ENERGINET
Elsystemansvar

SYSTEM PERSPECTIVES FOR THE 70% TARGET AND LARGE-SCALE OFFSHORE WIND

System perspective analysis for achieving the 70% CO_2 reduction target by 2030 and enabling long-term large-scale utilisation of the Danish offshore wind potential

March 2020

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Introduction

The Danish government has passed a climate law aimed at cutting Denmark’s greenhouse gas emissions by 70% by 2030 compared to 1990. The reduction target generally has broad backing from the Danish parliament and the energy sector. In addition, the Danish government’s paper of understanding from summer 2019 states that it will “*explore the possibilities of Denmark building the first energy island to be connected to at least 10 GW (wind turbines) by 2030*”.

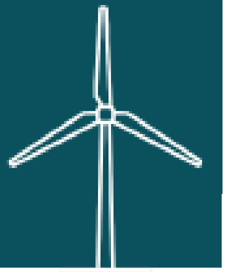
The purpose of this analysis is to contribute perspectives and insight into how the energy system can support the 70% reduction target by 2030. In addition, the analysis examines how the energy system can promote climate neutrality and effective integration and utilisation of Danish large-scale offshore wind in the longer term, where the 70% reduction target is a natural milestone on this path.

The analysis outlines a number of examples of possible long-term development paths for the energy system and is an important contribution to Energinet Elsystemansvar’s (Electricity System Operator) planning and development of the electricity system. The analysis focuses on infrastructure and system solutions which support cost-effective utilisation of the Danish wind energy potential – especially in the North Sea – and ultimately a climate-neutral energy system.

The analysis is organised in three parts:

- a focus analysis with examples of potential development paths for a Danish energy system capable of meeting the 70% reduction target by 2030 (part 1)
- a long-term system analysis describing the perspectives of large-scale offshore wind utilisation in 2035 (part 2)
- a summary of selected development areas for Energinet Electricity System Operator in relation to the 70% reduction target, large-scale offshore wind utilisation and the long-term planning and development of the electricity system (part 3).

The analysis is based on Energinet’s previous analyses *System Perspective 2035* (link), *PtX in Denmark before 2030* (link) and *R&I roadmap* (link), and the analysis should therefore be read in the context of these reports.



SUMMARY (1/2)

In light of the Danish climate law which aims to cut greenhouse gas emissions by 70% by 2030 and create a climate-neutral society, the purpose of this analysis is to contribute possible perspectives and insight into how the energy sector can support the 70% reduction target towards 2030. In addition, the analysis provides examples of potential development paths for how the energy sector can achieve climate neutrality in the long term by incorporating and utilising large-scale offshore wind, where the 70% reduction target is a natural milestone on this path. Based on the conclusions of the analysis, the report concludes with a non-exhaustive list of development areas selected by Energinet Electricity System Operator in order to contribute to the efficient planning and development of the electricity system. The analysis is organised into three parts:

- A focus analysis of potential development paths for a Danish energy system capable of meeting the 70% reduction target by 2030 (**part 1**)
- A long-term system analysis describing the perspectives of large-scale offshore wind utilisation in 2035 (**part 2**)
- A summary of selected development areas for Energinet Electricity System Operator relating to the 70% reduction target, large-scale offshore wind utilisation and the long-term planning and development of the electricity system (**part 3**).

Part 1 of the analysis sets out examples of how to achieve the 70% reduction target by 2030. The reduction target comprises Denmark's total greenhouse gas emissions, but there is no exact target for emissions in the individual sectors, including the energy sector. In this analysis, energy sector emissions are defined as all national energy-related emissions, including emissions from domestic transport, but excluding international aviation and shipping. A number of assumptions are made about reductions in sectors other than the energy sector, which present outcomes as a potential example of the sectors' emissions towards 2030. Based on these assumptions of reductions in sectors (which is one example among many potential scenarios) other than the energy sector, energy sector emissions must be reduced to 10-12.5 million tonnes of CO_2 per year by 2030 compared with approx. 31 million tonnes of CO_2 per year today (2019). The examples of reduction scenarios (10-12.5 million tonnes of CO_2) on which part 1 is based have been assessed on the basis of the cost of several reduction measures within direct and indirect electrification.

Achieving the 70% reduction target will significantly increase electricity consumption due to the enhanced direct electrification of heating, transport and industry. However, this direct electrification is not in itself sufficient to reach the 2030 target. Further reductions may be achieved through a combination of measures where RE electricity is used for fuel production (PtX) and/or measures involving carbon capture and storage (CCS).

The growth in electricity consumption relative to the analysis assumptions is subject to considerable uncertainty. This largely depends on the extent to which other measures such as energy savings, CCS, green fuel imports and initiatives outside the energy sector can successfully cut CO_2 emissions. Additionally, annual domestic electricity consumption and electricity generation will not necessarily match in 2030 – for example if there are net imports of electricity. As a result, the analysis presents broad outcomes for electricity consumption and generation. In the scenario with the highest direct and indirect electrification, electricity consumption will increase by up to 20 TWh. If this consumption is to be met by a corresponding build-out of production, more wind and solar will be needed. The analysis describes examples of build-out scenarios for wind and solar with up to 3 GW of additional offshore wind and an increased solar build-out of approx. 5 GW.

This development will put pressure on the electricity system to transport and balance electricity generation and consumption. Measures in the holistic energy system are important in order to ensure an optimal utilisation of the electricity system. This forms the basis for part 2, which looks towards 2035 and beyond.

Direct and indirect electrification as reduction measures
Reduction measures involving direct electrification of some parts of industrial process heat systems, replacement of oil-fired boilers with heat pumps and the introduction of heat pumps in district heating systems typically have a CO_2 shadow price of less than EUR 70 per tonne. Measures such as the replacement of large numbers of individual gas boilers with individual heat pumps, electrification of light transport (electric vehicles) and some areas of heavy transport typically have a CO_2 shadow price of approx. EUR 40-200 per tonne. For these measures, it is significant whether a natural transition is possible or if a forced transition is implemented.

Reduction measures involving indirect electrification (RE gases/RE fuels, including PtX) generally have a CO_2 shadow price of approx. EUR 200-400 per tonne, making them more expensive towards 2030. However, at EUR 1-1.2 per litre of petrol equivalent (compared to EUR 0.4-0.5 per litre of fossil petrol), excluding taxes and distribution costs, the international market price of green fuels (such as green methanol) is very high. Among other things, the high price of green fuels can be attributed to blending requirements and a growing premium market, which pays for the RE value. This means that the production and export of green fuels is commercially viable, even though they will be more expensive than the fossil reference in 2030. In addition, PtX enables flexible electricity consumption which may be used as a hedge against low electricity prices in connection with wind power investments towards 2030.

As far as the 2030 reduction target is concerned, PtX is an expensive measure, and there will be considerable uncertainty about the extent to which RE fuels can replace the fossil fuels included in the reduction target. For example, fuels used in international aviation and shipping are not included. The perspectives for PtX should therefore largely be seen in the context of the role that the technology may fulfil in the long term (beyond 2030) when it comes to harnessing Denmark's vast offshore wind resources. These perspectives are explored in part 2 of this report.

Part 2 of the analysis explores perspectives for large-scale offshore wind assessed in a number of scenarios with a time frame up to 2035 (and subsequent climate neutrality). As shown in part 1, the direct electrification of heating, transport and industrial process heat is vital to achieving reductions towards 2030.

SUMMARY (2/2)

Indirect electrification, including PtX, is of minor but nonetheless relevant importance towards 2030, while in the post-2030 scenarios it will be of particular importance to both reductions and the efficient utilisation of large-scale offshore wind. The efforts required to achieve the 70% reduction target, should PtX be used, thus have a significant development value in relation to the efficient use of the Danish offshore wind resources in the long term. Consequently, the 70% reduction target (part 1) is important to the perspectives of efficient sector coupling as well as the integration and utilisation of the Danish offshore wind potential (part 2). Part 2 of the analysis includes the following main conclusions:

- Sector coupling enables affordable large-scale energy storage.
- Flexibility and grid reserves may increase the electricity grid's utilisation rate.
- Sector coupling in clusters ensures synergy effects.
- Carbon may become a scarce resource and requires strategic considerations.
- Large-scale offshore wind requires sector coupling and new infrastructure concepts.
- Substantial CO_2 reductions can be realised with advanced sector coupling.

2035 system perspectives towards a climate-neutral energy sector

Towards 2030, PtX may be significant to achieving the 70% reduction target, and especially beyond 2030 it is expected to become a highly effective tool on the path to climate neutrality.

Part 2 includes a number of 2035 scenarios which analyse the addition of an additional 10 GW of wind power in the North Sea and 3 GW in the Kattegat and the Baltic Sea in relation to a reference build-out. In this context, the combination of the reduction target and large-scale utilisation of Danish offshore wind is examined. In order to effectively integrate and utilise large-scale offshore wind, several solutions are analysed in relation to CO_2 impact, economy and system robustness. The solutions consist of combinations of measures such as electricity infrastructure (HVAC and HVDC), PtX systems, hydrogen infrastructure and hydrogen storage, electricity storage and operating principles for the electricity grid.

Effective utilisation of 10 GW of additional offshore wind requires robust PtX upscaling towards 2035, and the analysis examines suitable locations for PtX assessed in relation to for example the electricity grid, access to CO_2, access to storages and the ability to utilise surplus heat. It is assessed that such a massive build-out of offshore wind may require up to 5-8 GW of electrolysis in Denmark around 2035.

Without the above-mentioned initiatives, only a relatively small amount of the additional 10 GW of offshore wind can be brought ashore and used effectively in Denmark, whereas a combination of the initiatives ensures the most optimum use and balance between CO_2 impact, economy and robustness. A tighter coupling of the market and the physical electricity system (for example with bidding zones and demand-side response as a grid reserve) as well as hydrogen transmission and storage are the most powerful means of boosting the value of additional offshore wind and maximising the CO_2 impact. The inclusion of hydrogen makes it possible to build a considerable and relatively inexpensive energy storage, which allows the electricity system to reduce electricity consumption for electrolysis via the market, while at the same time using hydrogen storage to supply the PtX industry with hydrogen.

Part 3 of the analysis provides a non-exhaustive overview of selected development areas in order to create the energy system analysed in parts 1 and 2. Most of the development areas are areas, where mainly Energinet Electricity System Operator plays a key role. Furthermore, part 3 highlights a selection of areas relating to other Energinet activities.

Development activities – from vision to reality

CO_2 emissions can be reduced significantly towards 2030 and beyond in combination with a massive build-out of offshore wind (10 GW), but doing so and ensuring a strong CO_2 impact, economy and system robustness requires a number of development activities.

For the **electricity system** a tighter coupling of the market and the physical system is imperative. The ability to better utilise demand-side response – both geographically and as a grid reserve – will affect whether offshore wind power can be transported efficiently. Demand-side measures applied in this way (ie in terms of scope, geography and time resolution) require a higher degree of system operation automation and increased use of artificial intelligence to assess the necessary response at near real-time prices in the bidding zones. Focus on digital solutions is therefore critical and crucial to realising some of the potential. The use of transmission infrastructure closer to its physical maximum entails a need for continuous monitoring, operation and settlement in relation to load, which, in turn, leads to an increased need for digitisation.

For the **gas system** the introduction of hydrogen presents new opportunities as well as challenges. The hydrogen can either be blended into the existing gas system, part of the methane grid can be converted to handle hydrogen, methanised or transported in new dedicated pipelines. Some of the Danish gas storages can also be converted to handle hydrogen, and new storages can be established. Exactly how the gas grid should be designed should be seen in the context of the development in the demand for hydrogen and methane as well as the development in the EU and the neighbouring countries which are supplied with methane from Denmark.

CCS and PtX place demands on carbon capture and handling

The development in PtX and CCS has a significant impact on both the electricity system and the gas system. Both technologies lead to a demand for 'green CO_2'. A dedicated effort to capture, store and transport CO_2 is therefore crucial, regardless of the balance between the use of CO_2 for deposition (CCS) or the production of green fuels (PtX).

LONG-TERM FOCUS SUPPORTS SOLID DECISIONS TODAY

A changing energy sector

The energy sector is undergoing major change. National and international agreements and targets for the transition to climate-neutral societies also affect the energy system in the long term.

In order to be ready for the transition and help facilitate it, Energinet Electricity System Operator regularly prepares system perspective analyses and scenarios with a view to creating a long-term outlook for the future development of the energy system.

It is essential to understand the potential future that the energy system should be able to support, as infrastructure solutions developed today often have a lifespan of 40 years or more. So the challenge is to ensure a level of flexibility and robustness that enables the energy system to efficiently deal with as many outages as possible – also in the long term.

The energy trilemma

Energinet creates value for society at large – for citizens, businesses, institutions and civil societies. Energinet's core task is to transition the energy system to renewable energy and ensure a high level of security of supply, while also ensuring affordable energy prices. This is commonly referred to as the energy trilemma; see figure 1.1. The energy trilemma is the cornerstone of Energinet's business, and so the trilemma is also an important prerequisite for the system perspective analyses.

System perspective analyses as part of Energinet Electricity System Operator's planning

Energinet Electricity System Operator actively uses the development of the long-term scenarios in the system perspective analyses as important input to its strategic planning and development work.

The system perspective analyses are used in conjunction with Energinet's long-term development plan (LUP) as well as the ongoing, broader system and market development, but the system perspective analyses do not in themselves reflect a concrete plan for the construction and reconstruction of the transmission grid. Rather, they are designed to illustrate different development paths and present outcomes for the planning basis – the Danish Energy Agency's analysis assumptions for Energinet (AA).

Scenarios for the energy system of the future

This system perspective analysis has been prepared on the basis of elements from political targets, including the 70% reduction target, the analysis assumptions and ENTSO-E/G's European TYNDP Scenarios (2018) for countries outside Denmark.

These elements have been aggregated and analysed, and the conclusions from this work are fed into perspectives for the continued development of the elements going forward.

This analysis will, among other things, provide input for the future development of the electricity system by contributing perspectives for Energinet's long-term development plan and provide a platform for the Danish contribution to the development of future TYNDP scenarios.

Delivering the transition to a climate-neutral society requires fundamental changes – both within and outside Energinet's areas of responsibility. The analysis identifies several areas within Energinet's area of responsibility where work is needed. These are presented continuously throughout the analysis, and, in addition, a number of areas outside Energinet's area of responsibility have been identified which need to be developed further in order to realise the scenarios analysed.

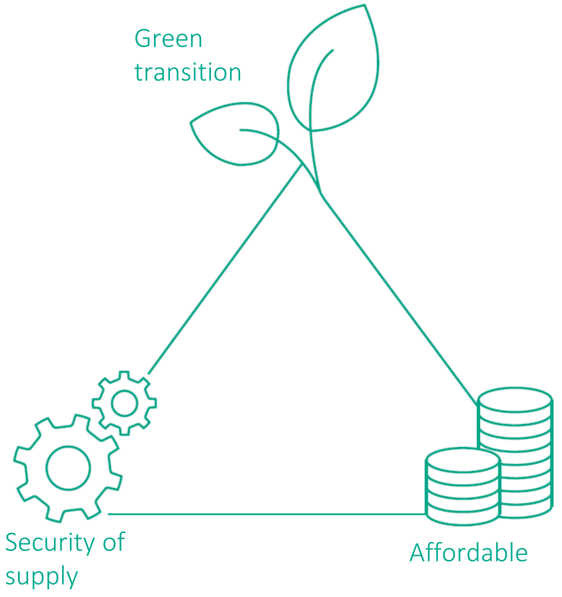


Figure 1.1: The energy trilemma
The energy trilemma is about balancing the different energy system considerations in order to ensure a high level of security of supply and provide consumers with affordable green energy. This is the task Energinet was set up by legislators to handle, thereby imposing on it a specific responsibility to society.

If Denmark is able to successfully carry out the task and demonstrate effective solutions in practice, the Danish energy system can be an inspiration to the rest of the world. In doing so, we contribute to the global fight against climate change.

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PART 1:

System perspectives for achieving the 70% reduction target by 2030

70% REDUCTION TARGET: A FEASIBLE BUT AMBITIOUS TARGET

Sizeable reductions required in all sectors

The climate law from December 2019 sets out a target for reducing national greenhouse gas emissions by 70% by 2030 compared to 1990 levels. The law also requires a reduction target to be set for 2025.

The total climate impact is measured in CO_2 equivalents. In 1990, Danish emissions of CO_2 equivalents were 75.5 million tonnes, and the 70% reduction target from this level thus allows 22.6 million tonnes of CO_2 equivalents in 2030 (incl. LULUCF). Compared with the Danish Energy Agency's Baseline Projection, it is 14 million tonnes below the level that is expected if no new initiatives are launched.

The above figures cover all sectors and also include elements such as land use, land use change and forestry in Denmark (LULUCF). Figure 1.2 shows the historical development by sectors and the 70% reduction target for 2030.

To assess the perspective for the electricity and gas systems, two examples of energy system development scenarios in a 2030 perspective which achieve the reduction target are presented on the following pages. The scenarios should not be regarded as a definitive solution, but merely as examples that enable an analysis of system perspectives. It is expected that non-energy sector emissions will continue in a trajectory corresponding to the reduction in the period 1990-2017 plus 15% reduction. This leaves approx. 11 million tonnes for the energy sector. Due to the uncertainty about the potential for reductions in sectors outside the energy sector, the analysis applies an outcome of 10-12.5 million tonnes of CO_2 in 2030. It should be noted that the energy sector primarily emits CO_2, which is why there is no conversion to CO_2 equivalents.

10-12.5 million tonnes of CO_2 require restructuring

A limit of 10-12.5 million tonnes of CO_2 requires a massive restructuring of the energy sector, and reductions will be necessary in the production, conversion and end consumption of energy.

In this part of the analysis, the energy sector is divided into the following seven categories:

1. Electricity generation and district heating production
2. Oil/gas production (offshore/refinery)
3. Process heat for industry/the service sector
4. Light transport (private vehicles and vans)
5. Individual heating of buildings
6. Heavy transport (trucks, buses, aircraft, ships)
7. Green fuel production, including biogas and PtX

Figure 1.3 illustrates the energy sector's greenhouse gas emissions which totalled approx. 31 million tonnes of CO_2 in 2019, broken down by the seven categories. International aviation and shipping is not included in the breakdown, as they are not covered by the 70% reduction target.

At approx. 9 million tonnes of CO_2 each, electricity and district heating production and light transport represent the largest categories.

Heavy transport and process heat for industry/service sector account for approx. 4.5 million tonnes of CO_2 each, while both individual heating and oil/gas production account for approx. 2 million tonnes of CO_2.

Green gases and fuels are (arithmetically) calculated using negative emissions, as they are currently primarily used to displace fossil fuels, where in 2019 biogas displaced approx. 1 million tonnes of CO_2 emissions from fossil gas.

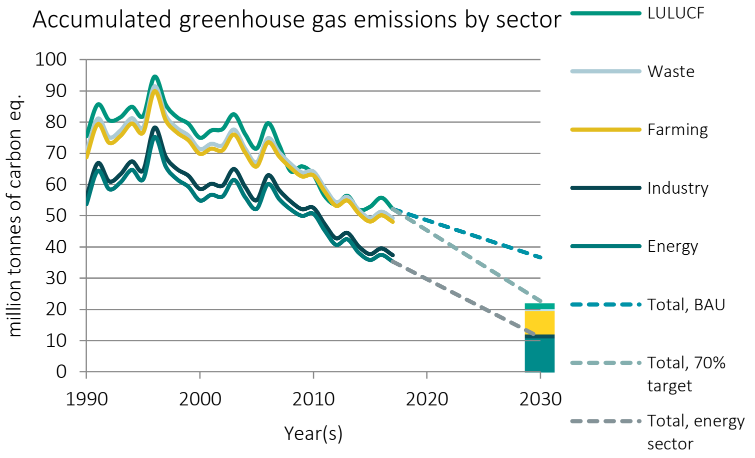

Figure 1.2: Historical greenhouse gas emissions broken down by sectors. The contributions from developments have been accumulated. At a reduction of 70%, combined Danish emissions of around 22.6 million tonnes of CO_2 equivalents are permitted in 2030. *UNFCC GHG inventory data.*

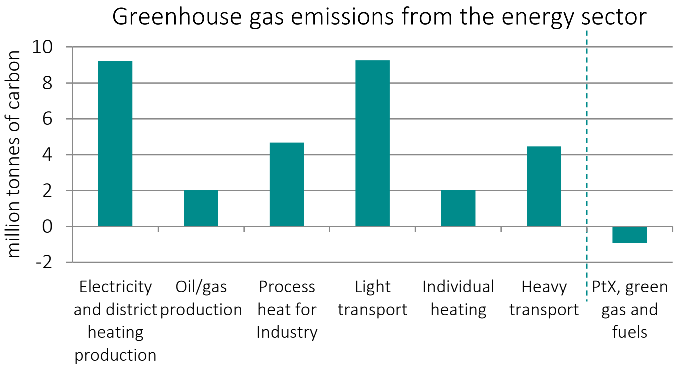

Figure 1.3: The energy sector's greenhouse gas emissions in 2019 broken down by the seven categories.

SCENARIOS FOR THE ENERGY SECTOR'S CONTRIBUTION TO THE 70% REDUCTION TARGET

There are many paths to achieving the reduction target towards 2030. However, the reduction is so dramatic that action will have to be taken in all seven categories in order to reach the target. The costs of the CO_2 reductions (the CO_2 shadow price) vary considerably within the categories. Direct electrification such as heat pumps replacing oil-fired boilers often has a low CO_2 shadow price. Indirect electrification such as PtX production of green fuels is still relatively expensive, but could be a means to achieve the target. In addition, CCS with carbon capture and deposition could be used to achieve CO_2 reductions. In the following, two development scenarios will be reviewed in which a reduction to 12.5 million tonnes and 10 million tonnes of CO_2, respectively, is realised in 2030, taking into account the CO_2 shadow price and the realisable potential. It is thus an estimate of which initiatives are necessary and where they should be realised first from an economic point of view.

1. Electricity generation and district heating production
Electricity generation holds considerable reduction potential, which primarily stems from the conversion of thermal power plants from coal to renewable energy – for example via:

- Conversion of large central coal-fired combined heat and power (CHP) plants to biomass CHP.
- Establishment of heat pumps for district heating.
- Building new green production capacity (wind/solar).

2. Oil/gas production
Oil/gas production from both the North Sea and domestic refineries is expected to continue in 2030. Reductions in refineries using green RE hydrogen instead of fossil hydrogen and production of RE gas and fuels have been included as reductions in the 'PtX, green gas and fuels' category. The following is assumed:

- Emissions from refineries remain at 0.9 million tonnes of CO_2 per year.
- Total emissions from North Sea extraction are assumed to fall by 10% compared to the 2030 baseline projection due to general energy efficiency improvements on the platforms. This is seen, for example, at Thyra, which is expected to be approx. 30% more energy efficient after its renovation.

For further reductions towards 10 million tonnes of CO_2:

- Total emissions from North Sea extraction are expected to decline by 33% compared to the 2030 baseline projection. This is achieved by electrifying processes on the platforms using offshore wind as seen in Equinor's Hywind Tampen project.

3. Process heat for industry/the service sector
There is considerable potential for converting energy consumption in industry, which is currently supplied by natural gas, coal and oil. Many low-temperature and medium-temperature processes can be electrified using heat pumps. Based on the process types and temperature levels, the following is assumed:

- General electrification of process heat from oil and gas. Around 50% electrification of low-temperature heat, 20% of medium-temperature heat and 4% of high-temperature heat.
- Reduction of coal and coke, which is to a large extent replaced by heat pumps and gas.
- Injection of 2% hydrogen in the natural gas grid.

For further reductions towards 10 million tonnes of CO_2:

- Increased electrification of process heat for approx. 50% of low-temperature heat, 40% of medium-temperature heat and 8% of high-temperature heat.
- Injection of 5% hydrogen in the natural gas grid.

Increased electrification already towards 2030 is possible but requires a massive effort and is therefore not included in the baseline for 2030.

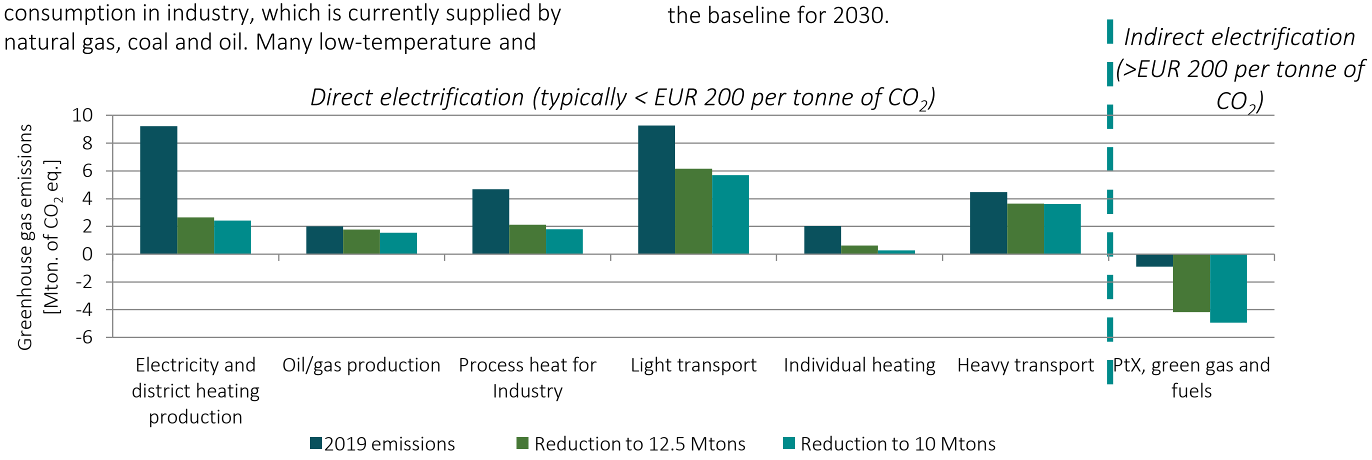

Figure 1.4: CO_2 emissions by sector in 2019 and scenarios for 2030.

SCENARIOS FOR THE ENERGY SECTOR’S CONTRIBUTION TO THE 70% REDUCTION TARGET

4. Light transport

Up until 2030, a standard projection of the transport need for private vehicles and small vans is assumed, and no major shift in modes of transport, for example to public transport, is assumed:

- A roll-out of 1 million green vehicles comprising 800,000 electric vehicles and 200,000 plug-in hybrid vehicles is assumed. New vehicles are expected to be competitive in terms of the total cost of ownership (TCO) from around 2025.
- Fossil diesel is hydrogenated with 3% hydrogen.

For further reductions towards 10 million tonnes of CO_2:

- The number of electric vehicles is increased from 800,000 to 1 million.

5. Individual heating

The primary reduction potential of individual heating lies in the transition from oil and natural gas-fired boilers to heat pumps.

- It is assumed that most individual oil-fired boilers are replaced by individual heat pumps. This is a relatively cost-effective measure, but it (only) contributes to a reduction of approx. 0.5 million tonnes of CO_2.
- Gas consumption for individual natural gas-fired boilers is reduced by approx. 50% and replaced by heat pumps and hybrid heat pumps, predominantly through natural replacement after the boiler’s lifetime.
- Establishment of new district heating to a further 2-3% of households outside the collective supply grid.

For further reductions towards 10 million tonnes:

- Individual natural gas-fired boilers are reduced by a further 20 percentage points (total of 70% reduction of baseline) and replaced by heat pumps. This share is more likely to occur in a forced transition, where boilers with any residual life are scrapped.

6. Heavy transport

Heavy transport remains difficult to electrify towards 2030, since the energy intensity of batteries is a challenge. With the technology projection of fuel cells, it is expected that buses and a small share of trucks may be converted to run on hydrogen (FCEV) in the years leading up to 2030. Diesel vehicles are still expected to dominate the market. In the field of heavy transport, the reduction scenarios comprise the following measures:

- Production of RE-based fuel via biomass and PtX.
- Fossil diesel is hydrogenated with 3% hydrogen.
- Hydrogen-powered trucks have competitive potential, and they are estimated to account for 5% in 2030.

For further reductions towards 10 million tonnes of CO_2:

- There is a strong commitment to the implementation of hydrogen-powered trucks, and the share is increased to 10%.

7. PtX, green gas and fuels

The production of RE fuels (gas or liquid) may replace fossil fuels in the energy system. According to the Danish climate law, reductions must take place on Danish soil. In relation to the 2030 reduction target, there is considerable uncertainty as to whether the ‘market’ will produce fuels to cover the consumption comprised by the 70% reduction target. PtX also poses certain challenges in relation to an implementation in 2030, for example with regard to the development of technologies capable of supplying carbon from biomass and flue gas for the PtX process. Consequently, the build-out towards 2030 should largely be considered in relation to a more long-term perspective beyond 2030, where large-scale PtX may be an important step towards the efficient use of Denmark’s considerable offshore wind resources. With regard to PtX, green gas and fuels, the following is assumed:

- Biogas production is assumed to be increased to 35 PJ of methane annually, notably by utilising the growing share of straw as a resource in biogas plants. CO_2 from biogas plants is used for fuel production via PtX, increasing production to approx. 50 PJ of green fuels.
- It is assumed that a number of PtX energy industry ‘clusters’ are established towards 2030 (see the description in the *System Perspective 2035* and *PtX in Denmark before 2030* analyses). The plants are assumed to have an annual RE fuel production of approx. 12 PJ, equivalent to approx. 350 MW of thermal gasification/pyrolysis. Alternatively, part of the production can be based on carbon capture and utilisation (CCU) from bio-fuelled CHP plants and waste incineration . The two alternative paths are described in further detail in part 2.

For further reductions towards 10 million tonnes of CO_2:

- PtX production in clusters is upscaled to approx. 600 MW thermal gasification and a biofuel production of around 20 PJ per year.

However, if direct electrification is stepped up, more comprehensive reduction initiatives are implemented outside the energy sector, substantial investments are made in CCS or more RE fuels are imported, the demand for PtX is reduced accordingly.

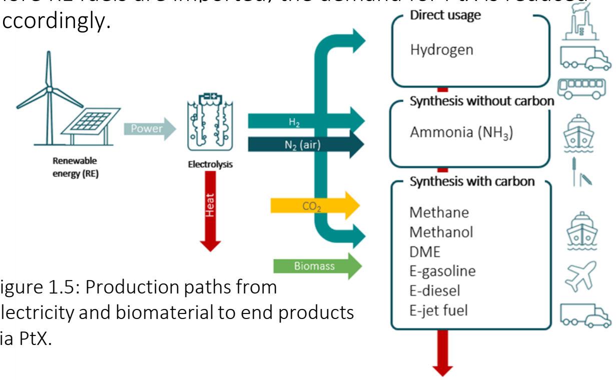

Figure 1.5: Production paths from electricity and biomaterial to end products via PtX.

THE 70% REDUCTION TARGET IMPACTS ELECTRICITY CONSUMPTION AND THE DEMAND FOR RENEWABLE ENERGY

The reduction target is feasible but entails a considerable increase in electricity consumption

The analysis points to a need for strong direct electrification of heating, industry and the transport sector. However, this is not sufficient in itself to realise the reduction target. At the same time, a firm commitment to the production of green fuels is needed. Production of green fuels via PtX as a means to achieve the 70% target is one of several options. For example, CCS in combination with imports of biofuels could be an alternative to national PtX production within the reduction target. It is also possible that sectors other than the energy sector are able to deliver larger emission reductions than expected in this analysis. Generally, a classic electricity consumption and a data centre consumption as in AA19 are assumed. A development towards, for example, fewer data centres and/or greater savings on classic electricity consumption as a result of energy efficiency improvements may reduce total electricity consumption.

In the case of PtX production, the production of the biofuel methanol is mainly analysed. The costs associated with refining or marketing via an international market for a Danish consumption mix of oil products fulfilling the blending requirements are not included in the analysis. Gas-to-liquids (GtL) from produced RE gas has a perspective towards 2030, but is also regarded as a refining process and is not included specifically in the analysis.The analysis shows that direct electrification increases the amount of electricity used for electric vehicles, heat pumps in individual heating, district heating systems and process heat in industry and the service sector by up to 7 TWh compared to a reference based on Analysis Assumptions 2019 for 2030. Indirect electrification with the production of fuels via PtX increases electricity consumption to just over 12 TWh. Overall, electricity consumption is increased from just over 50 TWh in the Analysis Assumptions to as much as 70 TWh in the highest scenario. As such, there is a considerable range for electricity consumption; see figure 1.6.

More RE electricity generation is needed to cover electricity consumption

In Analysis Assumptions 2019, there are approx. 5 GW offshore and near-shore wind turbines and 6.6 GW solar which are expected to produce approx. 40 TWh of electricity (incl. production from onshore wind). To this should be added electricity generation from central and local power plants in the order of 10-15 TWh, depending on international market prices.

If electricity generation is to match electricity consumption in 2030, additional RE electricity generation is needed compared to the reference. This may be achieved by combining wind and solar, for example by adding up to 3 GW of offshore wind combined with an additional 8 GW of solar in the high scenario.

Large solar plants are generally cheaper than offshore wind[1]. However, wind power ensures that electricity generation is more evenly distributed over the year. A unilateral effort to cover the increased electricity consumption by means of solar plants will place greater demands on seasonal energy storage, for example in hydrogen caverns. The need for new RE capacity in order to achieve the 2030 reduction target may result in a significant wind power build-out. However, on its own, it is not necessary to realise 10 GW of additional offshore wind already towards 2030. A large-scale build-out is particularly relevant beyond 2030 in step with the transition to climate neutrality and the utilisation of the Danish offshore wind potential in an international perspective.

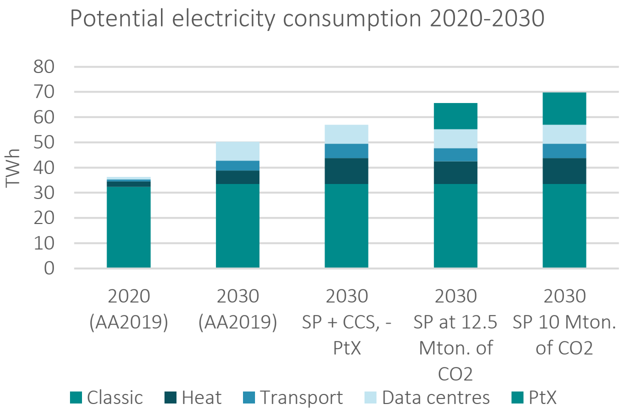

Figure 1.6: Electricity consumption in 2020-2030 in Analysis Assumptions vs System Perspective Analysis 2030 (2030 SP variants).

	2020 (AA2019)	2030 (AA2019)	2030 SP + CCS, -PtX	2030 SP at 12.5 Mton. of CO$_2$	2030 SP 10 Mton. of CO$_2$
Electricity consumption (TWh)	36	50	57	66	70
Additional offshore wind at ref. Solar (GW)	-	-	1	3	4
Additional offshore wind at add. solar in addition to AA (GW)	-	-	0-1	1-2	2-3

Figure 1.7: Examples of increased electricity consumption in relation to Analysis Assumptions

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[1] *LCOE in 2030 of approx. 2.4 EUR cent/kWh for solar vs approx. 3.8 EUR cent/kwh for offshore wind at a 4% discount rate.*

LONG-TERM PERSPECTIVES FOR ENERGY SYSTEM DEVELOPMENT AND CO_2 REDUCTIONS

ENTSO-E/G has translated the Paris Agreement's 1.5 °C target into a climate gas budget for the EU's accumulated emissions towards 2050. The accumulated emissions towards 2050 are approx. 50 Gtonnes of CO_2 equivalents or 63 Gtonnes if negative emissions are achieved after 2050. This budget approach has allowed ENTSO-E/G to establish scenarios in the Ten Year Network Development Plan 2020 which are compatible with the goals of the Paris Agreement (COP21). Denmark does not have a firm reduction target for the period 2030-2050, but a carbon-neutral energy sector (including international aviation) towards 2040 and negative emissions beyond 2040 may be needed if accumulated emissions matching the COP21-compatible scenarios are to be realised. The aim of part 2 of this analysis is to couple the 70% reduction target in 2030 with the long-term transition of the Danish energy system to climate neutrality. Scenarios are assessed in which the Danish energy system's emissions match the above-mentioned perspectives to varying degrees.

The long-term transition to climate neutrality

The energy sector's further transition from the 70% reduction target in 2030 can be achieved by transforming segments that are particularly difficult to decarbonise. These are especially found in heavy transport, aviation and shipping, gas consumption in high-temperature industrial processes, peak-load power stations as well as oil/gas production. This also includes the emission-heavy international transport sector which is not included in Denmark's UNFCCC-calculated emissions which are subject to a reduction target (United Nations Framework Convention on Climate Change). A common feature of most of the remaining CO_2 emitters is that their energy demand is expected to be met by various high-energy density fuels that are easy to store like traditional fuels. In an electricity system dominated by fluctuating, renewable energy generation there will be many hours of surplus electricity which it is not worthwhile (from a cost efficiency perspective) to transport around in the electricity system. This results in a 'use it locally or lose it' situation which ties in well with flexible, local electricity consumption in new energy clusters that are capable of producing green fuels (explained in more detail on page 20). The clusters may thus be instrumental in balancing the system and making hard-to-decarbonise sectors greener in step with the increased build-out of renewable electricity generation.

2035 as the next milestone

Towards 2035, in particular, electrolysis, a number of direct applications of pure hydrogen and the ongoing conversion of hydrogen to green fuels using PtX such as methane, methanol and jet fuel are expected to reach a reasonable level of market maturity. The biogas potential of using for instance manure towards 2030 'only' represents CO_2 equivalent to 0.5-1 GW of electrolysis, resulting in a need for carbon from straw in biogas and new applications of wood chips, from carbon capture and utilisation (CCU), from flue gas or through thermal gasification/pyrolysis. On the face of it, the latter is the most effective option, but it also needs to be developed further in the coming years. A common feature of the above is that carbon is used in most green fuels, which paradoxically makes carbon a limited resource for PtX purposes (see page 21). A large share of the current gas consumption may potentially be converted to enable incineration of pure hydrogen for process heat, and for trucks hydrogen fuel cells may prove competitive. In the shipping industry, carbon-free fuels such as ammonia or liquid hydrogen may be an option.

System perspective with utilisation of large-scale offshore wind

PtX build-out is a measure which, in addition to affecting the 70% reduction target, also has a major impact on the efficient utilisation of large-scale offshore wind. Specifically, part 2 of the analysis investigates a case involving 10 GW of additional offshore wind in the North Sea (connected to DK1) and an additional 3 GW in the Kattegat and the Baltic Sea. A complete overview of significant development areas in relation to the 70% reduction target and the PtX build-out in combination with large-scale offshore wind is provided in part 3 of the analysis. Overall, there is great potential for both increased RE production and PtX towards 2035, but a full upscaling of both will be difficult to implement by 2030. If the production of RE fuels established in one of the 2035 scenarios is used domestically, it could in principle make the Danish energy system fossil-free by 2035, as the amount of produced fuel is so vast that it could displace fossil fuels. However, PtX remains an expensive CO_2 displacement tool towards 2030.

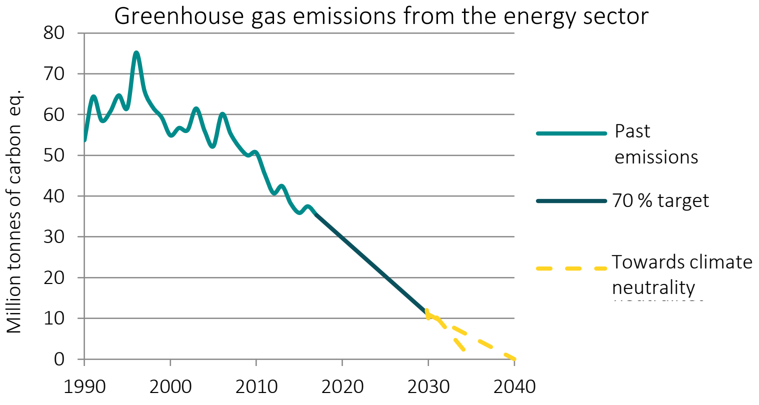


Figure 1.8: Reduction scenario for the energy sector towards 2030 – and perspectives on the path to climate neutrality.

ENERGINET

PART 2:

System perspectives for 2035 towards climate neutrality through large-scale offshore wind utilisation

DENMARK'S OFFSHORE WIND RESOURCES ARE AN IMPORTANT STEP ON THE PATH TO CLIMATE NEUTRALITY

Denmark is located in a windy region
Denmark benefits from excellent wind conditions for both onshore and offshore wind. The total wind power potential of the North Sea amounts to more than 180 GW which may cover more than 20% of the EU's expected electricity consumption by 2040. Up to 40 GW of the North Sea's wind power potential is found in the Danish part of the North Sea and it is very competitive in terms of production costs. In addition, Denmark also has considerable wind resources in its internal waters (such as the Kattegat and the Baltic Sea). In terms of supplying Denmark with electricity, 40 GW is a very substantial output, as the current electricity consumption is in the order of 3-6 GW. Even with a full transition to an RE-based Danish energy system in 2050, Denmark 'only' needs around 10 GW of offshore wind in the North Sea despite strong direct and indirect electrification.

The North Sea is a regional RE powerhouse
Electricity consumption in the European region is considerable (approx. 100 times that of Denmark), and the EU's ambition is that this consumption must be covered by low-emission energy sources. The North Sea is therefore regarded as an RE powerhouse, leading to expectations that the potential can be unlocked. For many hours, production will cover the classic electricity consumption in the region (and parts of Europe), but analyses also show that there will be periods when renewable electricity generation exceeds electricity consumption. This results in an 'electricity surplus' which may potentially be refined via PtX.

Perspectives towards a climate-neutral energy sector
According to policymakers the 70% reduction target should not be the energy sector's sole target, but a milestone on the path to climate neutrality. At the same time, some are advocating that Denmark should harness the considerable offshore wind potential in the Danish part of the North Sea. Given this focus, there is a concrete political desire to assess the possibility of utilising a cluster of this by connecting up to 10 GW of offshore wind in combination with one or more hubs for bringing ashore and distributing the energy. Through a number of scenarios, part 2 of the analysis explores the perspectives for utilising the offshore wind clusters and integrating offshore wind into the energy system, including the need for energy infrastructure. The analysis has a 2035 perspective, but concepts are applied which can be established before or after 2035.

There are several factors which are essential to the efficient build-out of large-scale offshore wind.
The economics of wind power is very much affected by the extent to which electricity production which is not used directly in Denmark can be integrated internationally via export or sector coupling with PtX in Denmark or its neighbouring countries. Even though electricity from the Danish part of the North Sea is relatively cheap to produce, several factors determine the cost-effectiveness of harnessing the considerable potential. These include, in particular:

- **Infrastructure solutions**: Energy must be transported from production sites to consumption sites in Denmark, in the region around the North Sea and in central parts of Europe.
- **Energy storage:** Large imbalances between production and consumption must be balanced through energy storage, direct electricity consumption and/or sector coupling. Energy storage also contributes to maximising the value of offshore wind.
- **Flexibility and grid reserves:** The electricity price in the individual bidding zone is currently the same, regardless of whether new consumption is located close to or far from the infeed of electricity generated by for example offshore wind turbines. Consequently, there is no incentive to place new consumption expediently in relation to the costs associated with transporting the power within the bidding zone. Flexibility may help to ease the load on the transmission grid, which means that it can be used as a supplement to electricity grid reinforcements.
- **Sector coupling:** Effective sector coupling can contribute to balancing production and consumption in time and place. Denmark has a number of strengths in terms of PtX and sector coupling, and a sector-coupled energy system can efficiently cut greenhouse gas emissions.
- **Carbon resources:** Carbon from biomass or CCU must be available to the extent that electricity via PtX is used for the production of liquid fuel.

The following pages describe how these issues are handled in different scenarios.

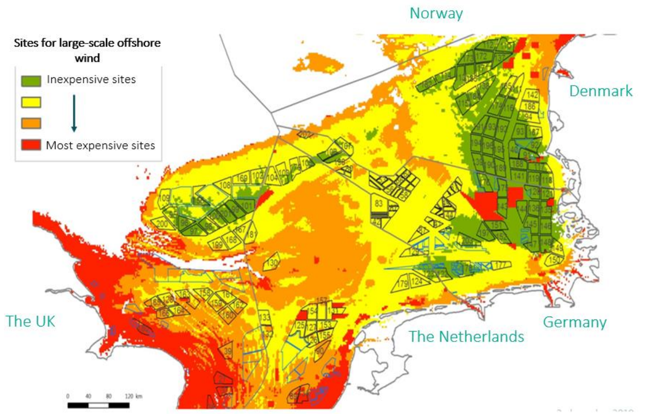


Figure 2.1: Indicative map of the North Sea with electricity generation costs for wind power.

INFRASTRUCTURE SOLUTIONS MUST BE CAPABLE OF HANDLING LARGE ENERGY VOLUMES

Transport of energy as electrons
A build-out in the North Sea (or other Danish waters) as a powerhouse for renewable energy requires the necessary infrastructure for transporting the energy from the production site to the consumption site.

Taken in isolation, wind power can compete with fossil energy, but as wind power fluctuates and most of the potential is located in the North Sea far from the consumption sites, the costs of transporting and balancing the energy are crucial to the value of wind power. This makes it important to examine the different solutions that can be used to transport the energy from offshore wind.

The energy can be brought ashore by means of HVDC connections or as alternating current after which the energy can be transmitted in overhead lines or underground AC cables.

In its own, transporting electricity via overhead lines is cheap, but it is also a visually intrusive solution which means that it is often met with local opposition. Energy transmitted in underground AC cables presents technological challenges, as the cables may emit electric noise which may render the operation of the electricity system unstable. In addition, AC cables are more than twice (up to 4 times) as expensive as overhead lines.

If energy is brought ashore by means of HVDC, the cost of a 150-kilometre stretch is approx. three times as high as the cost of AC cables. Moreover, HVDC substations with such a connection account for a significant portion of the costs, which is why it may be worthwhile to bring the connection from an offshore wind site further ashore to strong hubs/consumption points in the electricity grid such as the Tjele or Revsing substations; see figure 2.2.

Transport of energy as molecules
Wind power can also be converted to hydrogen via electrolysis for subsequent transport through hydrogen pipes. Electrolysis plants are quite expensive, but if the transported energy is still to be used as hydrogen for the production of green fuels, it may be worthwhile to convert electricity to hydrogen close to where it is brought ashore before transporting it to energy industry sites and locations where a large-scale hydrogen storage can be established (presumably as a cavern). If the pipeline is fully utilised, transporting energy as hydrogen is considerably cheaper than transporting energy via electricity cables. Figure 2.3 shows examples of indicative unit costs for different transport solutions.

Offshore conversion of offshore wind power to hydrogen may potentially reduce the need for electricity cables from the offshore wind clusters to the shore and thereby the total build-out costs.

In this system perspective analysis, a number of different combinations of the above-mentioned solutions have been examined. Reinforcements of the electricity infrastructure will be needed, but a combination with other measures such as a coupling with hydrogen infrastructure may reduce the need for reinforcements of the electricity grid.

The infrastructure solutions analysed are described in further detail on [page 22.](#)

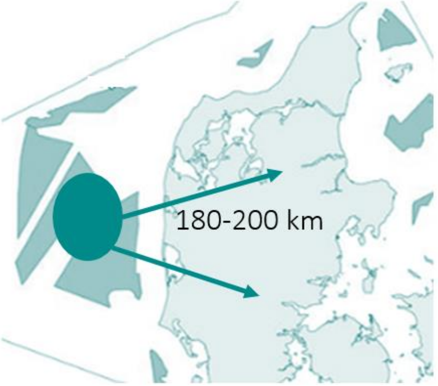


Figure 2.2: Example of wind power brought ashore from the North Sea.

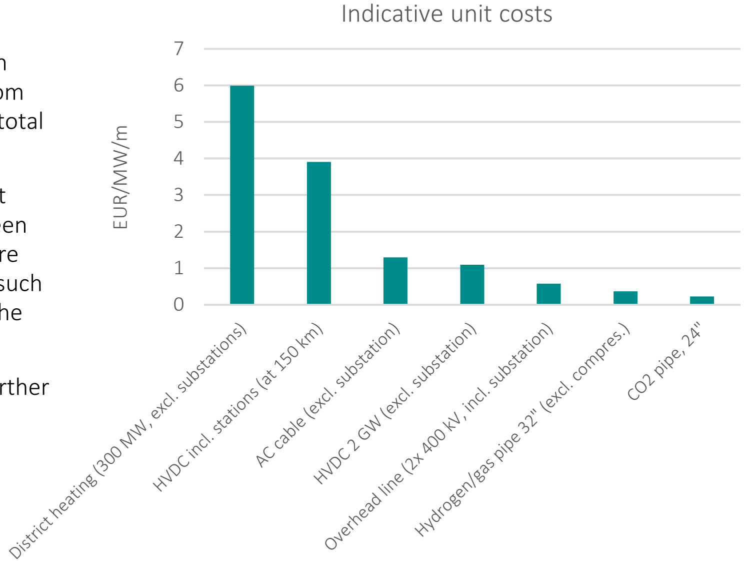


Figure 2.3: Unit costs of energy transport in different electricity solutions compared with gas and heat transport. The costs of overhead lines may be higher in specific projects, among other things due to the need for partial cable laying when using proximate routing etc.

SECTOR COUPLING ENABLES AFFORDABLE LARGE-SCALE ENERGY STORAGE

The need for storage in the short and long term
The analysis assesses a scenario in which, in addition to the general build-out of wind and solar, 10 GW of additional offshore wind is established in the North Sea 80-200 km from the coast of West Jutland as well as 3 GW in other waters which is fed into East Denmark. With such a massive build-out, wind and solar represent just over 30 GW of fluctuating electricity generation.

At present, classic electricity consumption amounts to 3-6 GW and even with a very substantial electrification of heating, industrial process heat, light transport and parts of the heavy transport sector, the total electricity consumption (excluding PtX) in the scenario is only around 4-10 GW.

The difference between production and direct electricity consumption varies between -8 and +20 GW in the delivery hours as illustrated in figure 2.4 which shows wind power and solar production less electricity consumption exclusive of PtX (hourly imbalance). In addition to the hourly imbalance, there is also a seasonal imbalance. On average, a surplus of approx. 6 GW is available for exports and PtX, but during a year, the imbalance varies by a seasonal profile corresponding to storing upwards of 8 TWh of electricity (accumulated imbalance).

In recent years, batteries have become significantly cheaper, but even with an expected fall in the price of large-scale batteries to less than USD 100 per kWh, 'hypothetical' electricity storage of energy of this magnitude would require a battery with an investment price of more than EUR 800 billion. The investment would be around 15 times higher than the cost of the wind power build-out, making it difficult to achieve an economically efficient energy system.

Figure 2.5 shows energy storage costs (excluding conversion) for batteries, heat storages and gas storages, including hydrogen storage in salt caverns.

Storing energy in batteries to smooth out seasonal variations remains an expensive solution. Storing energy as fuels such as hydrogen, methane gas or liquid fuel is more than 100 times cheaper than storing energy as electricity in a battery. Gas/hydrogen storages (such as caverns) may also have a certain 'buffer effect' on PtX production, thereby increasing the number of delivery hours – even when the wind is not blowing for the production of green hydrogen at the electrolysis plants.

Even though batteries (in relative terms) have an extremely high price per stored unit of energy, they may still be suitable for handling variations within a 24-hour period, within the operation hour and/or for delivering ancillary services.

In addition, batteries (see page 34) may be an important addition to grid reinforcements and not least in dedicated applications in the transport sector, local solar solutions etc.

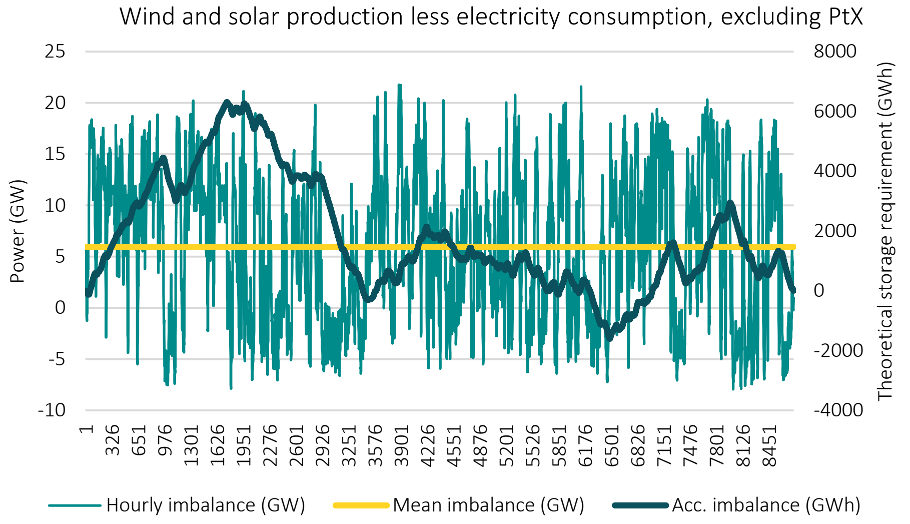


Figure 2.4: Annual imbalance at 10 GW of North Sea wind, including infrastructure solutions (see page 19).

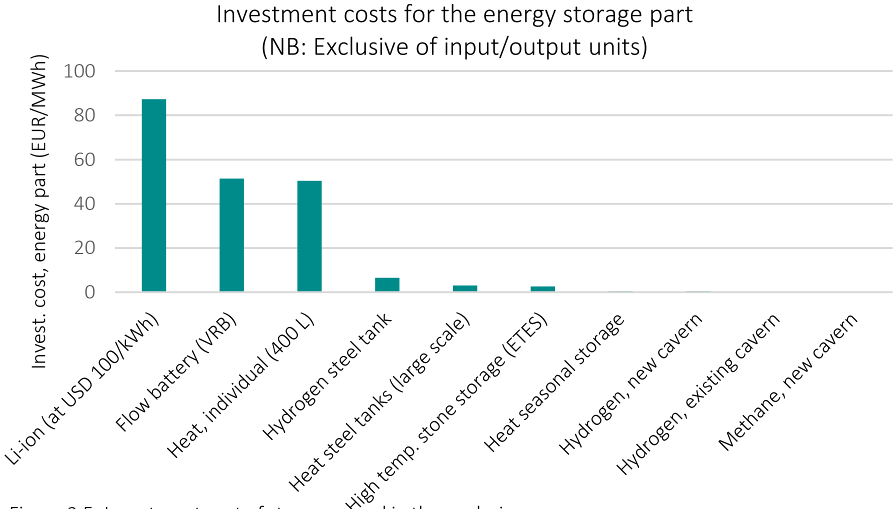


Figure 2.5: Investment cost of storages used in the analysis.

FLEXIBILITY AND GRID RESERVES MAY INCREASE THE ELECTRICITY GRID'S UTILISATION RATE

Market solutions and flexibility
In the analysis, bringing ashore large-scale offshore wind from the North Sea is assessed in relation to the capacity of the electricity grid as stated in Energinet's Reinvestment, Expansion and Restoration Plan (RUS plan) towards 2026.

In the existing market, Denmark is currently divided into two bidding zones, DK1 (Western Denmark) and DK2 (Eastern Denmark). The market price in the individual bidding zone is currently the same, regardless of whether new consumption for the energy industry (for example PtX for fuel production) is located close to the infeed of offshore wind or far from the electricity production. Consequently, there is no incentive to place consumption expediently in relation to the costs associated with transporting electricity within the bidding zone.

In order to put flexibility and sector coupling in competition with investments in strengthening the electricity grid, the grid is divided into smaller bidding zones in the analysis. There is no clear division; nevertheless interfaces which typically constitute congestion have been chosen in the analysis.

The capacity between the bidding zones in the analysis is based on the available grid capacity between the individual zones (in simplified terms); see figure 2.6. The black figures in the figure show the available physical capacity between zones in the reference build-out; see Energinet's RUS plan. To make the system resilient to infrastructure breakdowns, capacity is currently being reserved which is the capacity shown in red in figure 2.6. If a unit breaks down, the 'overload' on the rest of the grid must be handled thermally and with regard to dynamic voltage stability.

At the same time, the market's handling of internal congestion enables flexibility (demand-side response or electricity storage such as batteries) to support internal congestion in the electricity system. See also appendices on page 34.

Demand-side response as a potential grid reserve
Large volumes of demand-side response and electricity storages may potentially be included to ease the load on the transmission grid in the event of breakdowns or faults in the infrastructure. These solutions have not yet been developed at scale, among other things because rapid and secure management is required. This means that there is an untapped potential for development, as the volume of momentarily interruptible demand-side response is limited and small with respect to its use in system operations.

In the long term, large volumes of rapidly interruptible demand-side response may potentially be brought into play as supplementary grid reserves.

Increased operational complexity requires new tools
However, the division into minor bidding zones and the increased use of flexibility as a grid reserve also enhance system operation complexity. There will be a significant increase in the demand for information and data when the market, system operations and security of supply are combined and new infrastructure concepts are developed. In the long term, a manual overview alone will make it difficult to respond fast enough, and further automation of system operations will be needed in order to be able to handle complexity.

Increased automation is a natural step in managing complex systems. Realising the system operations assumed in the analysis will require investments in and development of new solutions.

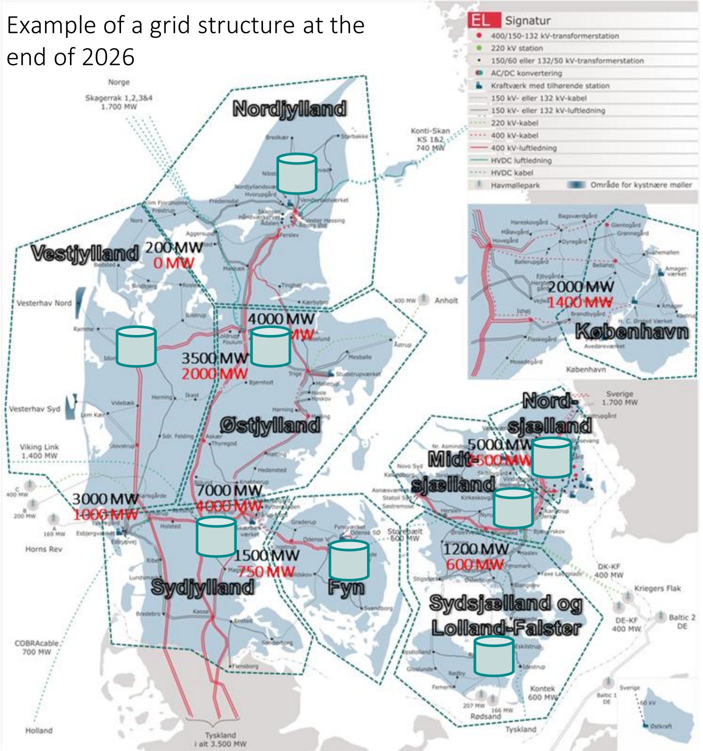

Example of a grid structure at the end of 2026

Figure 2.6: Division of bidding zones used in the analysis. The storage symbol indicates the potential for investing in batteries in the individual zones. In the analysis, batteries have been used as an *example* of demand-side response/electricity storage. In reality, the market will decide which technologies can efficiently provide flexibility.
Capacity, marked in black, indicates the potential transmission at full grid capacity, while capacity in red indicates the available capacity if conventional grid reserves are used.

SECTOR COUPLING IN CLUSTERS ENSURES SYNERGIES

Sector coupling in clusters

As regards PtX activities, Denmark has a number of strengths when it comes to refining electricity together with carbon from biomass and utilising surplus heat from the process in district heating systems. Among other things, this concerns access to good wind power resources, good bioresources with carbon, a well-established gas system, cavern storages for storing hydrogen and other RE gas as well as an efficient district heating system where surplus heat can be utilised in district heating systems. Figure 2.7 illustrates an **example** of zones with favourable conditions for sector coupling, including PtX. These are areas with favourable conditions for large-scale electrolysis of electricity for hydrogen and/or conversion of biomass and biowaste to gas, which is further converted to for example RE fuels, RE fertiliser or RE plastic. The importance of suitable cluster locations, taking into account the aforementioned elements, therefore requires strategic planning of the energy system. Figure 2.8 shows examples of plants which can be placed in the zones indicated in figure 2.7. PtX begins with electrolysis, which is used directly or further processed into RE fuels and/or ammonia. Key elements are bio gasification, conversion of gas to synthetic gas, ammonia production, carbon capture and the provision of CO_2 for CCS, among other things. Analyses show that the interaction with methane, hydrogen, CO_2 and the heating system in an efficient infrastructure in industrial clusters is crucial to a competitive energy industry. This is due to the presence of several symbioses between the processes. For example, oxygen from electrolysis makes it possible to strengthen processes such as bio gasification and waste treatment, CCU from power plants and industrial processes. Similarly, there is the option of using thermal integration, a common market-based carbon storage, hydrogen, heat etc.

The sector coupling concepts are described in System Perspective 2035.

Sector coupling may support direct air capture in the long term

Carbon to PtX processes from biomass and CO_2 point sources are expected to be most cost-effective towards 2035, but in the long term it is expected that more carbon will be required. The removal of CO_2 directly from the air using direct air capture (DAC) may be competitive in relation to the production of green fuels.

The DAC processes that are thought to hold promising potential are endothermic (heat-consuming) and consume heat at approx. 100 degrees. In connection with high activity levels in areas with production of ammonia, wood chip and waste gasification and methanol catalysis, heat production may exceed the district heating requirement, and the heat may eventually be used for DAC. The district heating system can support a market connection between heat-generating and heat-consuming processes in both the short and the long term.

These perspectives are described in further detail in the appendix on page 35.

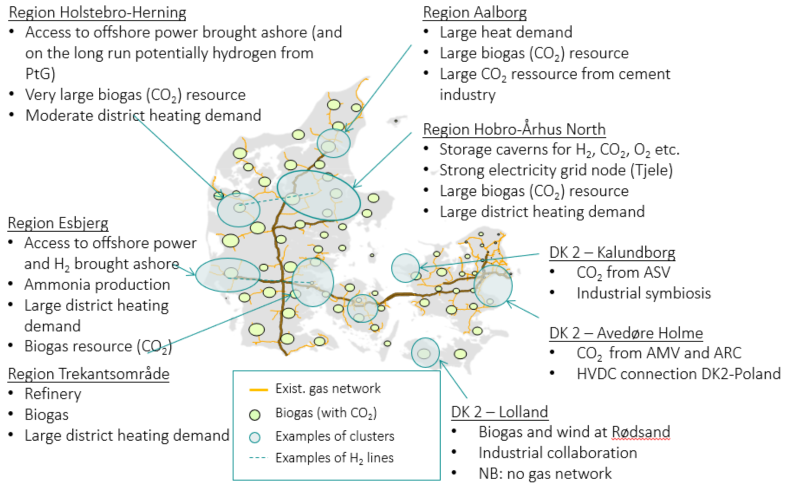
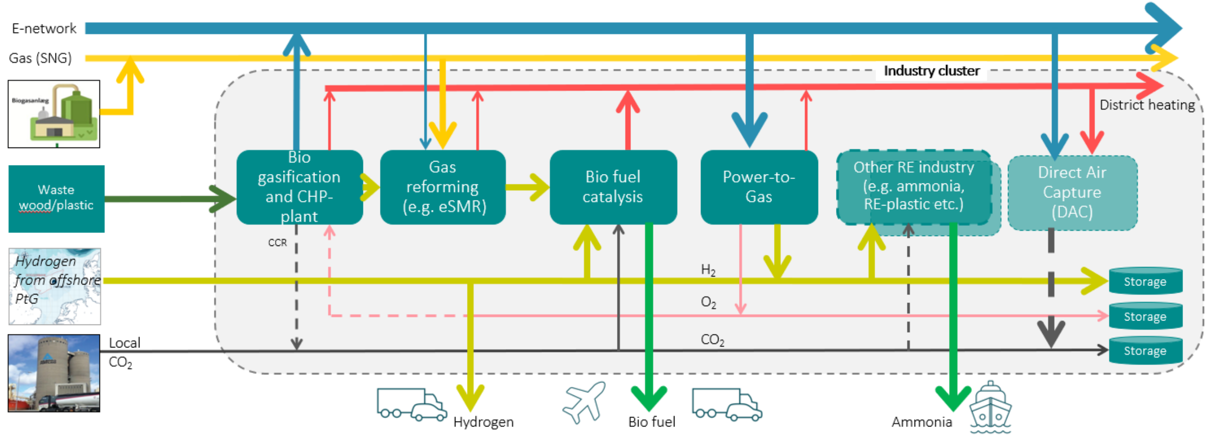


Figure 2.7: Examples of cluster areas included in the analysis.

Figure 2.8: Example of plants in a cluster of PtX and energy production.



CARBON MAY BECOME A SCARCE RESOURCE AND REQUIRES STRATEGIC CONSIDERATIONS

Strategic discussions on access to carbon are necessary
The analysis shows that PtX (or another increased or new electricity demand) is a prerequisite for the efficient exploitation of the wind power build-out. In many ways, the electrolysis part of PtX is approaching market maturity within some technologies (alkaline and PEM), but the analysis also shows that an absence of focus on carbon sources may slow the build-out of PtX; see figure 2.9. Denmark's wind resources have a PtX potential which far exceeds the amount of carbon available in the national biomass and waste potential. The analysis includes straw and biowaste for biogas production, and wood chip, wood and fibre waste is included as a carbon source for PtX via thermal gasification/pyrolysis or, alternatively, carbon capture from flue gas.

Biogas build-out with straw and biological residual waste
Straw represents a large energy and carbon resource. It is therefore important for the PtX build-out that this resource is used for fuel production. In the analysis, it is assumed that the resource is primarily converted to methane and CO_2 in biogas plants. Fibre residue from biogas is then used for a mixture of carbon sequestration (field), thermal gasification and combustion in power stations. Alternatively, the straw can be used directly for pyrolysis/gasification.

Ammonia as a key energy carrier for ships and green fertiliser
Ammonia can be used as both motor fuel and fertiliser in farming and together with hydrogen, it is one of the few RE fuels that do not require the presence of carbon when it is produced. As a result, the analysis estimates that there is a considerable potential for ammonia production. Specifically, in the Esbjerg region analyses have been conducted of the production of large volumes of ammonia for shipping and as fertiliser in farming.

Carbon from wood – pyrolysis plants or CCS/CCU at power plants?
Carbon from biomass and biowaste plays a key role in the large-scale development of PtX. Biogas (anaerobic) is suitable for liquid manure, biological waste and straw, but when it comes to the conversion of for example wood and plastics, there is a need for primarily two methods in order to access carbon:

1. Pyrolysis/thermal gasification combined with electrolysis hydrogen, where synthesis gas or pyrolysis oil is generated which can be used to produce fuels.
2. Carbon capture from flue gas in biomass and waste CHP plants (CCS/CCU).

Solution 1 provides the highest energy efficiency and is the most economical option in the long term. However, the solution needs to be developed further before it reaches market maturity. In the short term, solution 2 may seem obvious, as many CHP plants have been constructed for biomass/biowaste, but the analysis shows that biomass CHP plants will have relatively few operation hours in a wind power-dominated electricity system.

Captured carbon can be used for deposition (CCS) or PtX fuel (CCU)
CCS (carbon capture and storage) is a technology, where captured CO_2 from point sources etc. is deposited underground. Depositing captured CO_2 underground enables the rapid reduction of CO_2 from large point sources. This makes CCS an alternative to the use of captured CO_2 for PtX and is expected to affect the price of the 'CO2 raw material' for PtX as a result of stronger demand. The strategy for PtX should therefore be viewed in combination with the possibilities offered by the development of CCS. PtX solutions that do not require carbon, for example direct use of hydrogen or conversion to ammonia, are not affected by this higher CO_2 price. Direct use of hydrogen may therefore be more competitive in relation to carbon fuels. These issues are further elaborated in the appendices.

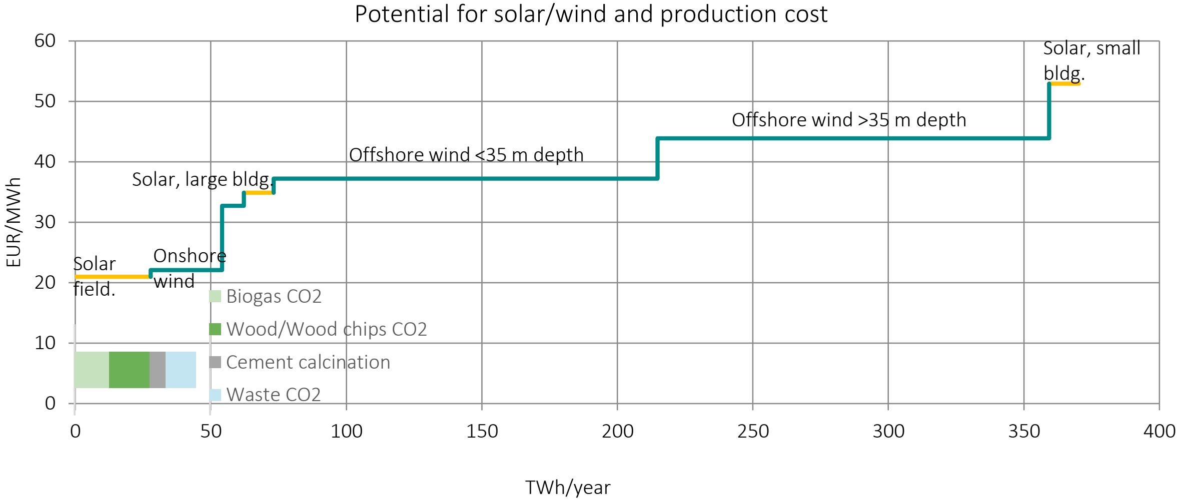


Figure 2.9: Wind/solar potential for electricity generation and LCOE at a 4% discount rate. In the bottom horizontal column, the figure shows the potential of national carbon sources for carbon PtX (diesel/kerosene), which is thus far smaller than the renewable energy potential.

VARIOUS INFRASTRUCTURE SOLUTIONS MAY FACILITATE OFFSHORE WIND BUILD-OUT

Suitable locations for new offshore wind

The Danish Energy Agency has screened potential locations for new offshore wind in Danish waters. The green areas in figure 2.10 illustrate areas identified in the screening. This analysis is based on these areas across the North Sea, the Kattegat and the Baltic Sea, with the North Sea holding the largest total potential.

Infrastructure solutions support offshore wind build-out

The idea behind a large-scale wind build-out with a hub solution is to combine energy from several large wind farms into one or more hubs and distribute the energy via electricity and/or hydrogen connections to the North Sea region. Examples of solutions are the North Sea Wind Power Hub project and the Danish government's ambition of a 10 GW energy island. This analysis examines the utilisation of Denmark's offshore wind potential and the interaction with the electricity and gas infrastructure as well as the conversion of energy from large-scale offshore wind clusters. Consequently, the analysis does not examine how offshore wind in the wind clusters may have to be erected around one or more hubs which can take different forms (platform solutions, islands etc.). To understand how different infrastructure solutions can facilitate the integration of large-scale offshore wind, the following infrastructure components are included in different combinations (as initiatives) in the analysis:

- HVDC connection from the wind clusters to Norway and Germany, respectively (1 GW).
- AC connection from the clusters to the West Coast connection. It is assumed that some of the production is located in zone 12. If all production is placed in zones 13 and 14, it should be assessed whether AC or DC technology is most advantageous.
- HVDC connection(s) from the wind clusters with transmission at Idomlund or Stovstrup, Tjele or Revsing/Landerupgaard.
- Establishment of hydrogen infrastructure from Aarhus to a hydrogen cavern storage near Viborg/Hobro and onwards to the Danish West Coast, where it is connected to Esbjerg. Two variants of a connection to production are analysed:
  - Onshore electrolysis plant close to the West Coast connection, Esbjerg and Aarhus.
  - As above, but there is also the option of offshore electrolysis in the North Sea.
- Internal grid reinforcements between subregions in the grid and internal grid reinforcements combined with electricity storage (batteries) to be used as a buffer in case of grid congestion; see figure 2.6
- Flexible operation of PtX and batteries as a grid reserve.

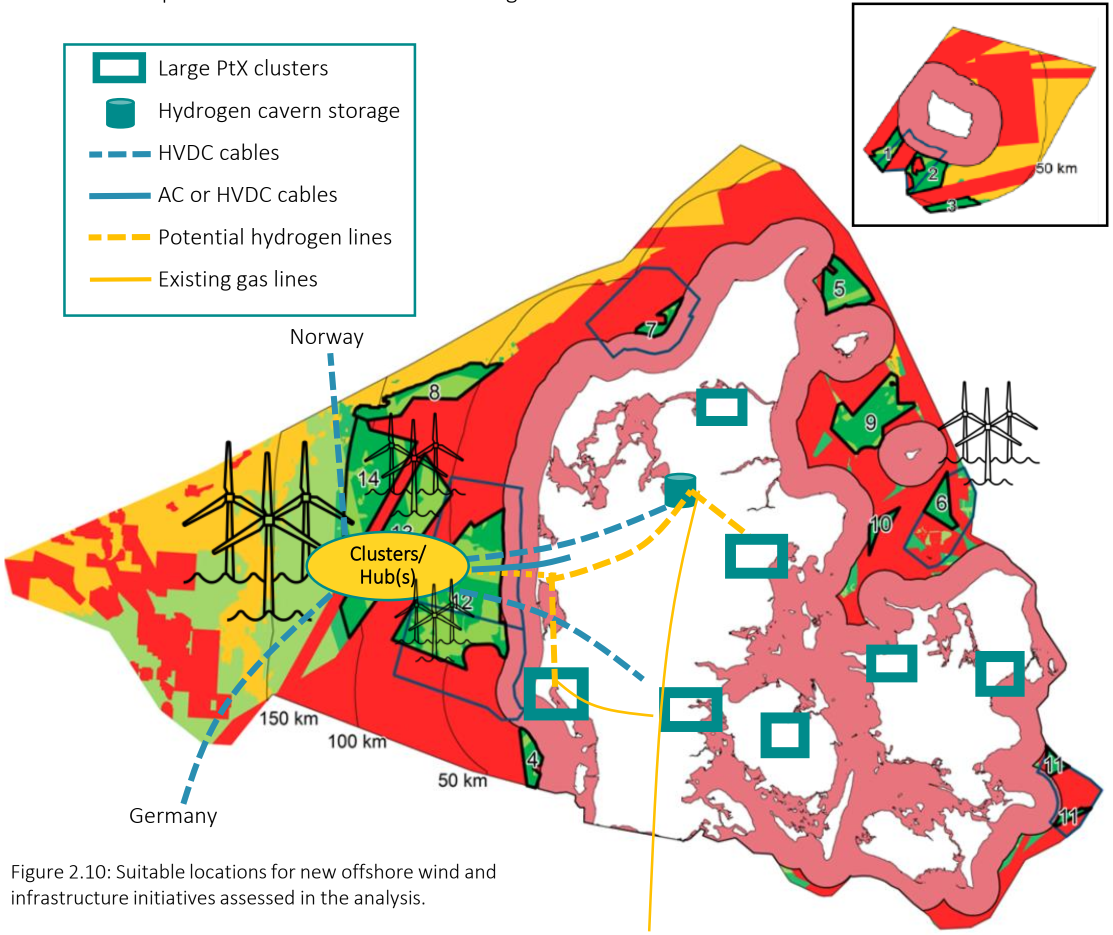


Figure 2.10: Suitable locations for new offshore wind and infrastructure initiatives assessed in the analysis.

LARGE-SCALE OFFSHORE WIND REQUIRES SECTOR COUPLING AND INFRASTRUCTURE CONCEPTS

Several combinations of the infrastructure solutions mentioned on the previous page have been assessed in a number of scenarios (elaborated on page 28). In the following, a selection of the scenarios (nos. 1, 2, 3 and 10) is presented to illustrate the effect of advanced sector coupling and infrastructure solutions in relation to reduction impact and the value of renewable energy. The analysis shows that without advanced sector coupling and a number of system initiatives involving advanced sector coupling, it will only be possible to integrate an additional 2-3 GW of offshore wind in the Danish electricity system. This is due to the fact that more wind power cannot be managed and utilised efficiently in the system which is expected to lead to increased downward regulation. In this respect, the analysis is in line with previous studies. Figure 2.12 shows that the market settlement of wind power is reduced to approx. EUR 9.4/MWh in the AA-E 2035 scenario inclusive of 10 GW of additional offshore wind in the North Sea.

SP 2035 (additional 10 GW of North Sea wind)

In the SP scenario, it is analysed whether it is possible for the market to integrate +10 GW of offshore wind in the North Sea and +3 GW in domestic waters. The analysis shows that there is a need for several additional measures in order to efficiently manage the increased wind power volumes:

- The possibility of large-scale ammonia production in the Esbjerg region.
- The possibility of using imported biomass and waste corresponding to the amount currently imported for heat and CHP plants. In this scenario, biomass is almost exclusively used in combination with electricity (PtX) to produce green fuels.
- The possibility of storing hydrogen in salt caverns.
- The establishment of hydrogen strings connecting large PtX clusters near Esbjerg and Aarhus with electrolysis on the West Coast and large hydrogen storages in the region, where they are physically located (Hobro/Viborg).
- The establishment of offshore electrolysis and hydrogen strings that connect the hub to onshore infrastructure.
- The possibility of exporting electricity to other countries (Norway and Germany as a case) via HVDC connections from offshore wind site
- The possibility of routing HVDC connections from the offshore wind site further into Western Jutland. This includes:
  - Tjele with an HVDC connection to Norway and geographical proximity to PtX at gas/hydrogen storages.
  - Revsing with a strong connection to the area round the cities of Kolding, Fredericia and Vejle with PtX and an AC connection to Germany.
- A district heating connection between large-scale PtX (including ammonia) in the Esbjerg region and the area of Kolding, Fredericia and Vejle.

Adding these elements will significantly boost the value of wind power and the overall economy in the scenario; see figure 2.12. The analysis shows that a further long-term build-out of RE electricity in Denmark's neighbouring countries may reduce the market value, so the results should be interpreted with caution. In this scenario, very large amounts of fuel are produced. If it is assumed that this fuel is used in Denmark or green fuel exports are accounted for, CO_2 emissions from the energy system as a whole will be close to zero as early as 2035. In the analysis, the production of RE methanol, RE gas and a small amount of ammonia is assumed. If the entire production is to be used in Denmark, the RE methanol will have to be refined into RE petrol, diesel and jet fuel. However, these costs and conversion losses are not included in the analysis. In addition, the use of ammonia for international shipping and fertilizer does not have a direct impact on the Danish energy system's climate footprint. As can be seen in figure 2.12, the analysis shows that advanced sector coupling initiatives are needed in order to maintain the value of a substantial build-out of offshore wind in the North Sea. By introducing PtX initiatives, dedicated hydrogen strings, HVDC infeed at key locations and not least increasing the utilisation rate of the electricity grid, it is possible to maintain a high market value and making the most of the substantial wind power build-out in the Danish part of the North Sea.

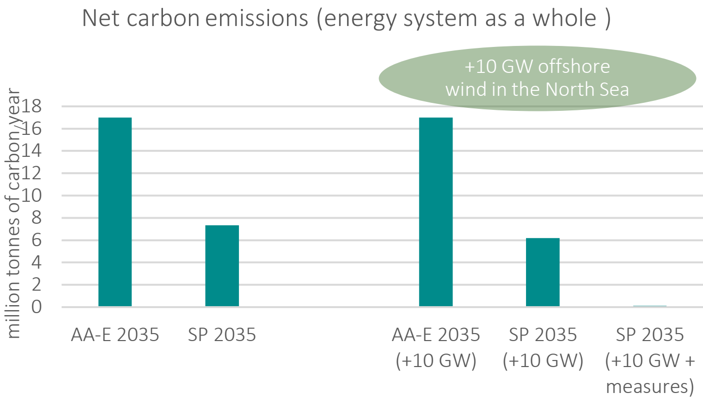


Figure 2.11 Net CO_2 emissions from the Danish energy system as a whole. Net emissions do not include an assessment of whether RE fuels are used domestically or exported to other countries. The initiatives (in the last scenario) comprise hydrogen infrastructure (including storages), HVDC infeed in zones and interconnections of 1 GW each from the 10 GW of offshore wind to Norway and Germany (see also page 22).

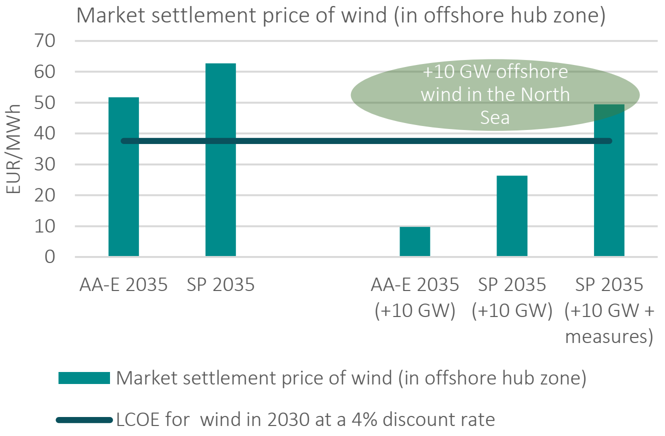


Figure 2.12: Market settlement of wind (in offshore hub zone) with/without 10 GW of additional offshore wind in the North Sea.

ELECTRICITY GENERATION AND ELECTRICITY CONSUMPTION IN 2035 SCENARIOS

As can be seen in figure 2.11, the addition of +10 GW of offshore wind coupled with efficient PtX production will significantly reduce net CO_2 emissions and may maintain the value of wind power. However, the increased wind power generation also leads to considerable growth in net wind power exports.

Exporting electricity to the international market
The scenarios with 10 GW of additional offshore wind in the Danish part of the North Sea include considerable electricity exports, bringing total net exports to 31-36 TWh per year in the simulated scenarios; see figure 2.14. With such a substantial build-out, Denmark will become an electricity exporter in hours of high electricity prices and in hours of low electricity prices, the electricity will be used in a relatively large number of PtX activities. The analysis shown in figures 2.11-2.14 uses a fixed international price margin from the ENTSO-E/G GCA scenario (TYNDP 2018), which includes a considerable wind power build-out in the North Sea region as well as an international CO_2 price of approx. EUR 100 per tonne. Specifically, the analysis focuses the integration between wind power and sector coupling in the Danish system. An analysis of the international price impact of a Danish wind power build-out is outside the scope of the analysis. Further studies into these issues in a North Sea context in relation to the price formation of electricity are needed. The settlement price of wind power should therefore be viewed with some caution due to these uncertainties.

International considerations concerning hydrogen
In its report 'The future of hydrogen', the IEA describes the production costs of global hydrogen production. The report shows that regions with conditions that are particularly favourable to electricity generation from wind and solar (such as Morocco) can produce hydrogen at a price that is approx. USD 1-1.5 per kg H2 cheaper than production in the North Sea region based on LCOE for onshore wind and solar. The report also describes the level of the expected costs of transporting hydrogen through transmission pipelines or by ship. These costs are in the order of USD 1-2 per kg H2, which roughly balances the difference in the level of cost between local production in the North Sea area and imported hydrogen.

As a result of the build-out of wind and solar to accommodate the large electricity consumption expected in Europe, it is expected that a considerable volume of electricity will be available in hours of electricity overflow. System solutions that strengthen the competitive utilisation of this electricity will therefore be crucial in the long term. This is described in further detail in part 3 of the report.

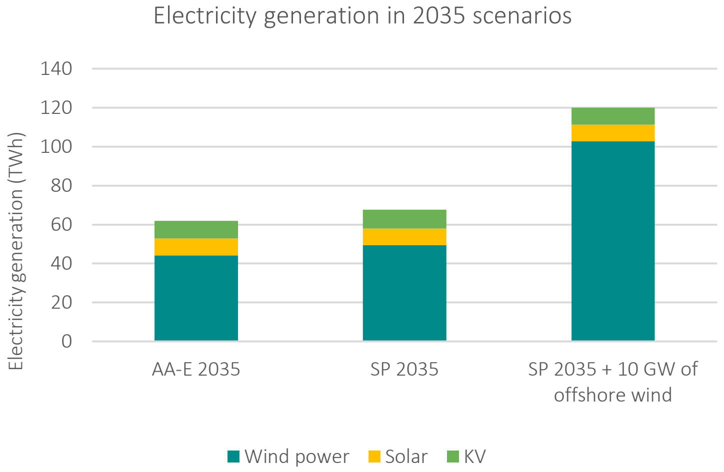


Figure 2.13: Electricity generation in the 2030 and 2035 scenarios without 10 GW of additional offshore wind.

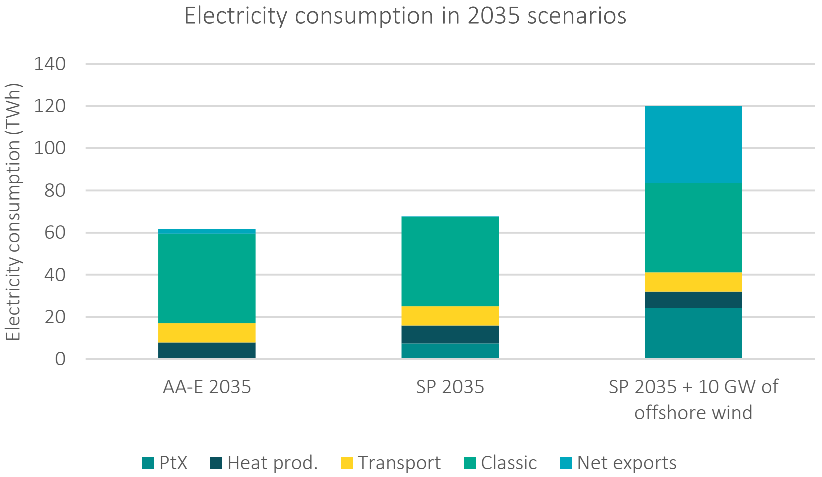


Figure 2.14: Electricity consumption in the 2030 and 2035 scenarios without 10 GW of additional offshore wind.

PART 3:

Selected development areas

SELECTED DEVELOPMENT AREAS FOR REALISING THE ENERGY SYSTEM OF THE FUTURE

Part 1 of the analysis set out two examples of potential development scenarios (among several possible) for the energy system in order to achieve the Danish government's target for a 70% cut in CO_2 emissions by 2030. **Part 2** of the analysis assessed the perspectives of large-scale offshore wind in a number of scenarios with a time frame up to 2035 (and subsequent climate neutrality).

Parts 1 and 2 show that the 70% reduction target requires significant direct and indirect electrification. As shown in part 2, direct electrification of heating, transport and industrial process heat is vital to achieving CO_2 reductions towards 2030. Indirect electrification, including PtX, is vitally important towards 2030, but in the scenarios it will be of particular importance to both CO_2 reductions and the efficient utilisation of offshore wind beyond 2030. The efforts required to achieve the 70% reduction target thus have a significant development value in relation to the efficient use of the Danish North Sea resources in the long term. Consequently, some activities should be focused on 2030 and a shorter time frame, while other activities should be seen in a longer-term perspective.

Energinet Electricity System Operator uses long-term system perspective analyses as an important input to planning and development work and based on the conclusions of the analysis, the following pages (**part 3**) provide a non-exhaustive overview of selected development areas in order to realise an energy system as analysed in parts 1 and 2.

Most of the development areas are areas, where mainly Energinet Electricity System Operator plays a key role. Furthermore, a selection of development areas relating to other Energinet activities is highlighted.

The selected development areas cover the following:

- Infrastructure concepts for handling large-scale offshore wind energy, onshore wind and large-scale solar plants in combination with sector coupling clusters.
- Market and system operation solutions capable of handling an RE-based energy system, where a tight coupling of the market and the physical system as well as increased automation of system operations are vital to ensuring economically optimum utilisation of the infrastructure.

In addition to Energinet's strategy, the work on Energinet Electricity System Operator's development areas is addressed in Energinet's R&I roadmap (research, development, demonstration and innovation) as illustrated in the figure on the right. Overall, the work is divided into different tracks focusing on infrastructure concepts, operational development, market development and security of supply.

The R&I roadmap are characterised by the fact that the tracks (market, operation and security of supply) will become more interconnected in the long term. At the same time, a tighter coupling is expected of the gas and electricity systems and the two systems are also expected to become more closely integrated.

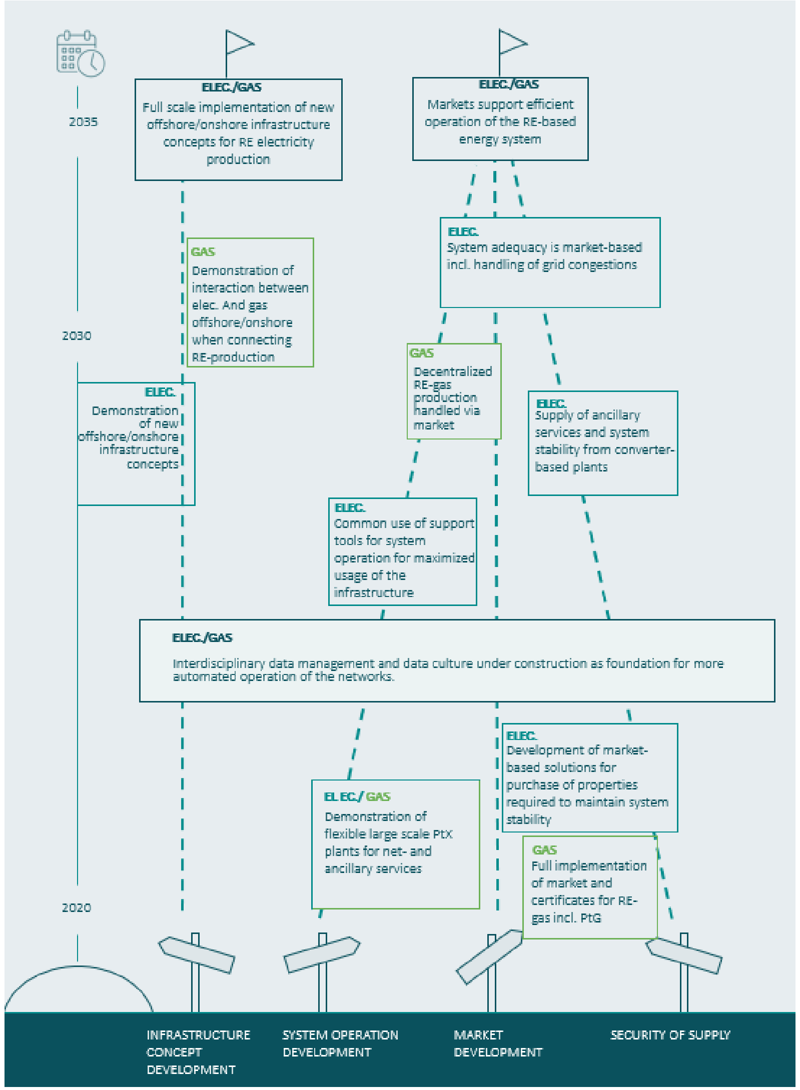


Figure 3.1 Energinet's R&I roadmap

DEVELOPMENT AREA: INFRASTRUCTURE AND PLANTS

A future, efficient and sector-coupled energy system requires planning and development that takes into account a number of elements and related initiatives.

Offshore concepts, where wind power is gathered in hubs and in cost-effective and reliable solutions combined with infrastructure (AC, HVDC and hydrogen infrastructure) are transported to shore. With a substantial build-out in the North Sea, solutions (such as hubs) for handling 10 GW (or more) may become relevant.

At present, the Danish electricity system is dimensioned to handle a production outage of up to 0.7 GW in Western Denmark and 0.6 GW in Eastern Denmark. Solutions where many gigawatts are fed into the system therefore require significant development measures in order to keep the system stable. In addition, the combination of hubs, AC, DC and PtX will affect system stability and system security. Offshore electrolysis may be an effective option, but it adds an extra layer of complexity to plant operations.

In this context, PtX system is a broad term for plants where electricity is converted to chemical energy products. There is a need for developing electrolysis for hydrogen and for developing processes for further processing (catalysis) of hydrogen and carbon (for example CO_2) for high-value energy products such as methanol, diesel, methane, ammonia and jet fuel. Preliminary assessments show that especially the electrolysis part of a PtX plant can be flexibly managed to deliver ancillary services to the electricity grid and be supplied as fast interruptible consumption (supplementary grid reserve). There is a need for development and demonstration of these possibilities.

In the analysis, clusters with sector coupling of electricity, gas, liquid fuels and heat are seen as being crucial to increased energy efficiency and cost-effectiveness. At the same time, hedging against market uncertainty is made easier, as conversion to different end products can be added to the cluster. The establishment of clusters with access to infrastructure and storages for hydrogen, CO_2, high- and low-temperature heat etc. is important to support this development. As a result, the designation of suitable areas, where clusters can be established and ensure the system development needed for the operation of for example hydrogen infrastructure is crucial. Energinet Electricity System Operator is actively contributing to this part (and the two following parts), but performance depends on planning and frameworks outside Energinet.

The establishment of large-scale storage of hydrogen, CO_2 and possibly oxygen is key to handling large imbalances in electricity generation from wind and solar.
The analysis shows that the use of caverns for hydrogen storage may be a cost-effective measure, but the necessary technical know-how, frameworks and regulation must be in place in order to unlock the potential for large-scale storage of hydrogen, CO_2 and potentially oxygen or a CO_2/oxygen mixture.

The establishment of hydrogen infrastructure and possibly a CO_2 infrastructure capable of connecting clusters with offshore hydrogen production and large-scale hydrogen storages. This is an area that requires a dedicated effort in terms of technical know-how, frameworks and regulation. Towards 2030, this may involve hydrogen infrastructure to connect hydrogen caverns with a cluster of PtX industry in for example the Hobro-Aarhus region and possibly the connection of the Esbjerg-Kolding-Fredericia-Vejle region. From around 2030, it may for example be a hydrogen string connecting these areas which also alleviates congestion in the electricity grid through the infeed of offshore wind.

System analysis at a general and detailed level
The many new elements are systemically closely linked. As part of both the long-term development plan (LUP) and more technical system analyses, it must be continually assessed how cost-effective concepts with a consistently high system security can be developed.

Initiatives launched:

- Analyses of the need for ancillary services and properties required to maintain electricity system stability
- Focus on risk-based approach to security of supply issues
- Grid analyses of the electricity and gas grids focusing on the development of grid solutions to deliver the green transition
- Analyses of connection concepts for large-scale offshore wind
- Ongoing assessments and analyses of electricity system stability and quality
- Gather lessons learned concerning the operation of hydrogen infrastructure and mixed infrastructure

DEVELOPMENT AREA: MARKET

Coupling of the market and the physical system is crucial as the electricity, gas/hydrogen and heat systems are integrated. At present, the market areas for both electricity and gas are large.

In terms of electricity, the price areas DK1 and DK2 cover all of Denmark, but the analysis shows that there is a growing risk of internal congestion in the electricity grid. Cost-effective market solutions that are capable of handling these bottlenecks are therefore important in order to ensure optimum, market-based utilisation of energy production, consumption and storages.

These could for example be market solutions in the regulating power market via a ‘geographical’ component/tag to make operations more flexible or the division into several smaller bidding zones.

Demand-side response as a grid reserve
Activation of demand-side response, production and storage in relation to system operation incidents (such as line breakdowns) may increase the grid utilisation rate, but this requires that market and system operation concepts are developed that support these possibilities.
In addition to geographical information, this also requires an appropriate time resolution.

Advanced ancillary services from converter-based plants
The analysis shows that in most of the hours of the year, conventional rotating electricity-generating plants are not in operation. The system must therefore be able to operate with less rotating mass (inertia) and plants for voltage control. Consequently, it is crucial that solutions ensuring system stability through converter-based production and consumption as well as possibly voltage control are developed. This includes delivering inertia from converter-based consumption and production (artificial inertia). This may be products such as fast frequency reserves which may lessen the need for inertia.

TSO-DSO interaction in the market and congestion management
As direct electrification gains momentum, the dispatchable distributed consumption capacity will increase from less than 1 GW today to more than 15 GW towards 2030. Such a high level of dispatchable consumption capacity affects system stability.

It also has a significant impact on the development of market solutions in the interface between TSOs and DSOs, where internal congestion in the outer corners of the electricity market must be handled during distribution in cooperation with electricity markets at TSO level.

A green gas market to handle local gas areas
In Denmark, there is currently only one zone for the gas system. With the original production of gas in the North Sea and a gradual drop in pressure, in addition to supply in Denmark, this made sense, but in step with the distributed production of biogas and new hydrogen zones, among other things, a market solution that can support this development is needed.

Coupling with heat markets
The analysis shows that the market value of district heating varies considerably over the year in many areas, but apart from an annual value there is no available market price of heat in most places. In order to create an efficient sector-coupled energy system, it is important that the market solutions for electricity and gas also have a market-based coupling with the heat sector.

International cooperation in development initiatives
The development initiatives in the market area depend on effective international cooperation. It is therefore crucial that the development takes place in close cooperation with the solutions devised in the Nordic and European markets.

Initiatives launched:

- Pilot projects with new types of flexibility services through for example demand-side response.
- Pilot project for renewable energy (solar and wind) as reserve capacity.
- Local flexibility markets for congestion management in the transmission grid.
- Cooperation with DSOs on a new tariff model, frameworks and market solutions with TSO-DSO interaction.
- Market products with fast frequency reserves.
- Tariffs (grid products) with interruptible discount.
- Implementation and development of Nordic and European market frameworks.

DEVELOPMENT AREA: SYSTEM OPERATION AND DIGITAL ARCHITECTURE

System operation development

System operations keeps the system stable, even though the market solutions are not entirely linked to the physical system. Internal grid congestion, voltage control, inertia and short-circuit power, mitigation of incidents in the event of outages and faults in plants or transmission lines, transformers etc. are handled via system operations. In order to address the development towards 2030, development initiatives are needed in the following areas:

The automation of operations must be increased in step with the growing complexity of the system. This is especially true for areas, where some of the above issues are increasingly addressed by market developments, thus requiring further system operation development to alert the market to the needs of the system and, to the extent that the market is unable to deliver what is required, intervene directly in operations. A finer time and/or geographical resolution and increased marketisation of ancillary services of for example voltage control and inertia requires interaction between the market and operations, which ultimately ensures that the physical system meets the needs of the market. At the same time, there is a need for improved system operation monitoring in order to manage the grid closer to the limit. This can be done by means of digital technologies such as AI to assess the condition of the system where direct measurements are inadequate. Furthermore, there is a need for more advanced forecasting routines capable of assessing power fluctuations and changes in production (gradients) with the significant increase in wind and solar production. As a result, digitisation is crucial to ensuring that the system operation development is able to handle the increased automation and introduction of advanced digital routines.

Dynamic Line Rating (DLR) is a technology where the capacity offered in the market is adjusted to the condition of the system. Measures involving increased utilisation of overhead lines during high wind speeds have been in development and use for several years, but a tighter coupling to for example an assessment of transformer and underground cable temperatures as well as other components may also form part of the capacity announcement to the market. These are all initiatives that require more data.

Resistance to critical events

As system monitoring and automation evolve and make it possible to ‘calculate’ how measures can deal with a critical incident, the system will become more robust. Unlocking this potential requires further development of system monitoring and automation.

Connection requirements for new units

As new plant types with converters become more ‘grid friendly’ and thus able to contribute to stabilising the grid, the development of connection requirements for new plant types is crucial to creating a robust electricity system in the future.

Digital architecture

The full transition of the energy system to new plant types with sector coupling, converter-based production and consumption, coupling of electricity/gas/heat, finer time and geographical resolution and increased utilisation of physical capacity significantly heightens the need for data and information.

A digital ‘platform’ in the energy system in the shape of IT architecture encompassing the entire energy system may enable the coupling of information from plants and infrastructure via market and system operations. This applies to large central units which may use demand-side response as a grid reserve as well as distributed units. For example, electric vehicles and quick-charging of electric vehicles may make consumption much more flexible, as the vehicles’ electricity consumption can in fact be moved in time and place to where electricity is cheapest in the grid and where the power can be supplied with the smallest possible loss and without congestion. Conversely, unintelligent management of the charging of electric vehicles will result in a situation where large power consumptions occur simultaneously and create instability in the transmission grid. Whether it will be possible to adapt solutions in such a way that the development will be a benefit rather than a burden to the system depends largely on the digital evolution and the extent to which the market is able to drive the development. A high level of **cybersecurity** is always important, and this importance increases in step with the complexity and degree of automation of system operations as well as the amount of system information made available to the market. A tighter coupling of the physical system and the market supported by data creates a more complex system which in the absence of adequate cyber security may be vulnerable to incidents.

Initiatives launched:

- Closer regional operational cooperation.
- Focus on agile working methods as well as data and digitisation.
- System condition monitoring with PMU/WAMS in international Nordic cooperation (NEWEPS).
- Focus on data-driven and probability-based decision-making support.
- Support society’s decisions by displaying data in Energy Data Service.

APPENDICES

SCENARIO OVERVIEW

Figure B1: Overview of key scenarios analysed

		No.	Scenario name	Description	Grid reserve from demand-side response (extended grid operation)	PtX		HVDC	Hydrogen system solutions		AC cable reinforcement between bidding zones and batteries in bidding zones
						Biogasification for PtX	PtX for ammonia		Hydrogen infrastructure and storage	Offshore PtG	
Reference scenarios		1	Reference 1: **AA-E 2035**	General reference scenario. The scenario represents a modelling of the Danish Energy Agency's Analysis Assumptions 2018, where electricity for transport corresponding to approx. 1.6 million electric vehicles towards 2035 and increased electrification of heating and process heat have been added. The scenario includes no PtX technology.							
		2	Reference 2: **SP 2035**	General reference scenario based on System Perspective 2035. In this scenario, effective sector coupling is introduced along extensive conversion of biomass use to green fuel production (PtX) and flexible electricity generation. Fuel production (RE gas/RE fuels) is combined with PtX within large central plants and distributed plants (biogas-based). Enhanced grid operation (see page 19) is expected. The scenario is described in detail in System Perspective 2035.	√	√					
+10 GW of additional wind in the North Sea		3	Reference 3 (R3): **SP 2035 (+10 GW)**	Same as reference 2, in which 10 GW of offshore wind from the North Sea is added. Serves as a reference for the next two scenarios.	√	√					
	Hydrogen infrastructure	4	R3 + onshore hydrogen infrastructure	In reference 3, the possibility of using PtX to produce ammonia and establish an onshore hydrogen infrastructure is added. District heating transmission from Esbjerg to the Kolding-Fredericia-Vejle region is established. Biomass equivalent to current imports is imported for use in carbon for PtX.	√	√	√		√		
		5	R3 + onshore and offshore hydrogen infrastructure	In reference 3, the possibility of using PtX to produce ammonia and establish an onshore hydrogen infrastructure to the wind turbines in the North Sea is added, so that PtX plants can be placed near the wind turbines.	√	√	√		√	√	
	HVDC	6	R3 + bringing power ashore via HVDC (normal grid operation)	In reference 3, an HVDC connection to bring power from the 10 GW wind turbines in the North Sea ashore is added. Normal grid operation is expected.		√	√	√			
		7	R3 + bringing power ashore via HVDC (enhanced grid operation)	In reference 3, an HVDC connection to bring power from the 10 GW wind turbines in the North Sea ashore is added. Enhanced grid operation is expected.	√	√	√	√			
	Hydrogen infrastructure and HVDC	8	R3 + bringing power ashore via HVDC or hydrogen infrastructure (enhanced grid operation)	The scenario is a combination of scenarios 5 and 6, where the power generated by the 10 GW wind turbines can be brought ashore via HVDC or hydrogen infrastructure. Enhanced grid operation is expected.	√	√	√	√	√	√	
		9	R3 + bringing power ashore via HVDC or hydrogen infrastructure (normal grid operation)	Scenario 8 with normal grid operation.		√	√	√	√	√	
		10	R3 + bringing power ashore via HVDC to DK, NO and DE and hydrogen infrastructure (enhanced grid operation)	Scenario with all the presented infrastructure options for both HVDC and hydrogen as well as HVDC from the North Sea to Norway and Germany. Enhanced grid operation is expected.	√	√	√	√ (+ Norway and Germany)	√	√	
	AC cables and batteries	11	R3 + AC cables, batteries and PtX for ammonia (normal grid operation)	In reference 3, the possibility of reinforcing the electricity grid between bidding zones is added in order to invest in batteries in the bidding zones and use PtX to produce ammonia. Normal grid operation is expected.		√	√				√
		12	R3 + AC cables, batteries and PtX for ammonia (enhanced grid operation)	Same as scenario 11, where enhanced grid operation is expected.	√	√	√				√

NEW INFRASTRUCTURE CONCEPTS REDUCE CO_2 EMISSIONS AND INCREASE THE VALUE OF WIND POWER

Findings for several scenarios
On the following two pages, net CO2 emissions, the value of wind power, electricity consumption and the volume of downward regulated wind are presented for a number of scenarios as described on the previous page. These scenarios should be seen in addition to the scenarios already presented on page 23.

The analysis shows that in the long term a +10 GW offshore wind build-out can deliver very substantial CO_2 reductions, while at the same time maintaining the high value of wind power. The analysis is based on a 4% discount rate (economic prerequisite), but with the efficient use of measures a slightly higher internal interest rate can be achieved. The analysis also shows that a classic build-out involving the use of existing measures cannot ensure efficient utilisation of such vast wind power volumes in the Danish system.

The analysis uses the reference build-out undertaken towards 2026 as stated in the RUS plan.

Overall, the analyses show that the build-out of both hydrogen infrastructure and HVDC connections holds considerable potential. The hydrogen infrastructure allows strategically placed PtX systems to alleviate congestion in the electricity grid, while at the same time providing a high degree of flexibility if cavern storages are established. HVDC connections can move the grid infeed point to strong hubs in Denmark and potentially abroad via interconnections.

Detailed findings are presented on the following pages. The scenarios can be divided into four categories:

- Reference scenarios (AA-E 2035 and SP 2035 with enhanced grid operation)

Scenarios, where 10 GW wind turbines in the North Sea are added in SP 2035:

  - + Hydrogen infrastructure
  - + HVDC
  - + Both HVDC and hydrogen infrastructure

Figure B2: CO_2 and wind power value in key 2035 scenarios analysed.

INCREASED OFFSHORE WIND IN HUBS REQUIRES NEW INFRASTRUCTURE CONCEPTS

SP 2035 scenarios with increased offshore wind build-out
The SP 2035 scenario assesses the possibility of adding 10 GW of offshore wind using a number of additional measures, in addition to the massive build-out established in the SP scenario. Additional measures in relation to the SP scenario are:

- The possibility of large-scale ammonia production in the Esbjerg region.
- The possibility of using imported biomass and waste corresponding to the amount currently imported for heat and CHP plants. In this scenario, biomass is almost exclusively used in combination with electricity (PtX) to produce large amounts of green fuel.

In this basic (minimal) version of the SP scenario, these measures have been added. In this scenario, approx. 25% of the established wind power is regulated downward. The value of wind power is reduced dramatically, and despite the relatively many measures implemented (see the SP description and the additional measures mentioned above) the internal return on the wind power build-out is barely maintained at 4%. A number of additional initiatives have been analysed in more detail in the SP 2035 scenario, including:

- The possibility of storing hydrogen in salt caverns.
- The establishment of hydrogen strings connecting several large PtX clusters near Esbjerg and Aarhus with electrolysis on the West Coast and large hydrogen storages in the region, where they are physically located (Hobro/Viborg).
- The establishment of offshore electrolysis and hydrogen pipelines that connect this hub to onshore infrastructure.
- The possibility of introducing HVDC connections from 10 GW wind clusters to key points in the electricity grid (Tjele and Revsing substations).
- The possibility of exporting electricity to other countries (Norway and Germany as a case) via HVDC connections from offshore hubs.
- A district heating connection between large-scale PtX (including ammonia) in the Esbjerg region and the Kolding-Fredericia-Vejle region.

SP 2035 with the above + hydrogen strings and hydrogen storage
Adding a hydrogen infrastructure significantly boosts the value of wind power and the overall economy in the scenario. This increases the internal interest on the build-out to about 5-6%, while downward regulation is reduced to approx. 8%. In this scenario, very large amounts of fuel are produced. If it is assumed that this fuel is used in Denmark or adjustments are made for green fuel exports, CO_2 emissions from the energy system as a whole will be close to zero as early as 2035. In the analysis, the production of RE methanol, RE gas and a small amount of ammonia is assumed. If the entire production were to be used in Denmark, this RE methanol will have to be refined into RE petrol and jet fuel. However, these costs and conversion losses are not included in the analysis. In addition, the use of ammonia for international shipping and manure does not have a direct impact on the Danish energy system's climate footprint.

SP 2035 with the above + hydrogen strings and storage + HVDC for Tjele/Revsing + HVDC to N/DE
In this scenario, the HVDC connections from the hub are routed further ashore so that they can be connected to key nodes in the grid. The nodes at Tjele with an HVDC connection to Norway and geographical proximity to PtX at gas/hydrogen storages. In addition, investments can be made in a HVDC connection to Revsing with a strong connection to the Kolding-Fredericia-Vejle region with PtX and AC to Germany. Furthermore, a build-out to Norway and Germany of 1 GW has been assessed.

This will also increase internal interest on the build-out to 5-6%.

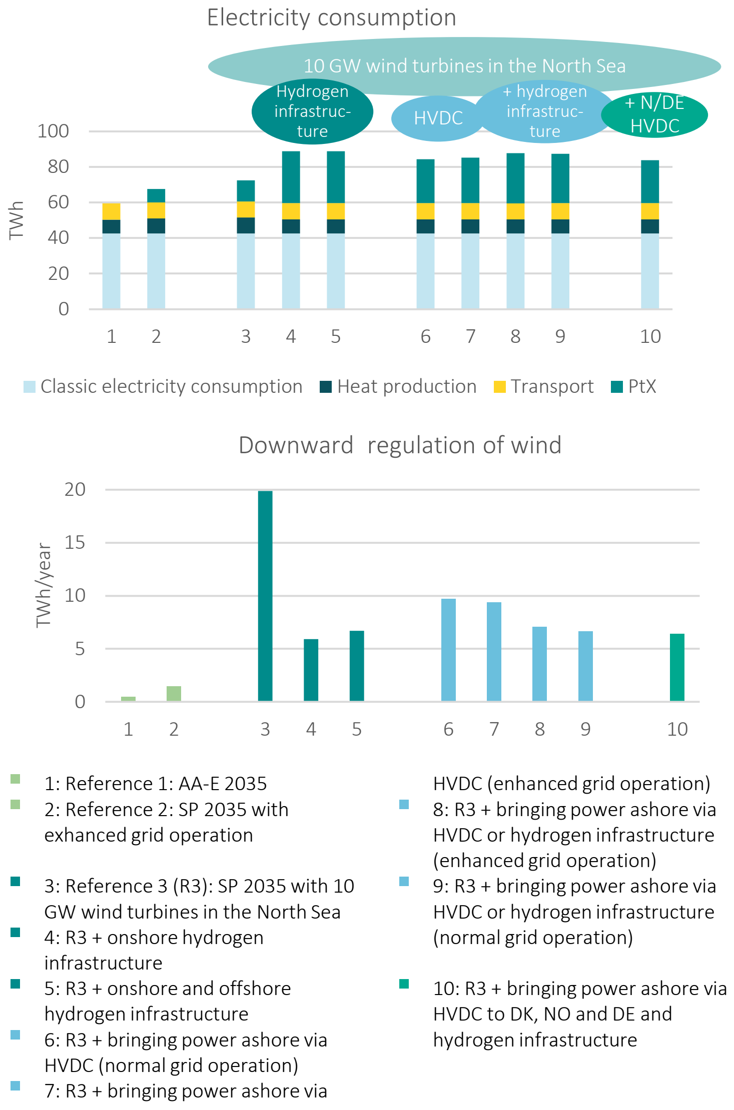


Figure B3:
Top: Electricity consumption in scenarios without/with a hub at different measures. Bottom: Wind regulated downward in scenarios without/with a hub at different measures

COMBINING FLEXIBILITY AND GRID REINFORCEMENT INCREASES UTILISATION RATE AND ROBUSTNESS

Interaction between grid reinforcements, flexibility and PtX
In the above analyses, it is assumed that the operation of PtX can be so dynamical that it can be used as a supplementary grid reserve in electricity infrastructure operations (referred to here as 'enhanced grid operation').

With enhanced grid operation supplemented by the infeed of 10 GW of North Sea wind at key points in the electricity grid and a hydrogen grid, there will be a limited need for grid reinforcements between the bidding zones.

If one or more of these measures cannot be implemented, the electricity grid must be reinforced, possibly supplemented by (large-scale) demand-side response (or electricity storage such as batteries) to alleviate internal congestion in the electricity grid.

Flexible electricity storage (such as batteries) may in some cases alleviate congestion in the electricity grid by acting as a 'buffer' in periods of congestion and moving the energy to periods without congestion.

It has been analysed how a reinforcement of the electricity grid in relation to the installation of batteries in the grid (as an example of flexibility) complements each other. The calculation assumes that the reinforcement of the electricity grid is carried out by means of cables. This measure involves some technical challenges, and it will require further detailed studies to assess whether technical conditions may be an impediment to these reinforcements.

As can be seen in figure B4, grid reinforcements affect the level of flexibility in the form of batteries which is economical. The investment in batteries is calculated on the basis of the system value of a build-out with batteries. Several factors pose a challenge to the feasibility of this investment. First, the value that electricity storage (batteries in this calculation example) has for the plant owner is often lower than the overall economic value of the entire energy system and, second, the investment in flexibility (such as batteries) assumes that a market model is developed which provides an incentive for flexibility to 'alleviate' congestion in the electricity grid, for example pricing in bidding zones as used in the analysis. In the analysis, it is therefore assumed that geographical bidding zones with prices are established; see the zone description on page 19.

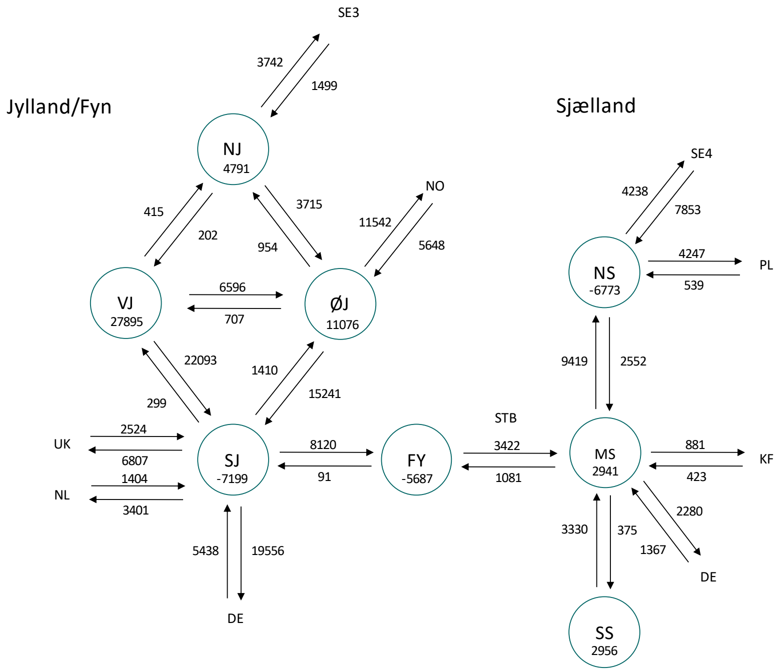


Figure B4 (right): Grid flow between regions in the SP 2035 scenario. As can be seen (the figures next to the flow arrows), there is a large wind power production to Western Jutland (VJ) which is sent to Southern Jutland (SJ), where consumption is high, and from here it is sent to Funen (FY) and exported to the UK (UK) and Germany (DE). There is also a large wind power production to Eastern Jutland in this simulation (Anholt offshore wind farm).

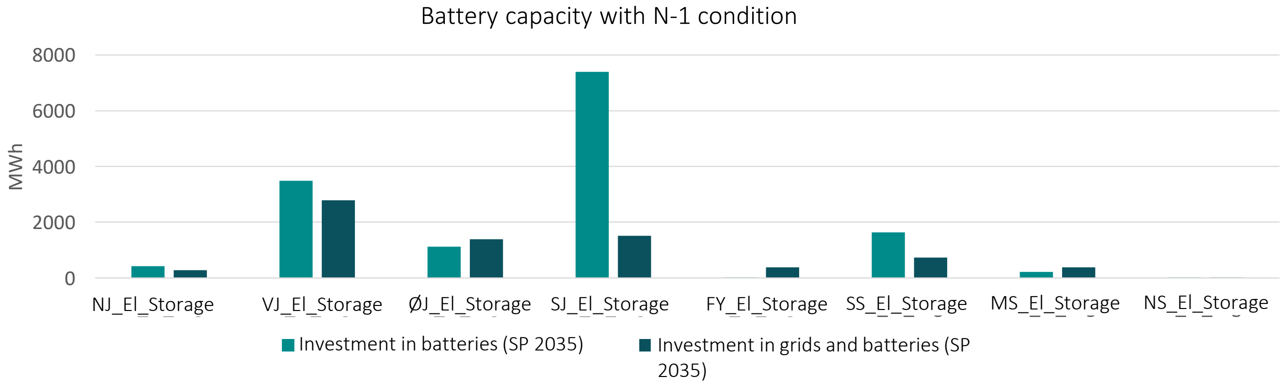


Figure B5: Investment in battery capacity (energy) as an example of flexibility with and without the possibility of AC cable reinforcement in the transmission grid.

LARGE HEAT VOLUMES MAY FACILITATE DIRECT AIR CAPTURE (DAC)

Heat surplus and perspectives for carbon capture technologies
The analysis shows that if the build-out with an additional 10 GW of offshore wind in the North Sea (up to 20 GW of offshore wind in total) is to be used effectively, a significant build-out with RE fuel production incl. PtX is key, as is a substantial build-out of biocarbon for PtX plants. Carbon capture utilisation (CCU) from waste incineration and cement production may reduce the need for biomass by 10-20 PJ.

In areas with high levels of PtX activity, fuel production processes generate sizeable amounts of surplus heat. This means that utilising the heat available in the Esbjerg region may make heat transmission to the Kolding-Fredericia-Vejle region worthwhile.

Relatively large amounts of heat are available in both the Esbjerg region and the Aarhus region. In the analysis, heat transmission from the Esbjerg region to the Kolding-Fredericia-Vejle region is established.

Figure B6 shows the annual curves for heat prices in a number of regions. Here it can be seen that for most of the year, heat prices in for example Esbjerg and TVIS (which is connected) is EUR 0 per MWh. In other words, there is a large surplus of heat. These abundant amounts of heat at relatively low temperatures may support the perspectives for direct air capture (DAC, the capture of CO_2 from the atmosphere), as it often happens via heat-consuming processes at low/middle temperatures.

Towards 2035, the price of DAC is expected to fall. Figure B7 shows the expected price development if surplus heat is available. This solution is still more expensive than the other solutions shown in the analysis. However, it may become competitive especially if surplus heat is available. Given the heat production, a strategic focus on PtX with existing technologies may thus promote PtX solutions with DAC technology. Efficient storage of the heat is important to unlocking this potential.

With a strategic location of plants for PtX and further processing of hydrogen in clusters, Denmark may be an attractive location for refining North Sea power into high-value products – in the first few years with carbon from biogas, biomass etc. and eventually from DAC.

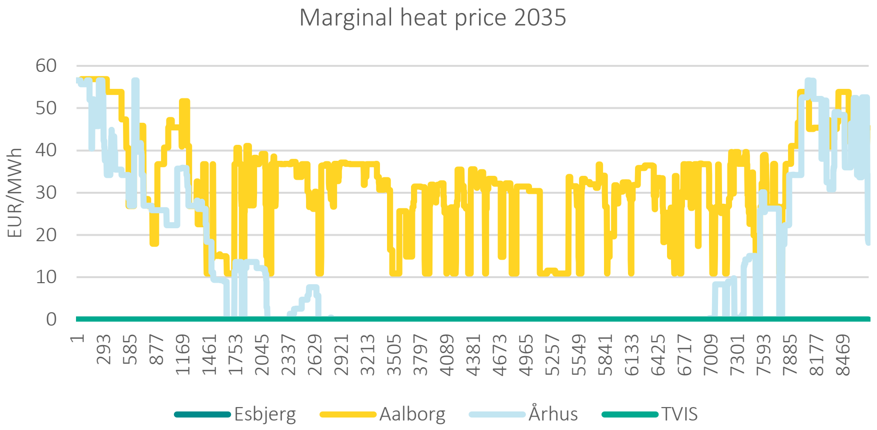

Marginal heat price 2035

Figure B6: Marginal heat price in the district heating areas Esbjerg, Aalborg, Aarhus and TVIS in the SP 35 scenario with HVDC and hydrogen infrastructure and storage.

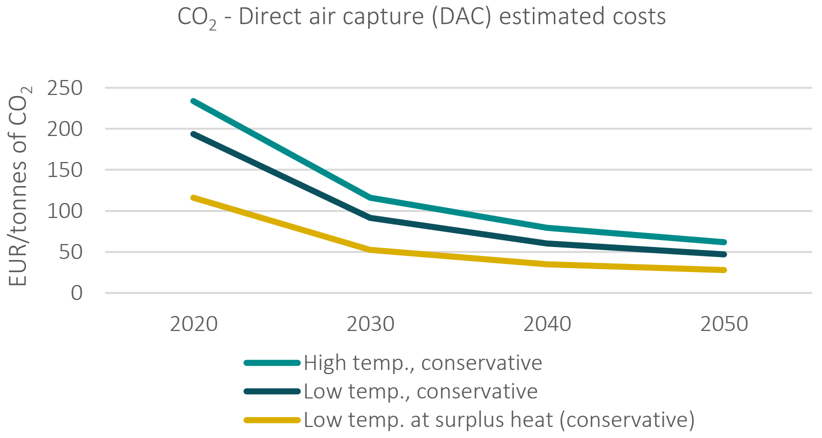
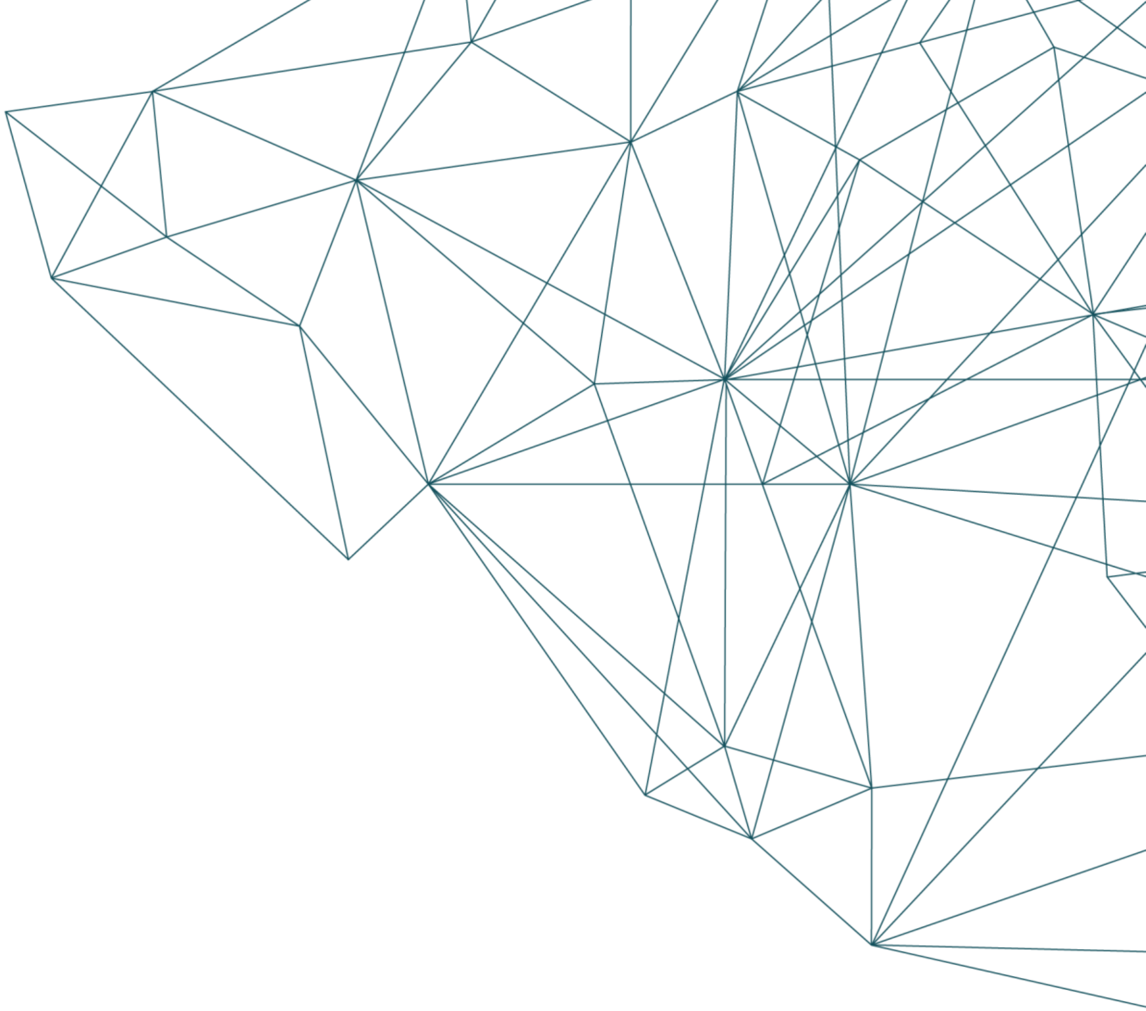

CO_2 - Direct air capture (DAC) estimated costs

Figure B7: Expected direct air capture costs towards 2030, 2040 and 2050.
Source: Techno-economic assessment of CO_2 Direct Air Capture plants
Mahdi Faishi et al, LUT University, Finland, March 2019.



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