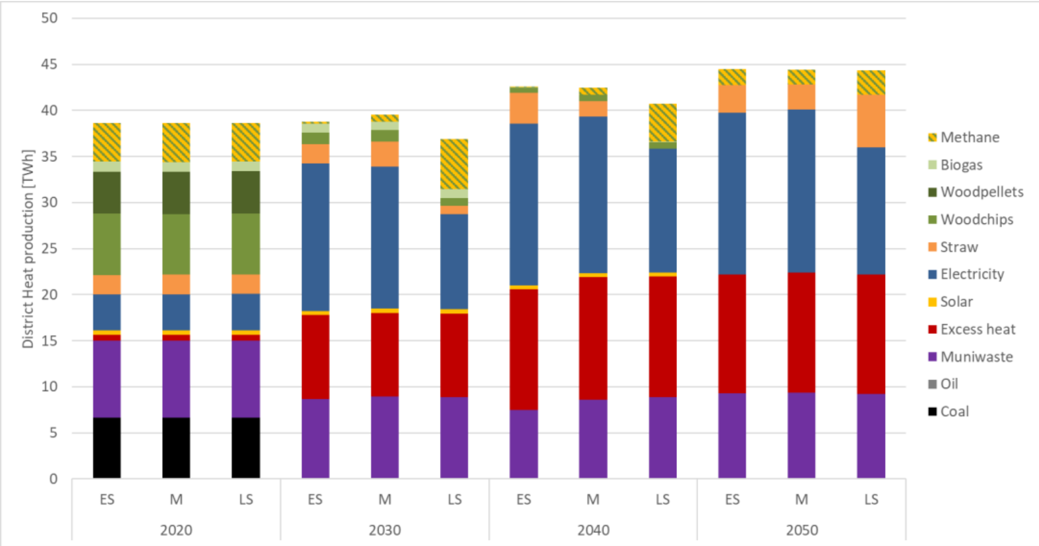
Figure 2.9 Electricity transmission capacity between DK and neighbouring countries in the different scenarios.



Key point Transmission capacities are similar for the different scenarios

In the district heating sector in Figure 2.10 a quick shift is seen away from coal and woodpellets, towards electrification and the local biomass, straw, as well as use of excess heat, while a continued high share of municipal solid waste is assumed. The high share of waste for energy is due to assumptions of growth in the economy, increased generation of waste and increased recycling resulting in similar residual waste amounts for incineration. The main difference between the scenarios is seen with regard to the use of gas or electricity. The differing levels of supply are due to different levels of consumption in the process heat sector. For the remaining heat sectors, the supply is assumed fixed. The methane is also here used to cover peak demands.

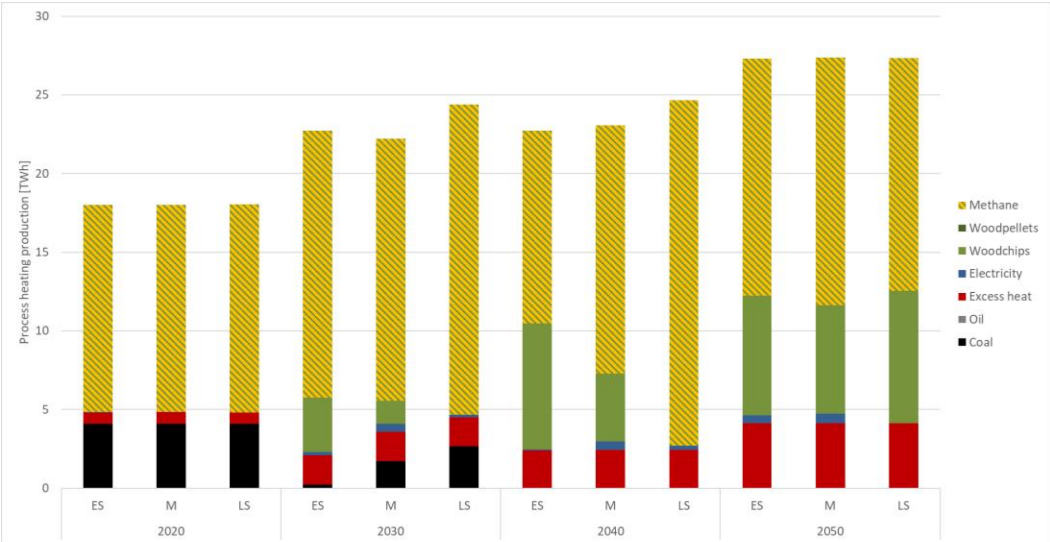
Figure 2.10 District heating supply from different energy sources in the different scenarios



Key point High share of electricity, excess heat and municipal waste in all scenarios

The demand of energy for industry is assumed to increase over the years as seen in Figure 2.11. Here, we focus only on the demand for process heat. The increase is due to an expected increase in production and demand in the Danish industry sector as forecasted in the NETP 2016. Some electrification takes place, but with the given assumptions, use of gas heat pumps, woodchip boilers and excess heat is found to be cheaper than large scale electric heat pumps. Three levels of process heat are modelled, high temperature (above 150 °C), low temperature (below 150 °C) and space heating. It is assumed, that waste heat can be used for low temperature process heat outside district heating areas. The high use of gas is impacted by the assumed availability of the cheap, efficient gas heat pumps (see the Background report). Furthermore, when allowing investments in CCS, this is found mainly to benefit the use of natural gas in industry and to a lesser extend impact the use of fossil fuels in transport when the agricultural sector is kept the same (see the Sensitivity Analysis Report).

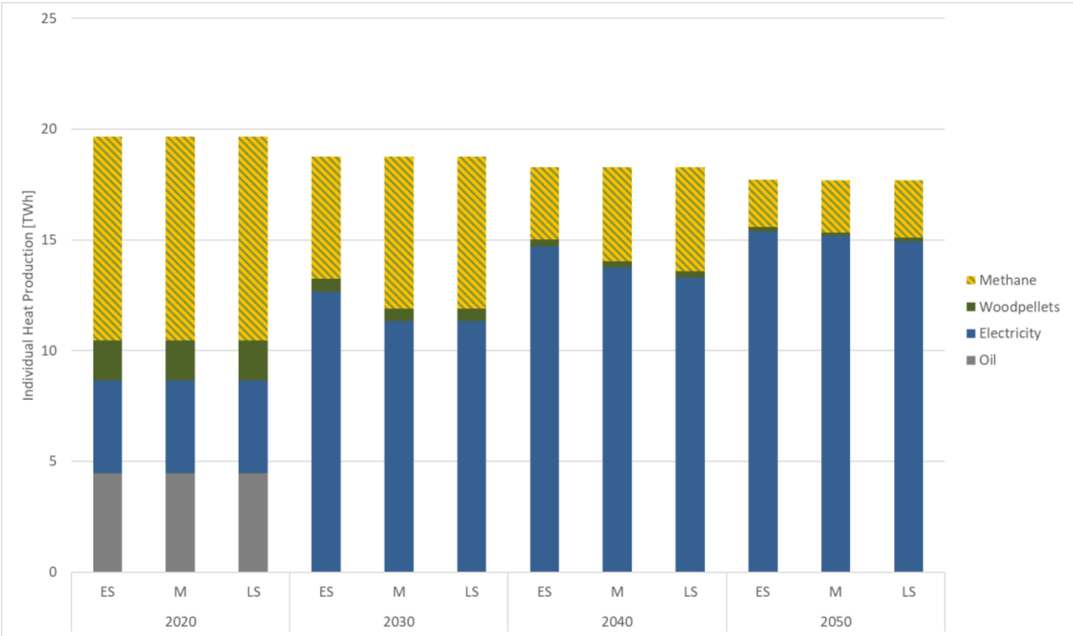
Figure 2.11 Process heat supply from different energy sources in the different scenarios



Key point	High shares of methane in all scenarios in all years as well as high shares of woodchips and excess heat for all in 2050

The individual heating sector sees a sharp decrease in oil consumption and a high share of electrification in all scenarios as shown in Figure 2.12, with the remaining share mainly being fulfilled with gas. There are high similarities between the different scenarios due to an assumed low willingness to shift of individual consumers (43% between each year modelled) applied in all scenarios (see Background report regarding modelling of individual heating and the main assumptions). A low willingness to shift can be interpreted as a low economic rationality and can be due to lack of knowledge, inconvenience with regard to shifting etc.

Figure 2.12 Individual heating supply from different energy sources in the different scenarios

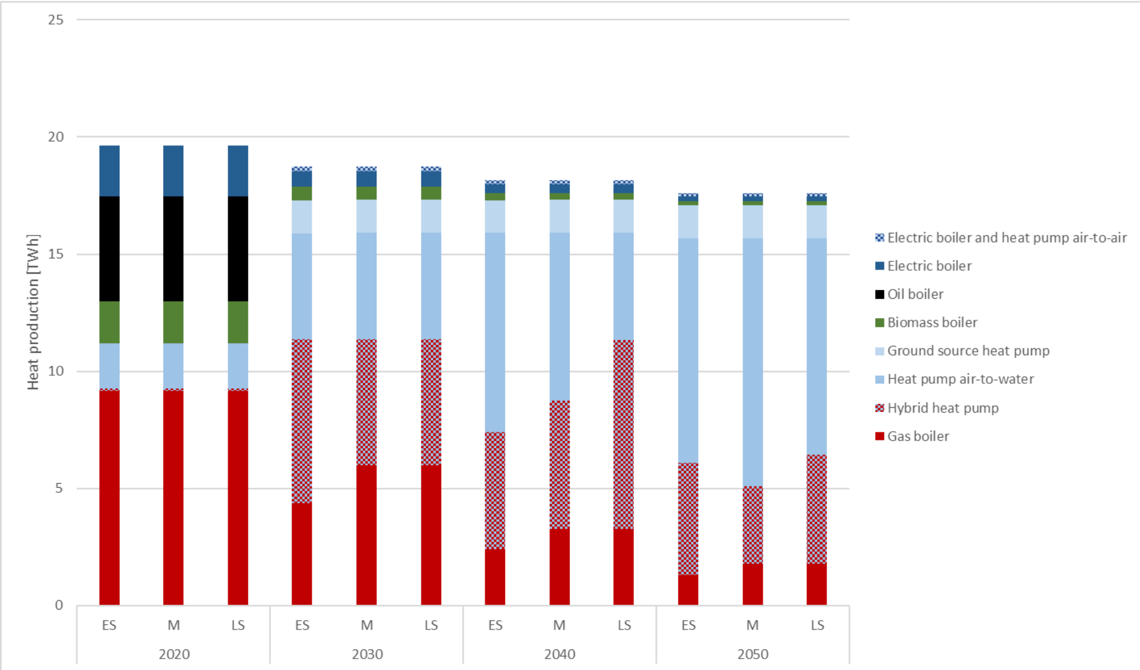


Key point High shares of electricity use and some gas use in all scenarios

Figure 2.13 shows the technologies used for production of individual heat. While gas boilers produce almost 50% of the heat in 2020, the share of electric air-to-water heat pumps quickly increases and is far above 50% in all scenarios by 2050. Particularly from 2030, hybrid heat pumps increase in share to around 25-30%. A limited share of gas boilers remains in 2050, due to the assumed low willingness to shift.

A potential shift to district heating was not optimized. Maximum levels have been implemented to wood pellet boilers, ground source heat pumps and solar heating. Furthermore, limits to shifts between different types of technologies e.g. due to availability of space have been implemented as explained in the Background report.

Figure 2.13 Individual heating supply from different technologies in the different scenarios



Key point Electric heat pumps are main suppliers in 2050 in all scenarios, but hybrid heat pumps and gas boilers are also present in all scenarios

Hybrid heat pumps have only recently started entering the individual heat market in Denmark and O&M costs are hence highly uncertain. A sensitivity analysis of increased O&M costs shows a high sensitivity to the changes with a substantially higher use of electric heat pumps. The results for individual heating are in general sensitive and changing the willingness to shift to 100% eliminates the use of gas boilers already in 2030, substituting it with hybrid heat pumps. From 2030 a cost reduction is found in all years if there is a 100% willingness to shift. Eliminating the possibility to use gas for individual heating from 2020 on the other hand results in a sharp increase in costs in the first years (mainly for investments) followed by a decrease in the last years (mainly lower fuel costs). In total, a cost increase is found (see the Sensitivity Analysis Report).

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Regulation

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With starting point in the socio economic base case (Marathon scenario) this section outlines the differences that appear when economic regulatory measures are introduced.

Main results of introducing economic regulation in the Marathon scenario

The existing regulation includes a mix of different taxes, tariffs and subsidies. In a socio economic world (as the Marathon scenario) also socio economic tariffs exist, while no taxes and subsidies are present. The CO_2-reduction targets are kept at the same level in the regulatory base case as in the Marathon scenario and the optimized energy system in the Balmorel model ensures that these targets are achieved also in the regulatory case.

In this section, the differences of going from a socio economic analysis to a private economic one are outlined. Methodologically this implies the following:

- The socio economic base case is the starting point, however without any socio economic tariffs (as these should not be counted twice, see below).
- Taxes, subsidies and (private) tariffs are added
- Taxes and tariffs are at the same level as today - throughout the analyzed time period
- Initially subsidies are at the same level as today, however they are gradually reduced assuming that renewable energy technologies are becoming economically competitive in the near future.

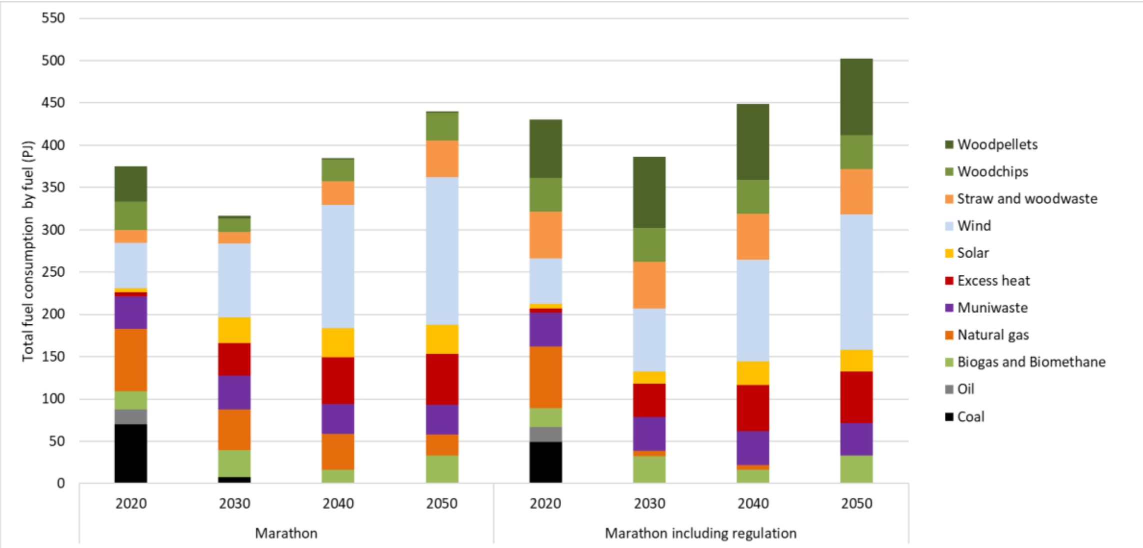
Finally, it should be kept in mind when interpreting the following results that:

- As is always the case in the Marathon scenario, not all Danish energy consumption is covered by the Balmorel model - excluded is non-electrified energy for transport and part of energy consumption in industry (only process related energy consumption is covered within industry)
- Services from the use of energy (demand) are kept at the same level as in the socio economic base case (Marathon). This implies that the introduction of taxes, subsidies and (private) tariffs do not change levels of service demand in households or industry.

Going from a socio economic base case with socio economic grid tariffs to one without these tariffs, does not make a significant change. Not surprisingly, we mainly see a minor increase in the production of electricity from wind turbines and photovoltaics (solar cells) at the expense of a mix of biomasses and a little natural gas. Thus the socio economic base case without tariffs is almost the same as the one with tariffs.

With the abovementioned assumptions, the Regulatory base case is constructed in the Balmorel model and the following results achieved.

Figure 2.14 Total fuel consumption in Denmark comparing Marathon with the Regulatory base case



Cases in figure 2.14	Marathon and Marathon including the regulatory base case

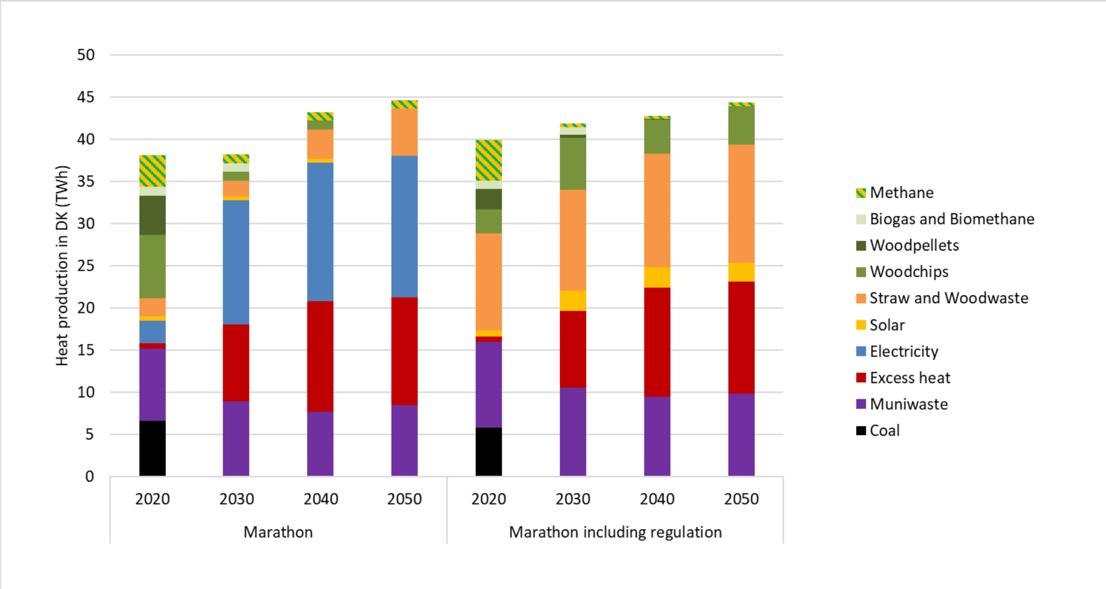
Figure 2.14 shows total fuel consumption for Denmark in the Marathon scenario (left) compared to the new Regulatory base case (right). The introduction of economic regulation gives rise to the following observations:

- A significant increase is seen in the use of biomass, especially woodpellets and to a minor extent woodchips and straw. The increased use of biomass is also the explanation behind the higher fuel consumption in the regulatory base case (lower efficiency).
- Biomass is substituting especially wind power and natural gas, where the use of natural gas is reduced significantly already from 2030.
- Coal is leaving the energy system entirely before 2030.

The above shown results do not come as a surprising as in the current legislation no tax is levied on the use of biomass while this is the case for electricity and gas, thus implicitly favoring the use of biomass.

The different sectors of the energy system are not impacted in the same way by the introduction of economic regulatory measures. In the following, results are shown for the district heating and the individual heating sectors to illustrate the development.

Figure 2.15 Supply of district heating in Denmark based on energy sources comparing Marathon with the Regulatory base case



Cases in Figure 2.15	Marathon and Marathon including the regulatory base case

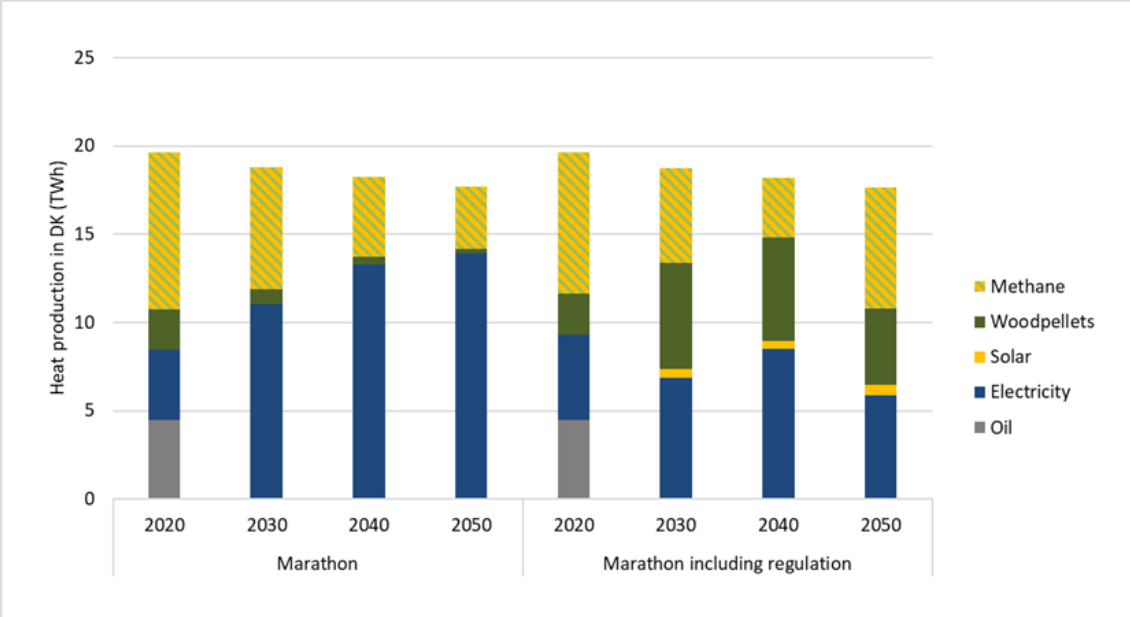
In Figure 2.15, the fuel consumption for the district heating production in Denmark is shown - we again have the Marathon scenario results (left) in comparison with the Regulatory base case (right). Main observations are the following when we compar the Marathon scenario with the regulatory base case:

- A significant increase is seen in the use of biomass, especially straw and woodchips
- Electricity is being squeezed out by biomass, already from the beginning of the analyzed time period
- Solar panels for hot water is entering the district heating system to a minor extent, while the role of gas (methane) is vanishing

Again the main explanation is that throughout the analyzed time period there is no tax on biomass.

The results for the individual heating sector is shown in Figure 2.16.

Figure 2.16 Supply of individual heating in Denmark based on energy sources comparing Marathon with the Regulatory base case



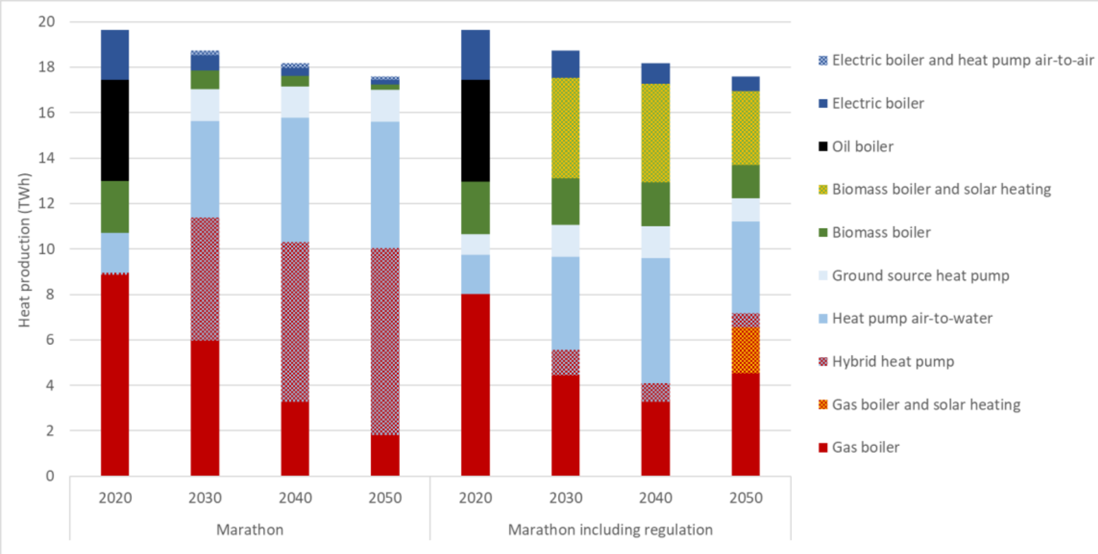
Cases in Figure 2.16 Marathon and Marathon including the regulatory base case

The results of the analyses for the individual heating system also show significant changes compared to the Marathon scenario:

- A large increase in the use of woodpellets, to a minor extent also solar, mainly substituting electricity
- Gas (methane) has a smaller role to play in the transition period (from 2020 to 2040), while the use of gas increases in 2050. When the use of gas is pushed out by biomass for electricity and district heating production, cheap biomethane is available for the individual heating as the amount of biomethane is the same as in the socio-economic case.
- Oil is leaving the individual heating system entirely before 2030

These results can be further detailed looking at the technologies being deployed in the analyzed time period as shown in Figure 2.17.

Figure 2.17 Supply of individual heating in Denmark based on technologies, comparing Marathon with the Regulatory base case



Cases in Figure 2.17	Marathon and Marathon including the regulatory base case

Looking into the use of technologies supplying the needed individual heat in Figure 2.17, we also see quite some important changes:

- A very strong deployment of biomass boilers combined with solar heating, to a lesser extent supplemented with biomass boilers only
- The electric heat pump air-to-water keeps a significant share of heat production
- The hybrid heat pump, which plays a large role in the Marathon scenario, has a much smaller role to play in the Regulatory base case.
- The gas boiler only technology plays a smaller role in the transition period, however coming back and increasing its share by 2050 where there is a high share of biomethane in the grid. By then gas boilers are also seen in combination with solar heating

The reason for the gas boiler entering the energy system again in 2050 is the same as in Figure 2.16: When gas is pushed out by biomass for electricity and district heating production, cheap biomethane is available for the individual heating as the amount of biomethane is the same as in the socio-economic case. It should further be noted that the results for the individual heating system are sensitive to the chosen assumptions - as is also seen in the socio economic base case (Marathon).

Finally, it should be mentioned that results also show a marked shift towards biomass in industry.

Sensitivity analyses for the Regulatory base case

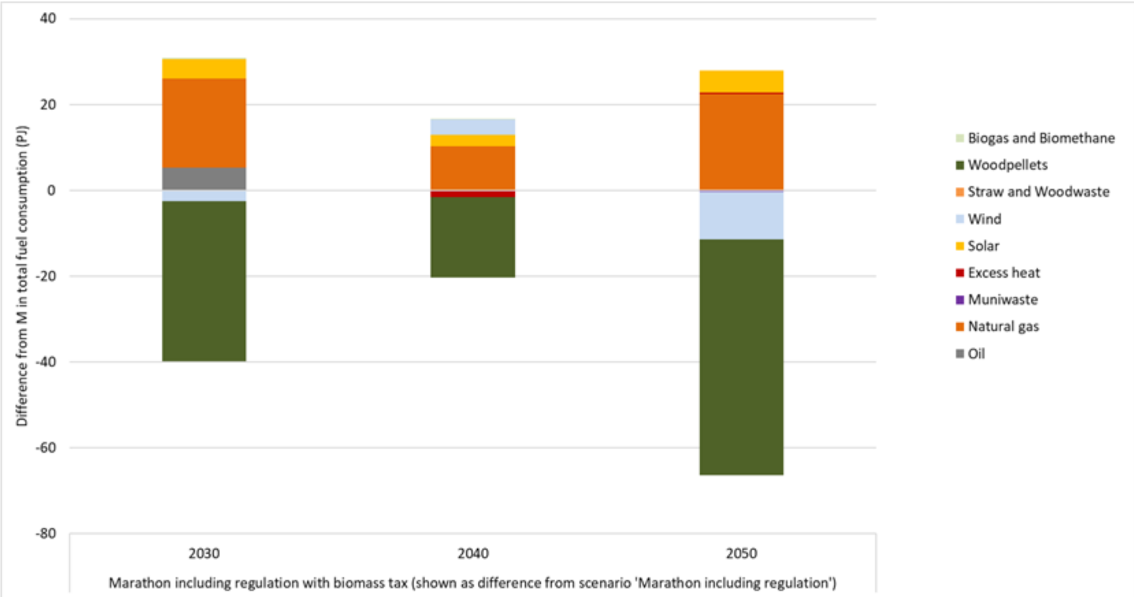
To test the results in the regulatory base case a number of sensitivity analyses are performed, including

- No tariffs, no taxes and no subsidies

- Introduction of a tax on all biomass: 8€/GJ in 2030 gradually increasing to 30 €/GJ in 2050
- A Danish CO_2 tax - gradually increasing from today's level to 1000 DKK/t CO_2 by 2030 and then kept constant until 2050

Results of the sensitivity analyses for tariffs, taxes and subsidies show that for tariffs and subsidies only minor and small changes are seen, when these are removed from the regulatory base case. However, when taxes are removed, we almost end up in the socio economic base case (Marathon). Thus, this underlines that taxes are the most important part of the regulatory measures.

Figure 2.18 Sensitivity on biomass tax introduced in the Regulatory base case - differences



cases in Figure 2.18	Marathon including the regulatory base case compared to Marathon including the regulatory base case and a tax on biomass

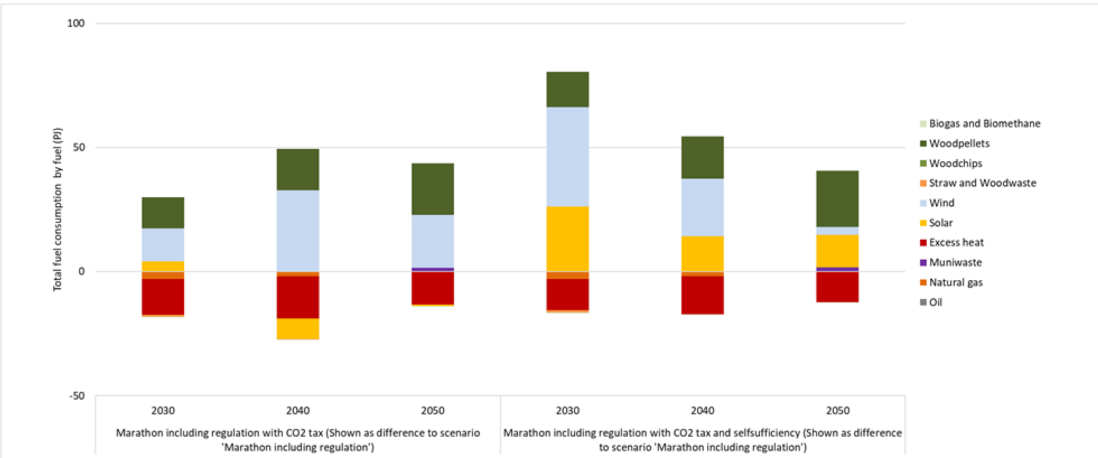
To illustrate the sensitivity of a biomass tax introduced in the Regulatory base case, Figure 2.18 shows the differences in comparison. Observe that what is being added to the energy system is shown as positive values, while what is being push out is shown as negative values. Of course, we see a marked drop in the use of biomass, but perhaps not as significant as expected

- The use of woodpellets are reduced by app. 75% compared to the Regulatory base case, however the use of woodchips and straw are not decreased.
- Especially natural gas is substituting the biomass

Finally, a sensitivity analysis is carried out for a general CO_2-tax supplemented by a CO_2-tax in the case of Danish self-sufficiency in use of electricity, see Figure 2.19. In the interpretation of these results please observe the following assumptions:

- The CO_2-tax is introduced at the level of today and gradually increasing to 1000 DKK/T CO_2 by 2030 and then kept constant until 2050.
- The CO_2-tax is substituting all other taxes and subsidies, while tariffs are kept at the same level as in the ordinary Regulatory case
- The CO_2-tax is raised to 1000 DKK/T CO_2 only in Denmark, while other countries in the analysis keep their CO_2 caps at the same level as in the ordinary Regulatory case
- Biomass is assumed to be CO_2-neutral
- As mentioned above, the CO_2-tax does not affect the level of consumption in any sector, only the configuration of the energy system is affected

Figure 2.19 Sensitivity on the introduction of a CO_2-tax and Danish selfsufficiency. Differences compared to Regulatory base case



Cases in Figure 2.19	Two cases compared to Marathon including the regulatory base case: 1) Regulatory base case plus a CO_2 tax gradually increasing to 1000 DKK/T CO_2 by 2030 2) Regulatory base case plus a CO_2 tax gradually increasing to 1000 DKK/T by 2030 plus Danish self-sufficiency

In Figure 2.19 the two cases of, respectively, regulation including a CO_2 tax and regulation including a CO_2 tax with selfsufficiency are compared with the Regulatory base case. Observe that what is being added to the energy system is shown as positive values, while what is being push out is shown as negative values. The following observations can be made from Figure 2.19:

- The CO_2-tax strengthens the use of wind, biomass and solar quite significantly from 2030 and onwards
- Self-sufficiency together with a CO_2-tax makes a strong case for wind, biomass and solar especially in the transition period

The result shown above is the outcome of a number of interactions in Danish and foreign energy systems, where the most prominent explanations are:

1) Net-import of electricity is found to be lower in this case - of course especially when selfsufficiency is assumed - and thus domestic production (wind, solar, biomass) increases.

2) CCS on biomass is found to be attractive, also in other countries.

Overall, the current regulation is shown to promote biomass use at a level which is not socio-economically feasible, taking raw costs, system integration and GHG emissions into account - even when assuming that all biomass is 100% CO_2 neutral.

Summarising the sensitivity analyses, it is shown that the dominance of biomass to a certain extent could be moderated by a tax on biomass. A CO_2-tax would strengthen the transition towards a green energy system and especially in the case of Danish self-sufficiency would have a strong effect.

Summary and major findings from systems analyses

Natural gas is a key energy carrier in the Danish energy system today, accounting for 17% of the total primary energy consumption. However, given the Danish long-term energy policy targets, combined with declining prices of renewable energy technologies, the transition away from fossil fuels and towards a renewable-based energy system is essential to investigate.

In the FutureGas-project a comprehensive energy system modelling complex has been utilized and further developed, especially to reflect the gas system, to analyze the transition towards carbon-neutrality by 2050. The systems analyses part of the project has entailed detailed scenario development and analyses, where three main scenarios are developed: 1) Early sprint, 2) Marathon and 3) Late sprint. The overall findings from these analyses given the assumptions outlined in the FutureGas Background report are summarized here:

- It is still feasible to distribute a significant amount of gas through the current gas system in the future.
- The most important sectors for gas supply will be industry, but also to a certain degree households as well as the power and district heating sectors. Direct use of gas for transport is not found to be competitive with the given assumptions. Results are sensitive to changes in costs and prices.
- In individual heating, hybrid heat pumps combining an electric heat pump with a gas boiler appear to be an interesting option, however with a high sensitivity to costs.
- Carbon Capture and Storage (CCS) has potential to become an economically viable option in 2050 and paves the way for more use of natural gas, especially in the part of the industry, where electrification is not feasible.
- Current regulation may lead to a higher use of biomass and a lower use of especially wind power and natural gas than what is found to be socio-economic viable.

More detailed observations concerning systems analyses include:

- All three scenarios end up at almost similar levels of use of gas by 2050 of approximately 60 PJ.
- The gas is used similarly in the three scenarios, with the main difference being for power and district heating, where the consumption is far higher in the Late Sprint scenario from 2030-2040.
- In general, the use of gas for individual heating decreases, while use for the industry sector increases slightly due to the increased demands assumed.
- By 2050, almost a doubling is found in the gas power generation capacity for all scenarios, although the electricity production decreases. This shows that the plants are mainly used for peak power production.
- All scenarios show net electricity import albeit at varying levels, unless self-sufficiency restrictions are imposed
- Biogas/biomethane is economically viable from 2030. It is mainly found feasible to produce biomethane via upgrading of biogas (CO_2 removal).
- Biomethane levels differ between the scenarios, but ends at comparable levels in 2050. The highest level of above 30 PJ is found in the Marathon scenario in 2050. Results are however highly sensitive to biomethane and natural gas prices.
- The results of the main scenarios show low levels of direct use of hydrogen, but in a situation where Denmark takes responsibility for producing green fuels for international transport bunkering in Denmark and if import of biomass or biofuels is discouraged, hydrogen is used as feedstock to produce liquid fuels (PtX) for the transport sector.

From the sensitivity analyses on regulation some of the more detailed observations include:

- The dominance of biomass can to a certain extent be moderated by a tax on biomass.
- A CO_2-tax would strengthen the transition towards a green energy system and would especially in the case of Danish self-sufficiency have a strong effect.

Chapter 3. Technological Deep Dives

This chapter presents technological deep dives into:

a) Renewable Gas Production
b) Hydrogen
c) Biomethanation
d) Dedicated grids and Individual biogas consumers
e) CH_4 emissions
f) Gas in transport
g) Value creation through improved modeling

Renewable Gas Production

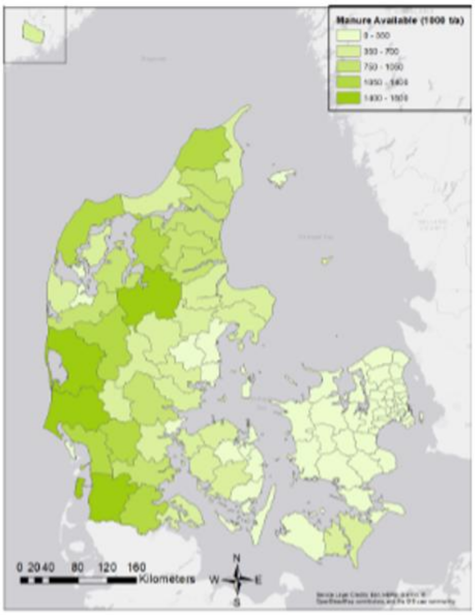
Rasmus Bramstoft, DTU Management

This deep dive outlines key results obtained from the integrated energy systems analysis using the developed modelling frameworks in the FutureGas project.

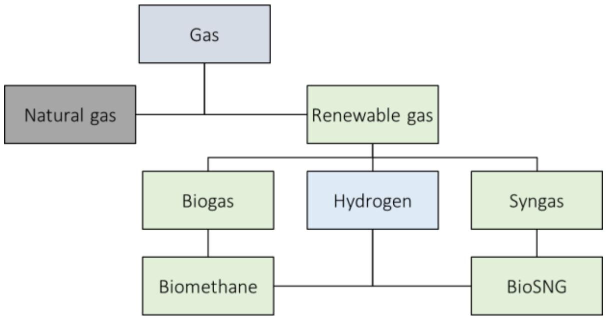
As a result of the FutureGas project, renewable gas production is analysed in an integrated energy system context in a deep dive assessment. The assessment covers an extensive catalogue of renewable gas and liquid fuel production pathways, which is investigated with a high spatial and temporal resolution energy system context.

During the FutureGas project, a deep dive into renewable gas production and its subsequent use downstream to the production of renewable liquid fuels has been made. To facilitate this deep dive assessment, a comprehensive catalogue of renewable gas and liquid fuel production pathways is analysed. A detailed modelling of the pathways is implemented in the spatio-temporal network optimisation model, OptiFlow, which is linked to Balmorel, allowing synergies between renewable gas and liquid fuel production and the power and district heating systems. As the transportation costs of transporting low energy content fuels, such as manure, is determining for the production costs of biogas, a detailed spatial resolution is implemented. Consequently, the availability of resources is at the municipal level and that transportation of resources between areas can happen if it is an economically feasible solution. In this way, an assessment of the supply chain from locally distributed biomass resources, via transportation means to conversion technologies is enabled, which then convert the biomass to renewable gas. The renewable gas can subsequently be cleaned and upgraded to natural gas qualities; stored; used directly; or used in other conversion technologies to, for example, produce liquid fuels for the transport sector. The synergies between the renewable gas and liquid fuel production and the power system occur mainly in the production of hydrogen from electrolysis, where electricity is used as input in the process, and the electricity prices are determining for the production pattern of hydrogen. The synergies with the district heating system are, in particular, when excess heat is generated, for example from thermal gasification processes or the production of liquid fuels, and subsequently used as heat supply in the district heating network. The geographic availability of manure, renewable gases and fuels are illustrated in Figure 3.1.

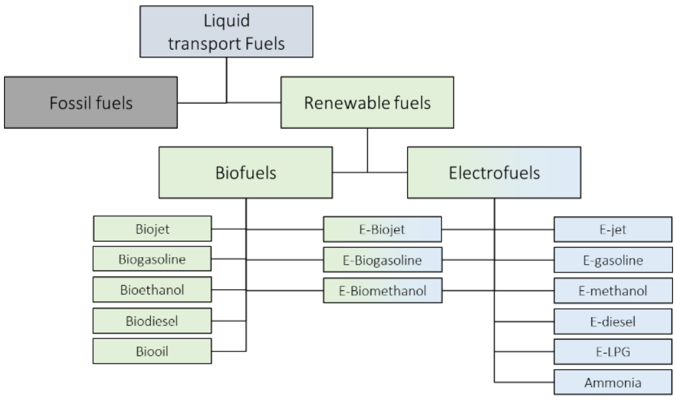
Figure 3.1 High spatial resolution assessment of an extensive catalogue of renewable gas and liquid fuel production pathways



a) Available manure for biogas production



b) Renewable gas production pathways

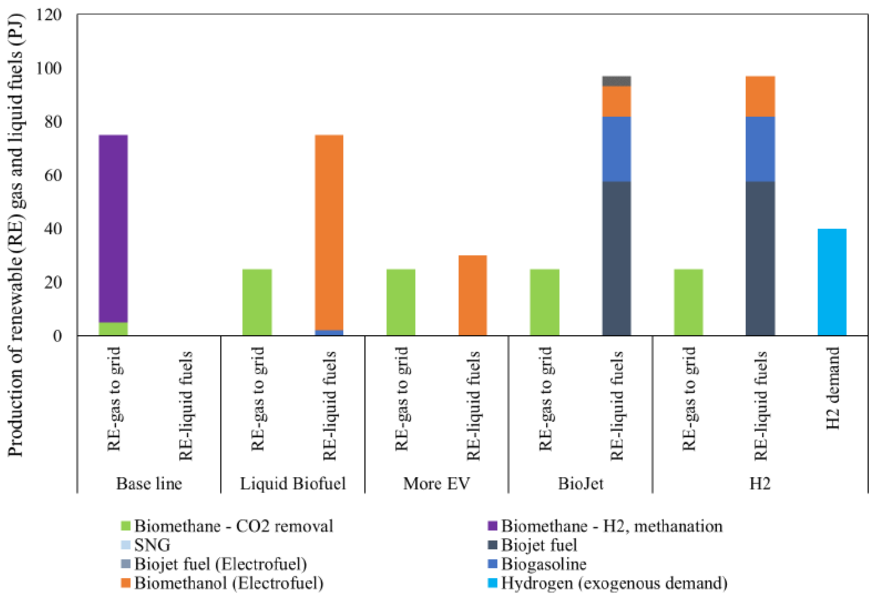


c) Renewable liquid fuel production pathways

Key point The availability of resources is implemented at a municipal level, where transport of resources can occur between areas, if economically feasible. The catalogue of implemented production pathways is extensive and include many possible production pathways for the future.

Figure 3.2 presents results for renewable gas and liquid fuel production in various scenarios for a Danish carbon neutral energy system by 2050. In the following a brief description of the key finding is presented, however, further details regarding the results can be found in the paper by Bramstoft et. al. [3], and for results regarding future electrofuel production pathways can be found in the paper by Scott Lester, Bramstoft and Münster [4].

Figure 3.2 Renewable gas and liquid biofuel production by 2050 in Denmark for various investigated scenario pathways



Key point

Biomethane is upgraded via CO_2 removal in low gas demand scenarios, while methanation is used in a high gas demand scenario (Base line).

Electrofuels – in particular, electrofuels using biomass and hydrogen – can play a prominent role in the future. Finally, Denmark can produce biojet fuel in Denmark, however, it puts high pressure on the sustainable national biomass resource.

The results regarding renewable gas, in the investigated scenarios, show that biomethane produced from anaerobic co-digestion of a mixed feedstock and upgraded via CO_2 removal would be the preferred option, however, in high gas demand scenarios, methanation is used as shown in Figure 3.2. Results from the high spatial resolution energy system analysis showed that biogas plants would be located in the countryside since the transport cost of manure is a determining factor.

Results of renewable liquid fuel production pathways in a 2050 climate-neutral energy systems show that electrofuels – in particular electrofuels using biomass and hydrogen – can play a prominent role in the future, to supply the transport sector. To produce these electrofuels, thermal gasification is used as a part of the process, which emphasises the need for developing and commercialising thermal gasification, as well as electrolysis. However, new technologies, for example, pyrolysis could potentially also play a role in the future, but this production pathway is not included in this analysis.

Furthermore, in a plausible scenario where Denmark produces fuels to supply aviation demands and do not import biomass or biofuels, the national biomass resources would be under high pressure. Consequently, in such scenario, a high share of the transport sector would be electrified and to supply the liquid hydrocarbons, e.g. for long-haul transportation, in a sustainable way, there would be a need for hydrogen to boost the production, or carbon-free fuel production like ammonia, or more sustainable carbon, e.g. potentially use carbon capture technologies or restructure the way of producing biomass for energy use.

Moreover, the spatial-temporal energy systems analysis showed that production of renewable liquid fuels might occur near larger cities, with large district heating networks and demands. In this way, excess heat can be sold to the district heating network. The results show that excess heat from renewable gas and liquid production could supply a significant share of the Danish district heating demand.

Finally, between the different production pathways for renewable liquid fuels, in particular, the biomass costs, fuel demands and electricity prices are the determining factors for the choice of the least-cost pathways.

This deep-dive assessment of renewable gas and liquid fuel production pathways shows that renewable gas may play a key role in the future to supply gas demands or to be used in other conversation technologies to, for example, produce renewable liquid fuels for the transport sector.

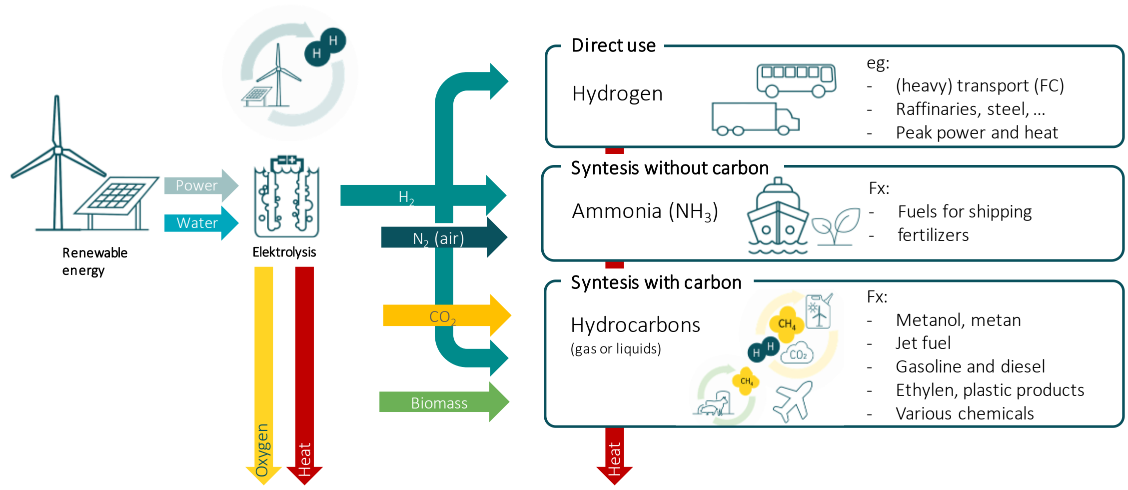
Hydrogen

Morten Stryg, Danish Energy Association

This section outlines the potential for hydrogen and hydrogen derived fuels in the Danish energy system. Further, the need corresponding for new renewable capacity and infrastructure is discussed.

In the future decarbonized energy system, hydrogen (H_2) will most likely play an important role. The application and distribution of hydrogen in the energy system is not yet known, but several studies [5] show that hydrogen will play a significant role. Hydrogen is a crucial part of Power-to-X (PtX) processes. Renewable-based hydrogen is produced using electrolysers. The hydrogen can then be used as an energy carrier or as feedstock in different industry processes e.g. steel or to produce ammonia (syntesis with N2). By adding carbon to the process, it is possible to produce fuels and gasses that can replace traditional fossil fuels in shipping, heavy transport or aviation. An overview of the hydrogen conversion processes is shown in Figure 3.3.

Figure 3.3 Overview of hydrogen use for Power-to-X fuels

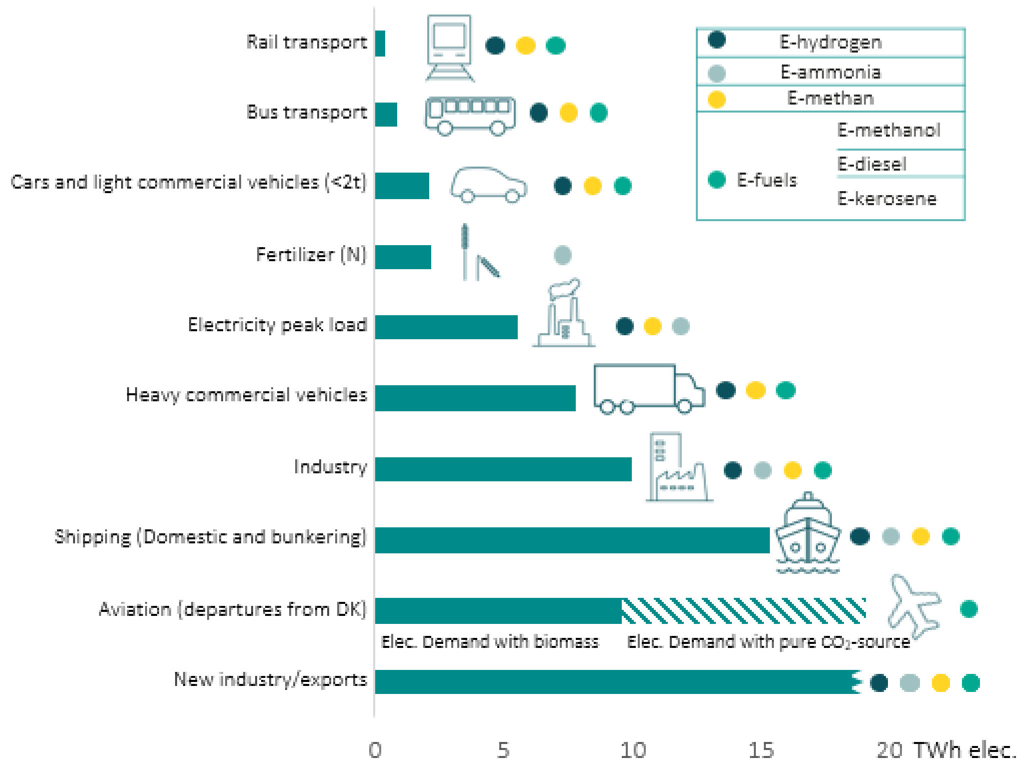


Source Energinet

Potentials for hydrogen use in Denmark

Figure 3.4 shows an estimate of the Danish potential for PtX use in hard-to-abate sectors. The potentials are based on replacement of existing fossil fuel consumption in Denmark, assumptions regarding each sector are found in the report [6].

Figure 3.4 Potential electricity demand for Power-to-X in Denmark



Source "Gamechangers for PtX and PtX-infrastructure in Denmark", (Dansk Energi, Energinet, 2020)

The potential demand for electricity to produce PtX products to replace the current fossil fuels consumption[1] in hard-to-abate sectors is up to 60 TWh in Denmark. The upper range imply a strong uptake of hydrogen and hydrogen-derived fuels in all sectors in Denmark. The lower potentials is roughly estimated to 15 TWh in a scenario where e.g. use of biofuels is promoted in transport.

To create a breakthrough of Power-to-X in Denmark several barriers regarding technical, economical, infrastructure and regulation must be solved. Hence, the sector with the most likely PtX-breakthrough depends on how fast these barriers are removed. Seen from a Danish 70%-reduction target perspective (focus on reducing national emissions) heavy duty land-based transport and subsequently industry are the most important places to introduce hydrogen and hydrogen derived fuels. Seen from a global perspective Denmark can contribute to the development of PtX-fuels in aviation and shipping, leading to climate impact in international transport. Further, export of hydrogen or hydrogen derived fuels from Denmark can lead to reduced fossil fuel consumption in neighboring countries. As an example, export of green hydrogen could replace the existing black hydrogen demand in the European industry (Today, EU's ammonia industry alone uses fossil-based hydrogen equivalent of 150TWh) [7]. Adding new applications of hydrogen and at wider use of green hydrogen in industry process to help decarbonize

[1] including fuel bunkering for ships in Danish territory and Danish fuels-share of international aviation

the industry. Studies [8] suggest the EU's demand for green hydrogen could be up to 1.700 TWh pr. year in 2050.

Status of hydrogen and Power-to-X development in Denmark

With support from the EUDP three hydrogen pilot projects have been announced in 2019.

- Green Lab Skive announced a 12 MWe electrolyser plant.
- HySynergy announced a 20 MWe electrolyser plant at the refinery in Fredericia.
- In Copenhagen, Ørsted and 7 industry partners announced a 2 MW plant including hydrogen storage.

In 2020 the Danish parliament agreed upon a new energy and climate action plan. It includes initiatives such as:

- An energy island in the North Sea connecting 3 GW offshore wind, and up to 10 GW in the future along with possible onsite offshore hydrogen production.
- A 2 GW offshore wind farm near Bornholm with interconnectors to Poland and possible onshore hydrogen production.
- Plans for 3 GW electrolyser plants in 2030 along with 500 MDKK/year support until 2025.

After the introduction to the Danish parliament 'Energy and Climate action plan', Ørsted, SAS and Mærsk along with other partner announced ambitions of a large scale hydrogen factory in Copenhagen with 1,3 GW electrolysis. SEAS-NVE, PFA, Pension Denmark and CIP have ambitions to build and run an energy island with up to 10 GW offshore wind and possible onsite hydrogen production. Lastly Shell have plans of building a PtX factory with 1 GW electrolyzer plant on their refinery in Frederica.

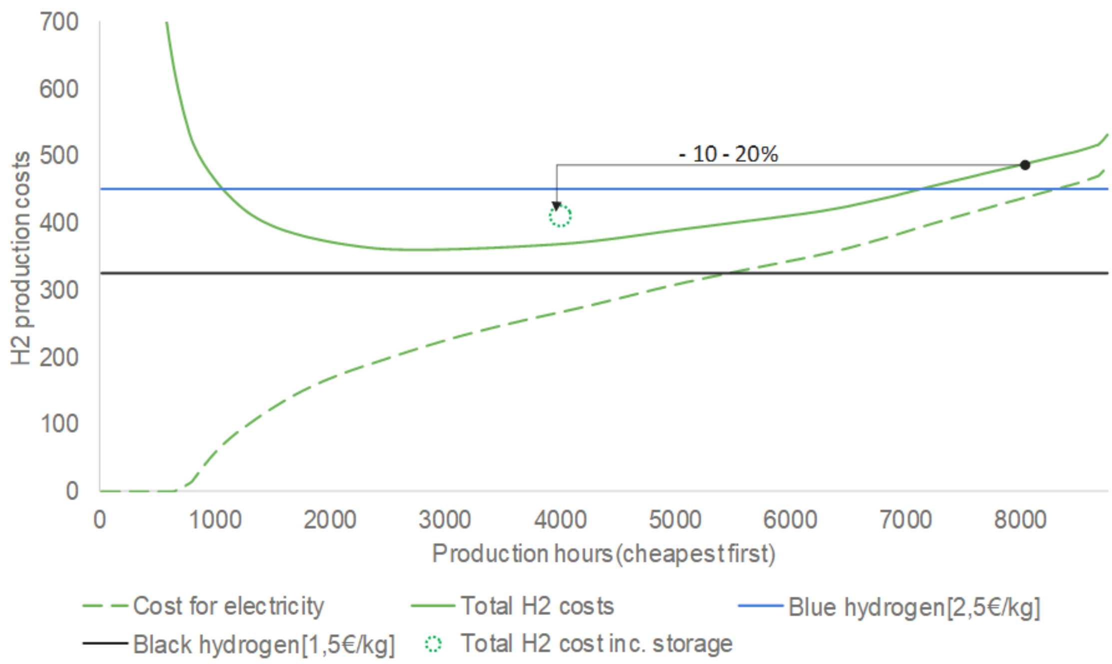
Production cost for hydrogen in Denmark

Assuming there will be a demand for 25PJ of hydrogen (equivalent of 10TWh of electricity demand) produced in Denmark in 2030, hydrogen cost is estimated using the Balmorel model.[2] The calculations show an optimal of 3.000-4.000 full load hours, in which case the capital cost for the electrolyser is then fairly low, hence the cost of electricity becomes the primary cost driver for hydrogen production cost. Green hydrogen can then be produced at around 350-400 DKK/MWh H_2 in 2030. At that price it is possible to compete with decarbonized fossil hydrogen ("Blue hydrogen"[3]), and it is almost on pair with traditional fossil based hydrogen ("Black hydrogen"), assuming prices of 440 DKK/MWh and 325 DKK/MWh, respectively.

[2] Calculation by means of Danish Energy's Balmorel model. The fundamentals of this Balmorel version is the same as the Balmorel version DTU used for the main FutureGas results, but some input parameters and functionality are slightly different between the models. Most importantly, the demand for hydrogen is exogenously given in both models, but different amounts due to the scenarios analysed.

[3] Hydrogen produced with natural gas in Steam Methane Reforming (SMR) and CO2-capture and storage (CCS)

Figure 3.5 Production cost of hydrogen in 2030 based on Dansk Energi Balmorel model



Key point: A reduction of approximately 10-20% is shown between unflexible production at around 8000 hours and flexible production via hydrogen storage at around 4000 hours per year.

By assuming a steady *consumption* of hydrogen in the Balmorel model (8.000 hour/year), the model can then choose an optimal combination of hydrogen storage and production facilities to provide the *supply* of hydrogen. The model results show that optimal investment in hydrogen cavern storages[4] will increase the production by roughly 50 DKK/MWh of hydrogen, to pay for storage and hydrogen infrastructure. With storage the electrolysers will operate around 4.000 hours pr. year. In these 4.000 hours the electrolysers will both fulfill the hydrogen demand and produce hydrogen to store. In the other 4.000 hours the hydrogen storage will discharge and thus fulfill the demand for hydrogen. Figure 3.5 shows that without storage or other forms of flexibility the production cost would increase with about 100-150 DKK/MWh to 500 DKK/MWh (electricity cost at 8000 hours).

However, the balance between storage and electrolysers is very dependent on the assumptions in the model. Both capital cost of storage and electrolysers and the volatility in electricity prices can change the balance a lot. Scenarios with low capital cost show an optimal utilization of plants as low as 2.000 hours pr. Year. In the calculations above, electrolyser costs of 300 EUR/kW in 2030 is assumed - according to the Danish technology catalogue the electrolyser costs could be as high as 550 EUR/kW [9], while BloombergNEF suggests prices as low as 100 EUR/kW [10].

[4] Hydrogen grid and storage costs of 400 DKK/kW based on costs for 10GW and 200 km hydrogen system.

Flexibility via hydrogen storage or synthesis plant end-use?

The flexibility needed when producing green hydrogen, can come from different places. As explained above hydrogen storages can provide flexibility. Another option is that the use of hydrogen can be flexible and adapted to the variating output of hydrogen from the optimized production from electrolysers. According to the Balmorel model the cost reductions via flexible synthesis plant end-use, ie. electrolyser and synthesis (e.g. e-ammonia or e-kerosene) plant operating at flexible load in a 'landing zone', is found to reduce the hydrogen production price in the same range as a large hydrogen storage. The calculation shows that the optimal solution between flexibility from either hydrogen storage or synthesis plant end-use operation will most likely depend on several factors:

- the size of the hydrogen system, i.e. the economy of scale effect
- the costs, load/unload capacity and round-trip efficiency of hydrogen storage
- the flexibility range of the end-use plant
- the capacity cost of both electrolyser and synthesis plant

Hence, the choice between power or hydrogen infrastructure will depend on both type, size and location of hydrogen demand and RE production, respectively.

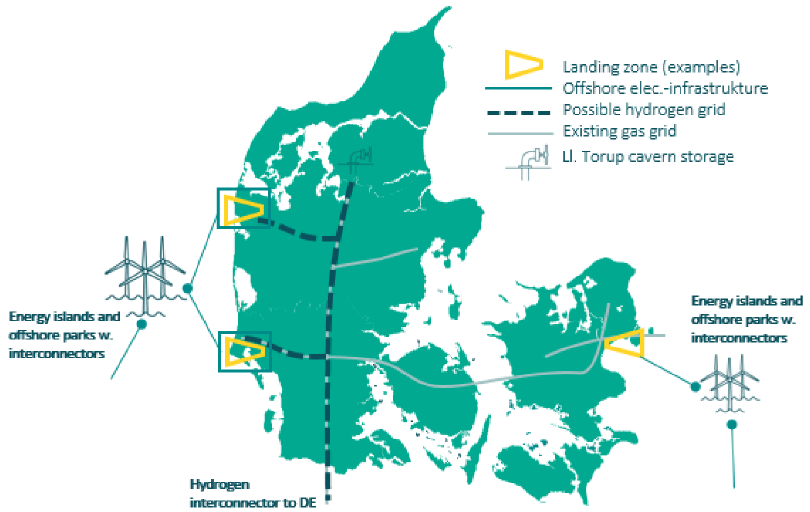
Hydrogen infrastructure

If the hydrogen demand increases significantly in Denmark and/or neighboring countries, dedicated hydrogen infrastructure could be needed, in order to bind together largescale productions facilities with demand, but also to ensure flexibility and security of supply. A hydrogen grid is possible both at distribution and transmission level. This chapter mainly focus on transmission level considerations. The infrastructure needed for hydrogen production and consumption, depends on the location of both in respect to other feed stock and infrastructure available:

- No hydrogen grid: Hydrogen production and demand is located at the same place. The power grid supplies RE power to the hydrogen production or hydrogen is produced and consumed 'onsite', ie. at the location of the RE source.
- 'Medium' hydrogen grid: The power grid supplies a large electrolyser capacity in a 'landing zone'. Hydrogen grid transports all or part of the hydrogen to customers.
- 'Full' hydrogen grid: Hydrogen is produced at the RE location (landbased or offshore at Energy Islands) and all hydrogen production is transported to consumers.

The distance of the hydrogen grid can be short (e.g. <100 km), long (e.g. 100-1000 km) or very long (e.g. >1000 km). Figure 3.6 show an illustration of a 'medium' Danish hydrogen infrastructure system where offshore wind production is converted to hydrogen in 'landing zones'. Subsequently, hydrogen can be transported to storages and large consumers within short to medium distance. Longer grid is needed to export hydrogen to Germany or the rest of Europe. The hydrogen infrastructure could be a mix of converted natural gas infrastructure (see Box 1) and new hydrogen infrastructure.

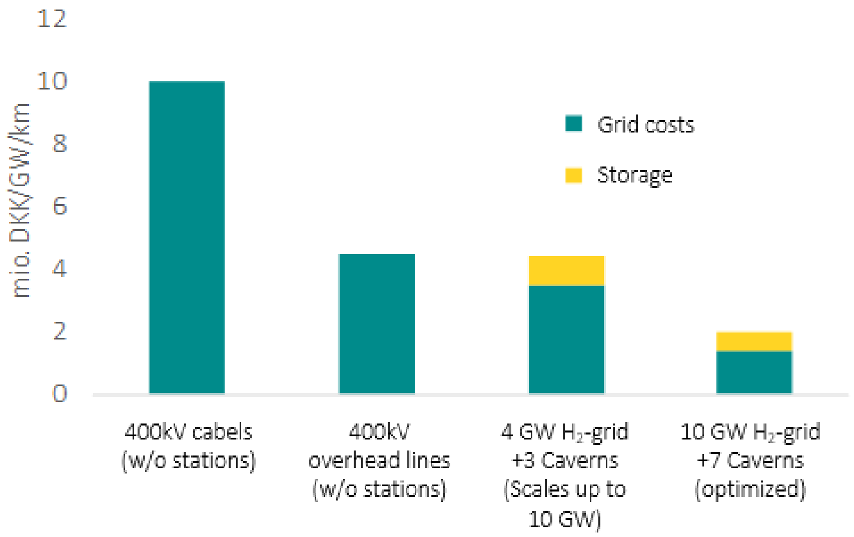
Figure 3.6 Illustration of hydrogen infrastructure in Denmark connected to landing zones



Key point Illustration of initial hydrogen infrastructure in Denmark (Dansk Energi, Energinet)

The specific capacity cost of power and hydrogen systems is shown in Figure 3.7. Large hydrogen systems (10 GW and cavern storage) have lower specific infrastructure costs compared to electric systems. Further, the visual impact of underground gas pipes is less that overhead power lines.

Figure 3.7 Specific infrastructure investment costs (Dansk Energi, Energinet)



Key point Large hydrogen systems (10 GW and cavern storage) have lower specific infrastructure costs compared to electric systems

A hydrogen backbone in Europe?

In May 2020 German gas pipeline operators revealed the blueprint for the world's largest hydrogen grid (5900 km fully built). The first section located in Northwest Germany is expected to be 1200 km and completed in 2030, where only 100 km would need to be built, with the rest being converted former gas pipelines [11]. This potential Northwest German hydrogen grid is also highlighted as one of the stepping stones needed to create a "hydrogen backbone" in Europe as illustrated in Figure 3.8.

Figure 3.8 2035-vision of the development of a hydrogen backbone in Europe

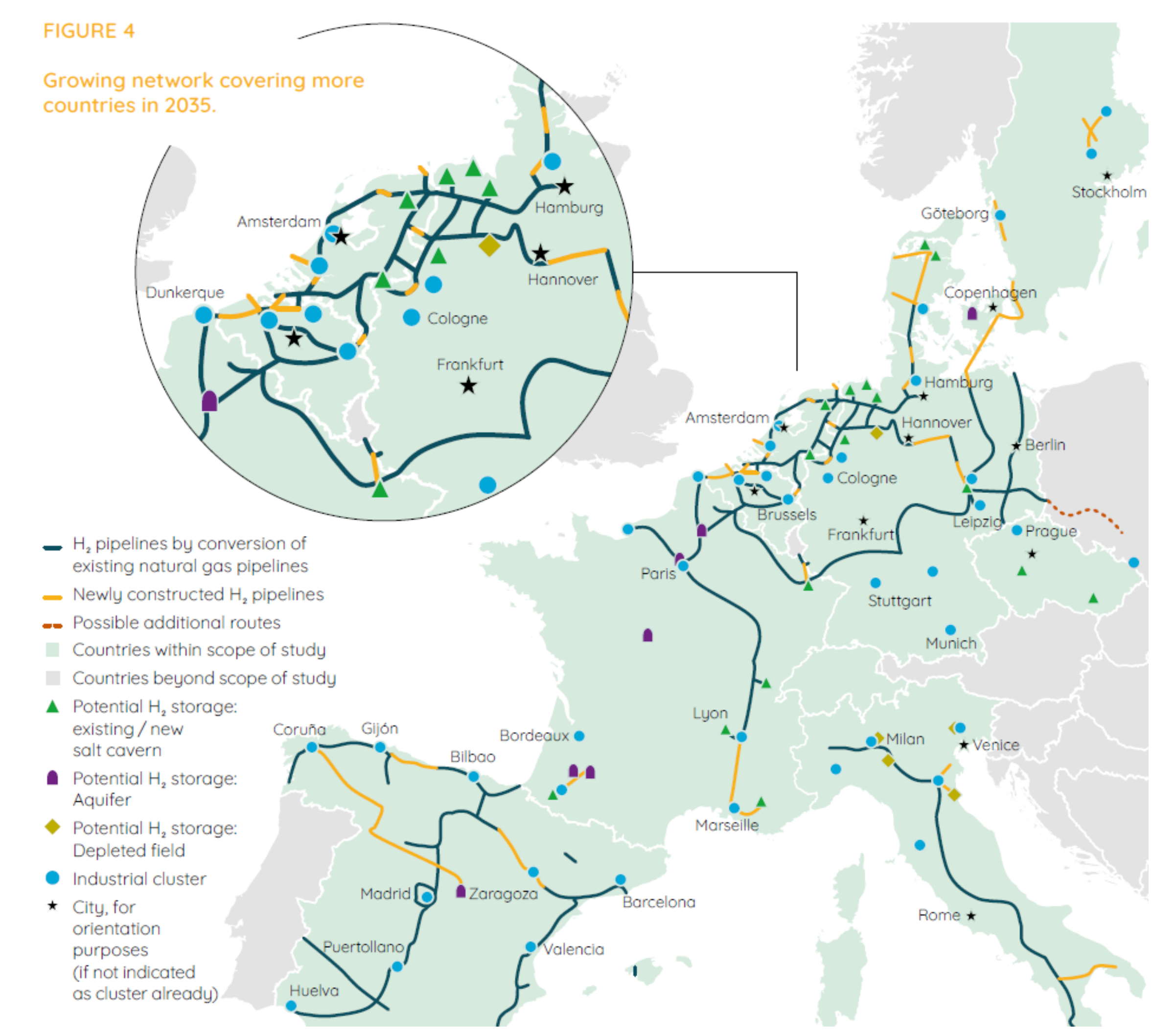


Illustration from "European Hydrogen Backbone" (Enagas, Energinet, et al., 2020)

As seen in the 2035-"Hydrogen backbone" vision Denmark could be connected to central Europe via the emerging hydrogen grid, both consisting of new grid and conversion of existing natural gas grids.

Biomethanation process and technology development

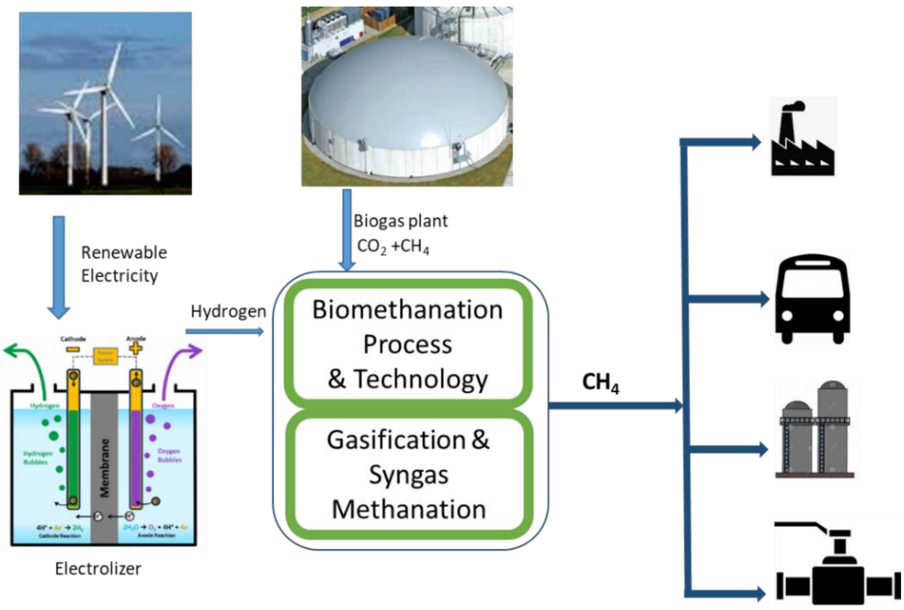
Nabin Aryal and Michael Vedel Wegener Kofoed, Aarhus University

A part of FutureGas was dedicated to identifying promising technologies currently under development, which could fit into a future energy system as part of the gas grid. The technologies all represent possible technologies for the sustainable production of biomethane, either by use of renewable electricity or recalcitrant biomasses. The identified technologies are at different technological readiness levels and combine energy conversion with CO_2 capture and utilization. The potential of these technologies were assessed through experimental testing to explore parameters needed to further mature the technologies.

Background

The aim of Work package 1 (WP1) was to compare different methanation and upgrading technologies based on available literature and test selected technologies in the laboratory. This deep dive presents the results achieved from lab-scale tests of a (1) biological syngas methanation technology developed during the project, and (2) technology for bioelectrochemical conversion of CO_2, which potentially can be used for biogas upgrading.

Figure 3.9 The role of hydrogen mediated biomethanation for production of methane



Key point: Carbon from biogas and gasifier can be coupled with H_2 produced from electrolysis for the production of CH_4 The produced CH_4 can be used for a range of applications, including transportation and industries, and can furthermore be stored or transported in the gas grid

Different promising biotechnologies currently under development within the fields of methanation and biogas upgrading to natural gas quality (biomethane) were investigated based on available scientific literature. The scientific review was critically done as reported in (Aryal et al., 2018 [13]) following technologies were identified:

1) **Syngas Biomethanation:** Syngas (CO_2, CO, H_2) biomethanation and upgrading
2) **Bioelectrochemical system (BES):** Biomethanation using CO_2 and electricity
3) **Hydrogen mediated biogas upgrading** (H_2/Biogas)**:** H_2 injection for biogas upgrading

These technologies are based on the microbial capability to convert the CO_2 present in biogas or syngas to CH_4. Using microorganisms to catalyze this conversion provides a platform that is potentially more robust and flexible in operation compared to non-biological technologies. (Aryal et al., 2018 [13]). Biogas often contains contaminants such as hydrogen sulfides, siloxane, which causes a detrimental effect on the chemical catalysts if the gas is not treated and purified prior to use. Biological systems for biomethane production offers a solution to overcome catalysis poisoning, cost of catalysis, and robustness of biomethane production compared to its chemical counterpart technology. Furthermore, syngas produced from the gasifier often contains dust, tar, and other contaminants that could poison the catalysts.

The biological catalysts are insensitive to the presence of these contaminants, which would poison chemical catalysts. In addition, the microbial catalysts gain energy from converting H_2/CO_2 and syngas and can therefore be considered to be self-sustaining and adaptive to changes in gas load. As shown in Figure 3.9, the conversion of biogas CO_2 and subsequent biogas upgrading requires the input of reduction equivalents either in the form of H_2 (H_2/Biogas), which can be produced from electrolysis of water or fed directly to the microorganisms via electrodes mounted in the reactor (BES). These approaches have some advantages and disadvantages, but all have the potential to utilize renewable electricity to convert CO_2, which presents some possibilities:

i) Utilization and conversion of CO_2 to CH_4 for use in the energy system (BES, and H_2/Biogas)
ii) Utilization of cheap electricity from renewable sources in a power-to-gas context, hereby allowing for large-scale storage of electricity (Syngas, BES, and H_2/Biogas)
iii) Utilization of waste material in the energy system to supplement the anaerobic digestion process (Syngas)
iv) Couple the electricity system and the gas grid through system integration (Syngas, BES, and H_2/Biogas).

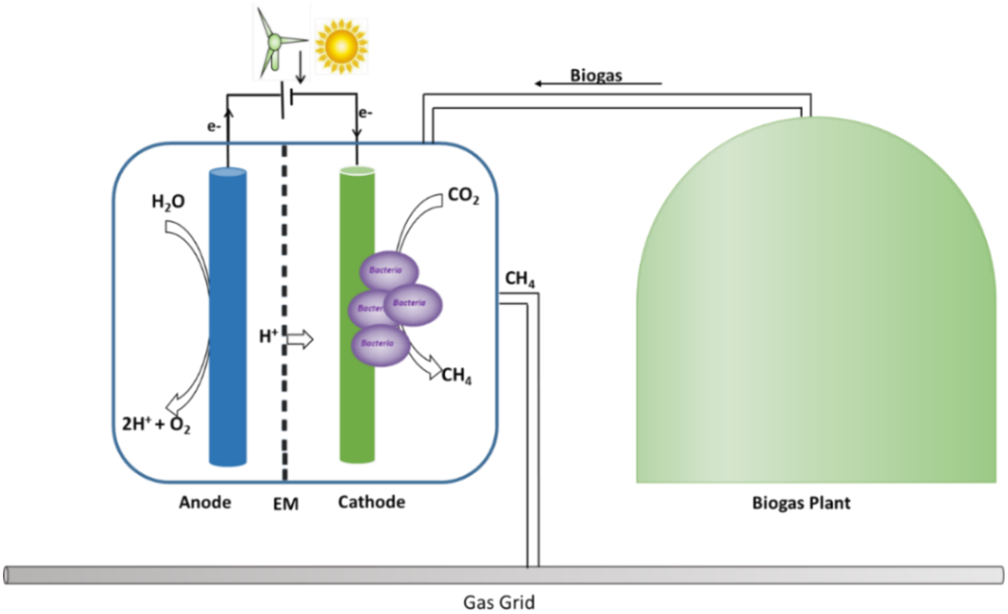
In the following two sections, tests on biotechnologies for CO_2 conversion using BES, and methanation of syngas is presented.

Methanation process and technology

Bioelectrochemical system for biomethanation

H_2/Biogas technologies are maturing at a rapid pace and has previously been successfully tested in lab-scale, as summarized in the review article Aryal, N et al., 2017. However, BES represents an interesting alternative because it allows for the construction of a compact system that combines electrochemistry and biology for biogas upgrading in one single system, in contrast to the H_2/biogas technology that requires separate processes of electrocatalysis and subsequent H_2/CO_2 conversion.

Figure 3.10 Proposed schematic for utilizing Bioelectrochemical systems (BES) for biogas upgrading



Key point The electricity is supplied directly to the microorganisms at the cathode of the electrochemical cell. The microorganisms use the added reducing equivalents for reducing the CO_2 fraction of the supplied of biogas to CH_4 (Aryal et al., 2018 [13])

The Technological Readiness Level of the BES technology is still low (~TRL 2), but it has, during the last years, been intensively researched for upgrading biogas (Aryal et al., 2018, 2017 [12]). The use of BES technology for biogas upgrading, using the direct transfer of reducing equivalents from an electrode to microorganisms, is primarily done in lab-scale, where development focus on (1) understanding the mechanisms of electrode-microbe interaction, and (2) increasing the CH_4 production rates of the BES technology.

A BES consists of an anode and a cathode separated by an ion-exchange membrane, which facilitates the transport of ions, as shown in Figures 3.9 and 3.10. The CH_4 production occurs at the cathode, where microbes reduce CO_2 by using electrons (or H_2) from the cathode (eq 1 & 2). In parallel, water is oxidized at the anode (eq 3).

$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$ (1)

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (2)

$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ (3)

Experimental work and results

Within WP1, lab-scale test with BES was conducted for bioelectrochemical production of CH_4 from added CO_2. An essential part of the further development of the BES technology is the design of a system that can handle and convert a continuous gas stream of CO_2. To this end, AU researchers within both biotechnology and electrochemistry designed a BES system that would facilitate continuous operation on CO_2 and, at the same time, facilitate an efficient supply of reduction equivalent to the microorganisms.

The BES system was equipped with packed-bed graphite granular electrode materials to provide the high volumetric surface area to enhance the microbes-electrode interaction. Following two months of operation, the results showed that the CH_4 production rate of 1.08 ± 0.17 $L_{CH4}d^{-1}\ L^{-1}{}_{\text{Inoculum volume}}$) (83.3 ± 12 $L_{CH4}d^{-1}\ m^{-2}{}_{\text{cathode surface}}$) was achieved, as shown in Figure 3.11. In comparison, H_2/Biogas experiments show production rates of 1.2-33.7 $L_{CH4}d^{-1}\ L^{-1}{}_{\text{reactor volume}}$ (Dupnock and Deshusses, 2017; Lee et al., 2012 [16]) when operating at the same reactor temperature and pressure as the BES experiments. The production capacity of the BES is, therefore, in the same range as the H_2/Biogas reactors with the lowest performance but also shows that some optimization is needed. The presence of unutilized H_2 showed that it was not fully consumed by microbes, thereby indicating that the cell was able to supply more reducing equivalents than could be used by the microorganisms. Our results, therefore, indicate that further work should focus on improving the microbe-electrode interaction.

Figure 3.11 BES performance with packed bed graphite granular electrode materials cathodes

Description	Value
CH_4 production rate (Ld^{-1})	2.5 ± 0.4
CH_4 production rate ($L_{CH4}d^{-1}\ m^{-2}{}_{\text{projected surface area}}$)	83.3 ± 12
CH_4 production rate ($L_{CH4}d^{-1}\ L^{-1}{}_{\text{Inoculum volume}}$)	1.08 ± 0.17
Unutilized hydrogen (Ld^{-1})	0.28± 0.14
Current Density with mixculture (Am^{-2})	-12.72± 6.31
Columbic efficiency (%)	42.09 %

The value presented is in STP conditions

Gasification, syngas methanation, and syngas upgrading

Organic waste material is often utilized as feedstock in biogas plants; however, fibrous materials, recalcitrant lignocellulose biomass can often be very difficult to degrade in conventional anaerobic digesters and thus remains undigested in the reactor. These biologically recalcitrant biomasses can be converted to syngas consisting of CO, CO_2, and H_2, through incomplete combustion in a gasifier. The produced syngas can be converted to a mixture of CH_4 and CO_2 either chemically or biologically.

The conversion of syngas to CH_4 follows the two overall reaction patterns as shown in eq 4 & 5 (Sancho Navarro et al., 2016 [21]):

$$4CO + 2H_2O \rightarrow CH_4 + 3CO_2 \quad (4)$$
$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (5)$$

The composition of the syngas is an important parameter for the stoichiometric composition of CO_2:CH_4 in the mechanized syngas, with high concentrations of CO and H_2, giving rise to the highest concentrations of CH_4.

Figure 3.12 Syngas composition produced from straw pellet gasification where long hydrocarbons were excluded.

Furnace Temperature (°C)	CO (%)	CO_2 (%)	CH_4 (%)	H_2 (%)
750	9.38	69.96	4.34	13.42
800	12.93	61.51	4.30	18.77
850	16.18	57.21	4.01	20.22
900	21.83	50.50	3.95	21.75
950	24.67	49.46	4.66	19.52

Key point Higher temperatures (900-950 °C) resulted in an increased concentration of CO and H_2

To test the potential of biomass gasification and subsequent biological methanation, straw pellets were used in an allothermal gasifier at 750°C, 800°C, 850°C, 900°C, and 950°C furnace temperature to evaluate the syngas composition (Rasmussen and Aryal, 2019 [20]). The test results demonstrated that higher temperatures resulted in an increased concentration of CO and H_2 but that catalyst and bed material agglomerated at a higher temperature (900-950°C) due to intrinsic property of high alkali content of the straw. The same effect was not observed when gasification was done below 900 °C. Based on the composition presented in Figure 3.12, the composition of the syngas, natural gas quality CH_4 can therefore not be obtained by converting the syngas without extra reducing equivalents in the form of H_2.

Realizing the need for adding extra reducing equivalents to the syngas, AU designed a biological reactor system that could convert both syngas and exogenously added H_2. The performed experiments successfully demonstrated that biological trickle-bed reactors could be used for simultaneous syngas conversion and H_2 mediated upgrading to natural gas quality (96% CH_4), as shown in Figure 3.13. A recent scientific paper from other research groups has reported CH_4 production rate (1mmol/l/h) without gas (CH_4, CO_2, CO, and H_2) composition in off-gas hereby, making direct comparison difficult (Asimakopoulous et al., 2019 [14]).

Our results show that conversion of syngas and added H_2 could be catalyzed simultaneously in a single reactor. However, the CO conversion rates were very low compared to the H_2/CO_2 conversion rates. The experiments, therefore, show that further work is needed on optimizing the CO-converting microorganisms, either by finding better-suited inocula than the biogas digestate used or by reconfiguring the reactor operation to promote the CO-converting microorganisms.

Figure 3.13 Syngas biomethanation and syngas upgrading

Details	Syngas (Without H_2 addition)	Syngas (With H_2 addition)
CO (mmol/l/h)	-0.05±0.02	-0.07±0.02
H_2 (mmol/l/h)	-0.37±0.13	Addition
CH_4 (mmol/l/h)	0.04±0.02	0.29±0.02
CH_4 (%)	37%	95±1
CH_4 (mmol/m^3/h)	40±20	300±21

Key point Biological trickle-bed reactors can be used for simultaneous syngas conversion and H_2 mediated upgrading to natural gas quality (96% CH_4)

Conclusion

Development and tests performed during WP1 resulted in the development of systems that could convert CO_2 to CH_4.

Tests of the developed bioelectrochemical systems confirmed that these systems are still at an early technological state. Although the BES still represents a compact technology that combines electrolysis and methanation in one single reactor, the technology is still in its infancy compared to the more mature technologies based on H_2 mediated biogas upgrading (H_2/Biogas), where both chemical and biological methanation technologies are currently under development (Dannesboe et al., 2020 [15]; Electrochaea.dk, 2017 [17]; Jensen et al., 2018 [18]).

The biotechnology developed for the methanation of syngas and its further upgrading to natural gas quality was based on a simple configuration using a single reactor platform. Although the tests demonstrated that the technology could be used for simultaneous methanation and upgrading, it also demonstrated that further development is needed to reach CO conversion rates that is high enough to be industrially relevant. Further development is, therefore, necessary to optimize the biological basis for CO conversion.

Dedicated grids and individual biogas consumers

Torben Kvist, Danish Gas Technology Centre

This section outlines an analysis of the potential for conversion of existing natural gas grids to biogas.

Gas Grid Operation

The gas grid in Denmark and the rest of Europe is based on transport and distribution of methane.

A green gas like biogas consists of around 60 % methane, 40 % CO_2 and different trace elements. Before biogas is injected into the gas network, it has been upgraded in order to meet the gas quality requirements of the gas system. Upgrading is associated with costs, and as a part of the FutureGas project various options for distribution of biogas without upgrading were examined. The presented analysis is based on case where the gas consumption is as it is today. If most households and industrial gas consumers stop using gas in the future, the situation may be different. In that case, the biogas may instead be best used as a raw material for e.g. a central eSMR/GtL plant. Such a situation is not within the scope of this analysis.

Biogas to large individual customers

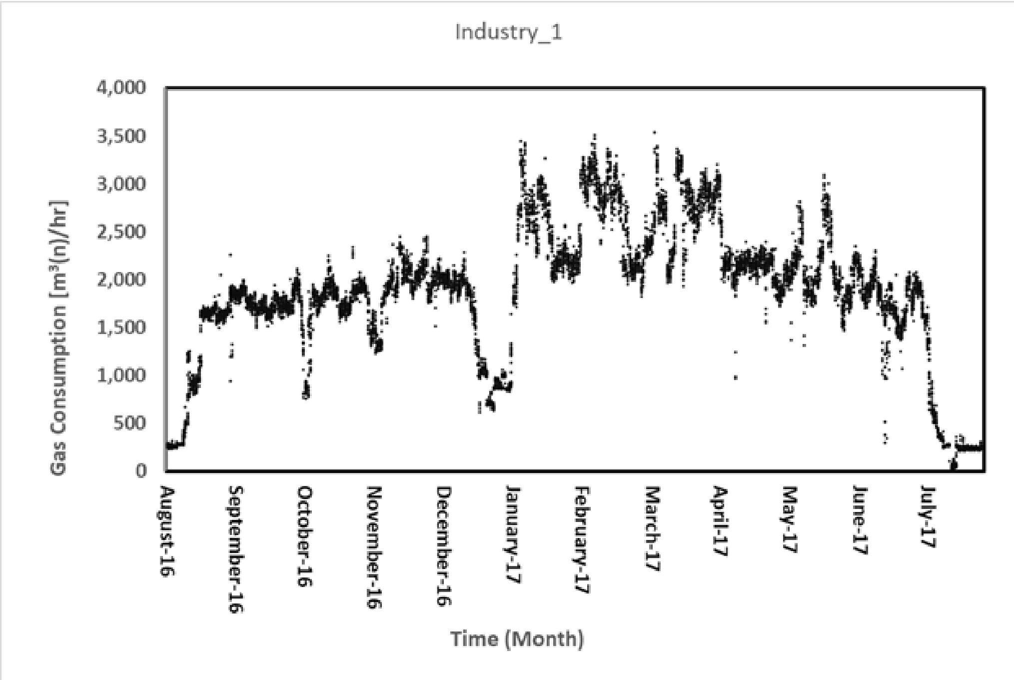
The focus of the scenarios and the modelling is on the Danish energy system.

A feasibility study regarding direct supply of biogas to large-scale industry consumers was conducted. It showed that the potential is very dependent on the consumption profile. Only in a few cases, the consumption profile is steady enough to be compatible with a biogas plant. Here there is a potential for direct sourcing of biogas to the industry, thus avoiding the cost of upgrading biogas to biomethane. An example of a gas consumption profile for an industrial gas costumer is shown in Figure 3.14.

Most of the general industry plants in the analysis do not have consumption patterns which can be combined with direct sourcing of biogas. However, there was identified one case which could be interesting, especially if it is combined with gas storage to better align production with consumption. The food industry plants included in this feasibility study show steady gas consumption throughout the year, which would make a good fit for a biogas plant.

The district heating plants have very fluctuating production patterns and often a gas consumption that is so low, that it makes direct biogas supply difficult.

Figure 3.14 A gas consumption profile for an industrial gas costumer



Key point Gas consumption fluctuates over the year

Conversion of a grid to biogas quality

Around 80 % of the biogas production in Denmark are today upgraded to biomethane for injection into the Danish natural gas grid. The purpose of this study is to clarify whether it could be more attractive from a socioeconomic viewpoint to convert local natural gas grids into biogas grids, thus saving the cost of upgrading biogas.

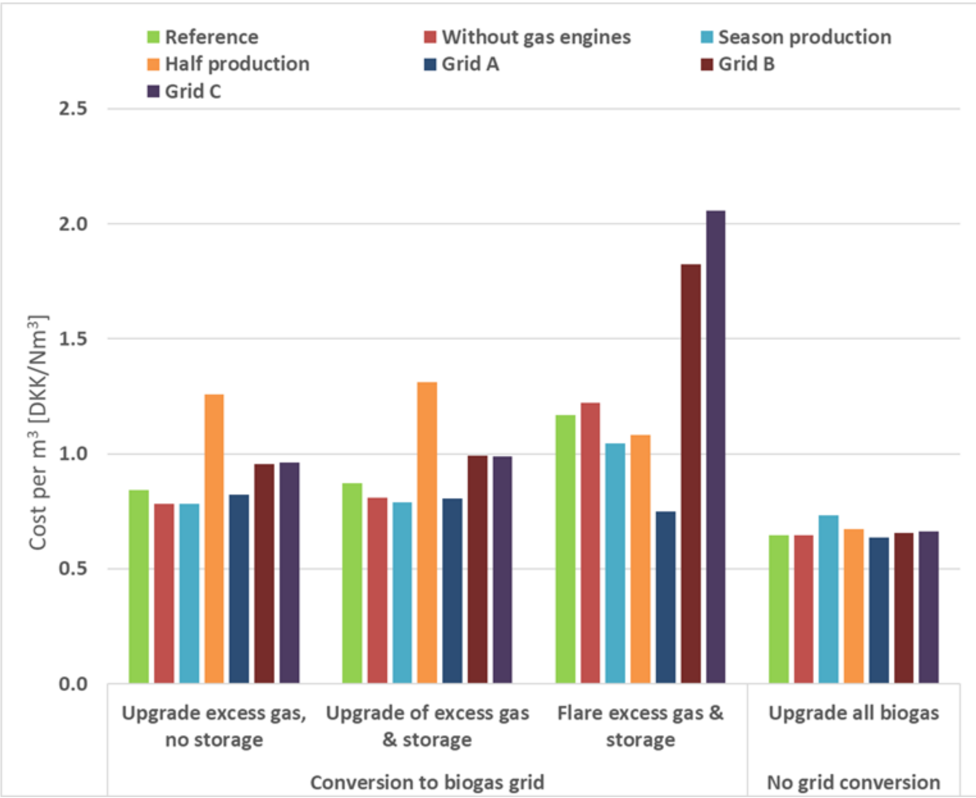
When converting a grid to biogas operation, grid capacity may pose a challenge if the natural gas grid is operated close to the capacity limit. Due to the lower heating value of biogas (~60 % of natural gas), the gas flow will increase accordingly, if the energy demand is kept fixed. Generally, most natural gas grids in Denmark have a high degree of excess capacity due to decreasing gas consumption.

The requirements for converting a section of the natural gas grid into a local biogas grid are:

- Change of Wobbe index classification from natural gas to biogas properties.
- In case of excess produced biogas, the biogas needs to be upgraded, compressed and injected into the 40 bar grid or, alternatively, flared.
- A shortage in biogas supply is supplemented by degraded natural gas (natural gas/air mixture) with properties corresponding to biogas.
- All existing appliances are converted to biogas operation or replaced, if it is not possible or feasible to convert the appliances.

The main conclusion from the feasibility study is that conversion of existing local gas grids from natural gas to biogas is generally not economically attractive as seen in Figure 3.15. The study finds that upgrading all biogas to biomethane for injection into the natural gas grid is the most attractive socioeconomic approach for biogas utilization. Results of the reference case and the variations of the reference case are seen in the figure below. The figure shows that the most economically attractive scenario for all cases is the scenario where all biogas is upgraded to biomethane for distribution in local natural gas grids.

Figure 3.15 Costs related to gas grid conversion for different scenarios



Key point Costs related to gas grid conversion for different scenarios. Grid A to C represent the introduction of other normalized consumption profiles

CH4 emissions

Torben Kvist, Danish Gas Technology Centre

This section outlines the magnitude of methane emissions in the full value chain.

Methane Emissions and Climate Impact

Methane is a strong greenhouse gas and, therefore, the emission of methane from production, distribution and utilization of the gas will affect the climate impact negatively. Originally, methane emissions were not included in the FutureGas project. As methane emissions potentially can jeopardize the positive climate impact of renewable energy, it was decided to arrange a workshop on this subject. This note presents some of highlights from the workshop.

Impact of biomethane production

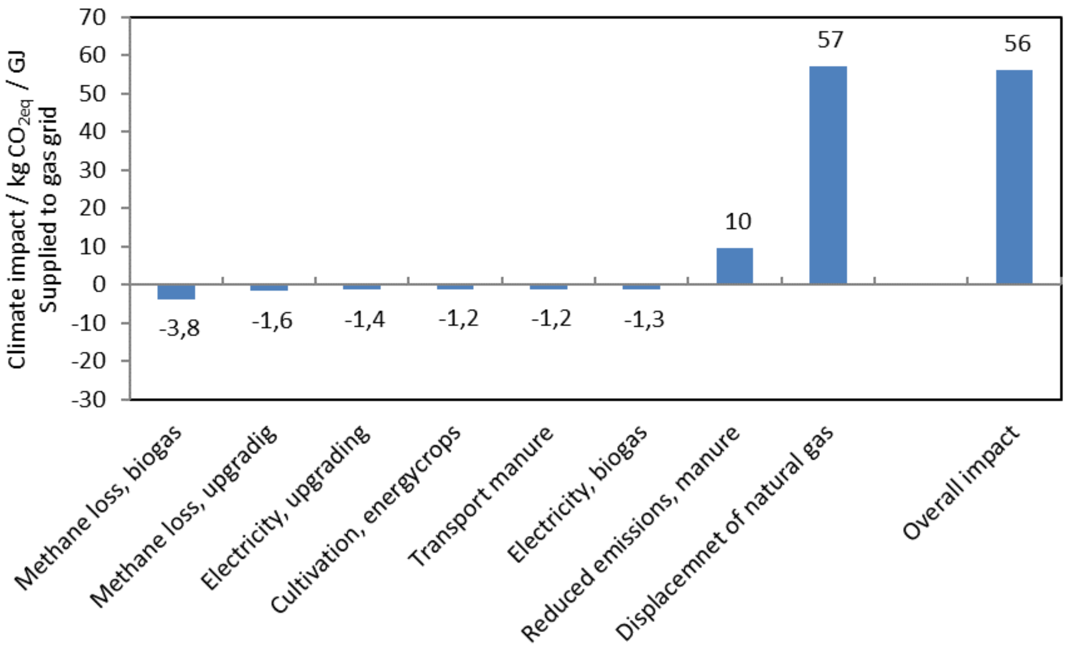
The focus of the scenarios and the modelling is on the Danish energy system.

Biogas plants are designed in different ways and they are supplied with a wide variety of biomasses, which all will affect the overall climate impact of biomethane production. Biomethane production affects the climate impact through e.g. transportation of biomasses as manure, degassing of manure, production of energy crops, usage of process energy, methane losses from biogas production and upgrading as well as the displacement of fossil energy.

The assessment of the different elements mentioned above was based average conditions for farm-based biogas production in Denmark, when it was possible.

Treatment of manure by degassing it in a biogas plant results in lower methane emissions during storage and when spread on farmland. This positive effect levels the negative climate impact from e.g. methane loss and process energy. This means that the overall effect of biomethane is approximately the same as the effect of displacement of fossil natural gas as illustrated in Figure 3.16.

Figure 3.16 Climate impact from biomethane supplied to gas grid



Key point	The overall effect of biomethane is approximately the same as the effect of displacement of fossil natural gas

Impact of methane loss from gas infrastructure

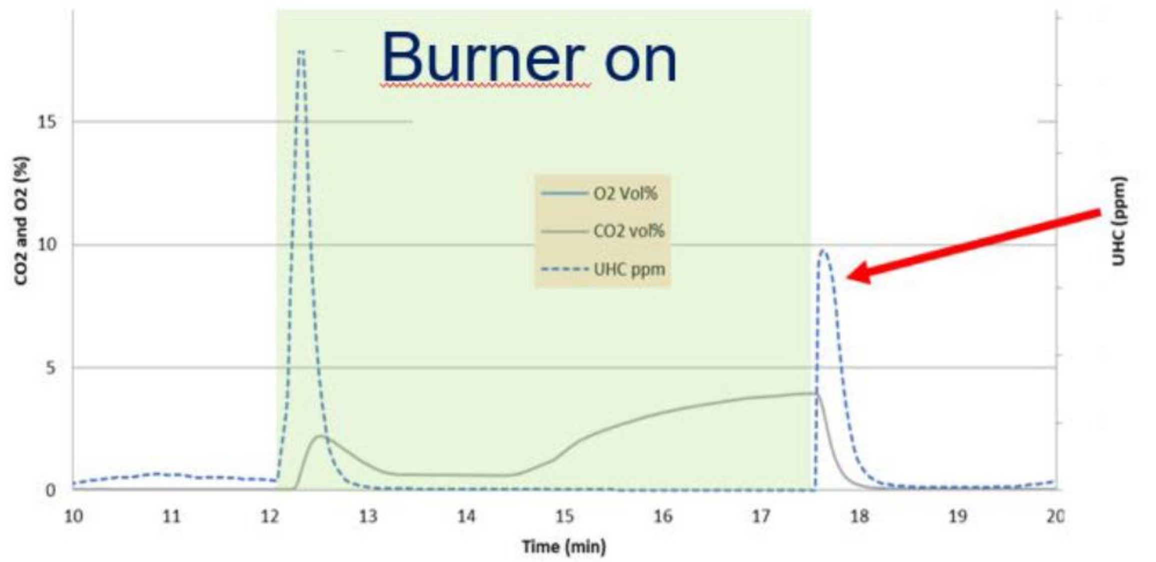
Gas is transported, stored and distributed via a widespread gas network in most of Europe. There are some methane losses from the network, which affect the climate negatively. Marcogaz, which is the technical association of the European natural gas industry, has conducted a survey among its members in order to determine the impact of these losses. They have included gas transmission, compressor stations, gas storage facilities, LNG stations, gas distribution as well as metering and regulator stations.

It was found that total loss of methane from the EU28 gas network is around 515.000 ton per year, which corresponds to 0.18 % of the gas consumption in the EU28. The Danish gas network companies are currently conducting measurements in order to determine methane losses from the Danish gas network. All measurements are not yet conducted and, therefore, it is not possible to conclude anything, yet. However, the conducted measurements indicate that the losses from the Danish gas network are lower than the 0.18 % of the gas consumption that was found for the EU28 [22].

Methane emissions from gas utilization

For most applications of methane as fuel, there are some methane losses. From continuous processes, as in burners, there is normally no losses. However, during start and stop of a burner some fuel will be emitted. This is illustrated in Figure 3.17.

Figure 3.17 Emissions during start and stop of burner



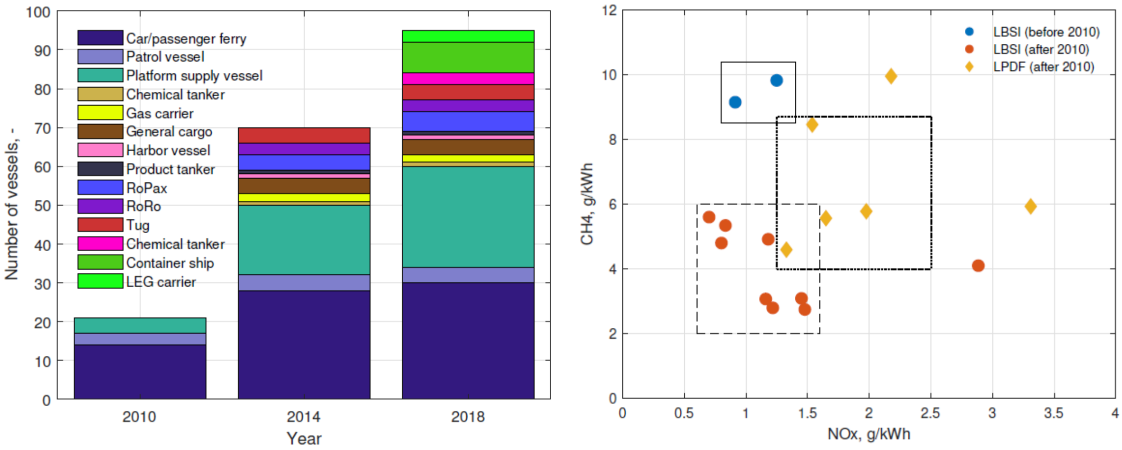
Key point During start and stop of a burner some fuel is emitted

Danish Gas Technology Centre and other labs have tested domestic boilers and found that the methane losses correspond to 0.1-0.3 % of the amount of gas supplied to the boiler depending on the start-stop frequency of the boiler.

Today, gas engines are main contributors to methane emissions from gas utilization in Denmark [23], [24]. However, engines with low emissions are available on the market, and it is possible to treat the flue gas from the larger gas engines in order to eliminate methane emissions.

The use of natural gas for ships is increasing as shown below in Figure 3.18. The different engine types have different emission levels. E.g. LPDF (low-pressure dual-fuel) engines have higher emissions than LBSI (lean-burn spark-ignition) engines. HPDF (high-pressure dual-fuel) engines have basically no methane emission [25].

Figure 3.18 Use of natural gas in ships and CH_4 emissions from different enignes



Key point	LPDF (low-pressure dual-fuel) engines have higher emissions than LBSI (lean-burn spark-ignition) engines. HPDF (high-pressure dual-fuel) engines have basically no methane emission

For further information please refer to [25].

Gas in transport

Erik Ahlgren, Chalmers University

This section outlines a deep dive into the use of gas for transport

Background

Natural gas is being used in the transport sector in different countries in different types of vehicles. Many of the countries where natural gas is used as a vehicle fuel there are national gas resources but there also other examples. Gas is mainly used for personal cars and for city buses but use as fuel for heavy duty vehicles and for marine transport is gaining increased interest. In Sweden, there is a large fleet of personal cars and buses running on biogas.

In a transition to a carbon neutral transport sector in Denmark, the use of natural gas and/or biogas might offer opportunities for a smart and cost-efficient transport sector transition, natural gas in the short term and biogas in the long term.

Aim

Thus, it was the aim of WP3, Gas in transport, to review the global use of gas in transport, to assess the potential and impacts of natural gas vehicles and supply infrastructures well-to-wheel for Danish conditions, and to model the cost-efficient long-term development of the Danish transport sector in order to find out if there could be a role for gas in transport.

Method

The work in WP3 was divided into three tasks corresponding to the three objectives of the work package. Different methods were applied in these three tasks.

First, in order to meet the first objective, the literature, scientific and grey, was reviewed. The review was divided into vehicle technologies, infrastructure and policy.

To meet the second objective, a well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures with Danish perspectives was carried out. Options and potentials of natural gas and renewable natural gas supply pathways and natural gas vehicles (NGVs) were identified, selected and evaluated with regard to well-to-wheel energy usage, greenhouse gas (GHG) emissions, and local emissions. This was done for specific Danish conditions. The vehicles included in the evaluation were passenger cars, light-duty vehicles (LDVs), and heavy-duty vehicles (HDVs) for road-transport applications, and a short-range passenger vessel for maritime transport applications.

To meet the third objective, cost-optimisation modelling was used. This was the major task of the work package. For this a bottom-up optimisation model already developed at DTU, TIMES-DK, was used as starting point and to that model, data and features of the transport sector in general and gas in transport in particular were added. The model was further developed to represent emerging transport technologies in road- and non-road transport applications, disaggregated transport technologies and service demands segmentation to capture some consumers preferences and heterogeneity, and to endogenize fuel infrastructures. The model applied in the project is covering the entire energy system of Denmark.

Model details

Vehicle technologies in the model: conventional vehicles and emerging transport technology vehicles, such as gas and hybrid, plug-in hybrid, battery electric and fuel cell vehicles, and also electric road vehicles. A detailed vehicle segmentation is also applied. Passenger cars are classified based on engine size (small, medium, and large). Driving patterns in all vehicle segments are classified as short, medium, and long-distance driving to mimic city, mixed, and highway driving conditions, respectively.

In maritime transport applications, fuel consumption is linked with the vessel size, cruising speed, and trip distance. Thus, engine capacity (kW), fuel economy (MJ/km), and trip distance (km) were main inputs in the model. For passenger vessels, based on existing routes, the service demands were segmented into four classes; less than 10 km, 10–20 km, 20–50 km, and greater than 50 km crossing distance. For freight shipping, vessel segmentation was done based on the type of cargo, vessel size, and cruising speed. Based on the existing fleet, five cargo types were included and the vessel sizes for each cargo type divided into three classes.

Additional major assumptions were:

- The assumed maximum biofuel blend is 10% in the existing passenger cars, 50% in new cars in between 2020 and 2030, and 100% afterwards.
- For both road and maritime transport applications, three commercially available gas engine technologies were modelled: port injection spark ignition (PISI) (100% gas), port injection dual fuel (PIDF) (max 60% gas in road transportation and 95% in maritime transportation) and high-pressure direct injection (HPDI) (fixed 95% gas) gas engine vehicles.
- In addition to CO_2 emissions, methane slip in gas vehicles is tracked. The SOX emission in marine transportation is tracked indirectly by assuming that all vessels will comply to International Maritime Organisation (IMO) regulations either by using low sulphur fuel (0.1% sulphur content) or by investment in sulphur scrubbers.
- In the model, for a realistic technology mix development and to account for consumer preferences, vehicle heterogeneity (small, medium, and large) is modelled exogenously using user constraints (kept at its corresponding historic shares with an assumed relaxation factor of 15–20%).
- Due to various driving styles and frequent start-and-stop in city driving, fuel economies were assumed to vary (highway driving was assumed to be 16–19% more efficient and city driving 20–30% less efficient than mixed driving).

The added investment costs of CNG/gasoline cars and CNG/gasoline vans were assumed to be 8% as the central cost assumption and 4–12% added investment costs were explored as sensitivity cases. For

PISI, PIDF, and high-pressure direct injection gas engine trucks and busses, the added investment costs are assumed to be 10%, 5%, and 15%, respectively.

Fuel and transport infrastructures are modelled endogenously, except for bunker fuels in maritime transport. CNG/LNG filling stations, electric charging stations, and hydrogen filling stations are included in the model. Technology availability, economic feasibility, and current trends in Denmark were the basis for the fuel infrastructures model representation. The hydrogen fuel infrastructure was assumed to be an onsite electrolysis-based production, storage, and filling. The annual capacity factors for these filling stations was assumed to grow gently from 50% in 2020 to 75% by 2050 to capture the lower number of vehicles per filling/charging station at the early development stage and possible future developments.

E-road, underneath conductive charging, was considered suitable for all vehicle segments, assumed available for investment after 2030, and modelled as an energy commodity where all vehicles driving on it would virtually consume it as an auxiliary input.

The model runs optimise the societal surplus in between 2010 and 2050. They were based on the project scenarios *Marathon* and *Late Sprint*, applied the FutureGas transport technical alternative scenarios and also other assumptions.

First, a more general modelling was carried out, addressing cost-efficient transport solutions under different types of assumptions. Then, a more gas specific modelling was done, targeting rather how gas in transport could be introduced also given a rapid development of electric mobility.

The model results were based on an optimisation of the entire energy sector including the transport sector but the analysis has focussed on the transport sector results taking into account that an understanding of the stationary energy sector dynamics is essential for fully interpreting the transport sector results due to competition for resources, primarily solid biomass and electricity. There was strong co-operation with the project´s WP4 through model soft-linking (data exchange) between the WP3 TIMES model and the model package (Balmorel) used in WP4.

Results

In the first task, the gas in transport review, we could conclude that there is much more widespread use of gas in transport globally than is usually well-known. Much of this gas is used in personal cars. The development has happened at national levels and to various extent been supported by national policies. There is not an extensive coverage of this in the scientific literature.

The results of the second task, the identification of options and special Danish conditions for the use of gas in transport, showed that, compared to conventional fuels, in both transport applications and for all vehicle classes, the use of compressed and liquefied natural gas has a 15–27% GHG emissions reduction effect per km travel. The effect becomes large, 81–211%, when compressed and liquefied renewable natural gas are used instead. The results are sensitive to the type and source of feedstock used, the type of vehicle engine, assumed methane leakage and methane slip, and the allocated energy and environmental digestate credits, in each pathway. In maritime applications, the use of liquefied natural gas and renewable natural gas instead of low sulphur marine fuels results in a 60–100% SOx and 90–96% PM emissions reduction.

Further, the results (not taking any CO_2 emissions target into account) indicated that owing to the alternate gas distribution mechanisms and filling stations configuration, there are substantial fuel production cost differences between the studied gas pathways. Despite its long-distance shipping and distribution, imported LNG showed significant production cost advantages over compressed natural gas (CNG) and liquefied renewable natural gas (LRNG) pathways. All NGVs were found to be competitive corresponding to gasoline cars, but not compared to diesel cars due to the lower price gap between CNG and diesel. In the heavy-duty vehicle and passenger vessel segments, however, owing to the high price gap between LNG and diesel/marine gas oil (MGO), all NGVs and LNG passenger vessels showed high competitiveness compared to their conventional counterparts.

The results of the third task, the cost-optimisation modelling of gas in transport in Denmark, were many and rather diverging due to strong dependence on different types of modelling assumptions. The results showed that the combined use of liquid biofuels (mainly biomethanol), electricity, and hydrogen and upgraded biogas would deliver cost-effective deep decarbonisation by 2050. However, their various decarbonisation roles vary within and across transport segments. Fuels based on solid biomass (2nd generation biofuels) were cost-effective primarily since 2nd generation biofuels do require only very limited vehicle cost additions and also since the excess heat from the biorefineries (production plants for the 2nd generation biofuels) was assumed to be utilised in district heating, and they were primarily found cost-effective in scenarios with no biomass/biofuel import restriction and not including any climate targets for aviation and the maritime sector. When there is a climate target also on these two transport segments, 2nd generation biofuels will primarily be used in these; showing the importance of correct system boundaries in these types of modelling studies and the role of competition between sectors.

Electrification is important but not the only solution. With a more rapid battery cost decrease, electric mobility will be the dominating future transport energy supply in road transport. With a more rapid decrease of the cost of fuel cells, hydrogen fuel cell vehicles would similarly strongly increase their cost-efficient market shares.

Further, the results show that in between 2020 and 2040, natural gas could cost-efficiently serve as a transition fuel. Decarbonisation pace and fuel infrastructure assumptions were found to have a large impact on the NG adoption levels. Liquefied biogas could play a role for shipping towards the end of the studied time horizon, when much more stringent carbon emission constrains apply.

The results thus showed that there is no entirely robust solution and still large uncertainty about the future most cost-efficient solutions. They also show the importance of carrying out wide sensitivity analysis before drawing any firm conclusions about transport futures at different time scales, and it also shows that policy may play a key role.

The analysis carried out has also led to the identification of a large number of critical model issues, which have been analysed and in turn led to further model modifications and improvement in order to make the model represent the reality better. However, the model is based on pure cost minimisation and thus the results should not be interpreted as any type of forecasting study but rather as a what-if analysis.

Key findings

There are a number of different options towards a future cost-efficient transport sector in Denmark and various combinations of these will lead to the lowest system cost. The option with the lowest system cost depends assumed vehicle and fuel characteristics and rather small assumption differences changes the cost-efficient solutions chosen by the model. Electrification is important but not the only solution, natural gas could play a role as a cost-efficient transition fuel in some transport segments and up-graded biogas were in many scenarios included in the final year cost-efficient fuel mixes both in road transport and in the maritime sector, in the latter case as liquefied biogas.,

For the final FutureGas analyses, costs of vehicles were updated and as a result, more electric vehicles were seen.

Value creation through improved modeling

Stefanie Buchholz and David Pisinger, DTU Management

This section outlines the main results obtained from the advanced mathematical modelling analysis carried out in the FutureGas project (work package 5). The focus is on time aggregation and how this technique can be improved to achieve a more optimal balancing of computational resources against solution quality. A secondary focus is on studying how time aggregation techniques can be used to either obtain optimal solutions faster or to obtain robustness measures for investments.

Decarbonization of the energy system replaces fossil fuels by *variable renewable energies* (VRE) creating the need for efficient modeling of system flexibility. As gas potentially could provide this flexibility, a proper modeling of the model flexibility is crucial in the FutureGas project. Optimal levels of flexible capacities are identified by simultaneously optimizing long-term capacity expansion decisions and short-term operational decisions. The improved energy models therefore not only have to optimize a broader sector-coupled system but also have to consider a sufficiently detailed time resolution. The transformation of such comprehensive energy systems into mathematical optimization models frequently leads to high computational complexities wherefore more efficient solution procedures are needed. This deep dive therefore concerns improved mathematical modeling acting as a support to the FutureGas project by providing a toolbox of methodologies that help regaining tractability of current and future comprehensive energy system models.

An increasingly popular approach to regain tractability is to strategically reduce the time domain. In that sense, time aggregation approaches aim at gaining a significant reduction in problem size with limited decrease in solution quality. The increased shares of VRE challenge the existing aggregation approaches in properly capturing the variability in the supply side. The main outcomes of this deep dive therefore firstly concerns improvements of time aggregation techniques and secondly how the good performance can then be exploited to improve either the optimality or the robustness of the solutions. Highlighted results of the work are summarized in Figure 3.19 while the subsequent sections describes these in more detail.

Figure 3.19 Highlighted results of the improved mathematical modelling deep dive

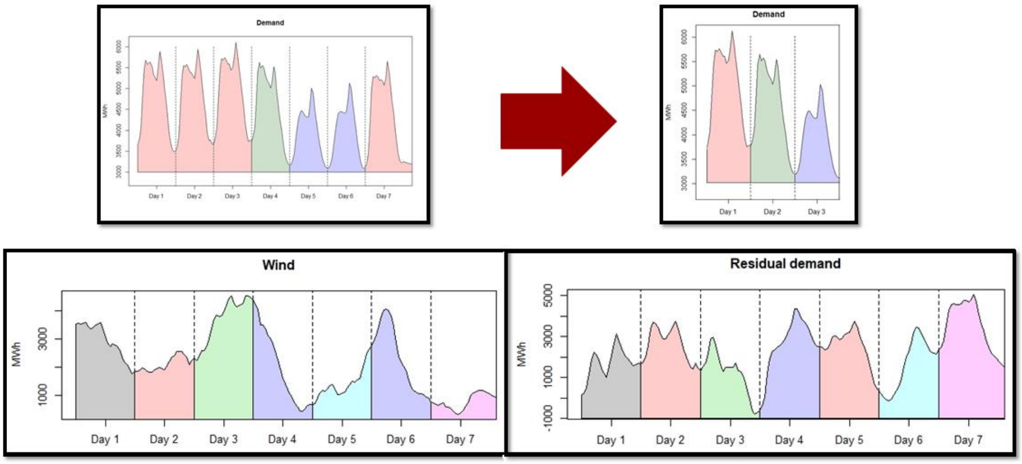
1) Developed several new aggregation techniques relating to multiple configurations of aggregation techniques. Additionally, implemented and studied many aggregation techniques from the literature.
2) Suggested methodologies for systematic validation of time aggregation techniques.
3) Provided several comparisons of time aggregation techniques from very different energy system perspectives.
4) Provided new acceleration methods for speeding up the solution procedure of capacity expansion energy systems models which potentially reduce solution times of up to 92%
5) Introduced a new framework that makes it possible to find a portfolio of very diverse solutions to energy investment models. Additionally, it accounts for errors introduced by simplifications and measures the robustness in investment decisions.

Key point This deep dive contributes with new and improved methods to efficiently solve the new paradigm of energy system models.

Time aggregation

Time aggregation is the approach of constructing or selecting representative time elements from a larger time horizon, so that the reduced selection replicates essential features of the non-aggregated time series. This approach has been succesfully applied to systems with low levels of VRE since the demand patterns historically have been quite predictable. However, with the VRE getting increasing dominance in the energy systems, the aggregation techniques based on predictable pattern recognition are highly challenged, see Figure 3.20 for an illustration.

Figure 3.20 Aggregation according to predictable pattern recognition

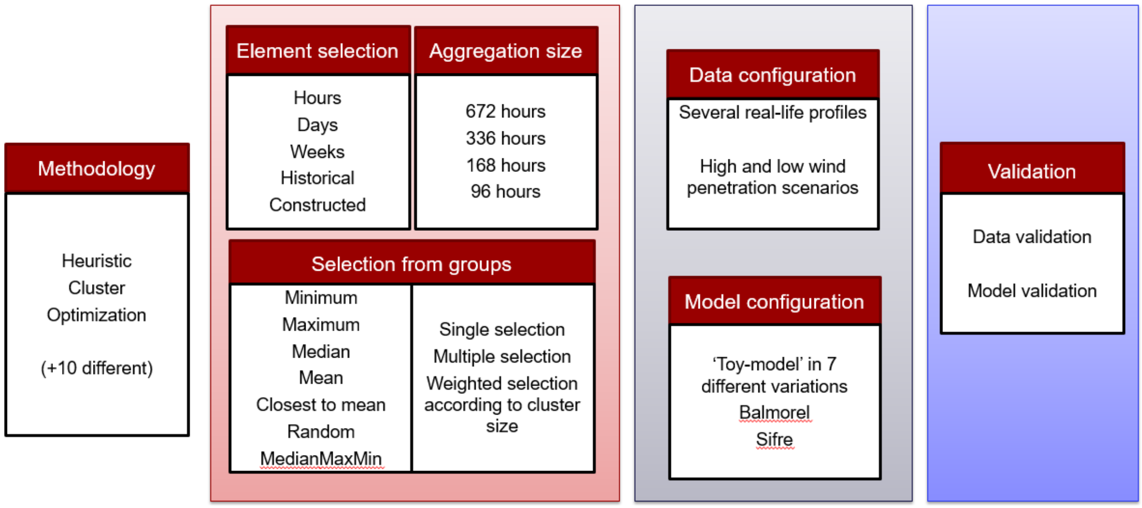


Key point: Demand patterns have been fairly predictable causing aggregation techniques to have high performance. With increasing shares of VRE the profiles become unpredictable which challenges the existing aggregation techniques.

The focus has therefore been on developing new aggregation techniques, that capture the increased level of variability in the supply side more efficiently. For this purpose, also methodologies to strategically validate and compare different time aggregation techniques within a broad spectrum of possible energy system challenges have been developed. Through various case studies not only the value of the time aggregation tool to the current and future energy system models have been illustrated, but the work also identified a series of key properties of aggregation techniques constituting a foundation for the further development of aggregation techniques. The newly developed aggregation techniques are based on methodologies spanning from simple rule based heuristics to novel optimization approaches.

The main outcomes of the work cover a *comprehensive literature review of time aggregation techniques, the development of new methods, suggestion of a systematic validation methodology and stress testing the performances with respect to different sensitivities*. The twofold purpose of the latter was firstly to study the performance consistency of the single aggregations for different problems, and secondly to analyze the ability of the aggregations to replicate different problem aspects. The aggregation techniques are applied to real life energy systems which both validates the results and further illustrates the advantages and disadvantages of the aggregation techniques. A detailed overview of what the analysis have covered is seen in Figure 3.21 while Figure 3.22 list the main conclusions from the analysis.

Figure 3.21 Aggregation technique configuration and problem settings that the analysis cover



Key point: The many different problem settings make sure that the developed aggregation techniques perform well independently of what problem setting they are applied to. Additionally they enable the identification of general challenges for aggregation. The many different configurations of the techniques enable the identification of key properties of aggregation techniques, which are valuable to develop new techniques.

As stated in Figure 8.3, the results have not only been applied in the analysis of the FutureGas project but are also implemented to be used on a daily basis in the analysis in Energinet. The work is covered in 4 papers which act as a foundation to various future research paths.

Figure 3.22 Main conclusions from the time aggregation analysis

1) Good performance is observed for both very simple aggregation techniques as well as for complex techniques. Promising performance is seen for;
   a. Aggregations arising from a categorization of all non-aggregated data such as a clustering where random elements are selected from clusters.
   b. The aggregated time series consists of days selected from the non-aggregated space.
   c. The aggregation preserves around 8% of the non-aggregated data. In general, the more data being preserved in the aggregated problem the better the performance, however also the higher the solution times.
2) Due to a poor validation methodology in the literature the term *Model Validation* is introduced as a systematic way of validating aggregation techniques using similarities between aggregated problem and non-aggregated problem solutions. The otherwise used *data validation* in the literature is shown to lead to aggregated model solutions that poorly replicate the non-aggregated model solutions.

3) Aggregated model performance seems to suffer from uncertainty in the wind penetration profiles. In that sense, it has high impact if aggregation is made on assumptions of wind availabilities, which may not be correct.
4) For each aggregation technique, the most challenging models to replicate are those including seasonal storage since electricity storage investments are generally underestimated, with the degree of error being related to the aggressiveness of the aggregation. In more general terms, investment decisions are sensitive to aggregation with a tendency of favouring wind turbine investments.
5) Aggregation might have the drawback of distorting the distribution of market price levels but fuel use shows to be fairly robust to aggregation.
6) The choice of aggregation techniques has high impact for problems including a Value of Lost Loads feature.
7) Aggregation techniques may be overfitted to specific energy systems.
8) A new, multi-element selection strategy is suggested where both median, maximum and minimum elements are selected from each cluster.
9) Development of a new weighting approach that constructs fewer clusters and then selects more elements from each cluster so that the amount of selected elements represents the relative importance of each cluster in the non-aggregated data. This showed to have very good performance.
10) This work is the first to quantify the quality of strategically aggregated Balmorel and Sifre models. The results are used both to make analysis in the FutureGas project and in the daily analysis in Energinet.

Key point	Good performing aggregation techniques have been identified along with general challenges for the aggregation methodologies. Apart from the already implemented work in both Balmorel and Sifre, the results also lead to various future research paths

Improving the solution quality

Despite the high quality of the aggregated solutions, many tests did turn out sub-optimal. This work therefore exploits the fast found aggregated problem solutions to speed up the solution procedure of the corresponding non-aggregated problems while getting closer to optimality. For this purpose, three new acceleration methods have been developed which builds on the aggregated problem solution in different ways. Generally, they search the neighborhood around the investment decisions obtained from an aggregated problem with the goal of closing the optimality gap. This approach therefore act as a quality guarantee that may account for what the aggregated problem is not capable of capturing.

Shrink-and-Expand: *solves the aggregated problem to optimality, scales up the solution and uses it to warm-start the solution procedure of the non-aggregated problem.*

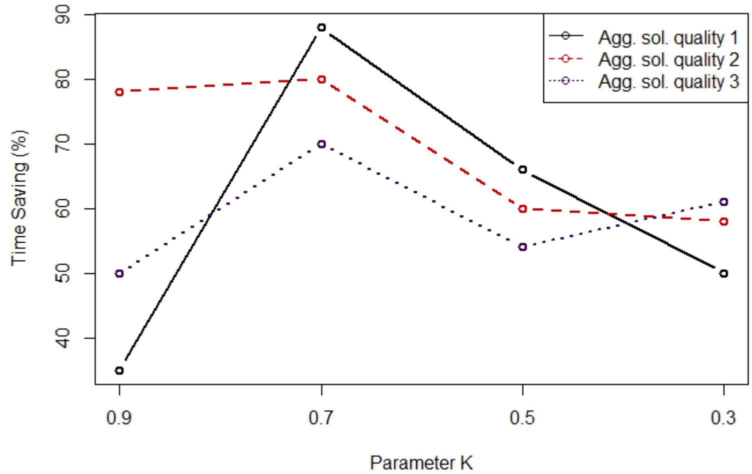
Proximity Heuristic: *uses the investment decisions of the aggregated problem to limit the non-aggregated solution space. Initially it solves the aggregated problem to optimality and then imposes a proximity constraint on the investment variables, saying that they can not deviate too much from the aggregated solution. The non-aggregated problem is then solved to optimality with the proximity constraint imposed. The analysis covers 8 different configurations of this algorithm, which deviate in how the proximity constraint is defined, in the size of the proximity area and in the way technologies are limited.*

Radius search Heuristic: *combines the shrink-and-expand and proximity heuristic approaches by searching the neighborhood around the aggregated solution with the aggregated solution also acting as a warm-start for the search. The aim is for the algorithm to start the exploration in the center of a promising area, and for the proximity constraint to limit the search to this neighborhood.*

The shrink-and-expand is categorized as an exact approach, while both the proximity heuristic and the radius-search-heuristic are classified as math-heuristics, meaning that they do not guarantee optimality. The approaches are tested on a small energy system model and through these experiments, advantages and disadvantages of the suggested algorithms are quantified.

The main conclusions are that the proximity heuristic has the potential of significantly reducing the solution times while obtaining high quality solutions. Depending on the algorithm configuration, up to 10 times faster solution times are observed. Figure 3.23 shows some of the speed-ups obtained by using the proximity heuristic to solve a small energy system model. The parameter *k* indicates different limiting degrees of the proximity constraint with a higher *k* representing a more restricted solution space. The different lines in the graph correspond to different aggregation strategies applied to obtain aggregated solutions, which then differ in solution quality. Generally it is seen that the obtained speed-up is higher, the better the aggregated solution replicates the investment decisions of the non-aggregated solution. Also, the highest speed-up is obtained for a high, but not the highest limiting parameter caused by the most restricting parameter forcing the optimal solution to be excluded from the restricted solution space.

Figure 3.23 Potential of the Proximity heuristic



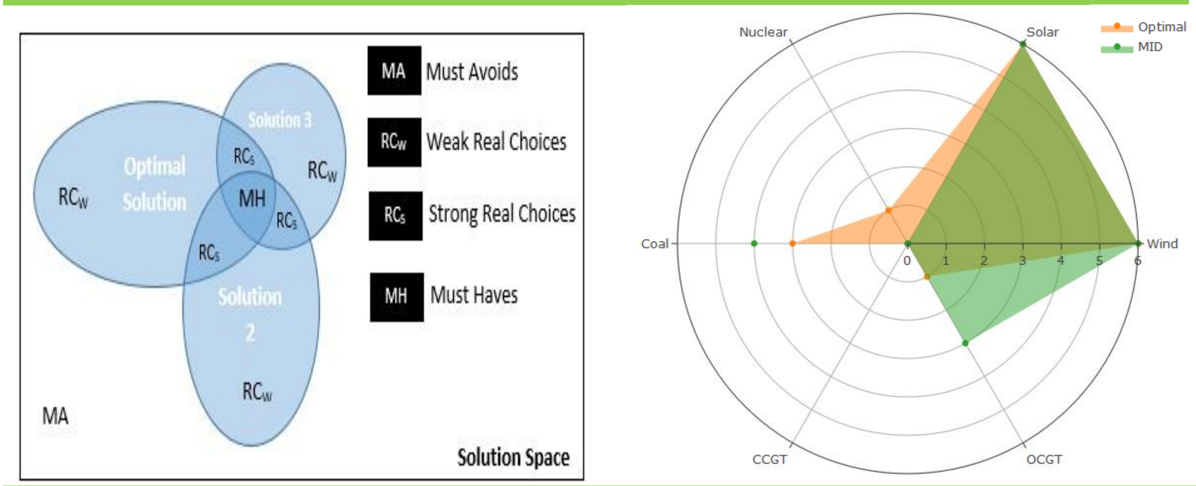
Key point: Highest speed-up is achieved when aggregated solutions of higher quality are used in the heuristic. An optimal, non-aggregated solution can be found 90% faster.

The potential of the shrink-and-expand is overshadowed by a significant amount of runs failing to find a solution within the given time-frame. Since failed runs also appear in the radius search heuristic for some configurations, the warm-starting technique is seen as the challenging factor. Nevertheless, if high quality aggregated solutions are used in the radius search heuristic, the reduction in solution time is increased to a factor of 12. The main conclusion is therefore that, with the heuristic approaches, optimal solutions can be found much faster, but one may only hope to get closer to optimality as no guarantee for optimality is given.

Robustness measures through near optimal aggregated solutions

Energy system models are frequently simplifications of real world systems wherefore the one optimal solution likely is an approximated solution. Therefore, this work alternatively exploits the speed-up effects of aggregation techniques to find multiple solutions. The idea is to iteratively find new solutions, which are as different as possible from earlier solutions with respect to investment decisions. A set of near optimal approximated solutions might be as good as the optimal one, wherefore a set of very diverse solutions would give decision makers a much better understanding of the problem and an indication of the robustness of the results. For this purpose, a *Portfolio of Maximized Diversity Solutions* (PoMDS) algorithm is developed that explores the near optimal solution space such that the diversity in investment strategies is maximized. The algorithm initially finds the least-cost optimal solution *x* to the aggregated problem and the near optimal solution space then consists of all solutions which are at maximum *z*% more expensive than *x*. The second iteration then finds the solution in the neighborhood that is the most different to *x* with respect to invested capacities. The algorithm continuously finding new solutions in the neighborhood, which are as different to the previous found solution as possible. To visualize the theoretical idea, assume a solution space consist of one optimal solution and two near optimal solutions as seen in Figure 3.24 (left). Each solution has a set of investments and if an investment is activated in all solutions, despite the objective of maximizing the difference in investment decisions, this investment must be highly important to the feasibility of the system and hence a very robust decisions. Such an investment is referred to as a *must have*. Opposite, if investments are not made in any of the solutions it is referred to as a *must avoids*. In between the two extremes we have the *real choices* which have different degrees of strength dependent on the number of solutions they appear in.

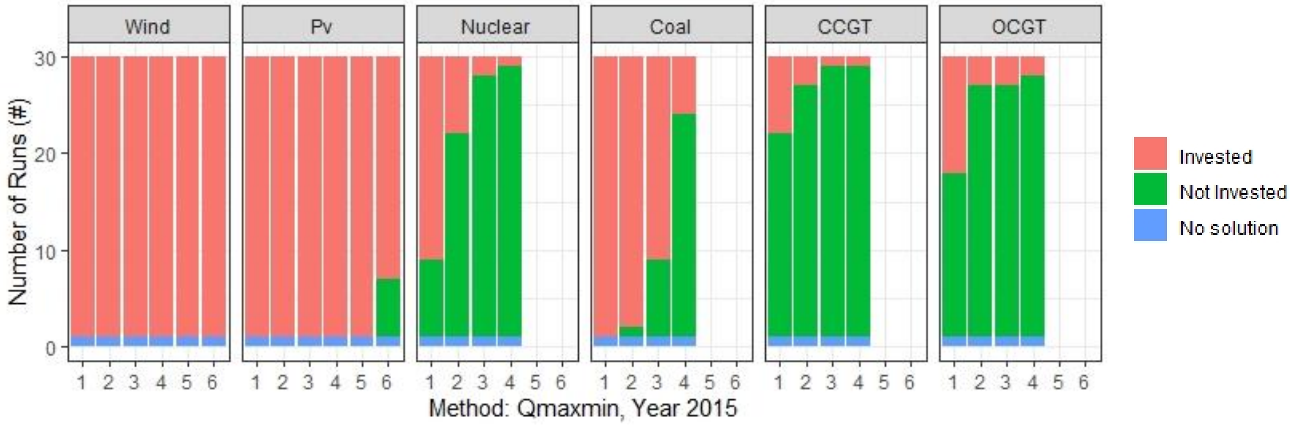
Figure 3.24 Valuable information gained from the set of sear optimal solutions



Key point: Valuable information is gained by looking into near optimal solutions. First, indications of the robustness of the investment decisions. Secondly how sensitive the results generally are to the system assumptions and thirdly indications of potential needs for regulation.

Transforming this into experimental results, Figure 3.25 shows an example where each unit of each technology type is represented by a color indicating whether it is invested, not invested or if no solution was found in the respective run. From this case study, most renewable units are *must haves* except for one which is a *strong real choice*. Also, the majority of the coal units show high importance to the system.

Figure 3.25 Robustness indication of individual investment decisions



Key point: With the suggested near optimal solution framework one can obtain robustness measures for the individual investment devisions. As an example, an investment made in each alternative solution, despite an attempt to maximize the diversity in investments, must indicate that the respective investment is highly important to the system and hence a very robust decision.

The PoMDS differs from approaches in the literature since it maximizes the difference in investment decisions among alternative solutions instead of just finding the *k* most similar solutions. A valuable information is how much system configurations can differ, within an acceptance span of the optimal system costs. This information is achieved already in the second iteration of the PoMDS approach. Experimental results show that while the PoMDS algorithm spends 5-14 min on finding an investment strategy being 40% different from the optimal one, the so far best known *Near Optimal Solution* (NOS) algorithm from the literature is not able to find a solution that is as different within 48 hours. An example from the case study illustrates the information contained in such a solution, see Figure 3.24 (right). With an assumption of 0.5% uncertainty in the solution costs it is seen that nuclear investments may be exchanged by increased capacities of coal and gas units. Such analysis therefore not only shows how sensitive the results are to the system assumptions but it may also indicate potential needs for regulation.

Lastly, it was possible for the PoMDS algorithm to find eight solutions within the same time as a single run of the corresponding non-aggregated problem. Despite the eight solutions belonging to the aggregated solution space, the results show that the PoMDS approach illuminated errors introduced by aggregation through the multiple solutions, which further adds to the benefits of the suggested framework making it useful both for improving time aggregation and for illustrating uncertainties in results.

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