PATHS TOWARDS A FOSSIL-FREE ENERGY SUPPLY

DANISH ENERGY SUPPLY IN AN INTERNATIONAL CONTEXT

An analysis performed by Ea Energy Analyses for DONG Energy and Vestas Wind Systems

Ea Energy Analyses

CONTENTS

Introduction

DONG Energy and Vestas asked Ea Energy Analyses to clarify how the development of the energy supply in Denmark can be coordinated with those of neighbouring regions when the aim is to achieve a CO_2-neutral energy supply. The analysis included holding a mini-workshop for a number of professionals from the energy sector. We would like to thank Flemming Nissen from the University of Southern Jutland, Sigurd Lauge Pedersen from the Danish Energy Agency, Stine Grenaa Jensen from the Danish Energy Association and Paul Frederik Bach. In addition, Peter C. Brun and Erik Kjær Sørensen from Vestas, and Ulrik Stridbæk and Lykke Jeppesen from DONG Energy have contributed valuable comments and insight.

Principal results

The analysis covers the supply of electricity and heat in Denmark, Germany, Norway, Sweden and Finland, focusing on the years 2010, 2020, 2035 and 2050 – with a requirement for CO_2 emissions to decrease from current levels to zero in 2050. Production units are expanded on the basis of financial optimisation of the entire system throughout the region. It is assumed that the reduction of CO_2 emissions will be achieved in the geographical area and within the sectors included in the model. In practice, the international CO_2 quota market can use the quota price to share the burden between sectors and countries in the run-up to 2050 in a manner different to that presented in this study. The calculations produced the following principal results:

- *Throughout the entire area, the share of renewable energy is set to rise from 36% in 2010 to 50% in 2020, 65% in 2035 and 77% in 2050.* In the Baseline Scenario the share of electricity from renewable sources *in Denmark* rises from 30% in 2010 to more than 70% in 2020, and nearly 90% from 2035 onward. With a greatly expanded transmission network between the various areas, the share will reach 100% as early as 2035 in Denmark.
- The share of wind power in the Danish system will double between 2010 and 2020, when it will account for 50% of total Danish electricity consumption. Depending on transmission capacity, this share will continue to rise towards 2035, when it will reach 54% in the Baseline Scenario and 62% in the scenario with increased transmission capacity.
- Expansion of the transmission grid with the planned connections between the areas would mean an annual savings of DKK 6.4 billion. Investments in this expansion are estimated to total DKK 30 billion. Additional expansion to reduce the most significant bottlenecks would generate additional annual savings of DKK 15 billion for an estimated investment of DKK 125 billion. It therefore seems that the annual operating benefits would be able to recoup the investments in the transmission grid with a good margin.

Summary

Converting the entire region to CO_2-neutral energy supply is an appreciable but manageable task. There is a great deal of uncertainty concerning the role nuclear power will play in the region, the perspective for carbon capture and storage (CCS), and the potential for reducing the costs of solar cells, wave power, etc.

With moderate basic assumptions in all the areas mentioned above, it is possible to envisage a regional energy sector based on four pillars: wind power, hydropower, biomass and nuclear power. There will be appreciable exports of wind power from the northern area of the region, and biomass will be particularly significant in Germany. The demand for biomass will exceed the available local resources. Towards the end of the period, the import of biomass in the Baseline Scenario will reach such an extent that questions related to sustainability may be raised.

The amount of imported biomass required will be largely dictated by whether the transmission connections between the Nordic region and the rest of Europe can be expanded sufficiently to utilise the appreciable wind power potential in the Nordic region. The analysis reveals that there is a financial basis for major expansion of the transmission grid – even over and above what has already been adopted and planned. If this is to be possible, what is required is an international strategy combined with a credible timetable for the expansion of the necessary transmission connections as an integrated part of a shared policy for the reduction of CO_2 emissions from the energy sector in Northern Europe. In this context, a rapid and major expansion of wind power in Denmark appears to be a robust strategy, irrespective of other developments in technologies and fuel prices. There will also be grounds for significant expansion of wind power in the other Nordic countries.

The analysis also demonstrates that it is realistic to assimilate the large volumes of wind power into the energy system as a whole once the various production technologies have the possibility to interact with district heating, flexible electricity consumption and optimal utilisation of the transmission connections.

It seems likely that the Danish positions of strength in the field of energy – wind power, CHP based on biomass, and district heating – will continue to be key technologies in Northern Europe in the future, and a strategy in which Denmark commits wholeheartedly to expanding these positions of strength would be appropriate in a future with increased focus on the climate, security of supply and economic efficiency.

Starting point

CO_2 cap

The analysis covers the electricity and heat system in Denmark in conjunction with neighbouring countries (Norway, Sweden, Finland and Germany) under the assumption of a shared framework for the generation of electricity and heat. In the model, this is dealt with by applying a CO_2 cap on the emissions from the entire electricity and heat sector throughout the region. The CO_2 cap triggers a common shadow price on CO_2, which, as regards the model, replaces the existing national subsidy schemes, both direct and indirect. These could, for example, consist wholly or in part, of the cost of a global and/or regional (EU) CO_2 regulation. In the analysis, the CO_2 cap is tightened by approximately 5% annually, and it is adapted in such a way, that the cap in 2050 precisely matches the emissions from the fossil portion of waste incineration.

Market model with the opportunity to invest in production facilities

The analysis was carried out using the Balmorel energy market model, which simulates the cohesive electricity and heat system and optimises operation of the system over the course of one year. On the electricity side, the transmission grid is included with the existing limitations on transfer capacity between countries and sub-areas. As a starting point, the existing energy system is modelled. As demand for electricity rises, and as older production plants are progressively scrapped or discontinued, the model has the opportunity to invest in new production facilities. Both investments and operation are optimised so that the total energy supply occurs at the lowest possible cost. Data for the technologies the model can choose between are drawn from a new and comprehensive technology catalogue for the period 2010–2050 prepared by the Danish Energy Agency and Energinet.dk.

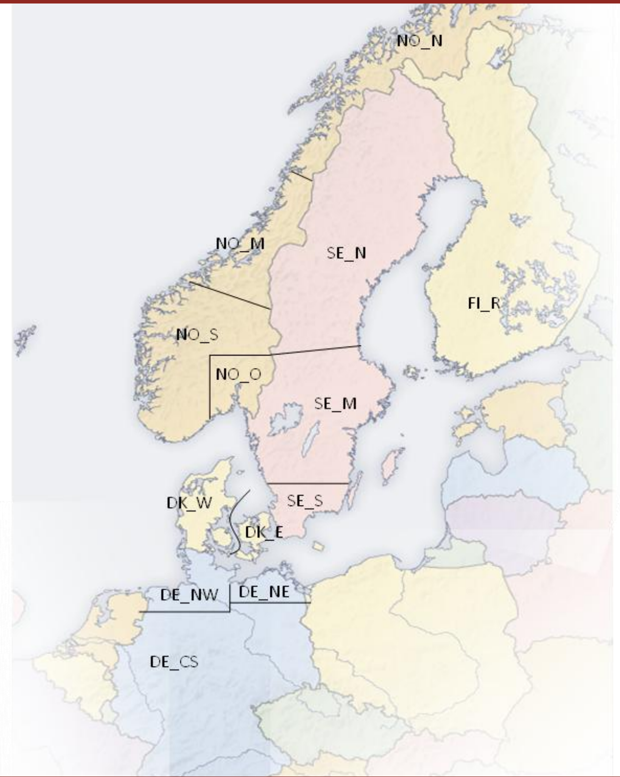
Four scenarios

A range of scenarios for future development have been generated. Each scenario has been generated for the years 2010, 2020, 2035 and 2050.

The development of electricity consumption

The analysis took, as its starting point, the Danish Energy Agency's most recent forecast for electricity consumption in Denmark. To ensure harmonised conditions, the same increase in electricity consumption has been assumed for all countries, and a rise in electricity consumption has been factored in for electric vehicles and heat pumps in all countries. In its optimisation routine, the model can choose to use electricity for the supply of district heating. Lastly, throughout the region industry is increasingly converts to electricity.

The model area



Wind power and biomass

Options for siting wind power on land are based on Danish analyses and have been harmonised for other countries on the basis of the area of agricultural land. Offshore siting options are graded into three classes depending on water depth and proximity to the coast. This division is not based on national sources, but is estimated. Lastly, the specific wind speeds are based on actual wind measurements in the different areas. The model can then optimise wind power production based on potential, wind speed, turbine features and turbine prices. Based on information from the European Environmental Agency, biomass resources have been calculated at the country level for wood chips and straw. In addition, it is possible to import wood pellets freely at prices corresponding to the Danish Energy Agency's assumptions.

BASELINE SCENARIO

Assumptions in the Baseline Scenario

Moderate development in fuel prices

The purpose of this work is to highlight effective strategies for significant CO_2 reductions in the region in an international context. Import prices for fossil fuels have thus been set on the basis of the assumption that reduction of CO_2 is not an isolated task in the region, but is based on a global target. According to the International Energy Agency (IEA), development of this kind will result in reduced demand for fossil fuels at the global level, which means that the prices of coal, oil and natural gas will be stable. The Baseline Scenario uses fuel prices from the IEA 450 ppm scenario up until 2030, with constant prices after this period.

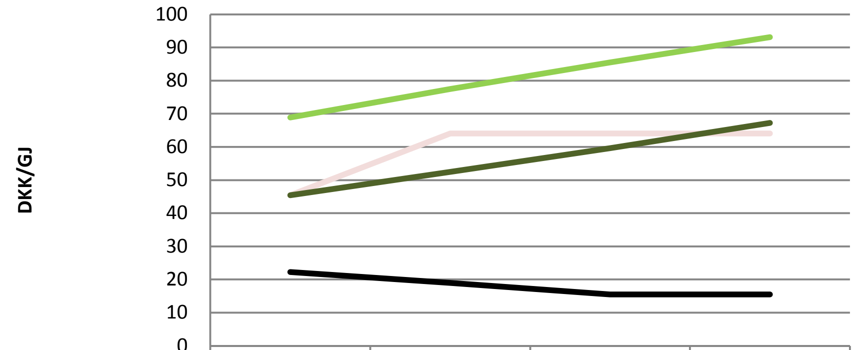
Technical opportunities

The model allows investments to be made in the following types of production facilities, based on data from the Danish Energy Agency's technology catalogue:

- Onshore and offshore wind power involving various types of wind turbines
- Biomass for the generation of heat and electricity through power plant construction and retrofitting
- Biogas facilities in CHP production, and upgrading of biogas for use in the natural gas network
- Solar cells and solar heating facilities
- New thermal power plants fired by coal, natural gas and oil
- Nuclear power plants
- CCS plants utilising coal or biomass
- Heat pumps, electric boilers, boilers and heat storage in connection with district heating.

The opportunities to invest in the different technologies are not uniform across the region, for example because there are differences in the availability of resources in the different countries. The opportunity to invest in nuclear power is limited to those countries that already use nuclear power. In Germany, it is assumed that half of the existing nuclear power capacity will be retained until 2050, while in Sweden, the current level will continue until 2050. In both countries, it is possible to invest in an expansion equivalent to a maximum of 20% of 2010 capacity – half of this in the period 2020 – 2035 and the remainder up to 2050. In Finland, the existing facilities and Olkiluoto 3 will be maintained up to 2050, and it is possible to invest in a new plant in the period 2035 – 2050. In regards to electricity generation from natural gas, it is assumed that it will be possible to increase 2010 production by 10% throughout the model area at the country level. The potential for CCS installations has been set to 10 – 15 major plants in the area.

Fuel price assumptions



	2010	2020	2035	2050
Wood pellets	68,9	77,4	85,5	93,1
Natural gas	45,4	64,1	64,1	64,1
Wood chips	45,4	52,5	59,6	67,3
Coal	22,3	19,0	15,5	15,5

Expansion of the transmission grid in the Baseline Scenario

In the Baseline Scenario, it is assumed that a range of adopted and planned transmission lines will be established – see the table below.

Connection	Area	Capacity (MW)	In operation	Status
Storebælt 1	West- and East Denmark	600	2011	Commissioned
Fenno-Skan 2	Sweden – Finland	800	2011	Under commission
Skagerrak 4	Norway – Denmark	600	2013	Decided
Sydvästlänken	Norway – Sweden	1200	2013	Decided
Cobra	Denmark-Holland	700	2016	Assumed
Fenno-Skan 3	Sweden – Finland	800	2020	Assumed
Nea – Järpströmmen	Norway - Sweden	750/600	2015	Decided
Nor-Ned 2	Norway – Holland	700	2015	Assumed
DK-Tyskland	West Denmark – Germany	+500	2025	Assumed
NordLink	Norway-Germany	1400	2025	Assumed

Results

Denmark
In Denmark, 500 MW of power plant capacity is converted to biomass before 2020, and a further 2,000 MW is converted to wood chips and wood pellets up to 2035. Wind power expands rapidly in the period up to 2020 and expansion continues after this date. At the end of the period, a coal and biomass fired CCS facility is established, while use of coal and natural gas is phased out.

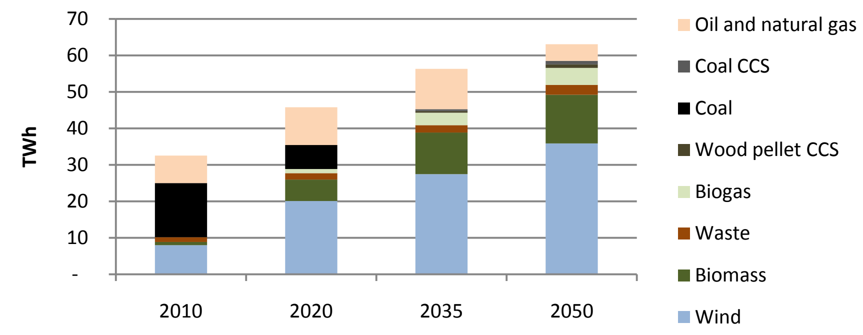
Conversion of energy supply throughout the region
In the Baseline Scenario, biomass and wind power undergo major expansion. Coal power is phased out, while both coal and biomass-fired CCS facilities are introduced at the end of the period. Even though the model invests exclusively based on economic aspects, a relatively diversified energy supply is achieved. The only reason why a more prominent role is not granted to renewable energy such as solar cells, is that despite expectations of an appreciable drop in price, solar cells remain a relatively expensive technology in 2035 and 2050.

Higher electricity prices in Germany
As the CO_2 cap becomes progressively tightened in the region, the demand for CO_2-free electricity production rises. Costs and potential for wind power are dependent on the local wind resources and on the opportunities for importing provided by the transmission grid. Once the local biomass resources have been exhausted, the model can choose to import wood pellets. The price for imported wood pellets is assumed to rise to almost DKK 100/GJ in 2050.

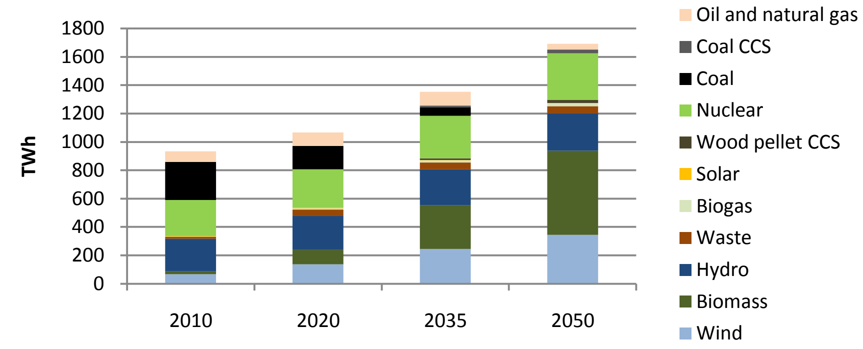
Due to poor access to good wind resources in Central and Southern Germany, the need to import wood pellets increases significantly here. According to the technology catalogue, other renewable energy resources such as solar cells and wave power are still too expensive to make them viable options. Lastly, there are opportunities to invest in nuclear power and in CCS technologies, but, as mentioned previously, limits have been placed on these technologies. For this reason, electricity prices rise in Germany in particular, which generates appreciable bottlenecks in the electricity system. This can be viewed as an indication of the need to develop the infrastructure.

CO_2 emissions
CO_2 emissions throughout the area (naturally) follow the requirements of the CO_2 cap. However, there are differences in how much the individual countries reduce CO_2 emissions from an overall financial perspective. As the figure to the right illustrates, Denmark needs to achieve a proportionally greater reduction than the region as a whole. The CO_2 emissions stated for 2050 stem from the fossil proportion of waste, which has been decided shall be excluded from the model's CO_2 cap.

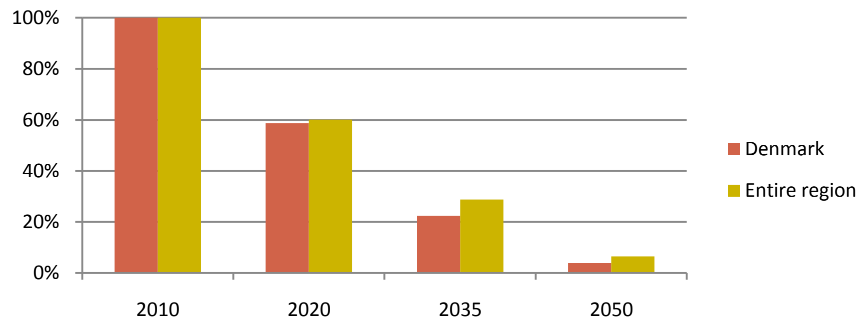
Electricity generation in Denmark – by type of fuel



Electricity generation in the entire area – by type of fuel



Emissions of CO_2



THEME I: THE IMPORTANCE OF INTERCONNECTORS

The starting point

While investments in electricity generation are made as part of the model's optimisation routine, the transmission grid is assumed in advance. A precondition of the Baseline Scenario is that the transmission grid between the areas will be expanded over time in accordance with a "small package" of cables that have either been adopted or are being planned. In addition, two alternative scenarios are evaluated: 1) Minimal expansion: Expansion is limited to the connections that have already been decided upon as of September 2010, and 2) Large package: Appreciable investments in the transmission grid, with bottlenecks being reduced when they reach significant levels.

The method chosen means that the model is fully aware of the limitations of the transmission grid when it makes investments in production facilities. Based on economic reasons, the model attempts to place its investments in such a way as to avoid the worst bottlenecks. It could be said that investments in the transmission grid and investments in electricity generation are competing solutions to satisfy electricity consumption. This means that the economic aspects of investments in infrastructure will be further challenged, and may be assessed in an overly pessimistic way in relation to reality.

Baseline Scenario and "Minimal Transmission"

In the Baseline Scenario, the transmission system is expanded through a range of agreed upon and planned cables. The "Minimal Transmission" scenario reveals the effect of only establishing the cables that have already been decided upon today.

Connection	Area	Capacity MW	In operation	Status
Storebælt 1**	West- and East Denmark	600	2011	Commissioned
Fenno-Skan 2	Sweden – Finland	800	2011	Under commission
Skagerrak 4	Norway – Denmark	600	2013	Decided
Sydvästlänken	Norway – Sweden	1200	2013	Decided
Cobra	Denmark-Holland	700	2016	Assumed*
Fenno-Skan 3	Sweden – Finland	800	2020	Assumed*
Nea – Järpströmmen	Norway - Sweden	750/600	2015	Decided
Nor-Ned 2	Norway – Holland	700	2015	Assumed*
DK-Tyskland	West Denmark – Germany	+500	2025	Assumed*
NordLink	Norway-Germany	1400	2025	Assumed*

*** Great Belt came online in August 2010. As connections are assumed to be in operation in whole years, the Great Belt is not included in the 2010 runs of the scenarios.*

Expansion scenario "Significant Expansion"

Utilisation of renewable energy increases throughout the region. Wind power is particularly popular in the North and West, which creates bottlenecks in the system. By using shadow prices, the model can calculate the value of expanding a bottleneck area by 1 MW. The value can be determined by adding together the difference in electricity prices between the two areas in question for all the hours of the year. In the process where transmission investments are planned, the shadow price is compared to the costs of establishing new capacity.

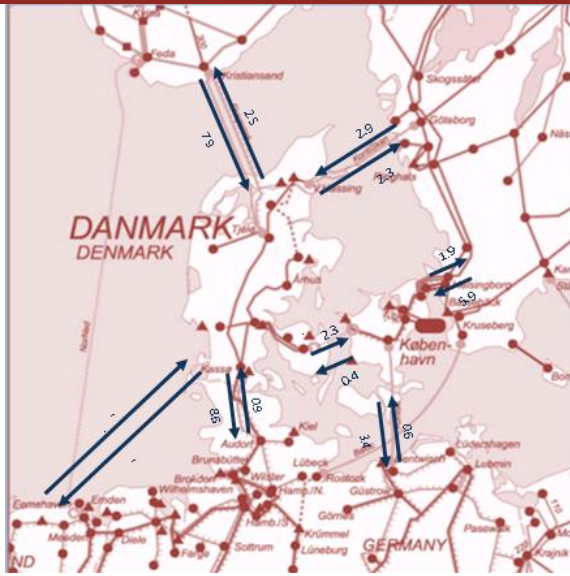
In the expansion scenario entitled "Significant Expansion", the individual investments are selected through a screening of the Baseline Scenario's shadow prices of transmisson, and when these exceed approximately DKK 150,000/MW/year, a decision is made to expand the connection. However, the expansion also includes an assessment of how the connections affect each other: reducing one bottleneck may cause changes in others.

The table below presents what is called the "Large Package" of transmission established in the "Significant Expansion" scenario, with shadow prices from the Baseline Scenario and with the assumed size of each connection.

New transmission connections in "Significant Expansion"

Notable bottlenecks	Value of the first MW transmission capacity 1000 DKK/year (2020-50)	Infrastructure expansion "Large Package" New transmission MW
Entrapped Norwegian hydro and wind potential		
North Norway to Mid Norway	157	1,500
Mid Norway to South Norway	343	3,000
Access to wind resources from west towards east		
Storebælt	154	1,200
Oslofjordssnittet	237	2,000
Fennoskan	161	1,600
North Sweden <-> Finland	191	2,000
Interaction wind-hydro		
Skagerrak	571	1,000
South Norway <-> North West Germany	372	1,200
Nordic transit from RE resources to centers of consumption		
Sweden snit 2	180	3,000
Øresund	365	2,000
Access to the large continental system		
West Denmark <-> Germany	285	2,000
West Denmark <-> Holland	262	1,000
North West <-> South Germany	557	4,000
North East <-> South Germany	483	2,000

2035 – Minimal Transmission



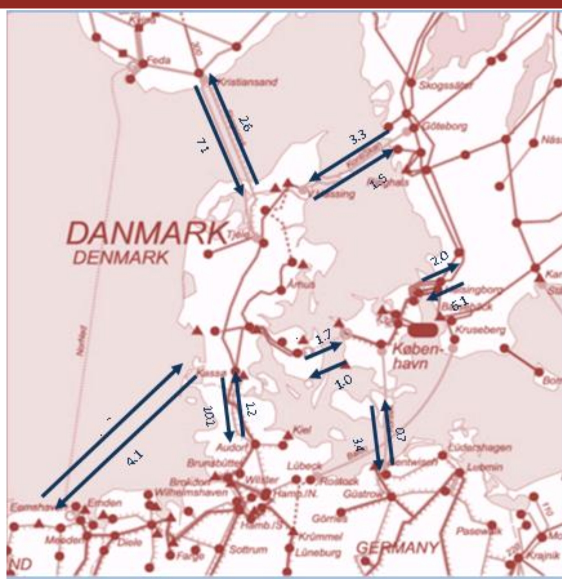
Transmission conditions

The figures display the annual flow in TWh in 2035 on the transmission lines to and from Denmark for the three scenarios.

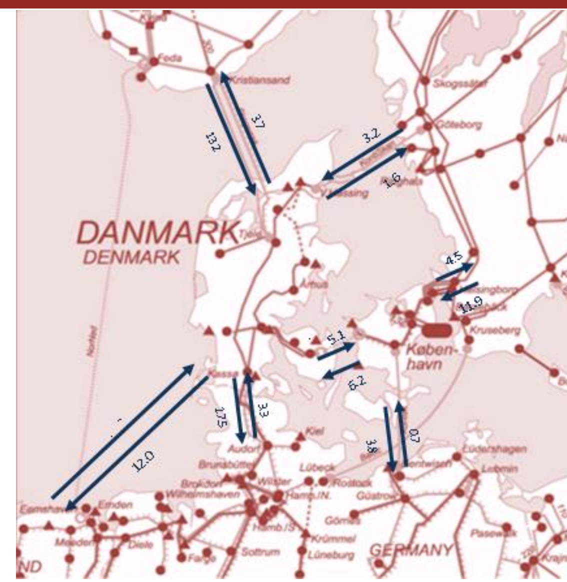
The overriding trends are:
- Increased flows southwards, particularly towards Germany (and the Netherlands), and also from Sweden and Norway via Denmark.
- Reduced net transmission eastwards. This is due to factors such as increased wind power generation in the Baltic region.
- Increased total transmission in both directions along the transmission connections.

The connection to the Netherlands (which, in the scenario model, feeds into Southern Germany), is heavily used southwards in the Baseline and “Significant Expansion” scenarios. This is due to factors such as the bottlenecks in the transmission between Northern and Central Germany.

2035 – Baseline (Small Package)



2035 – Significant Expansion (Large Package)



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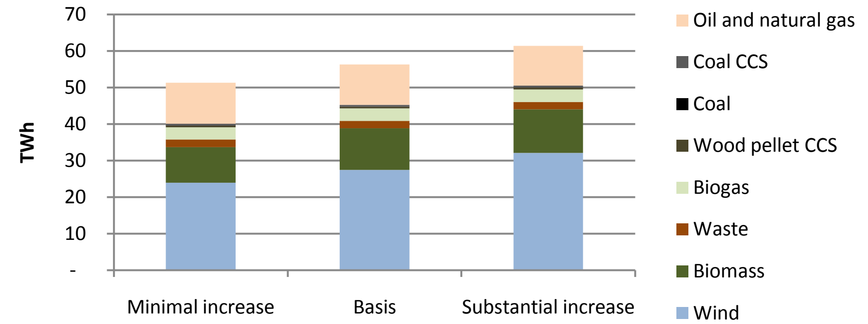
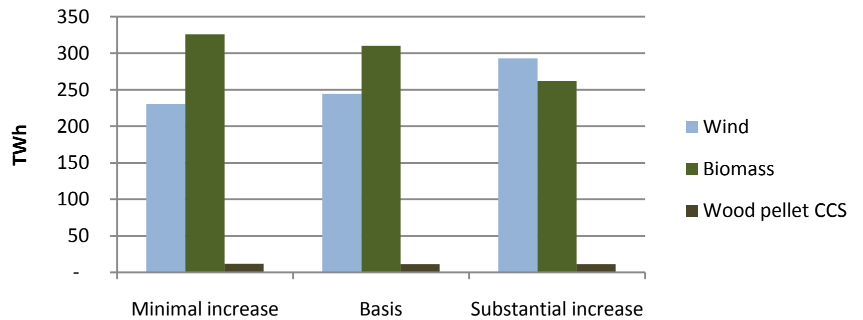
Electricity generation in Denmark in 2035



Electricity from wind power and biomass in 2035 (entire area)



Reduced annual costs of the two transmission packages (DKK billion)

	Bn. kr.
2020	
Small package	3,7
Large package	-
2035	
Small package	6,4
Large package	15,0
2050	
Small package	5,9
Large package	19,1

The benefits from the "Large Package" are stated in relation to the Baseline Scenario. In comparison with the "Minimal Transmission" scenario, the reduction in annual costs is therefore to be totalled.

Expansion packages of interconnectors

Stronger transmission connections make more wind power attractive

Stronger interconnectors make it more attractive to increase the exploitation of the major wind power resources in the North for the benefit of the entire region. This will make it possible to cut imports of relatively expensive biomass – especially in Germany. Wind power expansion increases markedly in Norway, and Danish wind power production rises from 24 TWh to 27 or 32 TWh, depending on the expansion of the transmission grid. The increased expansion also means a rise in exports of electricity from Denmark.

Economics of the infrastructure packages

As part of the project, a very general estimation has been made of what the two infrastructure packages will cost to establish. The estimate is based on figures from completed and planned projects:

- Infrastructure investments in the Baseline Scenario in relation to "Minimal
- Transmission" are estimated to total approximately DKK 30 billion (small infrastructure package)
- Infrastructure investments in additional transmission connections for "Significant Expansion" are estimated to amount to approximately DKK 125 billion (large infrastructure package).

The two infrastructure packages make appreciable contributions to the operational benefit of the electricity system. In 2035, operational benefit increases by DKK 6.4 billion/year when the small infrastructure package is applied, and by a further DKK 15 billion/year if the large infrastructure package is adopted. The simple repayment periods for the packages are app. 5 and 8 years, respectively. These payback periods could be deemed as particularly attractive. The application of both packages reduces fuel costs in particular, while the annual capital costs of the production system increase due to the switch from biomass to wind power.

Offshore grid

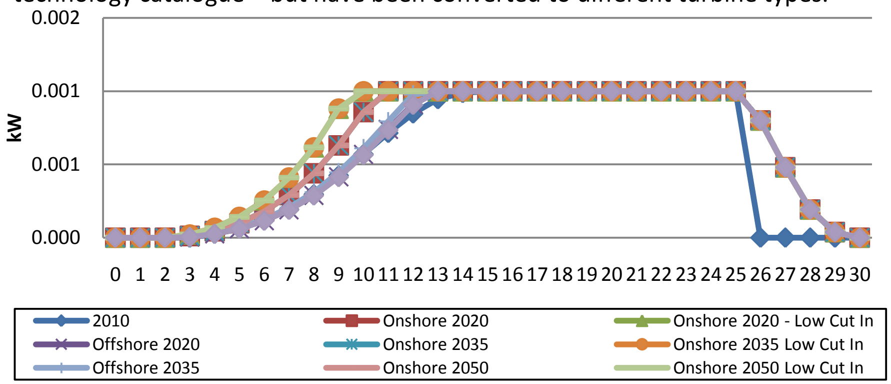
The composition of the large infrastructure package is not optimised through the model, and there may be other expansion solutions that would allow lower investments and/or generate higher operation benefit than those described here. For example, it is possible that the establishment of offshore grids would generate the same benefits at a lower investment.

The results from the analysis emphasise the need for clear focus on the relationship between the expansion of wind power and the expansion of the transmission grid in an international context, including the planning of offshore grids.

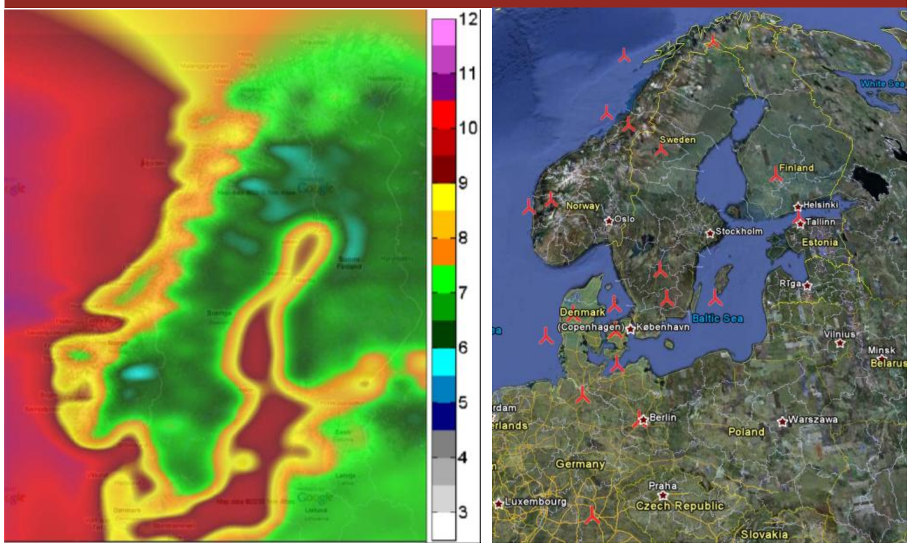
THEME II: WIND POWER AND BIOMASS

Wind power in the scenarios

The model has used data generated by simultaneous wind measurements throughout the model area. The wind measurements were carried out in a long series over numerous years. The hour series for wind speeds from 19 different measuring points at two heights are included in the model dataset. Wind turbine characteristics (power curves) are combined with the turbine height and the local wind conditions. On land, the model chooses between two options, where one is optimised for lower wind speeds (Low Cut In (LCI)). Turbine prices and operating and maintenance costs are drawn from the technology catalogue – but have been converted to different turbine types.



Wind power resources and measuring points used in the analysis



Levelised Cost of Energy

The turbine catalogue used in the model is harmonised with data from the technology catalogue. The purpose is to maintain the model's options between different turbine types, while ensuring that standard turbines have production costs (Levelised Cost of Energy) on a par with turbines in the Danish Energy Agency's catalogue.

The Danish Energy Agency's technology catalogue and conditions converted to cost of energy (DKK/MWh)

	2010	2020	2035	2050
Onshore	527	442	420	395
Offshore	756	599	550	493

** The same annual return requirements (11.75% or 10% over 20 years) have been used in all calculations.*

Onshore	2010	2020	2020 LCI	2035	2035 LCI	2050	2050 LCI
North Norway	544	461	474	437	450	410	422
Mid Norway	600	499	514	474	488	444	457
South Norway	565	487	511	462	484	433	454
Jylland-Herning	527	443	455	420	432	394	405
Mid Sjælland Holbæk	561	469	479	445	455	418	427
DE Berlin	712	575	570	545	540	511	506
DE Hamborg	582	482	493	457	468	429	439
DE Nurnberg	716	586	588	555	557	521	522
South Sweden Vaxjo	795	625	610	593	579	556	543
Mid SwedenJonkøbing	718	572	570	543	540	509	507
North Sweden Østersund	639	529	538	501	510	470	478
South Finland Tampere	822	641	617	608	585	570	548

Offshore	2010	2020	2035	2050
North Norway	749	595	551	493
Mid Norway	757	601	554	496
South Norway	816	647	599	535
Horns rev	692	550	507	454
Kattegat Anholt	756	598	550	493
Østersø Rødsand	773	611	562	504
South Sweden Gotland	776	614	566	507
South Finland Helsinki	886	694	634	569

Horns Rev has the best offshore wind conditions in the dataset.

In Southern Sweden, Finland and Germany, the model often chooses turbines that are optimised for lower wind speeds (LCI).

Illustration of interaction

As part of the analysis, an hour-by-hour simulation was run of the entire electric and heating system throughout the region for the Baseline Scenario in 2050. The objectives of the simulation included clarifying how electricity and heat consumption are covered, and how to assimilate the fluctuating production from wind power plants into the system.

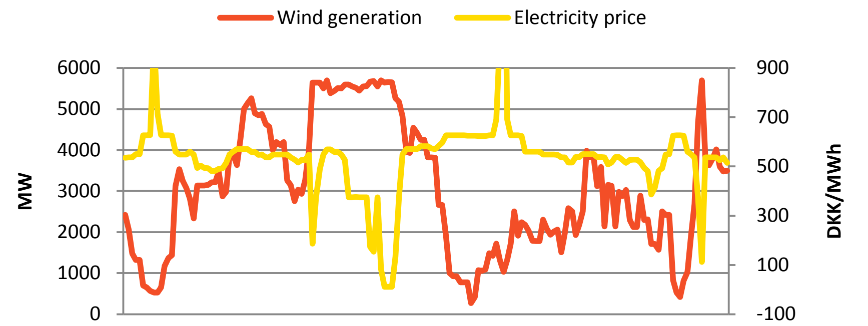
The simulation confirms that it is possible to assimilate large amounts of wind power in a cost-effective manner throughout the region. This is particularly interesting in this study, as it includes wind measurements at a detailed regional level.

There is potential for major dynamic interaction between wind power, hydropower, the thermal generation, flexible electricity consumption and, in particular, district heating.
Electricity transmission between the regions make it possible to activate significant flexibility outside the local area when necessary, and price signals in the electricity market function as the overriding control parameter for cost-effective operation.

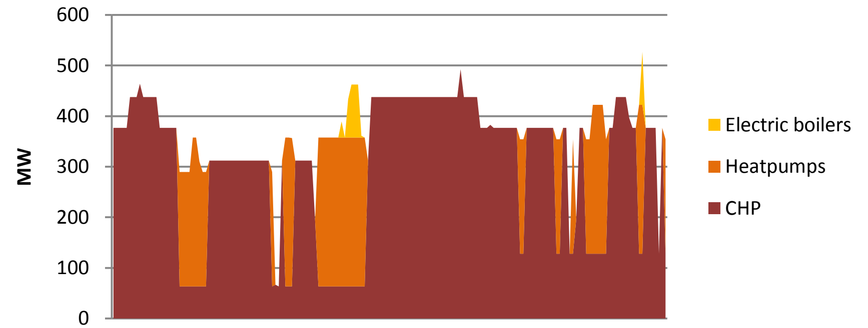
Interaction between wind power and heat – mediated by an efficient market
The model generates an electricity price on the basis of the marginal costs in the system. When there is a great deal of wind power in the system, pressure is exerted on electricity prices (see the top, right-hand figure). Even though heat consumption fluctuates from one hour to the next – just like electricity consumption – heat storage make it possible to decouple consumption time and production time, particularly in the winter months. It is therefore possible to use electricity for heat production when the electricity prices is low. With regard to investments, there is a balance to be found between electric boilers and heat pumps, which is defined by the frequency and duration of the low-price periods. When there is less wind power in the system, electricity prices are generally higher and CHP plants generate more heat. The interaction between electricity and heat applies to both planned production and regulation reserves.

District heating as an international form of supply
In the analysis it is assumed that the district heating system will be expanded to cover 55% of heat consumption in Denmark, based on the project entitled “Efficient district heating in the future energy system”. It is also assumed that district heating will expand in the rest of the region. Throughout the region, the model chooses to invest in technologies for the production and storage of district heating, and the district heating are therefore gets a significant role in the shared challenge of assimilating fluctuating electricity generation.

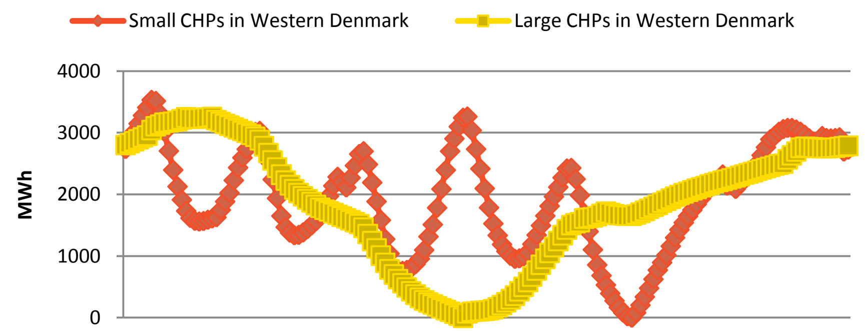
Wind power production, electricity prices in West Denmark, week 22, 2050



District heating production in decentralised areas in West Denmark, week 22, 2050



District heating storage in decentralised areas in West Denmark, week 22, 2050



Balancing, reserves and use of transmission connections

The need for regulation reserves is defined by wind power
Within the analysis it is assumed that the need for regulation reserves is defined by the wind forecast uncertainty. When the wind power contribution is forecasted to be high, then there is a particular need for upward regulation reserves to guard against the event that the wind power contribution is lower than predicted. In the case of medium wind power contributions, both upward and downward regulation reserves are required, and when a low wind power contribution is forcasted, the system must be prepared for downward regulation.

Technologies that deliver upward regulation reserves
Thermal capacity, which has been activated according to plan, but which is below maximum production capacity can regulate upwards. The reserve capacity is defined as the difference between capacity and planned production, and limited by the maximum upward regulation gradient of the plant.

Electricity for district heating production can be used downward regulation. This allows utilisation of the flexibility in district heating storages as well as the opportunity to switch between different heat production technologies. As a result, the requirements of the electricity system for flexibility and reserves (regional) are included in the model's prioritisation of which heat technologies to invest in for local supplies to the individual heat markets.

As a last opportunity, wind power can be planned with the potential for downward regulation, which would reduce the need for upward regulation capacity elsewhere in the system. This would naturally result in some wind power being curtailed, so the model only selects this solution if there are no other options.

Reserves are international
A free market for balancing reserves along the interconnectors is also assumed. The volume of reserves that can be delivered across a section of the transmission grid is, however, limited both by the physical capacity and by the planned utilisation for transmission.

Wind power production and electricity prices in West Denmark, week 22, 2050

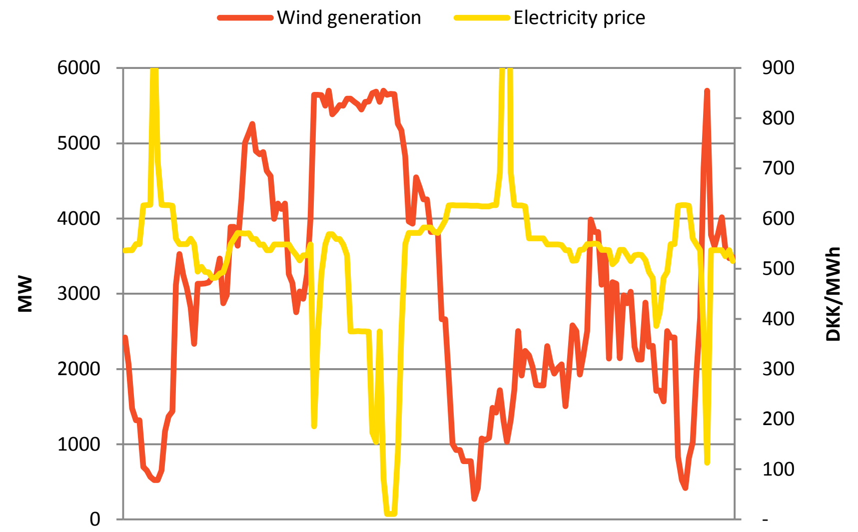
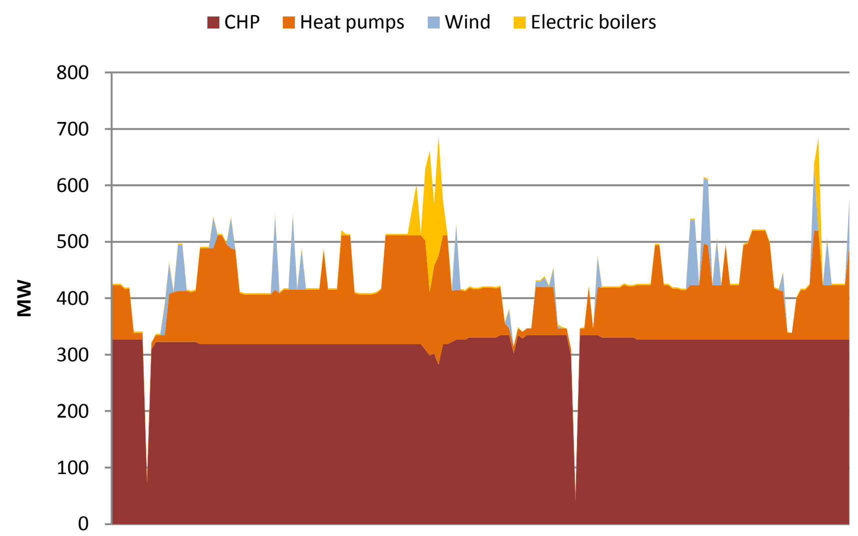


Illustration of upward regulation reserves supplied in West Denmark, week 22, 2050



Scenarios with other conditions for wind power and biomass

Wind power and biomass are, along with hydropower and nuclear power, the principal sources of CO_2-neutral electricity generation. In the Baseline Scenario, these two sources of energy deliver more than 40% of the total energy generation in the entire region in 2035.

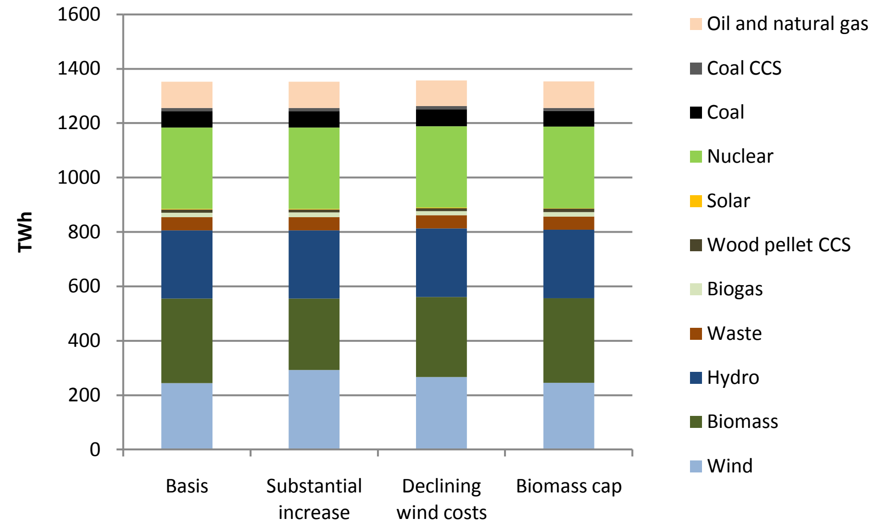
The analysis features various scenarios that examine the boundary conditions for wind power and biomass in more detail. One scenario illustrates the importance of the reduced construction costs for wind power. Another scenario introduces a cap on the amount of biomass that can be imported into the area. In the figures on this page, these two scenarios are compared with the Baseline and "Significant Expansion" scenarios for 2035 and 2050.

In the "Wind power price drop" scenario, it is assumed that the investment costs for wind power will drop by 10% in 2020, 20% in 2035 and 30% in 2050 as compared to the Baseline Scenario. This means that more wind power will be established in areas where wind conditions are relatively poor – i.e. Germany and Finland – while it has only a minor effect on the expansion of wind power in the other countries, where the good wind power sites have already been fully utilised. Due to bottlenecks in the transmission grid, the total expansion of wind power is not much larger in this scenario. In other words, the removal of bottlenecks has a greater influence on the expansion of wind power in 2035 than does a price drop of 20%

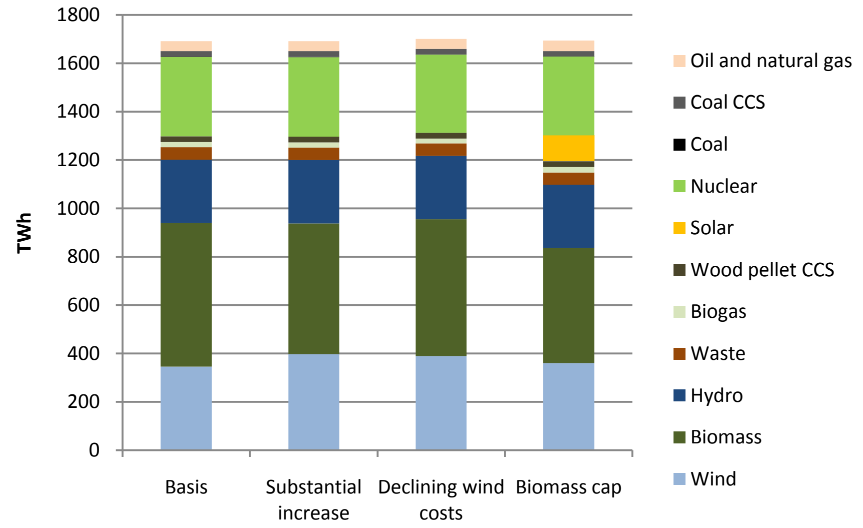
The "Biomass cap" scenario has been produced by placing a cap on the amount of biomass that can be imported into the model area. The level of the cap has been defined through multiple iterations and was initially set very tight and then relaxed. With a tight cap on biomass imports, CO_2-free supplies will dry up in Southern and Central Germany, which makes it impossible to cover electricity production during certain periods because there is already a cap on the expansion of nuclear power and CCS plants. A major expansion of solar cells will not alone deal with the shortage of output, as production from solar cells primarily occurs in the summer months. Increased transmission capacity or significant development in electricity storage technologies would help alleviate this problem.

Other alternatives to the high volume of biomass imports will depend on the political and technical opportunities for additional expansion of nuclear power, technological development and maturity of CCS, or the opportunities for a focused and significant effort to reduce energy consumption in the area.

Base – Significant Expansion – Wind price drop – Biomass cap 2035 (entire area)



Base – Significant Expansion – Wind price drop – Biomass cap 2050 (entire area)



Observations about wind power from four scenarios

The “Transmission connections” theme illustrates the importance and financial potential of ensuring a broad corridor from Northwest Europe – with its rich wind power resources – to Central Europe.

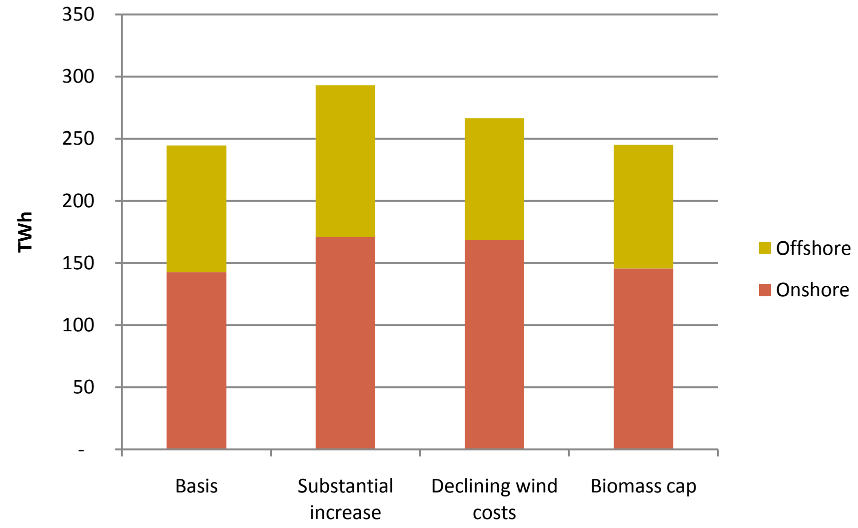
Onshore wind – a leading renewable energy technology
The analyses indicate that from a purely economic perspective, onshore wind power has a key role to play in a future energy supply scenario based on renewable energy. Step 1 in a cost-effective energy supply system based on renewable energy should therefore involve ensuring good siting options for onshore wind. Good siting options represent increasing value for the energy system in all the scenarios.

Limited siting options make efficient turbines attractive
In areas where low wind conditions arise regularly, the new “Low Cut In” turbine models will be very attractive on account of the lower energy costs. The limited siting options increase the value of the capacity to generate many kWh from the sites that are actually available. This may make it attractive to install the new turbine types, even in areas where more conventional turbines have the lowest energy costs.

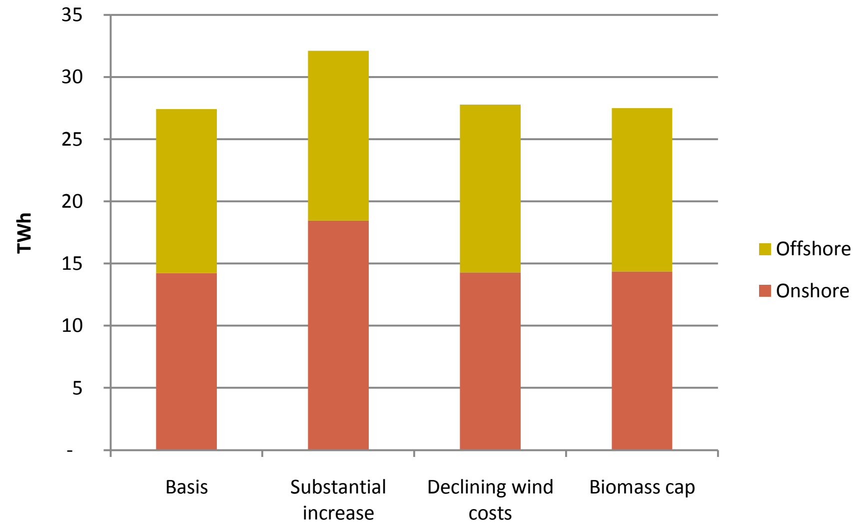
Attractive to use near-shore wind power potential
With the assumptions in the scenarios that near-shore wind turbine sites can be utilised with capital costs that are 15% lower than the general price level for offshore wind power, these options are attractive. If it proves possible to identify siting zones that do not give rise to opposition, near-shore wind power may be an inexpensive supplement to onshore wind power.

If backing for siting zones cannot be achieved, sites far from the shore will be required
The offshore wind power potential in the North Sea and the Baltic Sea is enormous, but the costs associated with energy supply based on renewable energy may be prohibitively expensive if all construction has to take place at deep-water sites. This simultaneously highlights the need to reduce the energy costs of wind power through investments in development, infrastructure and logistics, which can only be carried out if the long-term strategy is clear. A long-term expansion strategy will, for example, allow improved utilisation of the material required to install wind turbines at offshore locations.

Baseline – Significant Expansion – Wind price drop – Biomass cap (entire area)

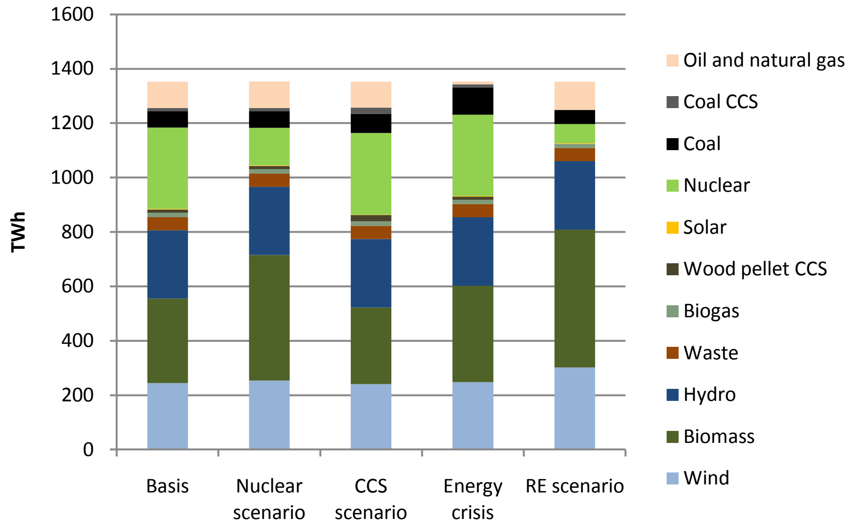


Baseline – Significant Expansion – Wind price drop – Biomass cap (Denmark)

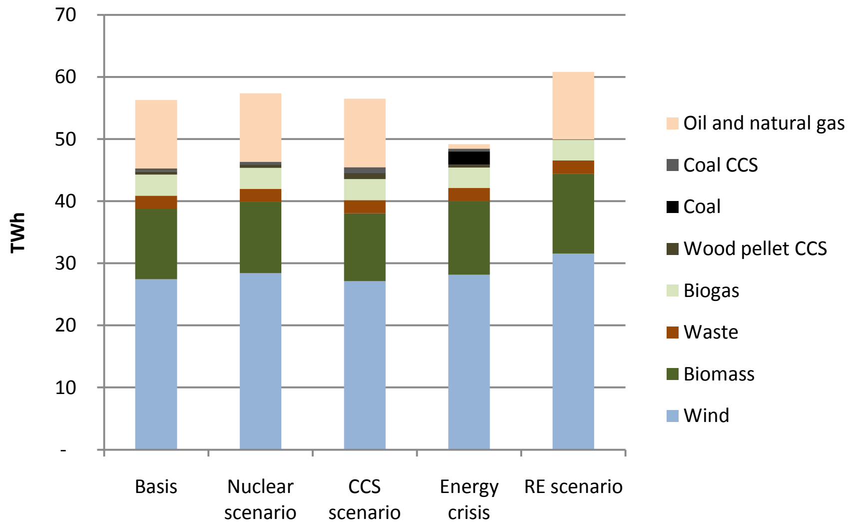


THEME III: SECURITY OF SUPPLY AND NEW TECHNOLOGIES

Electricity generation in 2035 (entire area)



Electricity generation in 2035 (Denmark)



The challenges posed by security of supply

Apart from the dependency on imports of biomass that was illustrated in the "Biomass cap" scenario presented under the previous theme, there are other significant parameters that may pose a challenge to the CO_2-neutral energy supply system outlined here.

To illustrate the security of supply issue, four sensitivity scenarios have been prepared:

CCS scenario: Europe has 50 GW of electricity capacity with CCS in 2050.
The IEA's World Energy Outlook 2009 450 ppm scenario includes 40 GW of CCS for the whole of Europe in 2030, which in this report is manifested as 25 GW in 2035 and 50 GW in 2050. Of this, it is assumed that 27% will be located in the model area (measured relative to current electricity consumption). This is twice as much CCS potential as assumed in this study's Baseline Scenario. More CCS contributes to extending dependence on fossil fuels and a reduction in the use of biomass.

Nuclear energy: Germany discontinuing nuclear power in accordance with updated agreement
When Germany phases out nuclear energy in 2050, even greater pressure will be placed on the biomass resources. This does not, however, translate into more wind power as the transmission conditions from the Baseline Scenario prevent untapped potential from the Nordic and Baltic areas of the region being used to supply Southern Germany.

"Energy crisis": fossil fuel prices doubled in relation to the baseline assumptions
This affects natural gas in particular, as this will have been phased out almost completely in 2035. On account of the unchanged CO_2 cap, coal will still be used in 2035. After 2035, coal will only be used in connection with CCS. In the medium and long terms (2035, 2050), the higher fuel prices will, however, mean that CCS will neither be attractive with coal nor biomass, as the savings in relation to pure renewable energy will have been cancelled out.

Renewable energy scenario: Assumption of complete nuclear phase-out before 2050 and no CCS
In this scenario, natural gas is still used in 2035 and coal is still in use in 2035 – but not in 2050. The share of wind power is increased and the scenario makes use of additional wind power sites – particularly in the Nordic region, including Denmark. However, the use of biomass increases dramatically.

Challenges linked to solar cells

The analyses in this project are based on the technology catalogue from the Danish Energy Agency and Energinet.dk, which also contains information about the expected development in investment costs and operating expenses in the future as a result of technological development.

The model used optimises investments and operations for the entire system, and consistently chooses the cheapest option. This means that the choices made in the scenarios are often more heavily based on a single technology than would be expected in practice.

Nevertheless, the model present clear messages about the roles of the various technologies in future energy supply solutions.

The figure to the right demonstrates – for three scenarios: Baseline, renewable energy and Biomass cap – how large a reduction in the investment costs for solar cells would be required for the model to consider this technology financially attractive.

For example, the (Baseline Scenario) figure shows that solar cells, that cost more than DKK 13 million/MW in 2035, would need to be 56% cheaper for the model to consider this technology competitive. In 2050, when the price for solar cells, according to the catalogue used by the model, has fallen to DKK 7.2 million/MW, the price would still need to fall by an additional 12% for the technology to enter into consideration. In a single scenario – Biomass cap – the price of DKK 7.2 million/MW in 2050 is sufficient for the model to make limited investments in solar cells. According to the figure, the price reduction necessary for the technology to be considered at that time is 0%.

Challenges of CCS

On the basis of the data from the technology catalogue, CCS utilising both coal and biomass is financially attractive in the long term.

This corresponds to the assumptions in the IEA's World Energy Outlook, whose 450 ppm scenario assumes that a technological breakthrough is made in the field of CCS technology. At the same time, the prices for fossil fuels are required to be lower on account of reduced demand due to CO_2 regulation.

However, CCS technology is far from fully developed today, and there may be risks associated with relying too heavily on an expected technological breakthrough. In the worst case scenario, there is a risk of fossil-fuel-fired plants that have been established on the expectation of their being "Capture ready", ending up as "stranded assets" within a CO_2-free sectorial framework.

In contrast, a breakthrough in CCS technology may result in increased demand for fossil fuels (especially coal) which, in turn, may cause fossil fuel prices to increase dramatically in relation to the prices assumed in the 450 ppm scenario used in this analysis, partly due to the increased fuel consumption for the CO_2 purification processes at the power plants.

Solar cells in Southern and Central Germany: necessary drop in costs