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IDA's Energy Vision 2050

A Smart Energy System strategy for 100% renewable Denmark

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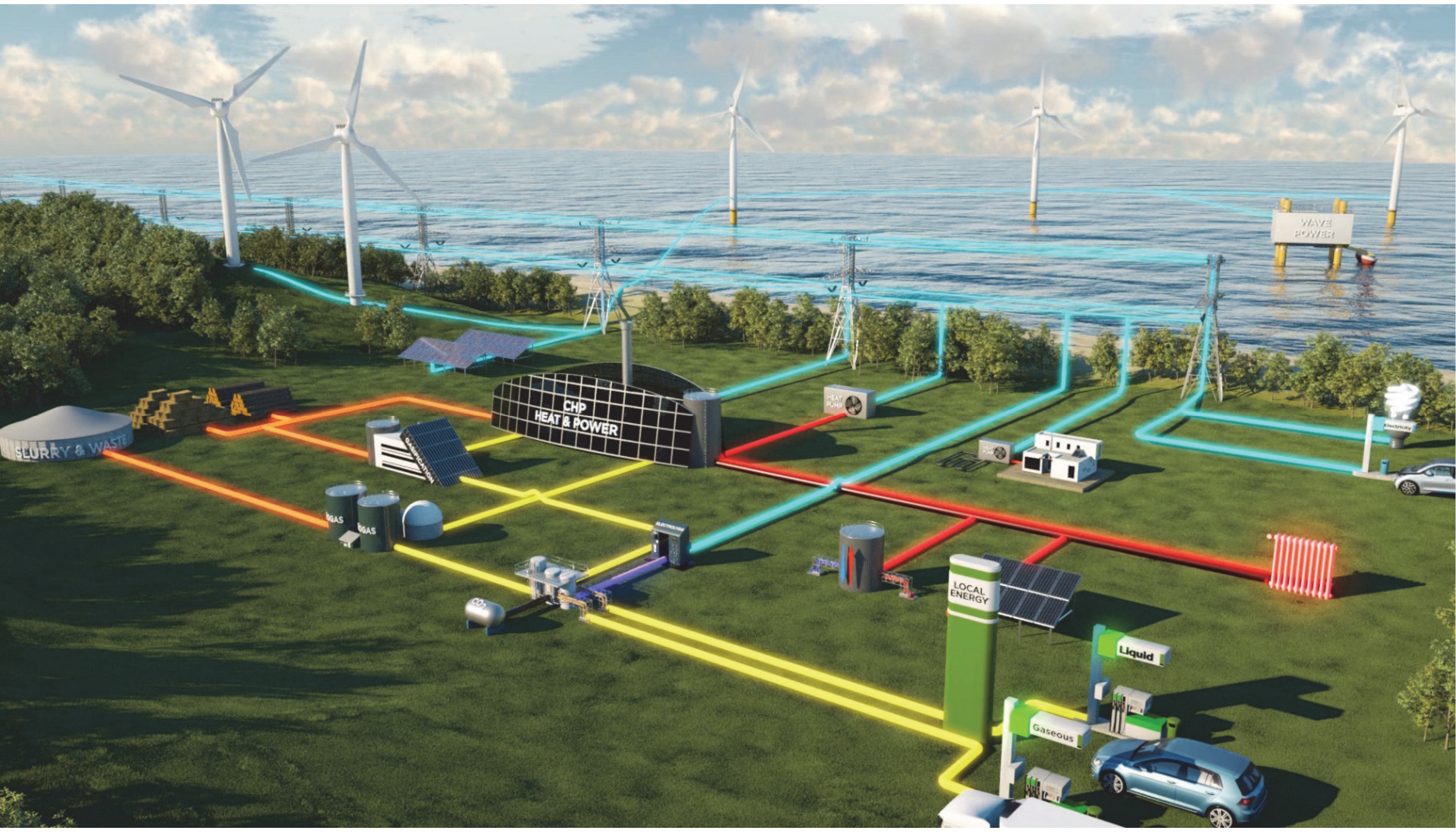
The Danish Society of Engineers, IDA

a modern professional association for
technical and science professionals

Executive Summary

IDA's Energy Vision 2050

A Smart Energy System strategy for 100% renewable Denmark



AALBORG UNIVERSITY
DENMARK

Executive Summary
IDA's Energy Vision 2050
A smart energy system strategy for 100% renewable Denmark

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Production courtesy of Blue Planet Innovation

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NORDIC ECOLABEL

IDA's Energy Vision 2050

This is IDA's Energy Vision 2050. With this vision, we bring into focus how an intelligent integration of the electricity, heat, gas and transport sectors can create a robust energy supply for Denmark in the future based on renewable energy.

IDA's Energy Vision is an input to the debate. Because we want a debate in Denmark on how we can reach the political goals of replacing fossil fuels completely. At the same time, we see the transition of the energy system as an exciting opportunity for citizens and businesses. The intelligent transformation of the energy system also creates a direction which can initiate export and jobs, benefitting all of us.

We have a certain responsibility to look at the energy system from a technological point of view. Where are we today and what can we expect from the energy technologies of the future? Fluctuating wind and solar energy production is already affecting our energy system, and it is a transformation which is here to stay. Luckily, the intelligent solutions can interact in smart systems which use sensor technology and automation to create dynamics between production and consumption.

An important conclusion from IDA's Energy Vision is that we need to stop thinking in sectoral terms and start considering cross-sectoral interaction. We can benefit greatly from perceiving the energy system as one system with the integration of sectors such as industry, transport, households and buildings. The electrified energy demand will play a more central role in the future, both for the individual house owner and in businesses. We need to adjust to the idea that the total energy demand in Denmark needs to decrease, while our individual electricity demand is allowed to increase.

IDA's Energy Vision 2050 builds on the work in IDA's Climate Plan 2050 (2009) and IDA's Energy Plan 2030 (2006). It is based on contributions and input from IDA's professional networks and from Aalborg University's long-standing work on energy system analysis. I wish to thank everyone who has contributed to IDA's Energy Vision 2050. I hope that the technological voice will serve as a valuable input to the discussion about how Denmark can develop a robust energy system based on renewable energy in the years towards 2050.

Frida Frost

President

The Danish Society of Engineers, IDA

Summary

This is an executive summary of the report IDA's Energy Vision 2050 - A smart energy system strategy for 100% renewable Denmark. The long-term governmental goal for Denmark in 2050 is to have an energy supply based on 100% renewable energy. The IDA Energy Vision 2050 is an input from The Danish Society of Engineers (IDA) in the important debate on how to implement this goal.

The IDA Energy Vision 2050 shows that 1) a conversion to 100% renewable energy is a technical option within economic reach, 2) an integrated Smart Energy System design can create a more robust and resilient system, and 3) there is a potential for creating more jobs than in a fossil fuel based energy system as well as lower health related costs from emissions from the energy supply.

The Smart Energy Systems concept

IDA's Energy Vision 2050 is based on the Smart Energy System concept, which is a cross-sectoral approach that makes use of synergies between the various energy sub-sectors by identifying suitable and cost-effective renewable energy solutions for the future.

The two key forms of energy production are bioenergy and intermittent renewable energy such as wind and solar power. Bioenergy is a direct substitution for fossil fuels, since it has many similar characteristics and comes in different forms, but in a 100% renewable energy system, bioenergy is a scarce resource and the current fossil fuel consumption cannot be met with bioenergy. Intermittent renewable energy sources are more plentiful, but they pose a challenge due to the fluctuations in their production, which need to be accommodated. Therefore, accommodating large amounts of intermittent renewable energy and limiting the bioenergy resource to a sustainable level are two key features of the Smart Energy System concept.

A smart energy system consists of new technologies and infrastructures which create new forms of flexibility, primarily in the 'conversion' stage of the energy system. In simple terms, this means combining the electricity, thermal, and transport sectors so that the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar. The smart energy system is built around three grid infrastructures:

> ***Smart Electricity Grids*** *to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power.*
>
> ***Smart Thermal Grids*** *(District Heating and Cooling) to connect the electricity and heating sectors. This enables the utilisation of thermal storage for creating additional flexibility and the recycling of heat losses in the energy system.*
>
> ***Smart Gas Grids*** *to connect the electricity, heating, and transport sectors. This enables the utilisation of gas storage for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilised.*

Based on these fundamental infrastructures, a **Smart Energy System** is defined as an approach in which smart Electricity, Thermal and Gas Grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system. Figure 1 and Figure 2 illustrate the overall Smart Energy System structure for a 100% renewable energy system and different storage options together with investment costs of technologies.

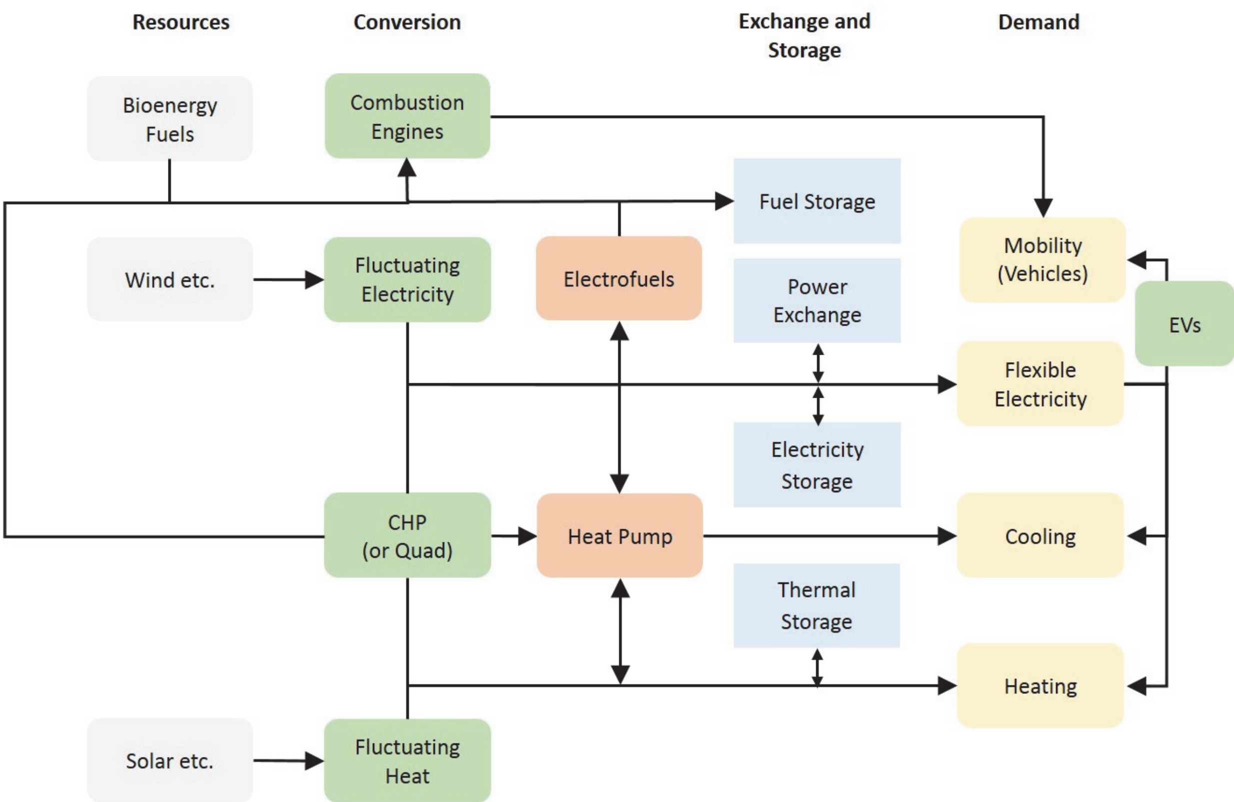

Figure 1. Smart Energy System structure. (EVs: Electric vehicles, Quad: production of four outputs)

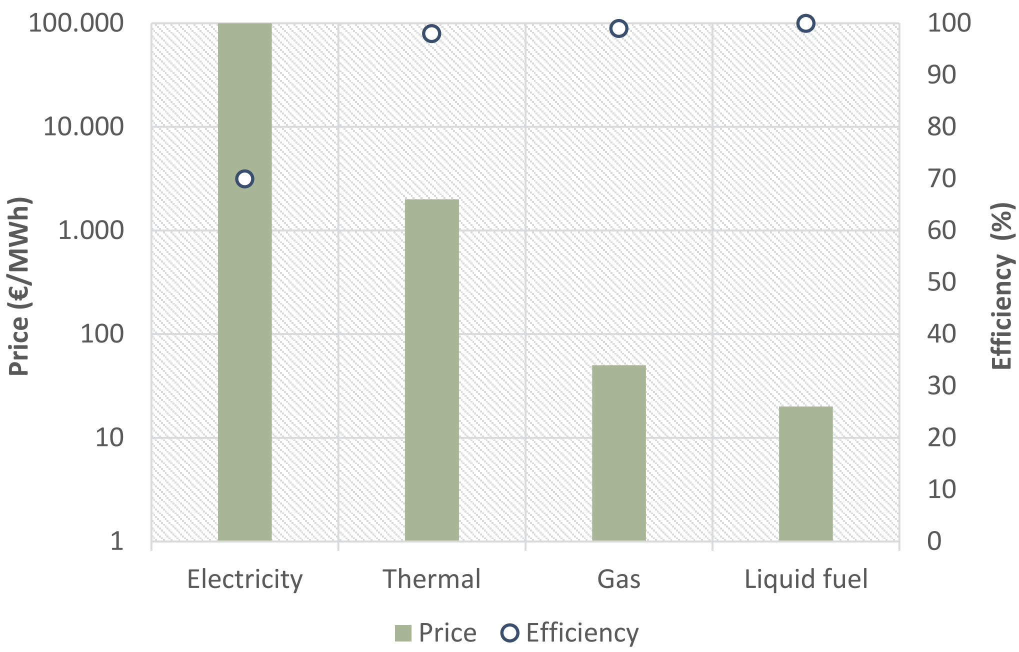

Figure 2. Investment costs and efficiency comparison for different energy storage technologies

The IDA Energy Vision puts forward a scenario and a roadmap to implement the goal of a 100% renewable energy system in 2050, in the following called *IDA 2050*. In order to assess the economic and environmental consequences, this scenario has been compared to two scenarios published by the Danish Energy Agency (DEA). One, called the *DEA fossil 2050* scenario representing a system like the present primarily based on fossil fuels, and another, called *DEA Wind 2050* representing what one might call a consensus scenario of the current strategy of implementing the 2050 goals of 100% renewable energy. All scenarios are also described in a 2035 step with the outset of the current 2015 energy system.

This vision builds on top of two previous energy strategies from IDA, namely the "IDA Energy Plan 2030" from 2006 and the "IDA Climate Plan 2050" from 2009. Both of these have already provided important inputs to Danish energy policy.

100% renewable energy is technically possible

The IDA Energy Vision 2050 shows that a 100% renewable energy system is technically and physically possible for Denmark as well as economically feasible compared to the fossil fuel energy system. In Figure 3, the primary energy consumption in IDA 2035 and IDA 2050 is shown. In IDA 2050, the total primary energy supply is decreasing from the current level of approx. 200 TWh to 160 TWh in 2050. Figure 3 also shows the primary energy supply of the current energy system and the DEA scenarios.

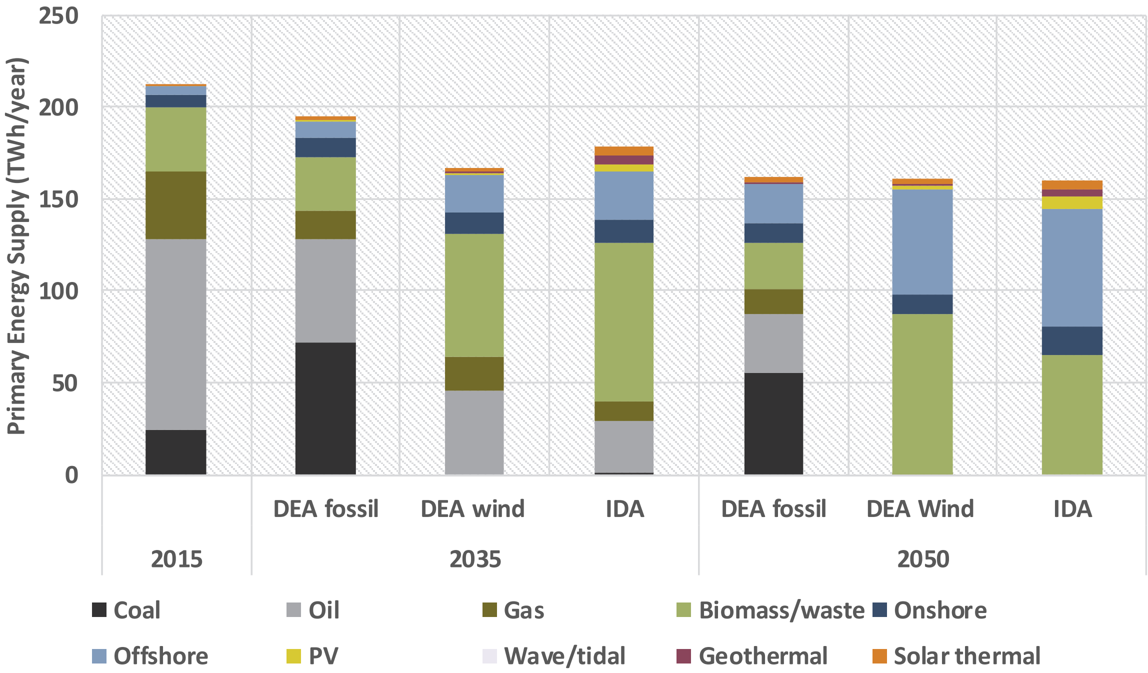

Figure 3: Primary Energy supply in 2035 and 2050 in the IDA Energy Vision, in 2015 and in the DEA scenarios

In the future energy system, the backbone of the energy system is fluctuating renewable electricity such as onshore wind power, offshore wind power, photovoltaic and wave power. More than 60% of the primary energy supply is from fluctuating renewable electricity sources, requiring vast amounts of flexibility in the energy system as such and in the electricity grid. In the district heating grid, low temperature heat from renewable sources is also harvested from solar thermal and geothermal. Including individual solar thermal, a total of 8% of the primary energy supply is provided by fluctuating renewable energy used directly for the heating sector.

Significant flexibility is implemented in the energy system between the production of renewable energy on one side and the demands for energy services on the other side. IDA's Energy Vision exploits storages between production and end demands in order to balance resources and to provide a cost-effective system.

Significant end demand savings are implemented in households, industry and businesses, while maintaining an economic growth. Electricity savings are implemented in all sectors, while significant heat savings are implemented in existing buildings combined with planned renovations and building improvement from now until 2050. New buildings and heat savings in existing buildings are done in a manner that emphasizes a balance between the costs of producing low temperature heat on one side and improving the building envelope on the other side. Within the industrial sector, knowledge about the end consumption characteristics has been used to save electricity and fuels.

In IDA's Energy Vision 2050, a significant part of the transport demand is covered by battery electric vehicles, plug-in hybrid vehicles, electric trams and trains as well as vans and busses using electricity. Meeting the transport demand for heavy-duty transport such as trucks, marine and aviation is a major challenge both in terms of costs and bioenergy resources needed. The demand is covered by *electrofuels*[1]. Investments in rails and charging stations for electric vehicles and other transport infrastructure are crucial for the assumed modal shifts and electrification. IDA's Energy Vision 2050 assumes a transport demand growth that is differently distributed than the growth in the DEA scenarios.

As illustrated in Figure 3, the DEA scenarios confirm that it is possible to convert to 100% renewable energy in 2050; however, the IDA Energy Vision has a lower biomass consumption based on the modelling assumptions used in this report regarding fuel prices and electricity exchange. In IDA 2050, it is possible to lower the biomass consumptions from the DEA Wind 2050 level of approximately 300 PJ to a level of 235 PJ. The replication of the DEA Wind 2050 scenarios shows a biomass consumption of 250-300 PJ and with fuel prices similar to the prices used by the DEA, the replication reaches a level around 250 PJ, equal to what is found in the DEA scenario report.

A smart 100% renewable energy strategy can be feasible

In the analyses of the costs of a transition to 100% renewable energy, the cost of each individual technology has been carefully assessed and implemented in the vision. Figure 4 illustrates the costs of IDA 2050 as well as the other energy systems. In the comparison of costs, the investments are annualised based on the technical lifetimes and an interest rate of 3%. The fuel cost levels correspond to the oil price of 105 $/barrel. This is an average price between the oil price level in June 2015 (62$/barrel) and the recommended level from December 2014 for long-term planning in 2035 (148$/barrel) by DEA. The total costs also include earnings on electricity exchange as well as operation and maintenance costs. An average price on the international electricity market of €77/MWh is used as a medium level out of a total of 10 price levels used. This level is the level recommended by DEA for analyses of the year 2035. The total costs give a comprehensive picture of the cost of the current Danish energy sector including transport as well as the future potential energy supply in IDA 2050, in 2015, in IDA 2035 and the DEA scenarios. The DEA scenarios have been recreated and the costs included here are based on the same principles as the costs included in the analyses of IDA 2035 and IDA 2050.

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[1] Electrofuels represent fuel production by combined use of electrolysers with carbon source. If the carbon sources are CO_2 emissions, the term CO_2-electrofuel is used; if the carbon source is from biomass gasification, the term bioelectrofuel is used.

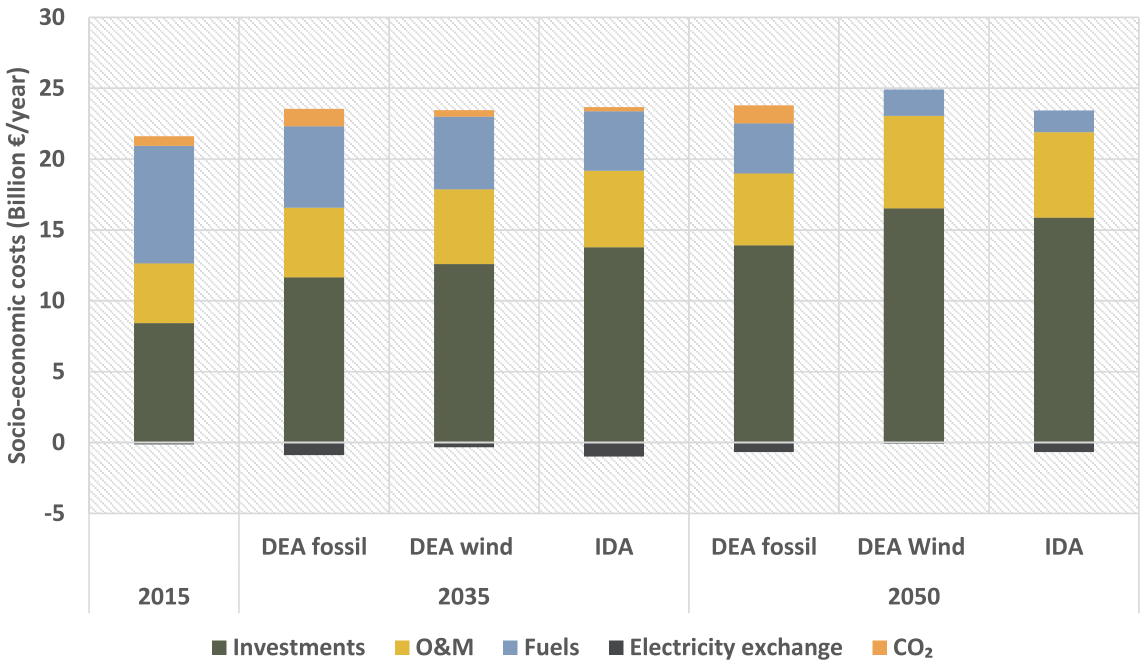

Figure 4: Socio-economic costs of the energy systems analysed including transport. Net earnings on international electricity markets are illustrated as a negative and should be subtracted to get the total costs of the systems

While the future IDA 2050 energy system is slightly more expensive than the current 2015 energy system, it should be noted that this system, like DEA Wind 2050, covers a significantly larger demand in regard to heat square meters, transport demand and industry.

IDA 2050 has lower costs than the proposal for a 100% renewable energy system in DEA Wind 2050. Sensitivity analyses have demonstrated that this conclusion is robust. The major differences in the costs are related to vehicle costs and can be explained by lower growth rates in road transport demands as a result of modal shifts to rail and biking/walking. Furthermore, the heat saving costs are lower due to a better strategy in heat savings in new and existing buildings as well as lower cooling costs due to a higher share of district cooling in comparison to individual cooling investments in the DEA scenarios. Finally, the fuel costs are lower in the IDA scenarios because of reduced biomass demand.

The fossil fuel based DEA Fossil 2050 has slightly higher costs than IDA 2050 and slightly lower costs than DEA Wind 2050. The major advantage of IDA 2050 is that it is able to exploit the synergies in the different grids in the energy and transport system, while DEA Wind 2050 to a lower extent does this.

In IDA 2035, the cost difference is less predominant, however, it should be noted that the costs for fuel are significantly lower and that the earnings on the international electricity markets are higher than in the DEA 2035 scenarios.

Going towards 100% renewable energy significantly changes the cost structure of the energy supply. In the future, much more costs are allocated to investments and much fewer to fuels. This is illustrated in both IDA 2050 and DEA 2050; however, IDA 2050 is a more fuel-efficient system and hence fewer costs are allocated to fuels in this case. The IDA Energy Vision and the DEA scenarios have been aligned to the degree possible regarding technological development, fuel prices and investment costs. The key technological specifications that have been altered include the type of electrolysers installed, renewable energy capacity factors and efficiencies for power plants and CHP plants. The impact of these alterations are analysed in further details in the report. Additional analyses have been performed investigating the impact of increasing the interest rate from 3% to 4%. The results show that all scenarios would have higher total socio-economic costs with the greatest in-crease around 7-8% in the DEA 2050 wind and the IDA 2050 scenarios compared to 4% in the 2015 reference. However, these higher costs do not change the relations between the scenario costs.

A robust and resilient strategy for renewables in an international context

Trade with fuels for electricity, heating and transport, as well as electricity exchange on the Nord Pool spot market are important parts of the current energy supply system. In the future, the characteristics of both the energy supply system and the consumer side will change; however, international cooperation is also important in a future renewable energy context.

Current electricity markets, both the Nordic electricity market, Nord Pool Spot, and the central European/German electricity market, EPEX, are set up based on the marginal price setting principle. With this settlement principle, a participant's profit depends on a more expensive unit also winning. In markets based on marginal price setting, participants submit bids equal to or close to the short-term marginal cost of participation, assuming that no one in the market is exercising market power. As such, the participants' bidding strategy normally results in units with the lowest *short-term marginal costs* being employed first; the market is therefore known for keeping total system costs low, even though this does not necessarily cover the *long-term costs* of the participants who own the power plants or wind turbines in the market.

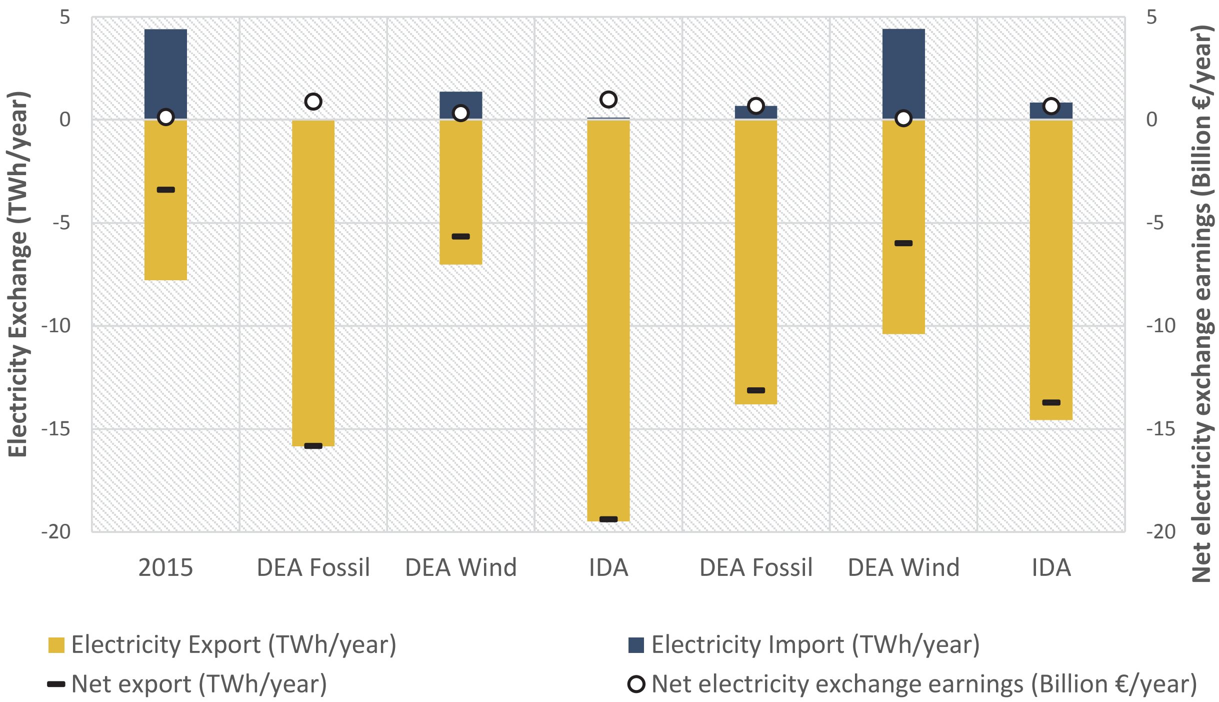

Figure 5: Electricity exchange and earnings on electricity import and export assuming three levels of fuel price assumptions for 2015 as well as the IDA and DEA scenarios

In Figure 5, the electricity exchange and earnings on electricity imports and export are illustrated. While the net earnings of IDA 2035 and 2050 are similar to those of the fossil DEA scenarios, the earnings in DEA Wind are lower. This is due to higher wind and PV capacities in IDA, flexibility on the consumption side in IDA, and higher efficiencies on the power plants and Combined Heat and Power (CHP) plants in IDA. The conclusion that the IDA scenarios have the ability to generate earnings on international electricity markets does not change significantly with ten other electricity price assumptions.

As illustrated in Figure 4, investments become extremely important in the future and while electricity exchange is important, the overall design of the entire energy system including thermal and gas grids is more important if a cost-effective system is needed. While investments are long term and will stabilize the overall costs, the costs of biomass and the ability to import and export electricity are important in the short term with the facilities installed. In the past, fuel prices have fluctuated significantly. The IDA Energy Vision has been analysed using three different fuel price assumptions as well as 10 different assumptions regarding future international electricity market prices for each of the scenarios. This has been done in order to analyse the ability of the energy system to make net earnings on import and export between Denmark and the surrounding countries, while also being subject to changing biomass prices.

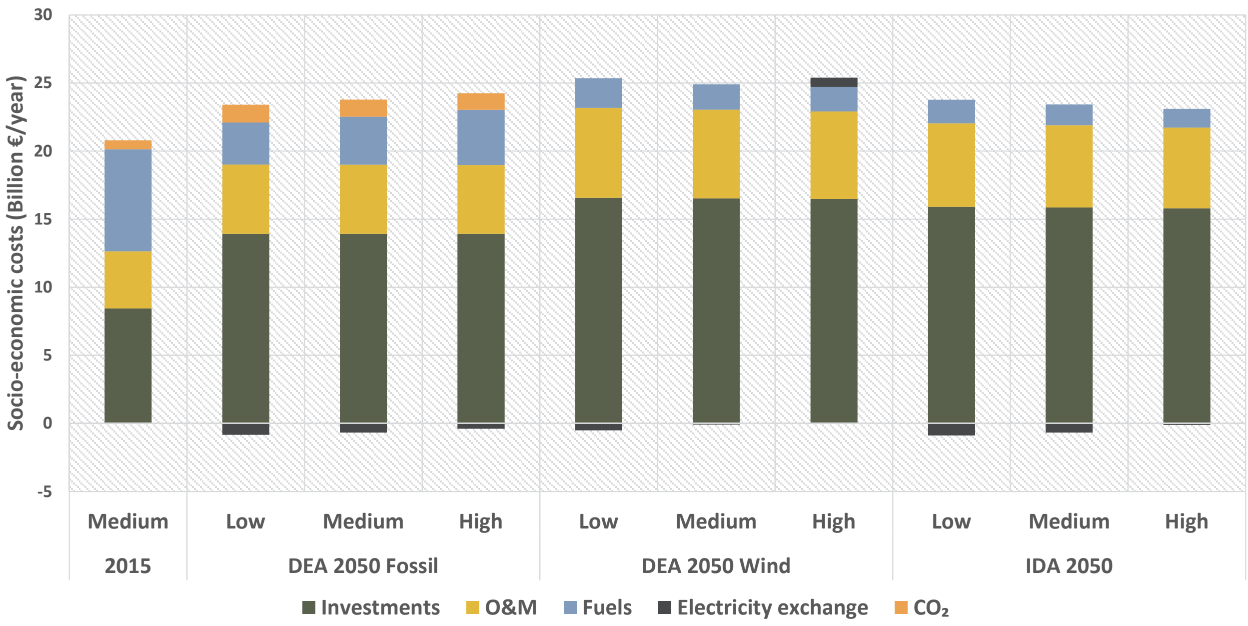

Figure 6: Socio-economic costs of the energy systems analysed including transport for the three different fuel price levels (oil prices equivalent to 62, 105 and 148 $/barrel and 77 €/MWh on the international electricity markets). Net earnings on international electricity markets are illustrated as a negative and should be subtracted to get the total costs of the systems

In Figure 6, the overall socio-economic costs of all three fuel price levels are illustrated. A change in fuel costs changes 1) the costs for using fuel domestically and 2) the ability to have an income from international electricity markets. While the costs do vary, the results show that IDA 2050 and IDA 2035 have lower costs than the DEA scenarios as previously described. With low fuel costs, the net earnings on electricity markets increase and the opposite is the case with high fuel costs. Again this confirms that a fuel-efficient energy system design increases the robustness and resilience overall in the fact that the IDA scenarios are better at exploiting all situations.

An important effect of different 100% renewable energy system designs is seen in the consumption of biomass. In the DEA Wind 2050 scenario, the biomass costs vary €300 million with the three fuel cost levels, from a total low level of €1,800 million. In IDA 2050, however, the costs vary €350 million from a low level of €1,400 million. One issue is the cost variation and the cost level; another is the effect on the biomass consumption in PJ. This difference reflects a span of using 367, 306 or 256 PJ of biomass with low, medium and high fuel price level assumptions in the DEA 2050 scenario. In IDA 2050, this span is 270, 234 and 180 PJ. Behind these results are naturally many system dynamics between power plant boilers and CHP. However, not only is it possible to create a more cost-effective scenario with overall lower fuel costs and higher earnings on international electricity markets. It is also possible to create a system which is more robust and resilient in a world where biomass resources may be expensive or scarce due to over exploitation. In Figure 7, the resulting primary fuel consumption is illustrated.

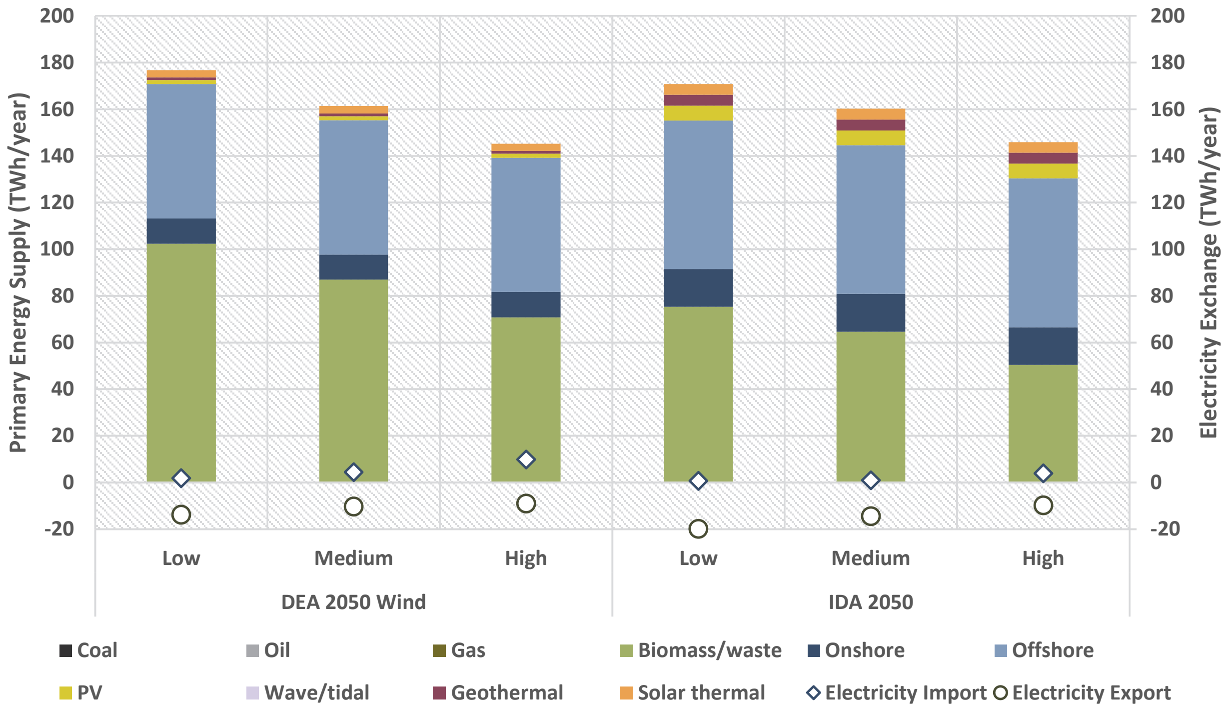

Figure 7: Resulting primary fuel production assuming three different fuel price levels (oil prices equivalent to low: 62, medium: 105 and high: 148 $/barrel and 77 €/MWh on the international electricity markets)

In the future energy system, it is uncertain whether this market principle of bidding using short-term marginal prices will be sufficient to ensure cost-effective electricity system investments. The reason is that wind power and photovoltaic have very low short-term marginal costs and will by far be the dominant technologies. This will bring down prices, and with very little price elasticity on the consumption side, this will make the short-term prices very low or negative. In the future, this will mean that 1) capacities with high costs and low operation time will not be able to cover the long-term investments costs, which was the assumption in the marginal price setting principle; and 2) unless feed-in-tariffs are regarded as investment markets and kept at a certain level, new technologies will not be installed, even though, e.g., onshore wind is now the lowest cost electricity producing unit. Currently, early warnings of this problem are present in Europe, the Nordic power market and Denmark with closing power plants and low earnings for power plant and wind turbine owners.

This dilemma will increase in the coming years as Northern Europe as such is expanding the level of renewable energy resources. As is shown in Figure 8, the wind power capacity is expected to increase substantially in Sweden, Northern Germany and Norway from 2014 to 2020. Towards 2050, the expansion of wind power and photovoltaic will be significant and will challenge the current market construction.

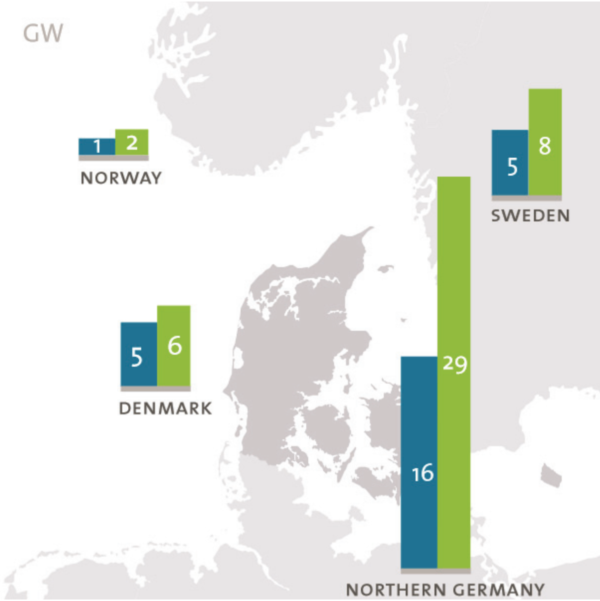

Figure 8: Installed wind power capacity in Denmark, Northern Germany, Norway and Sweden in 2014 (blue) and 2020 (green). Adopted from Energinet.dk

The IDA 2050 scenarios are, to a further extent than the DEA 2050 scenario, able to cope with a situation where Denmark is not able to export (physically or with low costs as a result).The electricity exchange between the Danish energy system and external markets is subject to both import and export risks.

The import risks exist in two forms; firstly, that there might be a lack of power plant capacity to produce electricity outside Denmark due to the current trend of declining capacities in Northern Europe. This means that situations might arise where it is not possible physically for Denmark to import due to insufficient power plant capacity in periods with low wind power production in Denmark. Secondly, in these periods with low wind power production, the electricity prices might become too high due to the increased demand across countries. Low wind power production is likely to also occur outside Denmark and power plant capacities will be needed outside Denmark as well. Export risks exist as the weather patterns are rather similar between neighbouring countries, which means that there will be an excess of wind power and PV power production in these countries in the same periods. Firstly congestion in transmission lines is likely to occur making it physically impossible to export even with higher transmission line capacities than today. Secondly if transmission capacity is available, the high wind power production occurs at the same time in the northern European area and hence this will lead to a decreasing or even negative electricity price.

These four electricity exchange risks are worth considering when planning for a future energy system. The IDA 2050 scenario represents an energy system design with electricity trade between sectors as a the main strategy to increase the cost-effectiveness using the smart energy system approach; i.e., that electricity can cost-effectively be used in heating and transport while also being traded on international electricity markets when good opportunities occur.

The DEA 2050 scenario to a larger extent represents an energy system which assumes that the integration of wind power mainly can be done in international electricity markets, i.e., that wind is not congesting transmission lines from the surrounding countries.

International electricity exchange analysis shows that in a situation where the electricity export is restricted due to congestion from wind power in Northern Europe in general, the IDA 2050 scenario can even have a lower biomass consumption compared to a non-restricted situation. This is due to the fact that the energy system design is done using synergies combining several sectors. Here, biomass can be replaced by wind power and photovoltaic in more corners of the energy system. This is not the case in the DEA 2050 scenario, where the biomass consumption remains rather high compared to IDA 2050.

International electricity exchange alone is not the best solution, when the Northern European regions go in the same direction as Denmark. Incentives for more technologies to behave flexibly in the energy system are important. Interactions between electricity and heating, gas and transport are needed in the future and these cannot alone be supported by a marginal electricity price market. A strategy in which each country increases renewables by exporting renewable electricity is a high-risk strategy for Denmark and countries in Europe as a whole in the long term. The Smart Energy System approach provides cost-effective synergies with the exchange of energy between sectors, while using cheap storages across smart electricity, smart thermal and smart gas grids. IDA's Energy Vision 2050 provides such a strategy for Denmark. A strategy moving from a single sector to an integrated approach would also be a more robust strategy for Europe.

Contents of the IDA scenario

This section summarizes and describes the main characteristics that were included in the IDA Energy Vision 2050 for the IDA 2035 and IDA 2050 scenarios. More information can be found in the report.

Heat savings

It is essential for the future smart energy system to reduce the heat demand substantially for buildings. However, there has to be a balance between heat savings and heat production. At a certain level, it becomes too expensive to save energy in comparison to producing energy. IDA's Energy Vision therefore tries to identify the point to which heat demand in buildings should be reduced.

As a result, the heat demand for existing buildings should be approximately 80 kWh/m^2 in 2050. This is a reduction of 40 % compared to today's demand. If Denmark achieves substantially less or substantially more savings in the existing building stock, the total cost of the energy system will increase, either due to more production units or due to saving measures with higher costs. To achieve cost-effective savings, the building renovation and improvement in energy performance have to be coordinated. It will be too expensive to refurbish the same building twice before 2050. Hence this level costs reflects that building owners reduce heat demands at the same time as they refurbish their building anyway. If this is not the case, the costs will be too high to achieve a 40 % reduction.

For new buildings IDA's Energy Vision suggests a heat demand of approximately 55 kWh/m^2 from now and until 2050. This demand only reflects the heat demand in the building, and not production units such as photo voltaics on the building that can reduce the total demand pr. m^2 of the building as such. The goal of IDA's Energy Vision is to have a focus on the actual heat performance of new buildings, and not as the Danish 2020 Building Code where production units such as photovoltaics can compensate for a lack of heat performance in a building. IDA's Energy Vision suggests an ambitious target for both heat demand reduction in new buildings and e.g. photo voltaics, solar thermal and other renewable energy production units.

Electricity savings in households

In the IDA 2050 scenario, electricity savings in households have been carried out in order to reduce end demands and stay within biomass potentials. Three different factors affect the future electricity demand; firstly, the increase in equipment that will lead to higher demands which is particularly the case for Information and Communication Technologies (ICT); secondly, the technical savings that are possible to implement, and thirdly, the savings that can be carried out due to behavioural changes. In IDA's Energy Vision, it has been estimated that a future increase in equipment of 4% in 2035 and 10% in 2050 will take place, thus increasing the electricity demand. On the other hand, technical savings in electricity demands of 6% in 2035 and 15% in 2050 are implemented, primarily due to an enhanced regulation and technology development. Additionally, also including emphasis on behavioural aspects can introduce savings in electricity demands. In IDA, savings of 8% in 2035 and 20% in 2050, respectively, have been assessed as possible. This leads to an overall reduction in the electricity demands of 10% in 2035 and 25% in 2050 for the IDA Energy Vision compared to the 2015 reference.

Principle transformation hierarchy for the Industrial energy demand

In the IDA Energy Vision, the industry and service sectors including agriculture and construction are assumed to have the same growth as in the DEA fossil fuel and wind scenarios, i.e., approx. 40% from 2015 to 2050. This means that the same demands are met. The IDA Energy Vision introduces a principle hierarchy giving priority to first savings, then smart energy coordination with district heating and cooling as well as electricity via heat pumps, and finally, the replacement of fossil fuels with electricity, heavy biomass and lastly high quality biogas upgraded with hydrogen (methanated biogas).

1. Priority is given to savings
2. Priority is given to district heating and cooling including the utilisation of waste heat from processes either internally or for district heating
3. Priority is given to heat pumps for remaining space heat demands
4. Priority is given to replacing fossil fuels with electricity
5. Priority is given to replacing fossil fuels with heavy biomass
6. Priority is given to replacing fossil fuels with green gas (methanated biogas)

The hierarchy is defined out of the wish to transform industry and service into a part of a future renewable system in which the energy consumption and the costs of the total energy system are minimized as much as possible.

The IDA Energy Vision assumes the same savings as in the DEA Fossil and Wind scenarios, since these savings are closely linked to the assumptions on growth. The main difference here is the focus on using energy efficient technologies, which means that the IDA Energy Vision includes more district heating and cooling and utilises more low-temperature industrial waste heat as well as more electricity and less biomass. An energy demand of 193 PJ in 2015 with a high share of fossil fuels is transformed into an energy demand of 189 PJ with no fossil fuels and with contributions from district heating and cooling as well as the conversion to electricity consumption and gas.

District Heating Expansions

The district heating supply in the IDA Energy Vision is assumed to be expanded to 66% of the total heat demand based on analyses in Heat Plan Denmark from 2008 and the IDA Climate Plan 2050 in 2009. The total district heating demand is assumed to increase from 22.8 TWh in 2015, corresponding to a share of 53%, to 30.5 TWh in 2035 and 28.2 TWh in 2050 achieving the assumed 66%. This is taking into account expansions of district heating coverage, conversion of industry, and general heat savings in buildings.

The expansions of the district heating systems will generate a number of benefits to the district heating production. Expansions in district heating will enable better integration of excess heat production from various processes including industrial excess heat, excess heat from biogas or *electrofuel* production and waste incineration. It will also improve the integration of the energy sectors as an increased number of consumers and demand will increase the flexibility of the total system and thereby increase the potential for integrating wind power through large heat pumps and combined heating, cooling and power.

In Denmark, currently heat is supplied by mainly CHP plants and fuel boilers. In the future, there will be many new forms of heat supplies available. These include wind power, which can be used for heat production with large-scale heat pumps, solar thermal, deep geothermal and surplus heat from industry. It is possible to extract more heat from these resources if their delivery temperature is lower. Thus, reducing the temperature in the district heating network will allow the utilisation of more renewable heat. Furthermore, if the temperature in the pipes is lower, then the amount of heat lost in the pipe is also reduced and more of the heat produced reaches the consumer. In the future, district heating distribution temperatures should be reduced from today's level of 80-100 °C to approximately 50-60 °C.

District cooling

Currently air conditioning units using electricity meet the majority of the cooling demand in Denmark. However, there is a large potential in supplying some of the space cooling demand as district cooling. District cooling incorporates some of the same advantages as district heating. The peak production demand is reduced by the fact that several consumers with different consumption profiles are connected; it is possible to incorporate large-scale storage and it is possible to include a mix of sources for the cooling production. The production of cooling in a district cooling system depends on local conditions. District cooling can be produced from a mix of sources such as groundwater cooling, free cooling from ambient sources and heat pumps. It is possible to utilise the heat produced on heat pumps at the same time as the cooling and thereby optimize the system performance. In the IDA 2050 Vision, 40% of the cooling demand is met by district cooling and it is assumed that 75% of the district cooling is produced in a combined production with heating.

Electrification of transport and electrofuels

In the IDA Energy Vision, the same assumptions for vehicle efficiency improvements apply as in the DEA Fossil and Wind scenarios, divided into different modes of transport. In the IDA Energy Vision, differently distributed growth rates in transport demands and modal shifts shape new transport demands for 2035 and 2050.

First priority is given to the electrification of the transport sector. The rest of the transport demand not suitable for electrification was met by electrofuels: bioelectrofuels and CO_2 electrofuels. The end fuels assumed to be used both in the 2035 and 2050 scenarios are dimethyl ether (DME) or methanol distributed evenly in the power trains running on liquid fuels. The direct and battery electrification is of high priority and large shares of cars, vans and rail are electrified. Total transport fuel demand is 133 PJ in 2050, of which 100 PJ are liquid electrofuels and 33 PJ of electricity is used for the electrification of transport. Half of the electrofuel demand is supplied by bio-based electrofuels, resulting in 47 PJ of biomass needed for fuel production, which is aligned with the biomass potential available for transport in Denmark. In order to achieve these levels, a reduction of transport demand growth, a high share of public transport, and a modal shift of road transport to rail were implemented, including the costs of such changes. The passenger transport demand was distributed so that 45% of the transport demand was met by vehicles, 29% by public transport, 5% were bikes and walking and 21% was aviation. The highest share of freight transport demand was met by marine at 82% followed by trucks at 13%, and vans and rail at only 1.3%.

In the 2050 scenario, battery electric vehicles meet 75% of the private car transport demand and the rest is met by electrofuels used in 10% of plug-in hybrid vehicles, 5% of hybrids and 10% of ICEs. Electric busses meet 15% of the transport demand while an even mix of bioelectrofuel and CO_2 electrofuels supplements the remaining 85% of internal combustion engines (ICEs). The rail is completely electrified, and both aviation and marine transport are met by an even mix of electrofuels. For freight transport, 35% of the vans are battery electric vehicles and the remaining 65% is met by ICE, ICE hybrids and ICE plug-in hybrids powered by an even mix of electrofuels. The trucks covering only national demands were assumed to be 75% ICE, 20% of ICE hybrid and 5% of fuel-cell hybrid running on electrofuels. The same assumptions apply for aviation and marine as for passenger transport.

The power-to-gas and power-to-liquid are of great importance to the smart energy system concept. By using electrolysers as a mediator for electricity storage by converting the intermittent electricity from renewable sources to the gases or liquids that can be used in energy sectors or stored in different storage technologies, we establish the interconnection between electricity, gas and transport sectors. These technologies therefore offer a solution for meeting different fuel demands while providing flexibility to the system. In this way, we compensate for the lost flexibility on the resource side by providing flexibility in the conversion processes. As the fuel production facilities produce excess heat, this is another important factor for the integration of fuel production and heating sector in the future.

The transformation of the transport sector into renewable energy is possible with affordable costs with a focus on maximizing the electrification of transport, minimizing the biomass share for transport, and reducing the transport demand by using more efficient technologies and lower growth.

Wind, PV and Wave power

The three main renewable electricity resources available in Denmark are onshore and offshore wind and solar PV. The potential of onshore wind is estimated at between 9-35 TWh, whereas the offshore wind potential is estimated at between 16-330 TWh. The solar PV potential is estimated at between 5-29 TWh. In addition, wave power is assumed to have a minor role of 300 MW installed capacity. The electricity production from each renewable resource is listed in Table 1.

Table 1: Electricity production from renewable fluctuating resources in the 2015 reference and the 2035 and 2050 DEA and IDA scenarios

Electricity production (TWh)	2015	2035		2050	
		DEA	IDA	DEA	IDA
Offshore wind	4.4	21	26	58	64
Onshore wind	7.2	11	13	11	16
Solar PV	0.6	0.9	3.8	2	6.4

In 2050, in the IDA scenario, the total installed capacity for onshore wind, offshore wind, solar PV and wave power are 5,000 MW, 14,000 MW, 5,000 MW and 300 MW, respectively. In order to achieve electricity production from these technologies, the installation of the new renewable electricity infrastructure would occur at different rates depending on the technology and the time period. PV would need to reach a level of approx. 150 MW per year. For onshore, the level would be 150-200 MW per year and for offshore wind power, 450-500 MW per year. This is a significant challenge, however, it should be kept in mind that these technologies replace imported fuels and are able to meet major parts of the demands in not only the heating and cooling sectors, but also the transport sector.

Sustainable Biomass and Waste Management

Additional to renewable sources such as wind, solar and geothermal, the IDA Energy Vision also uses biomass. However, the use of biomass, i.e., straws, wood, crops, biogas, etc., will influence greenhouse gas emissions depending on the nature of the biomass resource, how it is utilised and if, e.g., new trees are planted or not. Consequently, one should make an effort to secure that biomass is used in a sustainable way.

The IDA Energy Vision 2050 does this in two ways:

- First, the amount of biomass is reduced by utilising storages and integrating sectors allowing other resources into the energy system.
- Secondly, the type of biomass is limited to residual resources such as straw, wood waste from forest industry and biogas (manure and organic waste) and minor changes in agriculture towards energy crops with negligible or minor effect on food production.

The IDA Energy Vision does not entail any restriction to use domestic bioenergy. Certification systems or similar schemes are out of the scope of the analysis here. The aim is to design systems which are able to function fuel-efficiently and cost-effectively in a context where the availability of bioenergy is uncertain regarding costs.

IDA 2050 uses between 180-270 PJ/year, depending on the international electricity market conditions. This is in line with the level of the Danish share of the available world resources and the Danish residual resources. Using the same assumptions as in the IDA scenarios, the DEA 2050 scenarios use 256 to 367 PJ. When applying the high fuel prices as used in the DEA scenario report, the biomass consumption is around 250 PJ. This shows that with similar fuel prices the biomass consumption of 250 PJ reported in the DEA scenario report are similar to the replication with high fuel prices in this report. The biomass consumption in different situations is shown in Table 2.

Table 2: Bioenergy demands using different biomass price assumptions

	DEA Wind 2050			IDA 2050		
Fuel price level	*low*	*medium*	*high*	*Low*	*medium*	*high*
Biomass demands (PJ)	367	306	256	270	234	180

Several studies have shown the potential biomass resources in Denmark. Most focus on residual resources, other focus on also using algae and/or energy crops. In Figure 9, the studies in Denmark on biomass potential in the last ten years are listed. From these studies, it is evident that the biomass resources available are closer to 150 PJ than 250 PJ when not including energy crops and/or algae potentials. Advances in the design of energy systems have made it possible to reduce the demands for biomass; however, the challenge regarding biomass is not only the amount but also the types of biomass available.

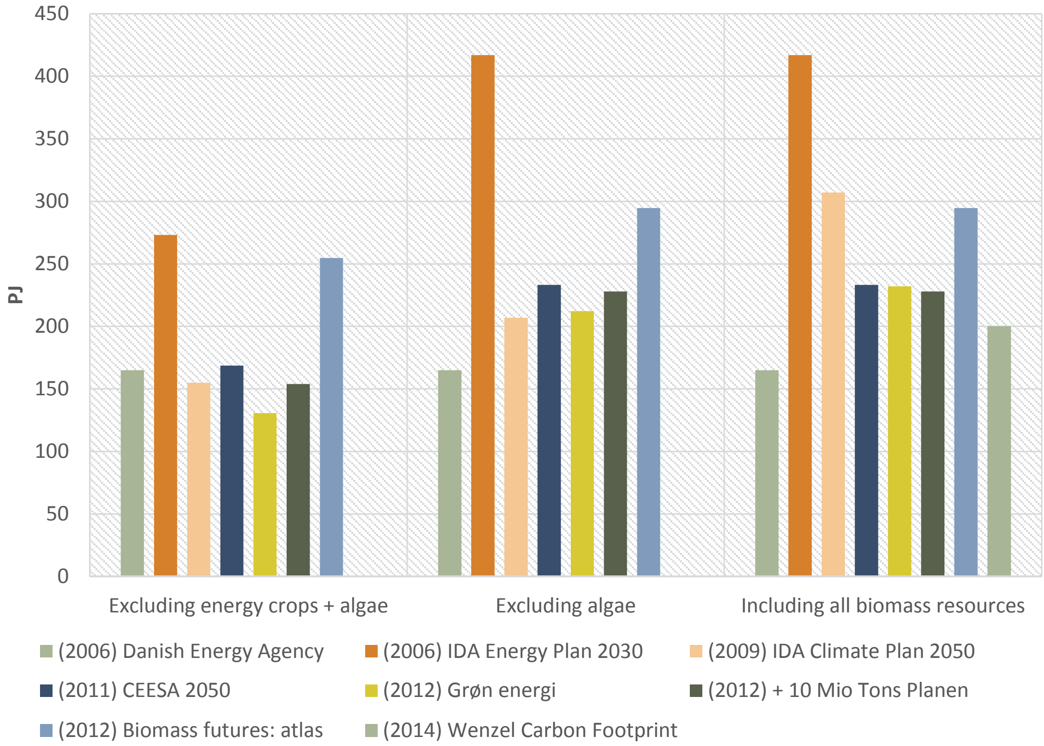

Figure 9: Biomass potentials according to studies in the last 10 years

The biomass demand for each technology (i.e. boilers) is met by different biomass types, for example wood, straw, energy crops and biogas. By comparing the biomass demand of the different technologies with the biomass potential from different resources, it is evident that there is sufficient potential to meet the demand of the technologies. In addition, it is evident for some scenarios that the combined biomass demand of all the technologies is close to the extreme upper limit of the biomass potential. The biomass consumption in the two main 2050 scenarios is illustrated in Figure 10.

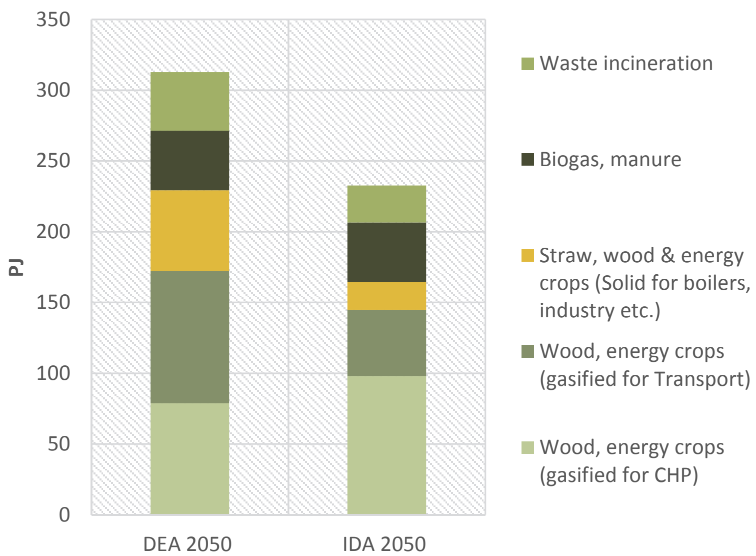

Figure 10: Biomass demands distributed on types in DEA Wind 2050 and IDA 2050

The IDA Energy Vision 2050 gives priority to waste management and recycling of waste. Only waste which is not recycled is used for energy purposes. Out of this fraction, priority is given to gas and liquid fuel production either as part of biogas and if possible thermal biomass gasification or as bio-oil production of organic waste. Remaining parts will be used in waste incineration together with similar fractions of biomass, which neither can be transformed into gas nor liquid fuel. These incineration plants are used for flexible combined heat, power and steam production, in which steam is used for geothermal heat or biomass conversion. As a consequence, the IDA Energy Vision uses 26 PJ/year in waste incineration which is less waste than in the two DEA strategies Fossil and Wind (44 and 41 PJ/year, respectively).

Flexible consumption and production technologies

In order to be able to integrate the increasing levels of fluctuating renewable resources, a high degree of flexibility is implemented in the IDA scenarios by introducing certain consumption and production technologies. On the production side, fast regulating CHP and power plants are installed based on gas consumption in order to ensure a high regulating ability. The thermal capacities installed are rather similar in the DEA and IDA scenarios with the exception of a slightly higher capacity in the IDA scenarios. In the IDA scenarios, the overall capacities are around 6000 MW, compared to 5500 MW in the 2050 DEA scenarios similar to a difference of around 10%. The installed production capacities are illustrated in Figure 11.

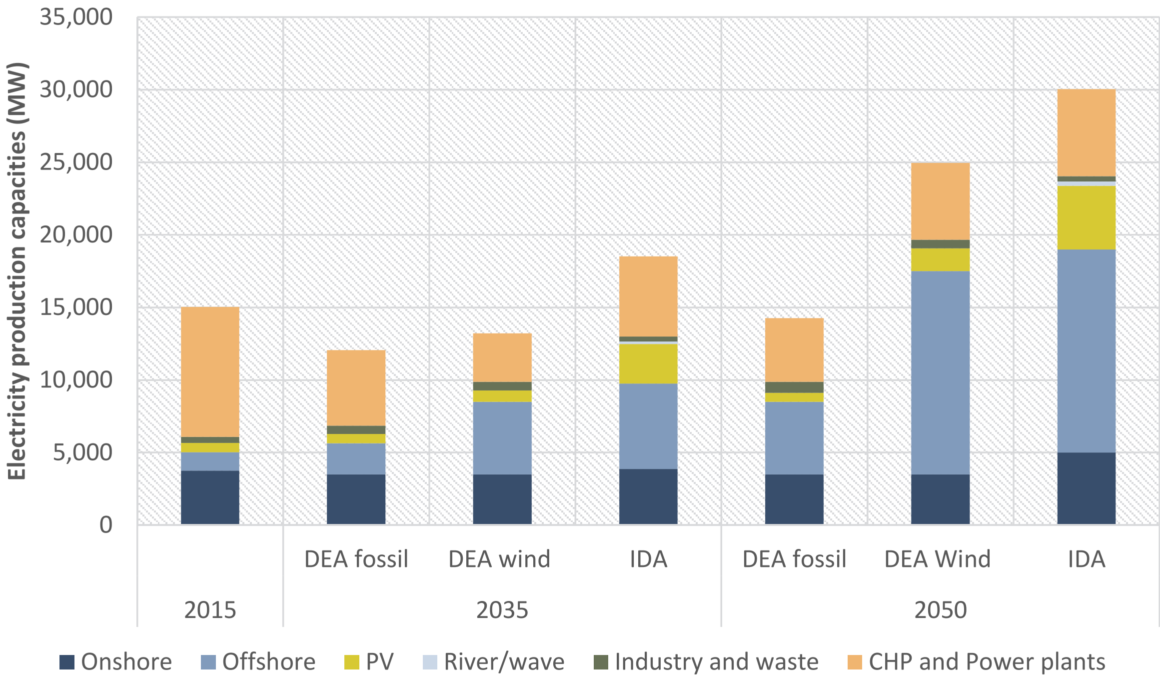

Figure 11: Electricity production capacities for the 2015 reference, the 2035 and the 2050 DEA and IDA scenarios

Some of the electricity capacity is only used in few hours throughout the year, which can be seen in Figure 12. The vast majority of the electricity production (around 80%) in both the DEA and IDA 2050 scenarios is produced by renewable electricity resources, while the thermal plants are used in case of low wind or solar production.

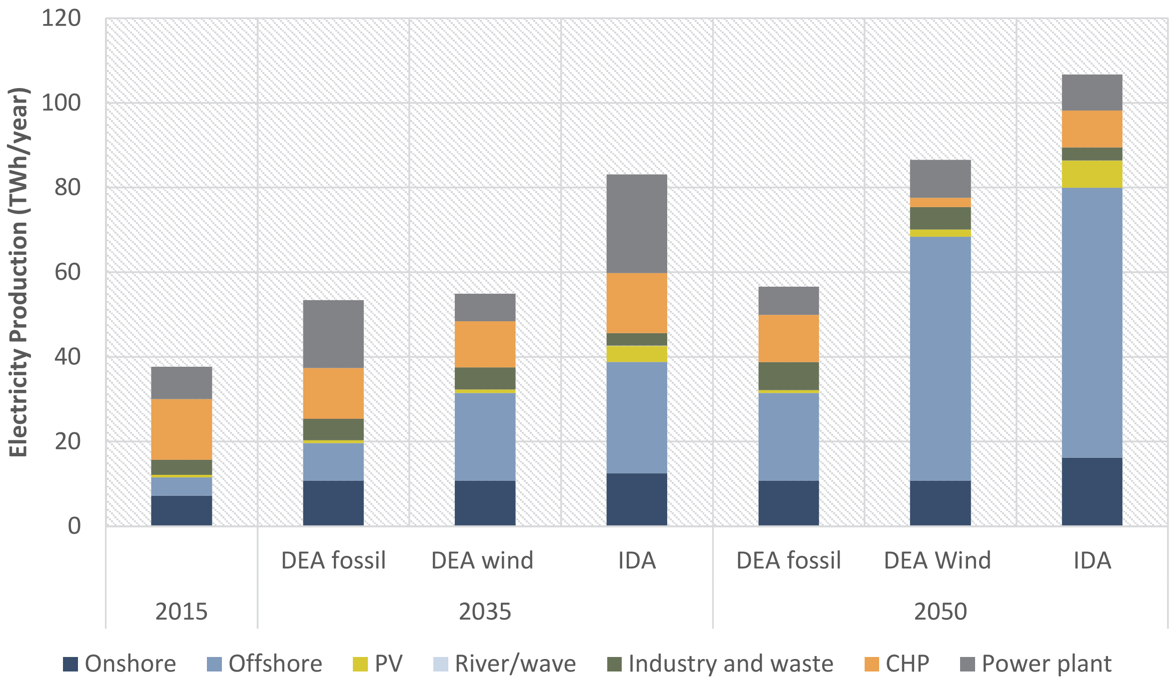

Figure 12: Electricity production for the 2015 reference, the 2035 and the 2050 DEA and IDA scenarios

On the consumption side, some key technologies are also installed in order to ensure flexibility in the system. The consumption capacities can be seen in Figure 13.

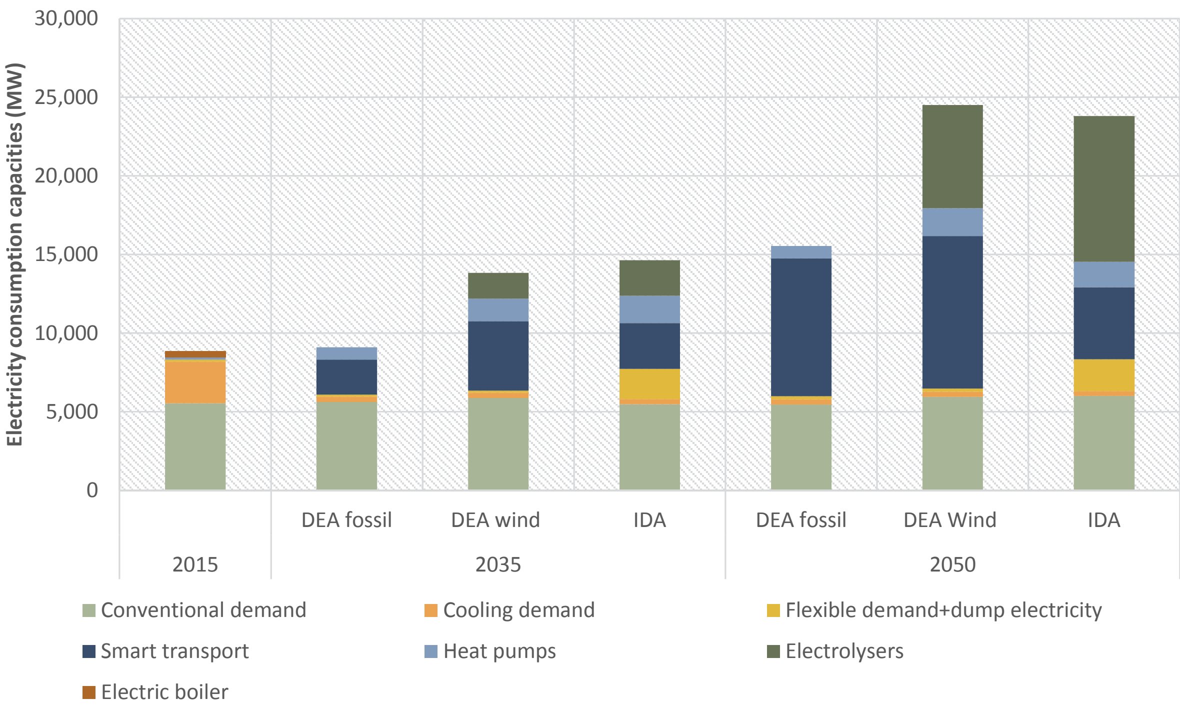

Figure 13: Electricity consumption capacities for the 2015 reference, the 2035 and the 2050 DEA and IDA scenarios

It is clear that there is a large difference in terms of electricity production capacity between the fossil scenarios and the DEA and IDA scenarios. Especially in 2050, heat pumps and electrolysers enhance the flexibility in the system, since these technologies can act as conversion technologies connecting the different energy sectors such as electricity with the heating, transport and gas sectors. The conversion of electricity into heating or gas has several benefits. Firstly, the increased electricity consumption replaces demands in other sectors that would otherwise have been supplied by biomass or fossil resources. Secondly, the conversion from electricity to a different energy carrier allows for less expensive storage options in the heating and gas networks. Thirdly, electricity consumption can ensure a more efficient use of energy resources through the use of heat pumps instead of boilers and electric vehicles in the transport sector. It is therefore essential that these technologies are installed to ensure sufficient flexibility in the system and allow for a conversion to 100% renewable resources.

The greater reliance on electricity in the future renewable systems are visible in Figure 14. Here, it can be seen that the heat demands are rather similar to today as the expected growth is outweighed by the heat savings implemented. The cooling demands are unchanged in the scenarios while the transport fuels are lower in the 2050 scenarios compared to the 2015 reference. This should not be seen as an overall reduction in transport demand, but rather as an indication of the increased efficiency in the transport sector due to the significant electrification of transportation in all the 2050 scenarios. Finally, the electricity demand is three times higher in the IDA 2050 scenario than in the 2015 reference, despite of end demand savings for households, but the electricity growth occurs due to the increased electrification of the heating, transport and industrial sectors. In the IDA 2035 and 2050 scenarios, more flexible and efficient technologies are implemented, which enhances the system efficiency and this results in a decreasing primary energy demand even with the significant increase in electricity.

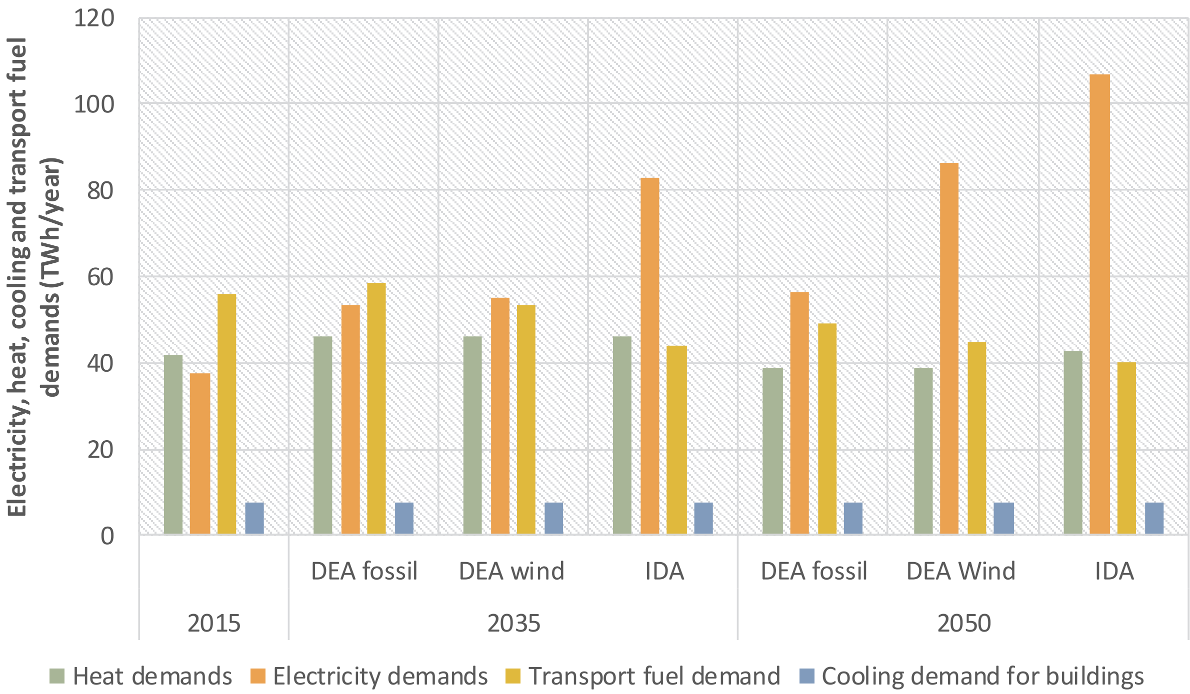

Figure 14: Energy system demands for heating, electricity, cooling and transport fuels, excluding losses in the conversion processes, transmission and distribution. Notice that some demands for e.g. heating using heat pumps might be counted twice as part of both the heating demand and the electricity demand

Health costs

Total health costs can be calculated based on the data on health costs originating from emissions from the various types of technology, fuel, and location of point sources. Costs are identified by counting the work days lost, hospital admissions, damage to health, deaths, etc. The health costs included are exclusively based on the six emissions and do not include the environmental cost of damage to nature and animal life or the cost of mining for fuels and materials overseas, e.g., from a coal mine in South Africa. Thus, the estimate is rather conservative.

In IDA 2035, health costs are reduced due to energy savings as they lower the consumption of coal in electricity production compared to DEA Fossil 2035. Similarly, the conversion to district heating, geothermal heat pumps, and solar thermal means that there is a reduction in the cost of emissions from the burning of wood in individual households. These trends continue up to IDA 2050 in which there are further conversions to biomass and more renewable energy is introduced into the electricity system, which replaces solid fuels. In addition, health costs originating from the transport sector are further reduced in IDA as the reliance on biomass is reduced. In IDA 2050, the total health costs are reduced to approximately €0.6 billion. Thus, if the initiatives in IDA's Energy Vision are implemented, there will be savings of approximately €0.9 billion in 2050, compared with DEA Fossil 2050 and about €0.1 billion in 2050, when compared with DEA Wind 2050. As the total costs are based on current emission factors, it must be emphasized that this type of estimate only gives an indication of the total socio-economic costs.

Employment effects

The potential employment effects from IDA Energy Vision have been investigated and estimated on the basis of the energy system analyses. Even in the case that the different scenarios do not vary much in total system costs, the difference in cost structures may have a significant effect on domestic labour demand. Compared to the fossil scenarios, both IDA Energy Vision and the DEA Wind scenarios contribute to higher levels of domestic turnover. This higher level of domestic demand can be expected to create additional employment in the Danish economy. In general, the renewable scenarios reallocate funds from fuel related costs into investments and expenses for operation and maintenance activities. Funds allocated for investments in production units, infrastructure, energy savings, etc., typically imply lower import shares compared to the handling of fossil fuels. Therefore, more domestic employment can be created for the same costs.

The job effect in 2050 is the same for DEA Wind 2050 and IDA 2050, due to similar investment levels and cost structures. The analysis suggests that both scenarios contribute with 50,000 jobs/year compared to the fossil alternative in 2050. The calculations indicate that the yearly job effect in 2035 is 30,000 jobs/year higher for IDA 2035 compared to DEA Fossil 2035. The DEA Wind 2035 scenario contributes with approximately 15,000 jobs/year additionally compared to DEA Fossil 2035. The higher job effect in IDA 2035 compared to DEA Wind 2035 is due to the fact that IDA's Energy Vision has a higher share of investment at this point in time, while the DEA wind scenario allocates more capital to the use of fossil fuels.

The conducted employment analysis thus concludes that 1) investing in a renewable energy system creates more employment and 2) the earlier these investment are made, the earlier the positive employment effect appear.

The line of thought behind this employment analysis is based on a demand side approach to employment. As such, labour supply is implicitly assumed available. Any shortage in labour supply 35 years ahead must be considered unknown today. If full employment should be permanently present in the Danish economy for the next 35 years - which in a historical perspective must be considered unlikely – a higher net import of labour would be necessary in the renewable scenarios compared to the fossil scenarios. In such a 'worst case' situation where domestic labour supply is not available, a renewable energy system will merely have to import labour instead of importing fuels as it is done in the fossil alternative. For the fossil alternative, however, a worst case situation of high unemployment would be further worsened by the outflow of capital for fuel import. In that respect, the renewable scenarios carry a lower economic risk - and greater opportunities.