Energy Concept 2030 – Summary

An analysis of concepts and development paths
towards a competitive and strong RE-based energy system

Contents

The report can be downloaded from www.energinet.dk

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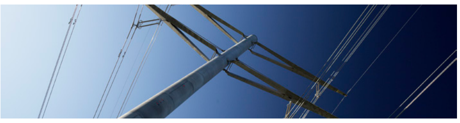
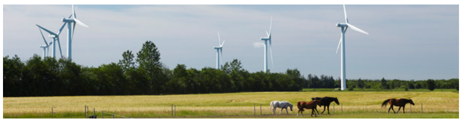




1. Summary

1.1 Background – Denmark in a region with great wind power potential

This document is a summary of the 'Energy Concept 2030' *(Energikoncept 2030)* report[1], which presents Energinet.dk's analysis of system solutions in an energy system with large volumes of wind power.

The objective is to assess whether new system measures can increase the cost-effectiveness and competitiveness of a wind power-dominated energy system using a fossil-based reference. The work is based on the energy agreement analyses prepared by the Danish Energy Agency with input from Energinet.dk[2], among others. Four future scenarios for Denmark with different volumes of wind power and biomass/waste and a fossil reference scenario have been analysed. In all scenarios, including the fossil reference, windpower volumes are expected to increase significantly compared to today, see figure 1.
In the wind scenario the biomass use is limited to an amount corresponding to the national potential. This is primarily chosen as a design criteria to obtain a sustainable use of biomass pr. capita, and not to be seen as a national binding on import and export of biomass. Based on the energy agreement analyses, this scenario is estimated to have the highest level of security of fuel supply.

1 The 'Energy Concept 2030' report is available (in Danish) at www.energinet.dk/energianalyse
2 The energy agreement analyses are a collection of reports from the Danish Energy Agency, May 2014 – including complete energy system scenarios and reports with analyses of electricity, gas, heating and biomass. Pursuant to link: http://www.ens.dk/politik/dansk-klima-energipolitik/regeringens-klima-energipolitik/energiaftalens-analyser

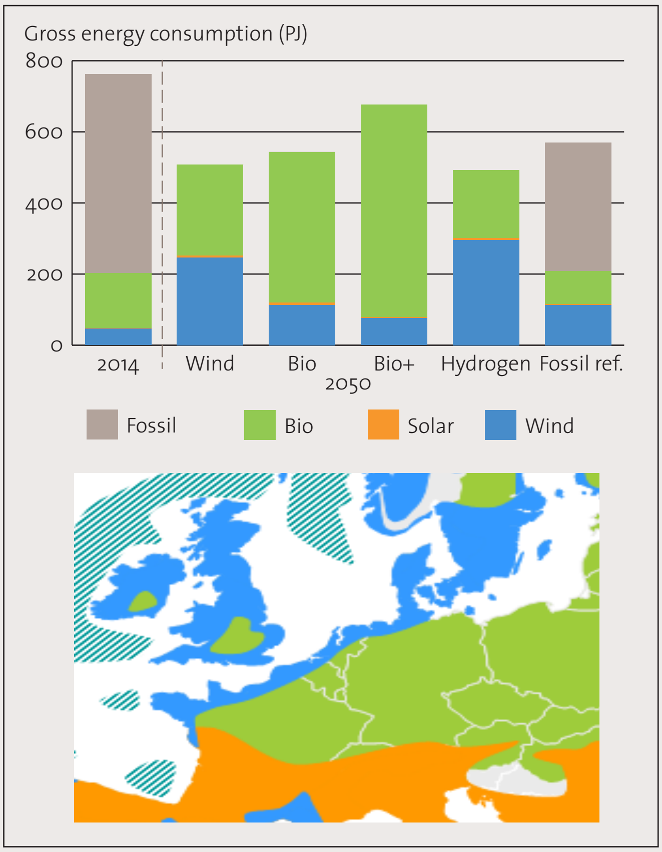


Figure 1: At the top – gross energy consumption in the Danish Energy Agency scenarios for 2050. At the bottom – RE strengths in the EU, source: EU e-Highway, 2014.

Located in the North Sea Region, Denmark is surrounded by several countries which have access to significant wind resources. Some of these resources are already being realised. Northern Germany expects to reach about 34 GW within ten years. In comparison, Denmark currently has just under 5 GW and is expected to reach about 7 GW by 2025.

Regardless of whether Denmark or Europe makes investments in wind power in this area, it will affect the electricity market in and around Denmark. Therefore, adapting the Danish energy system to an electricity market dominated by wind power would be appropriate regardless of the level of expansion of Danish wind power. The energy agreement analyses estimate that the wind scenario in 2050 will be about 8% costlier than a fossil reference. Seen in isolation, wind power – especially land-based wind – is estimated to be one of the most cost-effective energy resources for electricity generation. Nevertheless, when the share of wind power in the energy system increases, the integration of wind power can raise the total system costs. In particular, the costs of electricity capacity as backup for wind power, reinforcement of the electricity infrastructure and balancing of the electricity system contribute to making the wind scenario with very large wind power volumes more expensive than a fossil reference scenario. Therefore, system measures aimed at reducing these costs are essential.

The wind scenario (and hydrogen scenario) is characterised by very low consumption of fuel resources and a much more fluctuating primary energy supply. This represents a new and different way of operating a comprehensive energy system compared to both a fossil and a biomass-based energy system, both of which imply a relatively large fuel consumption. The report is therefore focused on cost-effective integration of wind- and solar in a high wind comprehensive energy system. Energinet.dk estimates that there are still a great deal of learning and efficiency gains in this type of scenario.

1.2. About the analyses and the results

A transition process aimed at ensuring fossil-free electricity and heat by 2035 has been analysed. In addition, a number of alternative scenarios have been analysed – including a path where fossil oil is phased out of the energy system towards 2035. This scenario still implies a certain amount of natural gas for peak-load electricity generation. In all the scenarios, focus is on achieving a competitive supply of energy services seen in relation to a fossil reference.

Overall, Energinet.dk estimates that a number of system measures, which are described in more detail in the report, can make the wind scenario more cost-effective, thus ensuring long-term competitiveness when using a fossil reference.

The described measures can particularly reduce costs in a scenario with large volumes of fluctuating electricity generated in or around Denmark. The measures are furthermore expected to reduce costs (albeit to a lesser degree) if Denmark chooses a scenario with a limited expansion of wind power and instead increases the volumes of imported biomass or continues using small volumes of fossil fuels. As such, it is generally a question of 'no regret' measures to prepare Denmark for possibly choosing the wind scenario at a later stage and for international develop-

ment with large wind power volumes in the region. The focus areas are summarised briefly.

Focus on measures reducing 'hedging costs' for energy services
A competitive energy system based on renewable energy means here that the energy system can provide energy services at a competitive cost with a fossil reference. In other words, the costs for end-users of energy services (heating, lighting, transport, cooling, process heating, etc.) form part of a more general assessment of the security of supply of the 'system'[3].

If the system is made more robust in the face of fluctuating resource prices, 'hedging costs' will be reduced, thereby contributing to more inexpensive energy services in general. Measures strengthening the robustness of the energy system are therefore introduced in the analysis. The interaction between the energy systems, electricity, heating, gas and liquid fuels increases flexibility, and the choice of solutions highly affects the robustness against fluctuating market resource prices.

Energy-efficient system integration reduces the need for the most expensive offshore wind power
The report points out system-efficiency measures which could potentially reduce the total need for wind energy by 15-25% compared to a traditional wind scenario, without using additional biomass. The reduction in wind power can derive from the last (and most expensive) offshore wind farms. Furthermore, the report points out that there could be a greater potential for inexpensive land-based wind power than the 3,500 MW limit of the energy scenarios, which can further reduce the need for offshore wind power. In general, energy efficiency improvements and better utilisation of wind resources in Denmark lead to fewer necessary investments in relatively expensive offshore wind power.

Less back-up capacity when cooperating across national borders and energy systems
Infrastructure and market integration over long distances can benefit from the fact that the wind usually blows somewhere – and that peak-load consumption rarely occurs everywhere simultaneously. A relatively comprehensive analysis of European time series of wind, photovoltaics and consumption over a ten-year period has been performed. This knowledge has been compared with scenario analyses for both Denmark and our neighbouring countries in the 2035/2050 scenarios. The analysis includes security of supply during shorter and longer periods with low levels of wind and photovoltaic power, both in Denmark and in Northern Europe. The analysis suggests a combination of flexible electricity consumption particularly capable of providing peak-load generation over minutes and hours and international market integration at distances of more than 500 km capable of delivering peak-load generation over several days. These solutions have the potential to reduce the need to pay for backup capacity (thermal power plants) by 25-35% in relation to a classic approach with peak-load capacity.

3 The overall security of supply is here defined as "the likelihood that energy services are available at competitive prices when demanded by consumers – without putting Denmark in a position of inexpedient dependence on other countries".
'Report on security of supply in Denmark' (*Redegørelse om forsyningssikkerheden i Danmark*), Danish Energy Agency, 2010.

Flexible consumption can ensure more efficient utilisation of the power grid

In the electricity transmission system today, a grid reserve (N-1) is used as a design and operating criterion. This means that reserve capacity must be available in the grid to allow handling of an outage of the largest unit (eg a transmission connection or an electricity-generating unit). A concept with focus on the long term has been analysed, where the flexible electricity consumption is used as a grid reserve which can be disconnected when required. New flexible electricity consumption will thus increase the overall level of utilisation of the grid, thereby reducing the need for long-term investments in grid capacity.

More inexpensive integration of green gases through interaction between different types of gas grids

The energy agreement analyses indicate that the gas system and RE gas[4] can be important instruments for ensuring security of supply and integration of energy from biomass and electricity from wind and photovoltaic power. It is also pointed out that the costs of upgrading RE gas to natural gas quality (SNG) can be relatively high. The report show perspectives on how local gas grids with RE gas (biogas, synthetic gas and H_2) and the overall gas grid can be integrated more closely in order to obtain security of supply, while at the same time limiting upgrading costs. Further analysis of these measures is required.

High-temperature waste heat must be utilised efficiently

A number of the conversion processes which will potentially be brought into play in the energy system in the coming decades emit or can absorb heat at a high temperature. These include power-to-gas, thermal gasification and fuel catalysis, among others. Using this high-temperature heat directly for low-temperature district heating leads to significant energy waste, since the energy from the heat can be further utilised before being used for district heating. An analysis has been carried out of the utilisation of this high-temperature heat for industrial process heating. Furthermore, an analysis has been carried out of system solutions where power-to-gas is controlled in a flexible manner in relation to the utilisation of this heat.

Research, development and demonstration (RD&D) and implementation

The majority of the described measures focuses on the long term, and to be realised in the energy system, RD&D efforts are required. It is therefore a prerequisite that the measures mature gradually over a number of years before being realised on a larger scale. Nevertheless, a number of technologies are ready to be rolled out, especially within electricity for heat generation (heat pumps), and it is important that the framework underpins the realisation of the potential of these technologies. The organisation of the regulatory framework must facilitate the realisation of the potential of these technologies to ensure an efficient transition.

4 RE gas is defined as gas produced without using fossil resources, in the same way as electricity from wind power is produced without using fossil sources.

2. Framework conditions – from a political and market perspective

2.1 Political vision for Denmark's energy supply

Denmark has a broad political vision of a transition of the energy system to renewable energy. This is a long-term vision where a complete transition is expected to be completed by 2050. In the electricity and heating sector, renewable energy is expected to play a major role already within 10-20 years. There is a political desire that Denmark carries out the transition in a cost-effective way to maintain an energy supply which aims to be competitive with a fossil reference.

In this report, the energy system is evaluated on the basis of the total system costs and the extent to which it is possible to ensure competitiveness in relation to the costs of the individual types of energy services. Energy services are here defined as the end product of the energy output, ie heating of buildings, transport, lighting, process heating etc.

The main requirements for political prioritisation are as follows:
- Competitive supply of energy services[5].
- High security of supply in the energy system and secure access to energy resources.

Independence from fossil fuels and transition to sustainable renewable energy resources.

With input from Energinet.dk, among others, the Danish Energy Agency has defined four long-term scenarios for an energy-based renewable energy system and a fossil reference scenario. The degree of biomass consumption varies in the four scenarios, where the wind scenario is characterised by the volume of biomass/biowaste being on a par with the Danish resources (a total of approx. 260 PJ).

2.2 Market framework conditions

Denmark is a small country with an open economy and a strong energy infrastructure to neighbouring countries. International development is therefore an essential prerequisite. The analysis is based on the IEA WEO 'New Policies' as a central estimate for fuel and CO_2 prices.

As shown in Figure 2, realised fuel prices (historical) are typically relatively fluctuating. The projection should be seen as a central average estimate, and fluctuations can be expected, also in the years to come. Robustness against fuel price fluctuations is thus an essential characteristic of the energy system as a whole. Equally important is robustness against the different transition scenarios chosen by the countries around Denmark and thereby also the electricity price in Denmark's neighbouring regions.

Sensitivity analyses have been made of alternative fuel and CO_2 prices from IEA's New Policies and Current Policies and of various scenarios for Denmark's neighbouring countries, see Figure 2.

2.3 System design strengthening security of supply with energy services

As electricity constitutes a relatively large share of the energy

5 Energy services are here defined as the end product of the energy output, ie heating, transport, lighting, cooling, process heating etc.

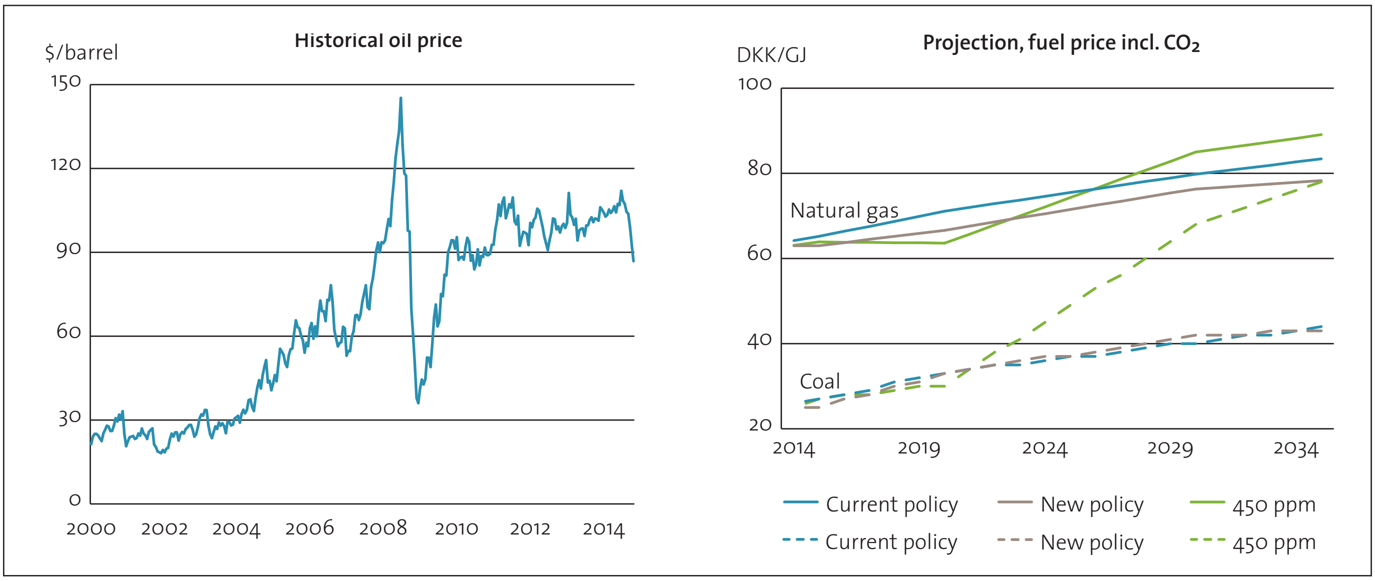


Figure 2: To the left: historical oil prices. To the right: IEA's expected fuel prices (IEA WEO scenarios).

supply, a holistic analysis of the security of supply is of increasing importance. In this context, the overall security of supply is defined as:

*"The likelihood that **energy services** are available at **competitive** prices when demanded by consumers – without putting Denmark in a position of inexpedient dependence on other countries".*[6]

Included in the calculation of the security of supply is the system's robustness against variations in wind/photovoltaic power, fuel and CO_2 prices, foreign electricity prices, new technology, new needs for new types of fuel for transport etc., see Figure 3.

In connection with a traditional (fossil-based) energy system, changes in resource prices will be reflected relatively directly in the energy service costs.

It will generally be possible to remove this uncertainty by hedging the energy resource for a longer period of time. The hedged costs of the energy service will therefore (simplified) be the expected costs of the energy service with additional payment for the hedging.

The analysis introduces factors (β factors) indicating the extent to which a change in resource prices on the input side of the energy system (see Figure 3) affects the costs of the energy service on the output side (covariance).
A β factor of 0 indicates that energy service costs are not affected by changes in resource prices, and a factor of 1 indicates that changes in energy resource costs are directly reflected in the energy service costs[7]. (A classic example of a high β factor here is Denmark's energy system before the oil crisis).

By ensuring this increased attenuation in the energy system, the β factors can be minimised, thereby reducing the uncertainty and the hedged energy price. The combination of CHP/heat pump/heat storage, for instance, provides a high level of decoupling between electricity prices and the price of generated heat.

Analyses show that efficient infrastructure and energy-efficient system integration between energy carriers in the form of electricity, heat and gas, including access to the respective energy storages in the energy systems, can ensure such robustness and attenuation to a great extent. It is estimated that a number of system measures can strengthen this attenuation and hence the overall security of supply, thereby strengthening the ability of the energy system to provide energy services at competitive prices. The costs of the measure should be seen in relation to the alternative costs of 'financial' hedging.

2.4 Denmark's strengths to realise the political vision

Denmark has a number of strengths making it possible to achieve an energy system which combines cost effectiveness with a complete transition to renewable energy supply. Particularly important strengths include:

6 Report on security of supply in Denmark (*Redegørelse om forsyningssikkerheden i Danmark*), Danish Energy Agency, 2010.
7 Energy service costs (hedged) = Energy service costs (expected) + β x Additional payment for hedging (resource).

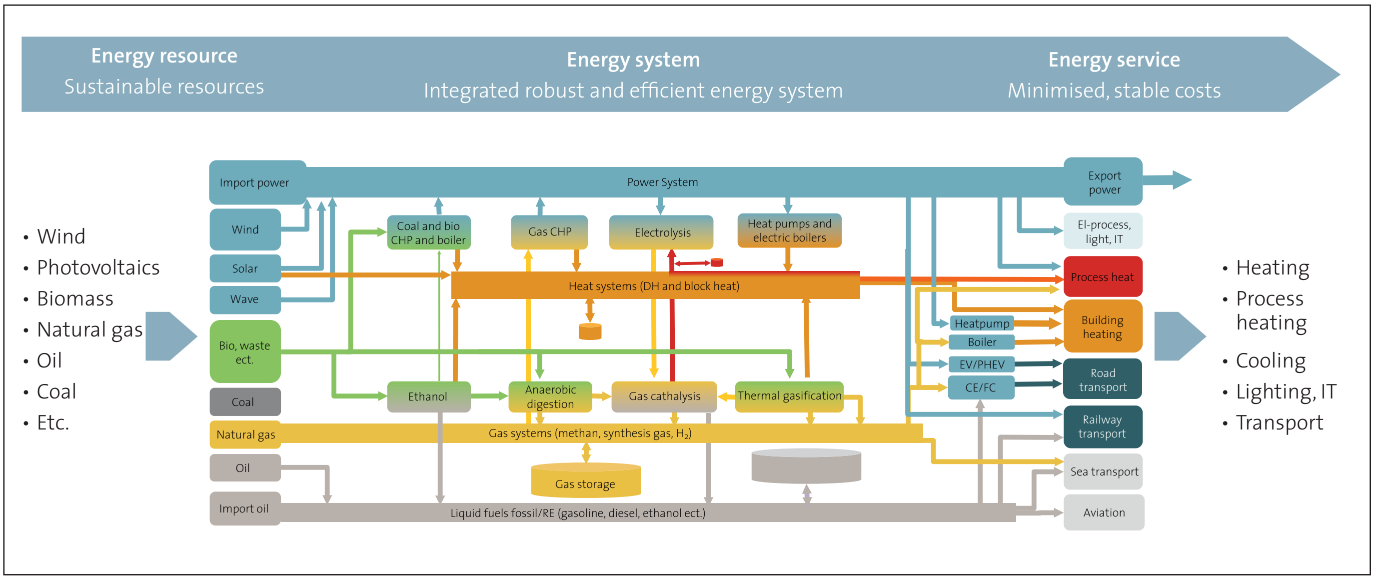


Figure 3: Value chain from resource to energy service. See also Appendix figure B1 with an overview of the value chain and a possible transition process.

- Good wind power areas with relatively low LCOE[8] (land-based wind, offshore, coastal).
- Major biowaste and residual resources from agriculture and the food industry.
- Energy system with good national and international energy infrastructure (electricity, heat, gas).

All in all, Denmark has a number of important comparative advantages when it comes to a wind/biowaste energy system.

2.4.1 Wind power as a competitive energy resource

As seen in relation to 'cost of energy', excluding integration and balancing, wind power is expected to be a relatively competitive resource for electricity generation in the long term[9].

It is also a non-fuel resource, thereby ensuring a relatively high level of security in terms of production price.
It is therefore considered crucial to reduce integration costs of wind power to a level where wind power is competitive, as well as ensuring system compatibility and a stable/reliable supply of energy services.

Analyses of the potentials of land-based wind power indicate that a significant part of the long-term expansion need can be realised onshore and at a considerably lower price than offshore wind power. Various degrees of expansion have been analysed, including simple 'repowering and upgrading' of wind farms and

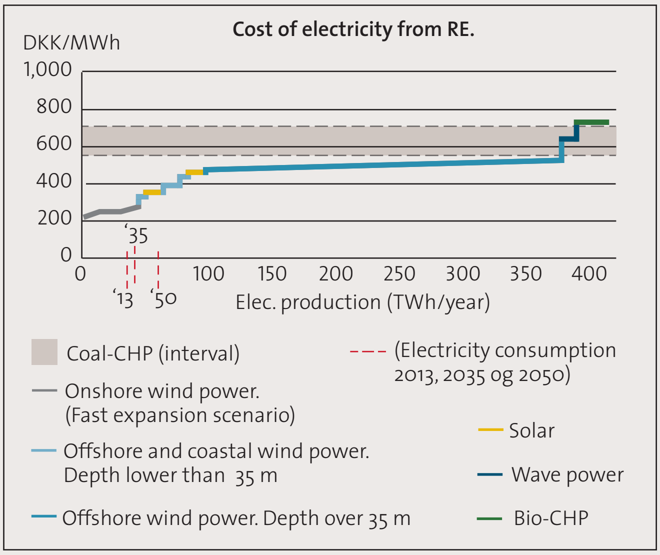


Figure 4: Long-term socio-economic costs, including investment (LRAC) in 2030, for electricity generation. Cost level for coal KV is indicated for IEA New/Current Policy and 450 PPM. Photovoltaic plants in empty fields are not shown in the figure. The Danish Commission on Climate Change Policy has previously suggested 25 TWh as an example of potential.

the construction of new wind farms to a greater or lesser extent. The production costs of wind power are growing significantly as the expansion of wind power is increasing, see Figure 4. Therefore, high energy efficiency combined with high flexibility in the use of electricity is also essential to the overall competitiveness.

8 LCOE: Levelised Cost of Energy = Total costs for (CAPEX+OPEX) energy production, but excluding integration in the energy system.
9 Technology data for energy plants, Danish Energy Agency and Energinet.dk, May 2012 with a few revisions in October 2013, January 2014 and February 2015.

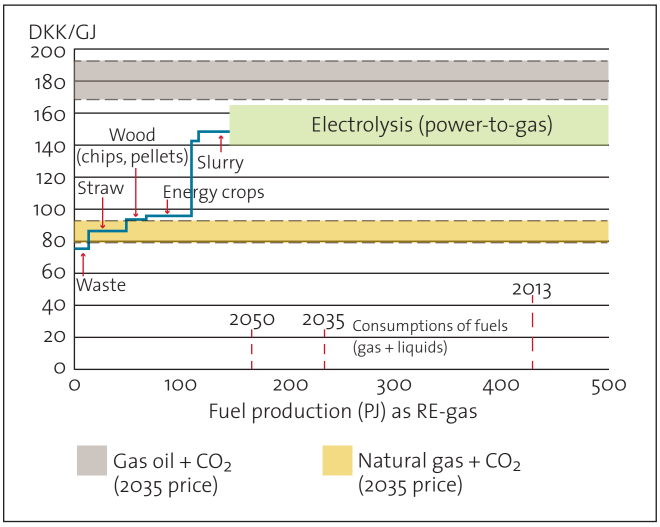


Figure 5: Long-run average costs including investment (LRAC in 2030) and the potential from Danish resources for RE gas production (potential/cost curve). Costs are indicated for non-cleaned and non-upgraded RE gas. Fuel consumption in 2013 and scenarios for 2035 and 2050 are indicated at the bottom of the figure.

2.4.2 Flexible production of RE fuels from biomass, waste and wind

In general, an efficient electrification of energy services is a significant measure to ensure cost-effectiveness in the wind scenario. However, a number of energy services will still require access to fuels – such as heavy transport, air and sea transport, certain types of high-temperature industrial process heating, peak-load power plants etc.

There is access to very large volumes of fuel production from power-to-gas, see Figure 5. In connection with an 'imagined' additional expansion of 22 GW wind power and power-to-gas, it would be possible to meet the current fuel consumption.

But this power-to-gas production is typically more expensive than the production of fuels from biowaste resources, and most biofuels require access to a carbon source (CO_2 source). Denmark has relatively large volumes of biomass and biowaste which can be included in the energy production. Seen in relation to the current fuel consumption, the existing amount of bioresources does not suffice for the production of biofuels and roughly covers the need for liquid fuels today, see Figure 5. Today, Denmark furthermore uses biomass for other purposes, including heat generation not related to fuel production.

As shown in Figure 5, there is only a limited amount of 'inexpensive' biomass and waste resources available in Denmark. Therefore, a gradual transition of biomass and waste, which today is used for heating purposes (boilers with no or little electricity generation), to fuel production is considered vital in terms of competitiveness. This is a process which involves waste management, and the transition is expected to take place over a number of years.

Similarly, reducing the fuel consumption from energy services that can be electrified is vital. Figure 5 indicates a possible reduction of the fuel consumption from 2013 up until 2035 and 2050 by means of efficient electrification and utilisation of surplus heat for heating and process heating. This conversion of the energy supply means that the remaining fuel-dependant energy services will become increasingly competitive with fossil solutions.

It is deemed necessary to adapt the current framework conditions to ensure that the microeconomic framework supports this transition to a greater extent. The figure indicates the costs of RE gas generated from biomass and electricity. Further conversion of RE gas to liquid fuels in the transport sector can be relevant, depending on the transport activity.

3 Concept solutions for an efficient sustainable energy system

3.1 General

Scenario analyses of a wind scenario show that even with high energy efficiency, it will be necessary to expand wind power to ensure wind power generation is three to five times higher than today. Challenges in relation to electricity infrastructure capacity, peak-load electricity capacity, electricity balancing and integration of wind power etc. will be significantly intensified in the coming decades. Therefore, identification of new types of solutions (concepts) that meet these challenges in a cost-effective manner is essential to allow for a system development strategy (RDD) and system planning of the electricity and gas infrastructure.

The concepts are particularly concerned with reducing system costs:

- Minimisation of costs for peak-load electricity capacity.
- Increased utilisation of the power grid (transmission/distribution).
- Minimisation of costs for electricity system balancing and ancillary services.
- Integration of biomass and RE electricity for flexible fuel production etc.
- Integration of the energy system across the energy carriers to incorporate resource price stability into the entire supply chain (low β factors).
- Cost-effective control of the overall energy system.

A number of concepts forming the basis of system design are described in the next sections and in further detail in the report.

3.2 A possible transition process taking into account socio-economics

An analysis has been carried out of a possible transition process up until 2025, 2035 and 2050 which meets the political visions, including the government's objectives for 2035. This socio-economic analysis incorporates the concepts for cost-effective integration of wind power which are further described in sections 3.3-3.8. The assessment is subject to uncertainty, but the overall situation is that both wind power and flexible electricity consumption is expanded to ensure gradual integration of increasing volumes of wind power in heating, process heating and the transport sector, see Figure 6.

In connection with an appropriate energy system design, it is assessed that most types of energy services in 2035 can be provided from renewable energy at costs equivalent to fossil reference costs. This assessment assumes a technology development which corresponds to the technology catalogue assumptions. It is furthermore assumed that the energy system is efficiently integrated to ensure that energy conversion facilities have good market access in relation to main and by-products, thus maintaining an appropriate number of delivery hours. Peak-load electricity capacity, high-temperature process heating and heavy transport constitute the energy services that are most difficult to make competitive with a fossil reference.

Natural gas remains a cost-effective type of fuel during the entire period. Natural gas may be appropriate for some of these uses and as a buffer and backup combined with RE gas.

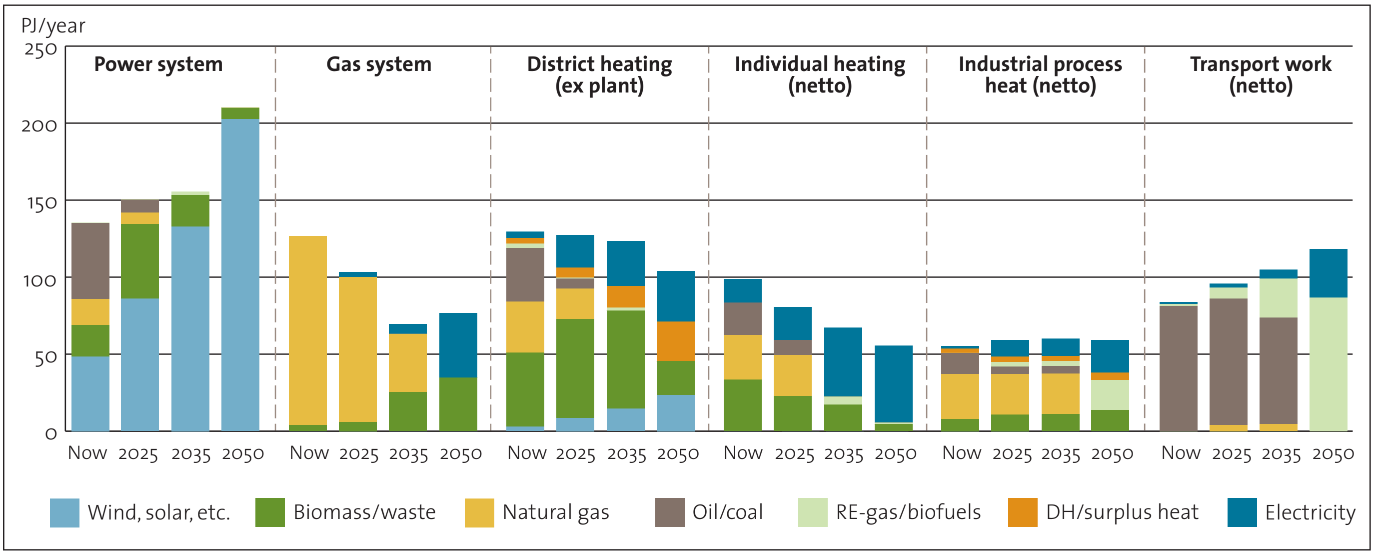


Figure 6: A possible socio-economically efficient transition process. See also appendix figure with an overview of the energy system.

The wind scenario demonstrates great robustness against external framework conditions, such as fuel prices and CO_2.

3.3 Optimisation of the system's energy efficiency

The production of RE power and the production of biofuels follow an increasing cost curve, see Figure 4. It is therefore essential that the energy system is energy efficient throughout the entire value chain. A large share of the energy loss (measured as exergy) occurs in connection with the energy conversion, and focus on energy-efficient conversion processes is essential to total system costs, see Figure 7 showing energy efficiency in connection with conversion. When the share of technologies with low conversion efficiency grows, see the right-hand side, the need for more expensive wind power resources in the wind scenario increases.

Focus in system design is on reducing the conversions which result in high energy losses, and which at the same time can be realised in a cost-effective manner.

Measures boosting energy efficiency:
- Conversion of boilers for heating to heat pumps.
- High-temperature heat pumps for industry process heating.
- Minimisation of biomass and waste as base-load heat and combined heat and power. Security of supply is ensured through peak-load power plants and interaction with other countries.
- Utilisation of high-temperature process heat from thermal gasification of biomass and biofuel production in a power-to-gas system and for process heating.
- Minimisation of the upgrading of RE gas by combining local RE gas grids with overall natural gas quality grids.

The development of energy losses in the system as a whole is shown in Figure 7. In the event of a complete transition to renewable energy, the system's electricity consumption will thus be approx. 60 TWh, which is about 20% less than a classic wind scenario. This means that the total need for wind power (land-based and offshore) is approx. 50 TWh. If priority is given to a significant expansion of land-based wind power, the wind power can be realised without using the relatively expensive deep-water areas, see Figure 4.

3.4 European time series for wind and photovoltaics are assessed in system design

Wind and photovoltaic power will play a key role in the wind scenario. An energy system which is generally robust (low β factor) against wind power fluctuations in both normal years and more deviant years is important as regards the general security of supply.

To assess these factors, an analysis has been carried out of Danish and European time series for wind and photovoltaics over a statistical period of ten years. This analysis has been combined with scenario analyses for both Denmark and our neighbouring countries in the 2035/2050 scenarios. For example, the analysis includes security of supply during shorter and longer periods with low levels of wind and photovoltaic power production, both in Denmark and in Northern Europe. The analysis indicates that flexible electricity consumption can be an efficient means to handle challenges with regard to rapid changes in wind power pro-

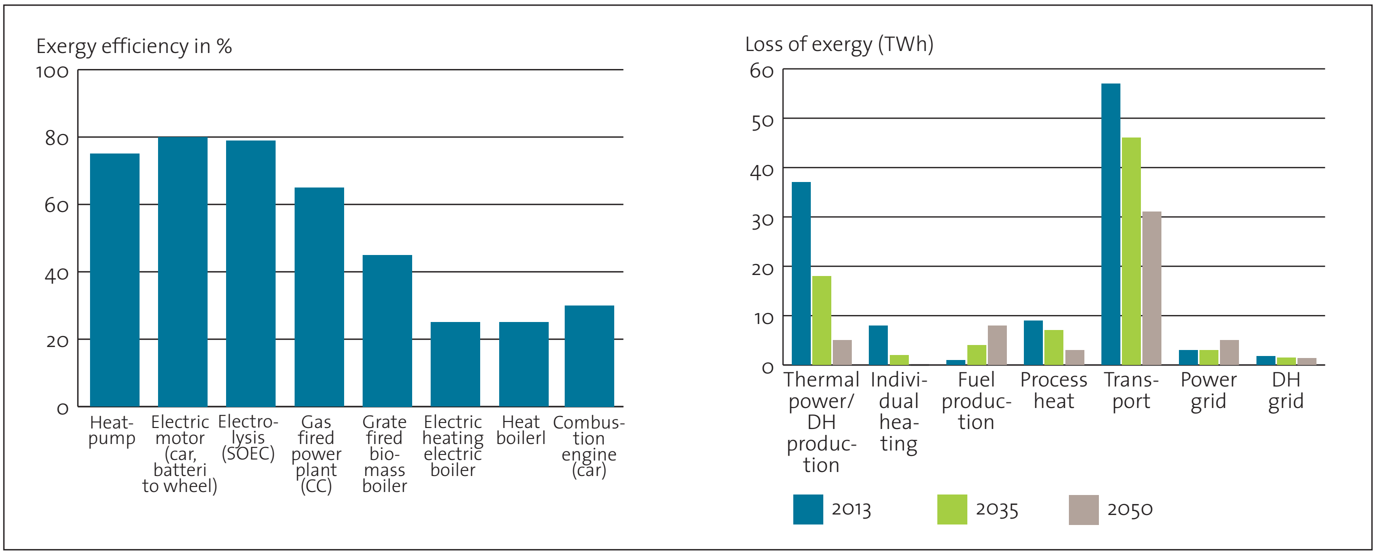


Figure 7: Technology efficiency (exergy) to the left and calculated exergy losses in a scenario with high energy efficiency to the right.
**1) Efficiency in connection with heating shown as Carnot efficiency and a district heating unit is 25% in relation to electricity and fuel.*

duction (ramps), such as regulating power services and interruptible consumption in periods of up to 12 hours with particularly low levels of wind and photovoltaic power in Denmark. However, in periods of more than 12 hours with low levels of wind, access to flexible electricity consumption is minimal, which calls for other means, see Figure 8. Here access to power from power plants and international connections are key factors in ensuring security of supply. Access to power from other countries in periods when Denmark is under particular pressure has been analysed.

The analysis shows that areas located more than 500 km from Denmark make the most efficient contribution in terms of power in these special periods – including Norway and the United Kingdom, among others. The analyses show that these areas have a power surplus in the special periods during which Denmark is under pressure in terms of capacity.

System analyses show that in combination with international connections, the energy system can, all in all, store the necessary energy to balance variations in both wind and photovoltaic power for the 2025, 2035 and 2050 scenarios. See Figures 10 and 11, which show the use of international connections for balancing purposes and access to storage in the 2035 energy system.

3.5 New principles for operating the power grid in combination with the rest of the energy system

The current electricity transmission system uses a grid reserve as the design criterion. This means that reserve capacity must be available in the grid to allow handling of an outage of the largest unit (eg a transmission connection or an electricity-generating unit). A concept has been analysed in which the flexible elec-

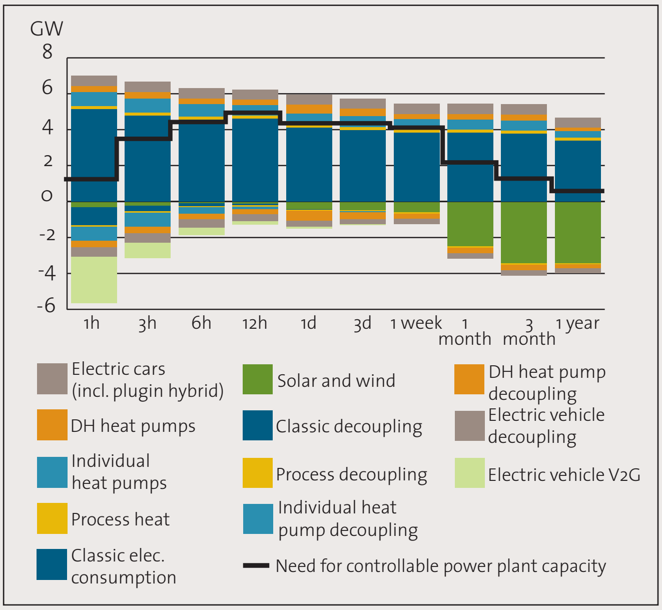


Figure 8: The figure shows the maximum need for residual production of electricity (electricity consumption minus wind/photovoltaic power production) in connection with different periods in the 2035 scenario. The calculation is based on variations in time series for wind and photovoltaics over a ten-year period. The positive part of the columns shows electricity consumption and the negative part shows wind/photovoltaic power and interruptible consumption. The black line shows the resulting capacity need.

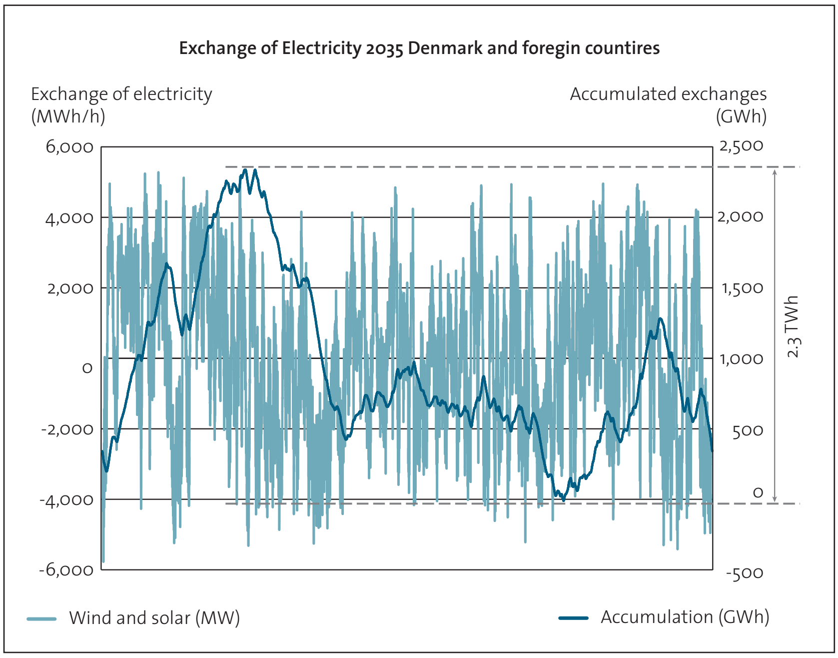


Figure 10: Exchange of electricity with international connections in 2035.

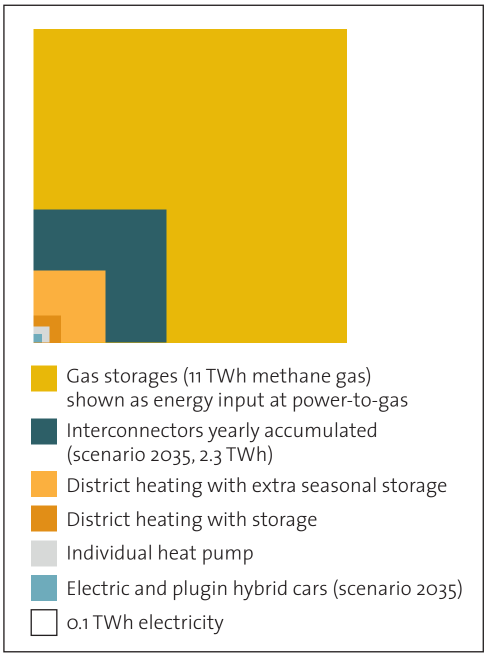


Figure 11: Storage capacities in the 2035 energy system shown as an area.

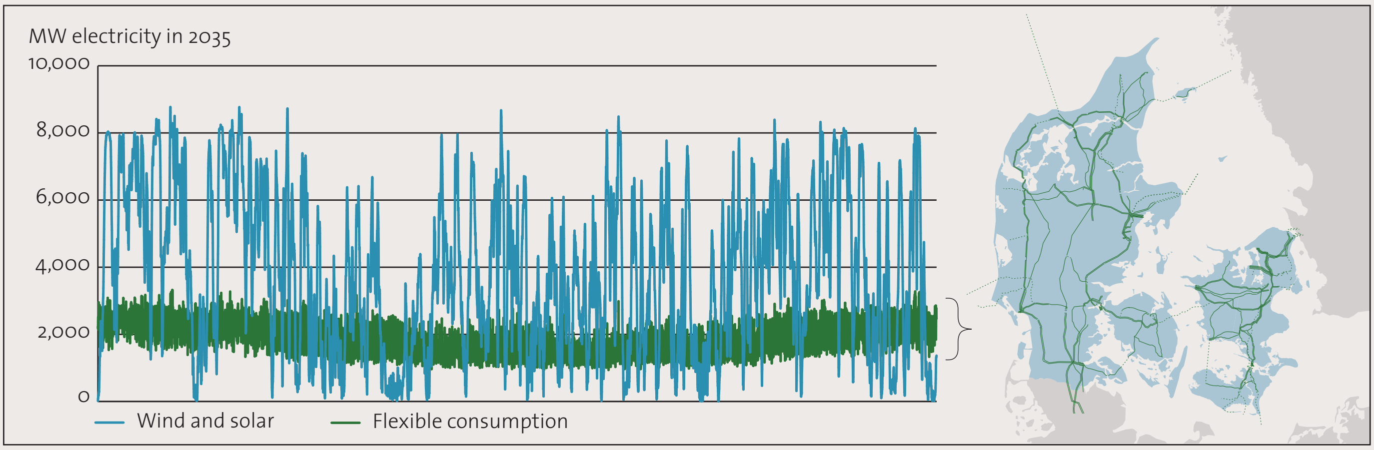


Figure 9: Flexible consumption per hour and geographical location in substations are analysed as a possible grid reserve in the power grid, which can increase the level of utilisation.

tricity consumption is used as a grid reserve. Also use of V2G[10] from electrical vehicles has been analysed.
In this way, utilisation of the transmission grid can be increased. Grid analyses carried out using a special edition of the 'PowerWorld' grid analysis tool currently indicate that this concept can increase utilisation of the electricity transmission system, thereby reducing the long-term costs of expanding the system. In the continued work of putting the Network Development Plan into perspective, Energinet.dk will analyse concepts for increased utilisation of the power grid.

10 V2G = Vehicle to grid (system solution where electric vehicles can reverse charging and provide power to the grid).

3.6 Ancillary services from flexible electricity consumption

Analyses suggest that an appropriate transition in socio-economic terms will result in relatively large volumes of flexible electricity consumption up until 2025/2035. Analyses have been carried out of the need for regulating power services with five-minute intervals in connection with increasing volumes of fluctuating wind and photovoltaic power. These have been compared with available, quickly adjustable electricity consumption. The 2035 analysis shows that more than 95% of the time, flexible consumption will, in principle, be able to deliver the necessary regulating power capacity within the delivery hour. Market

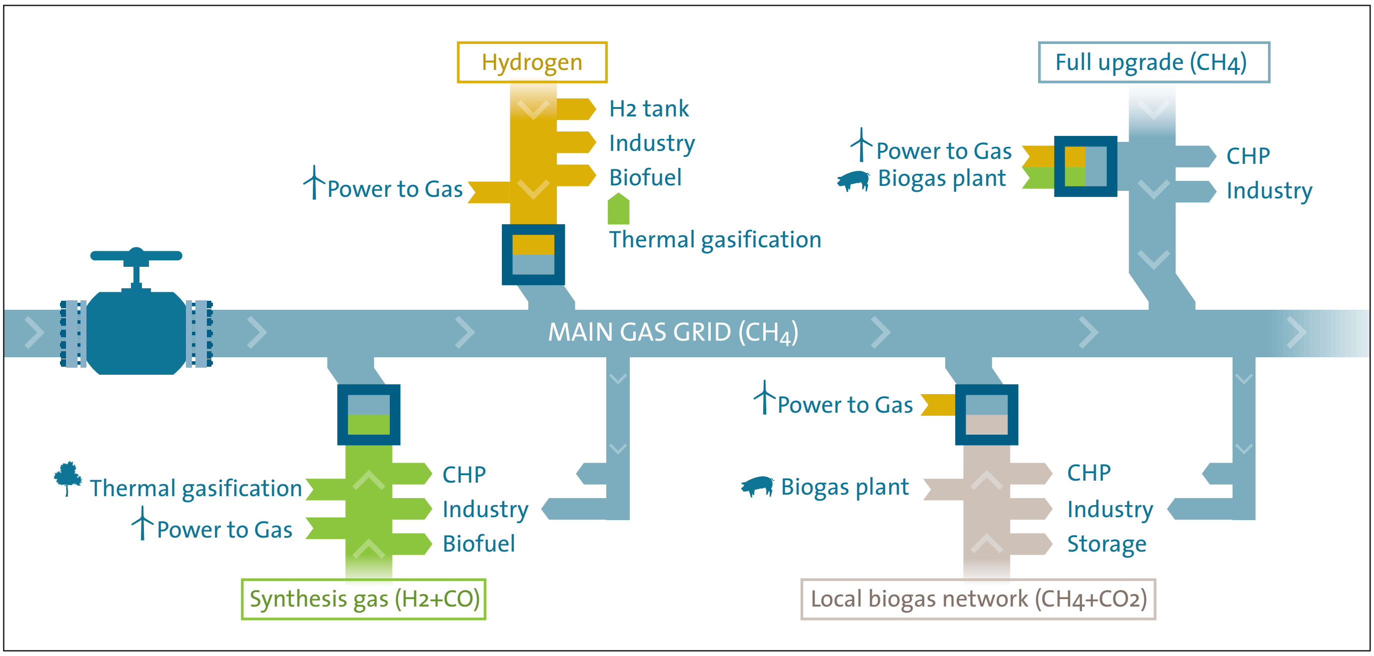


Figure 12: Principles for interaction between local RE gas grids (biogas, synthetic gas, H_2) and the overall gas grid.

solutions realising parts of this potential will be of vital importance in terms of adjusting market models to these resources.

3.7 Integration between new local RE gas grids and the overall gas grid

The energy agreement analyses indicate that the gas system and RE gas can be important instruments for ensuring security of supply and integration of energy from biomass and VE electricity from wind and photovoltaic power. It is also pointed out that the costs of upgrading RE gas to natural gas quality (SNG) can be relatively high. Therefore, a number of perspectives on how local gas grids with RE gas (biogas, synthetic gas and H2) and the overall gas grid can be integrated more closely to obtain security of supply by means of backup from the overall gas grid, while at the same time limiting upgrading costs, see Figure 12.
It is necessary to strengthen cooperation between gas TSOs and DSOs to integrate and analyse different types of solutions and handle gas quality requirements in local grids.

3.8 Perspective of increased high-temperature integration in the energy system

3.8.1 High-temperature heat pumps for industry/services

A number of new technologies are expected to increase the need for efficient high-temperature integration in the energy system. Analyses show that high-temperature integration is important for ensuring overall system efficiency, see also Figure 7.

Today, process heat for industry and services is primarily produced by means of oil or natural gas. Some industries are increasingly using biomass boilers. In recent years, technology for high-temperature heat generation from heat pumps has become commercially available. The potential for high-temperature heat pumps in industry has been analysed. Preliminary assessments indicate that a significant part of the industrial process heat can be supplied by heat pumps which are integrated into the electricity system and potentially also into the district heating system.

3.8.2 Integration of high-temperature heat in power-to-gas

Thermal gasification and fuel catalysis produce surplus heat, typically at temperatures of more than 350 degrees. New types of electrolysis (SOEC) can emit or absorb heat in a flexible way, depending on the state of the system. This opens up new possibilities for efficient use of high-temperature heat. Direct use of this high-temperature heat for district heating will result in significant energy losses (loss of exergy), and the analysis shows that the energy resource need and total system costs can be reduced by efficiently integrating high-temperature heat in the energy system.

3.9 Cost-effective control of energy system for new concepts

The (physical) basis for the necessary flexibility in the energy system is considered to be in place, see Figures 10 and 11.
To activate the flexibility available in the energy system, market solutions may be necessary in which electricity, heat and gas vary in price down to consumer level . Markets with real-time-prices can constitute a significant strength, but also present a challenge in terms of controlling system stability. Strong knowl-

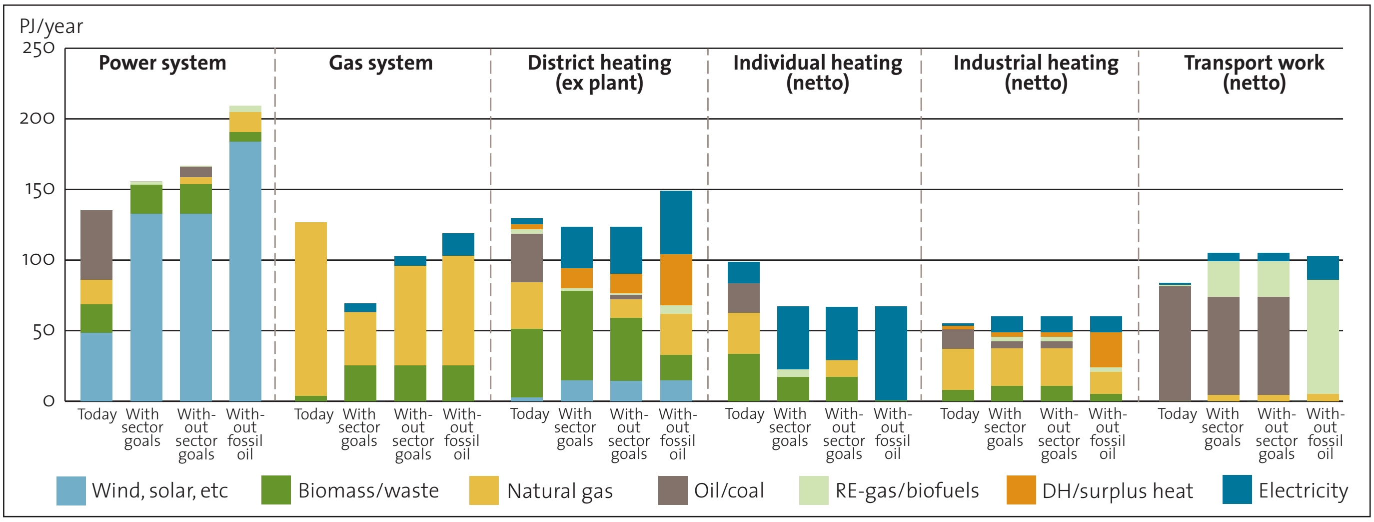


Figure 13: Scenarios for the 2035 energy system in connection with different transition processes. 1) With sector goals of fossil-free electricity and heating, 2) Without sector goals but still some biomass in electricity and district heating and 3) Transition to energy system without fossil oil and minimised biomass in electricity and district heating. Part of the RE gas is used directly in the production of fuel. See energy flow diagrams in the appendices.

edge of the interaction between market models for electricity, gas and heat and the underlying dynamics in the energy system is of particular importance to maintain stability in the entire energy system and to system security.

3.10 Robustness against changed environmental conditions

To assess the robustness of measures in the energy system, a number of sensitivity analyses have been carried out of the system up until 2035. The analyses include how changes in international framework conditions affect system development, given that the market ensures a socio-economically efficient transition. This includes an assessment of a 'green' and a 'blue' environmental scenario and a transition with/without sector goals in 2035 regarding optional use of fossil fuels in electricity and district heating. The international scenarios are based on ENTSO-E visions 1 and 4 for Europe. The described system measures are deemed to be robust against the development of foreign framework conditions.

In this connection, a scenario has been analysed in which fossil oil consumption is phased out of the Danish energy system up until 2035. This results in a need for increased production of biofuels from thermal gasification combined with power-to-gas. To realise this transition, biomass and waste must primarily be allocated to fuels, and to a much lesser degree to heat and electricity. In this scenario, there is also a higher proportion of land-based wind and photovoltaic cells and a larger number of electric and hybrid vehicles. However, the electric vehicles are only introduced as they become competitive, see data from 'Alternative propellants in the transport sector'.

There is an increased consumption of natural gas in this scenario in which oil is phased out by 2035, from approx. 40 PJ to 80 PJ of natural gas. However, as the oil is phased out of the energy system, there is a decline in overall CO_2 emissions from approx. 14 million tons in the 2035 reference scenario to approx. 6 million tons CO_2. In terms of cost effectiveness, this approach is comparable with the reference scenario, assuming a certain development in fuel prices, see the IEA New Policies scenario and technology data assumptions.

The competitiveness of this scenario depends on:

- Access to use surplus heat from fuel processes for industrial process heating, as input to power-to-gas and as district heating. This means that if this heating market only comprises established plants, it will result in poor economic performance.
- The gas system being integrated with these processes in such a way as to allow synthesis gas to form part of a market, see flow figure in Appendices and Figure 12.
- Inexpensive bio by-products and waste etc. not allocated to other parties (see Figure 5).
- The development of biofuel production technology, see technology data assumptions.

System-integrated fuel production activities can potentially take place in areas where power plants and waste incineration plants are currently located.

4. From research and development to implementation

The analyses suggest that a high level of energy efficiency and flexibility in the energy system is important for making an energy system with large volumes of wind power competitive with a fossil reference. Some of the main energy-efficient solutions for tomorrow's energy system are now ready for the market and can be implemented to a large extent, such as heat pumps for heat generation. However, a number of the potential future solutions require that efforts be made in terms of research, development and demonstration (RD&D) in order to be ready for large-scale roll-out.

Figure 14 indicatively illustrates the level of maturity and energy efficiency in different key conversion technologies. The figure indicates which solutions are ready for implementation, or which alternatively require RD&D.
As shown in Figure 14, existing technologies for electrification of heating are relatively mature for the market. It is important that the framework conditions support the realisation of these technologies to the extent it is deemed socio-economically appropriate.

Control and market are key factors in achieving efficient operation of the technologies. The Danish research programmes support the development of new components and solutions in a renewable energy system and the development of control solutions. Energinet.dk will give high priority to knowledge sharing between system analyses carried out by Energinet.dk and specific research environments at universities and support Denmark's strong global position in the area.

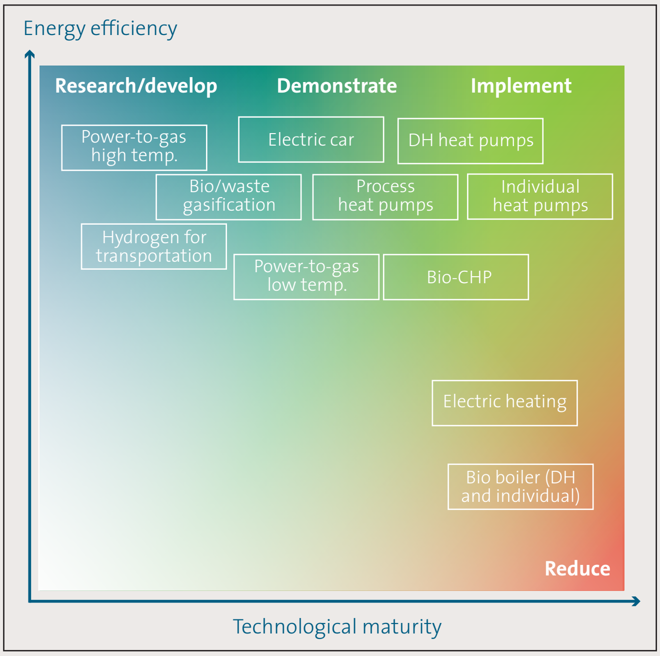
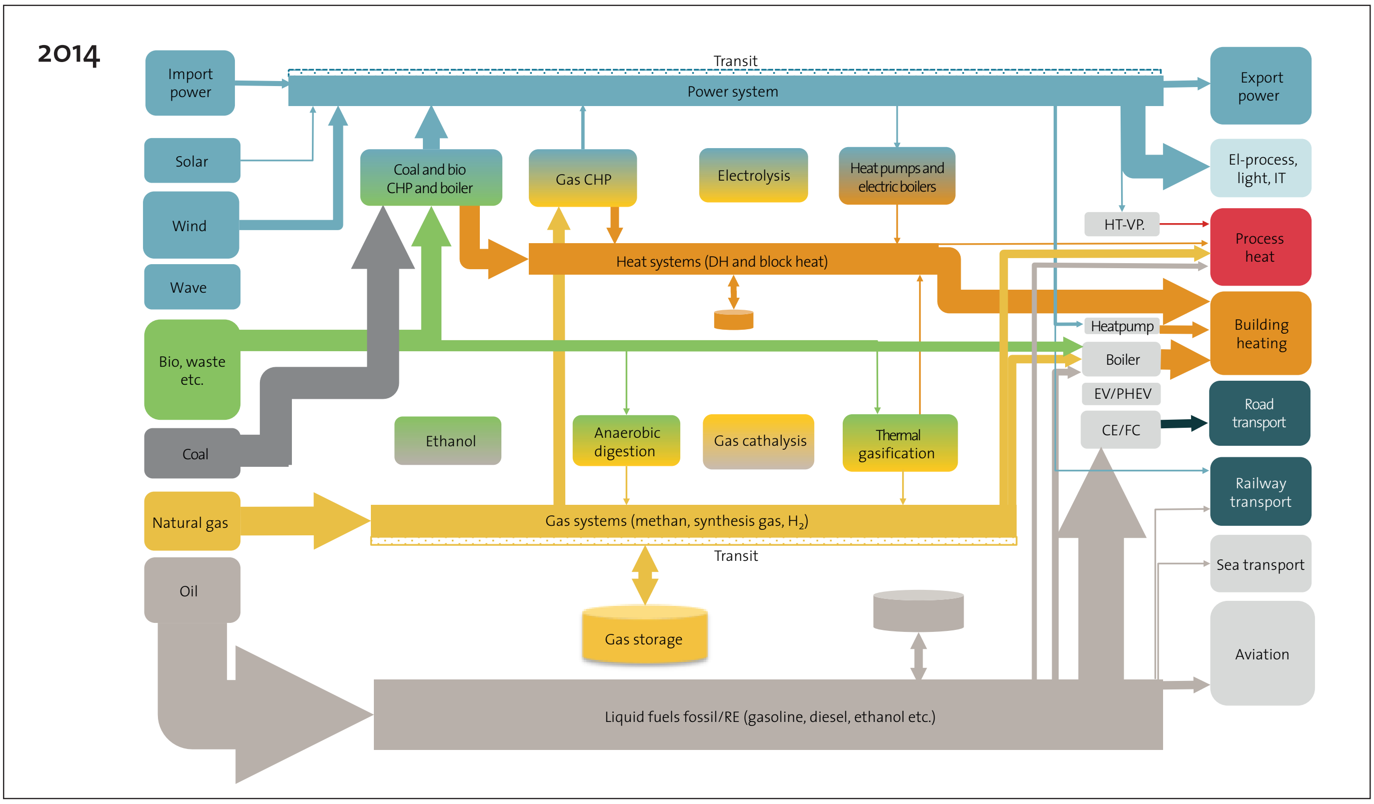
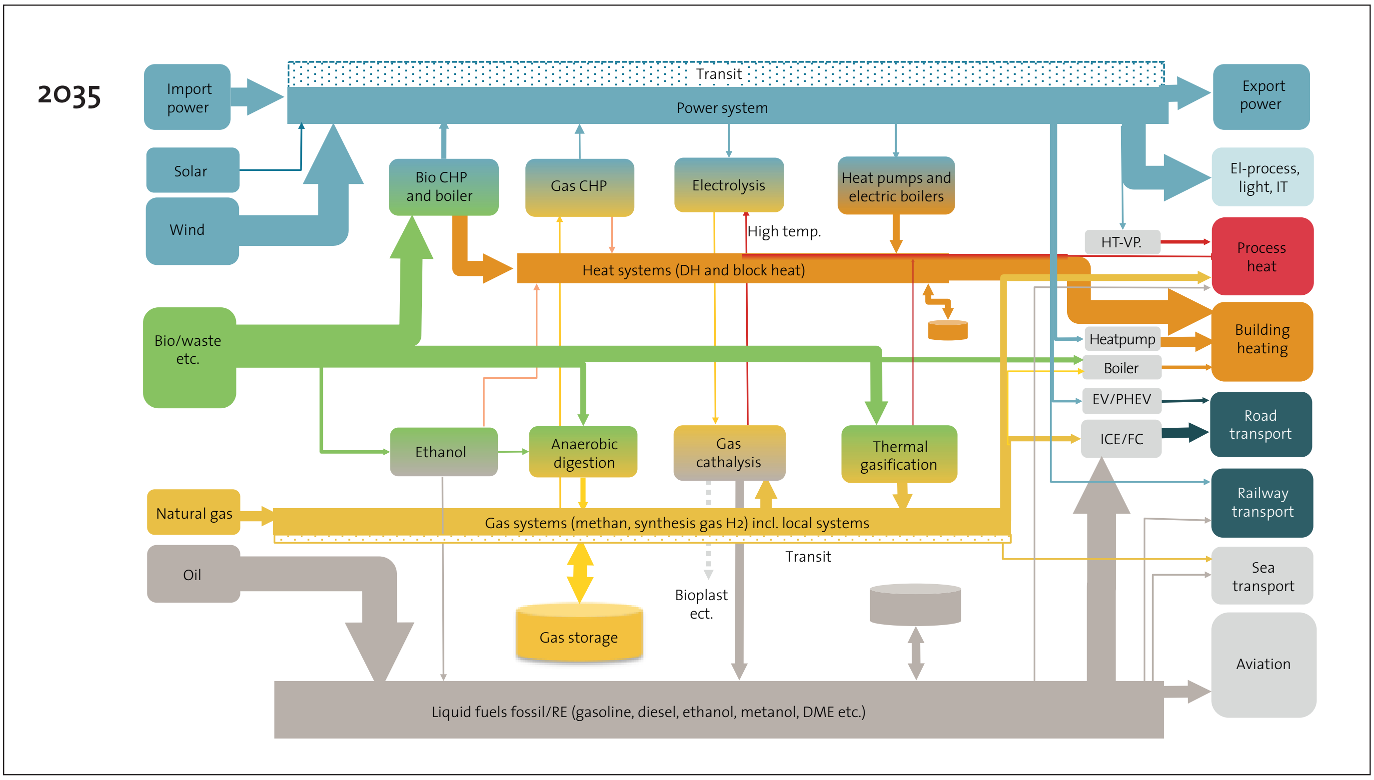


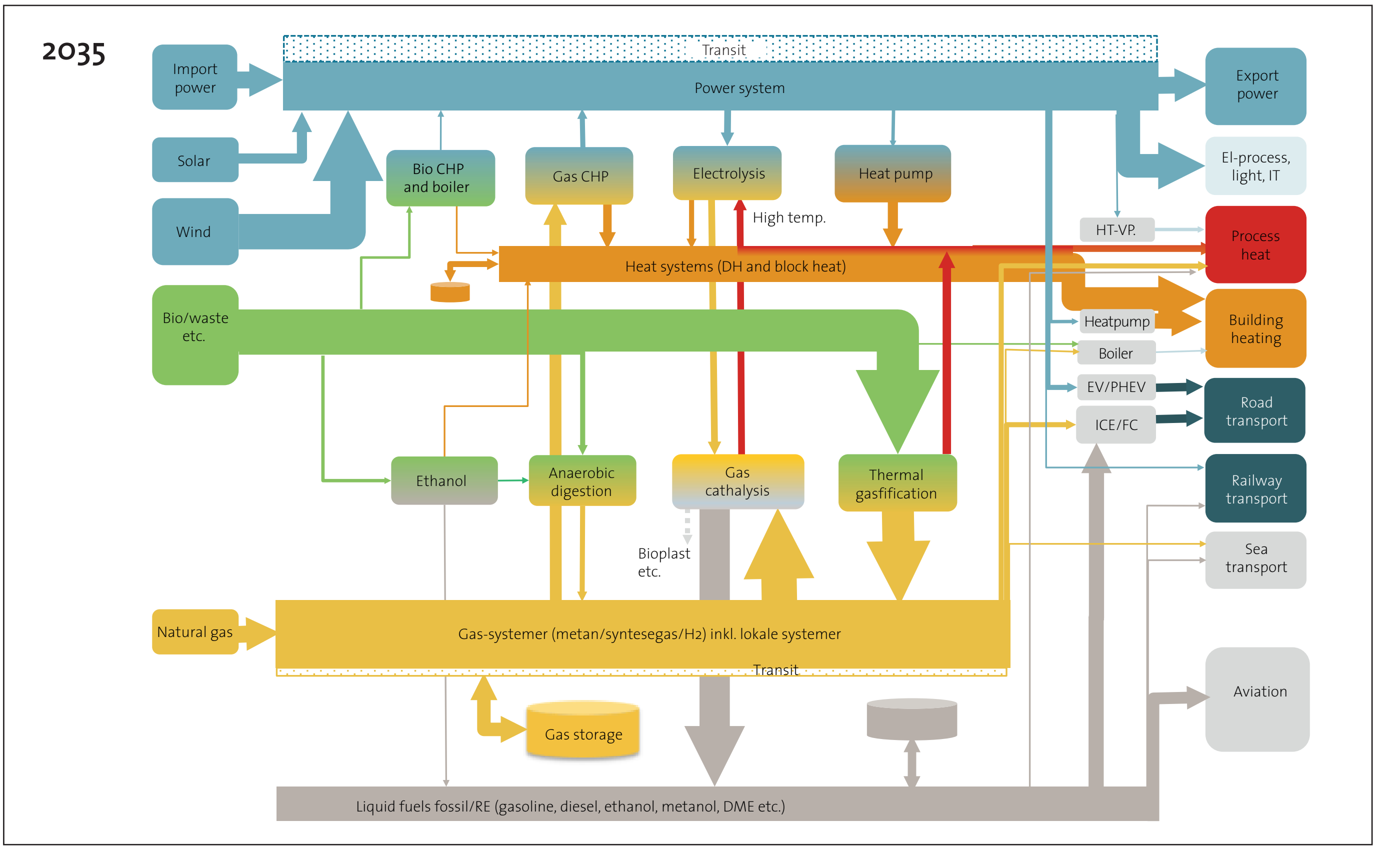
Figure 14: Indicative illustration of the maturity of energy technologies and energy efficiency.

Appendices

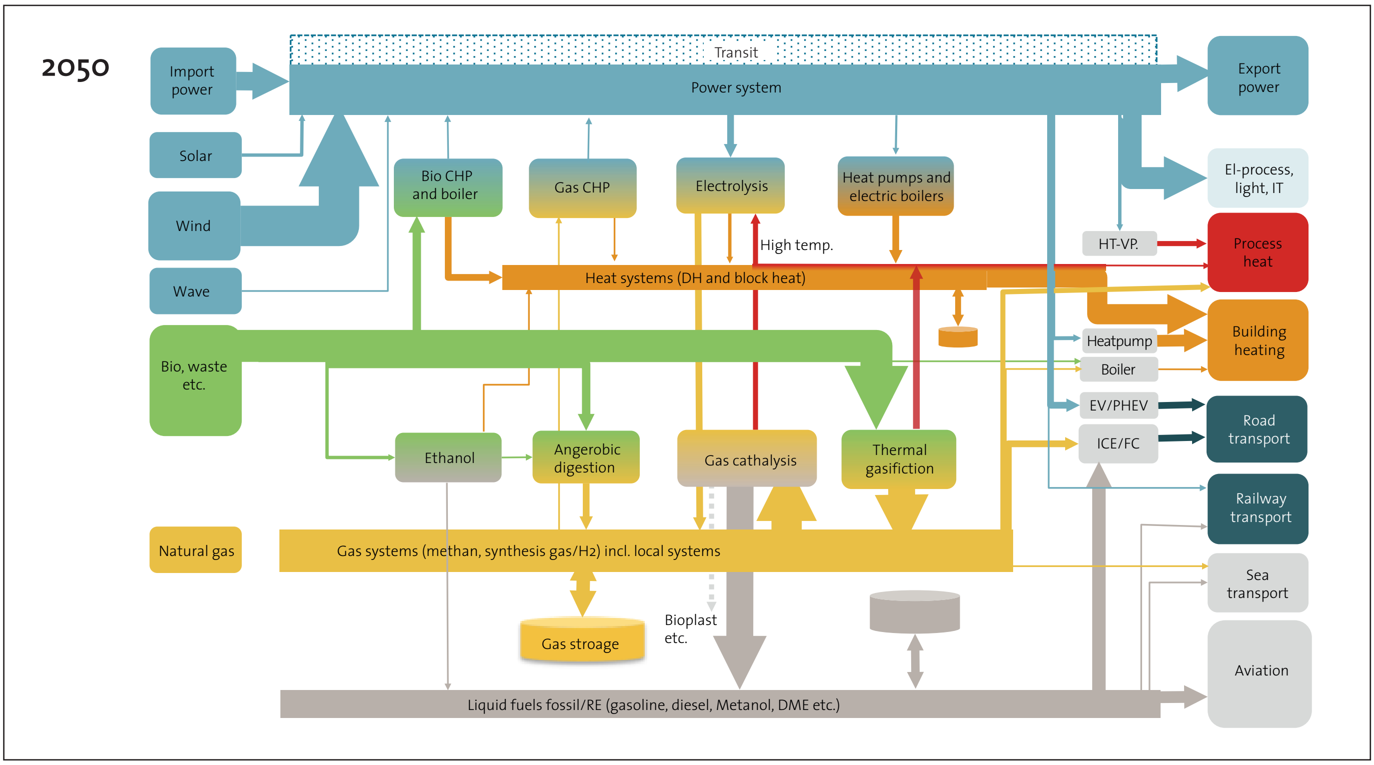




Energy flows in the 2014, 2035 and 2050 scenarios. Arrows with energy flows are scaled indicatively. Reference is made to background data for a more accurate description of energy flows.



2035 – Without fossil oil in the energy system



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