Ea Energianalyse

Integration af vindkraft

Viking Link og andre tiltag for integration af vind

Ea Energianalyse a/s

Denne rapport er udarbejdet af Ea Energianalyse a/s for Energinet.dk, november 2015.

Indhold

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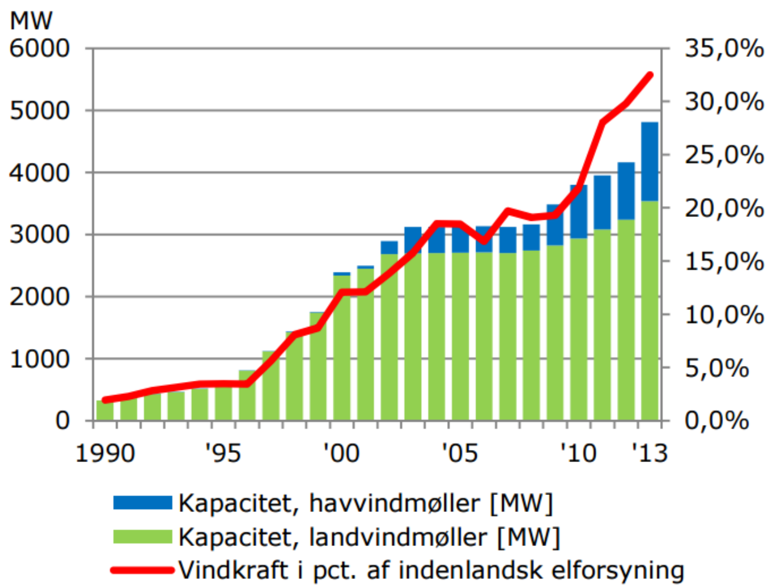
Introduktion

Denne rapport er udarbejdet af Ea Energianalyse for Energinet.dk

Siden midten af 1990'erne, er vindkraften i Danmark steget fra at udgøre knap 5% til ca. 33% af den indenlandske elforsyning i 2013, og ca. 40% i 2015. Energiaftalens målsætninger om at nå 50% inden 2020 vil ifølge Energinet.dk's forudsætninger for udbygning af vindkraft blive overopfyldt, og udviklingen ventes at fortsætte frem mod 2035, hvor vindkraft vil udgøre op til 84% af det klassiske elforbrug. Klassisk elforbrug er eksklusiv elforbrug til fjernvarme, individuelle varmepumper og elbiler. Samtidig viser de *nationale planer for vedvarende energi* en markant VE udbygning i landene omkring os. Elproduktionen fra vindkraftanlæg afhænger af, hvor meget det blæser, og det er velkendt, at udfordringerne ved at integrere vindkraften i elsystemet stiger efterhånden som vindkraftandelen øges.

Integration af vindkraft stiller krav om et fleksibelt elsystem med tilstrækkelige kapacitet til, at efterspørgslen efter elektricitet også kan dækkes med høj sikkerhed når det ikke blæser. Et udtryk for omkostningen ved at integrere vindkraft er vindmøllernes lavere afregningspris i markedet end gennemsnittet for de øvrige elproducenter. Energinet.dk har bedt Ea Energianalyse om at analysere effekten af forskellige tiltag til at integrere vindkraft, herunder Vikingforbindelsen, varmepumper og andre tiltag. Endvidere ses der på tiltagenes interne afhængighed.

En konklusion er, at Vikingforbindelsen og store varmepumper hver for sig har positiv samfundsøkonomi, samt at de to vindintegrationstiltag ikke væsentligt påvirker hinanden økonomisk. Værdien af at gennemføre begge tiltag er således større end blot at gennemføre ét af tiltagene. Det betyder at en "både og" løsning kan være en økonomisk attraktiv løsning i forhold til at integrere vindkraft på lang sigt.



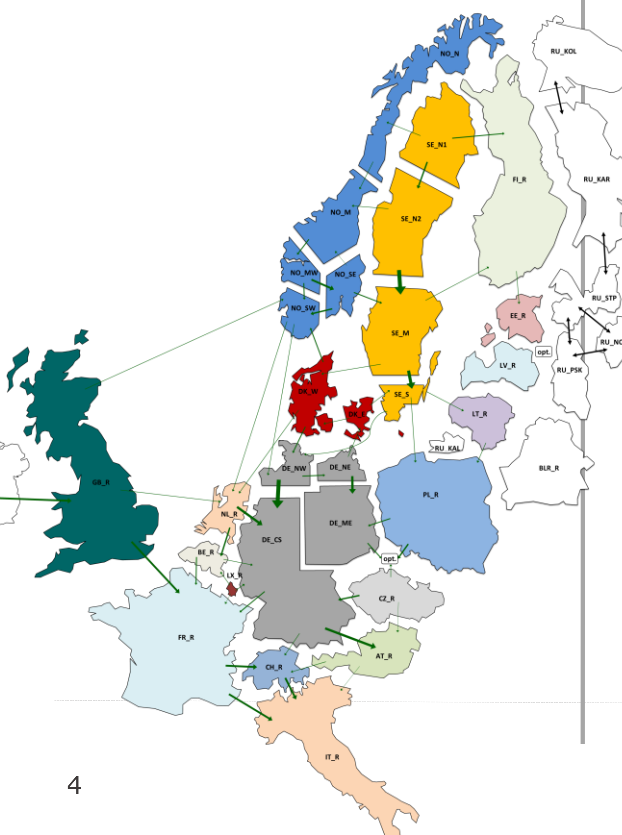
Kilde: Energistyrelsen

Metode

Modelberegninger

Beregninger og analyser er hovedsageligt udført med el- og varmemarkedsmodellen Balmorel. Modellen omfatter en repræsentation af el- og fjernvarmesystemet i Norden og store dele af Europa. Modellen beregner bl.a. produktion, transmission og elpriser baseret på forudsætninger for udviklingen af brændselspriser, udbygning med vedvarende energi og andre vigtige parametre.

Analysen er struktureret omkring et basis scenario, der beskriver en sandsynlig udvikling for el- og fjernvarmesystemerne. I dette centrale scenarie beregnes udbygningen af produktionsapparatet i en simulering med aggregeret tidsopløsning. For at analysere integrationen af vindkraft gennemføres efterfølgende beregninger på timeniveau, og samtlige resultater for drift og økonomi af systemet i denne rapport er baseret på timeberegningerne. Som væsentligste indikator for integration af vindkraft sammenlignes markedsværdien af vindkraft-el med markedsværdien af gennemsnits-el. Indikatoren for om et tiltag er attraktivt er, at tiltaget har positiv samfundsøkonomi for den samlede region.



Scenario (I parentes angives forkortet scenarienavn)	Scenarioanalyse (Ændringer i forhold til Basis scenario)
Basis scenario (Base)	• Sandsynlig udvikling af el- og fjernvarmesystemerne under hensyntagen til planlagt og aftalt energipolitik. Tilgangen svarer i store træk til tankegangen bag IEAs New Policy Scenario, som anvendes i den årlige publikation World Energy Outlook (WEO). Basisscenariet beregnes uden Viking kablet
Viking Link (VikingLink)	• Etablering af Viking Link i 2022. Produktionsapparatet fastholdes og er derfor det samme som i basisscenariet.
Udbygning med store varmepumper (Heatpumps)	• Gradvis indfasning af store varmepumper i det danske fjernvarmesystem. Forsyner 20 % af fjernvarmebehovet i 2030 (modeloptimeret)
Øget fleksibilitet på større kraftværker (CPP_flex)	• Installation af elpatroner/dampturbinebypass i 2020 på de større kraftværker i Danmark. I alt 3.500 MW varme (ikke modeloptimeret)
Øget fleksibilitet på individuelle varmepumper (Indiv_heatpumps)	• Øget fleksibilitet på elforbrug i individuelle varmepumper i form af mindre varmelager til ca. 4 timer.
Kombination af Viking Link og udbygning med store varmepumper (Combi 1)	• Udvikling af produktionsapparat som i varmepumpescenariet. • Etablering af Viking Link i 2022
Kombination af Viking Link og øget fleksibilitet på større kraftværker (Combi 2)	• Udvikling af produktionsapparat som i CPP_flex • Etablering af Viking Link i 2022
Kombination af Viking Link, udbygning med store varmepumper og øget fleksibilitet på større kraftværker (Combi 3)	• Udvikling af produktionsapparat som i varmepumpescenariet + CPP_flex • Etablering af Viking Link i 2022

Resultater

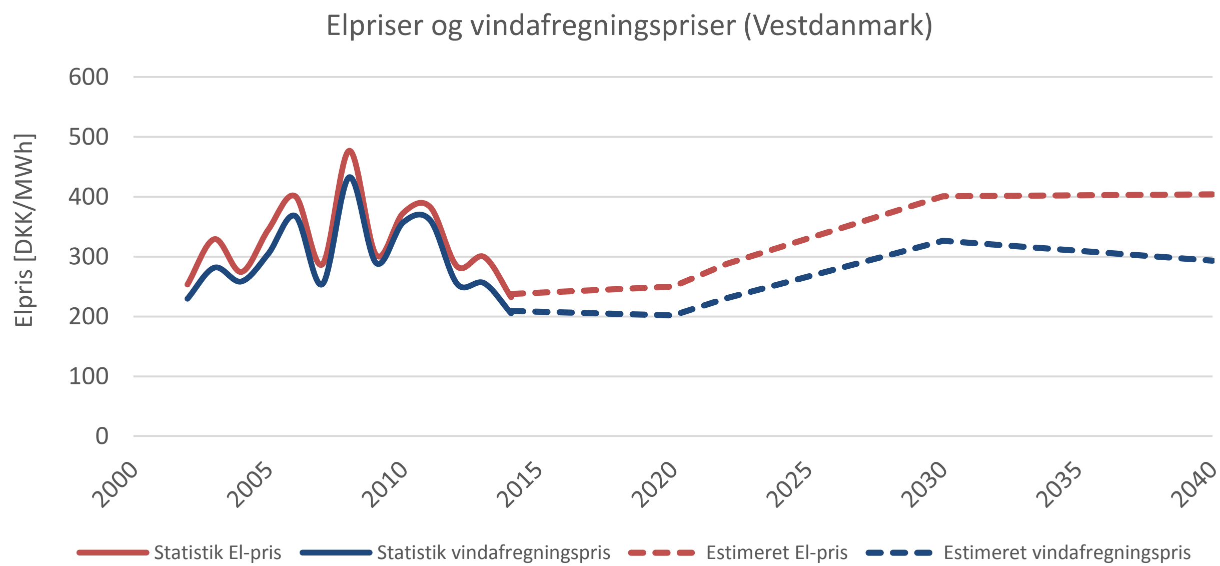
Basis scenario

Beregningsår 2014, 2020, 2030 og 2040.

Basisscenariet viser med de valgte forudsætninger en kraftig omstilling af det overordnede energisystem, hvor VE får en stigende betydning og udgør 2/3 af den samlede produktion i 2040 mod ca 1/3 i 2014. Fluktuerende VE fra vind og sol står for ca. 40 % i 2040, mens andelen i Danmark når op over 65 %.

På kort sigt betyder de stagnerende brændsels- og CO_2-priser, at elpriserne i 2020 er på niveau med 2014-priserne (2015-priserne er lavere, bl.a. pga. vådår). Efter 2020 forventes stigende priser på baggrund af stigende CO_2- og brændselspriser. Efter 2030 fører de yderligt stigende mængder VE til, at elpriserne ikke stiger yderligere på trods af en fortsat stigning i el- og brændselspriser. Der forventes dog et større antal timer med hhv. lave og høje elpriser.

Som følge af de øgede mængder vindkraft, stiger afregningsprisen for vindkraft ikke i samme grad som de gennemsnitlige elpriser. I Vestdanmark forventes den gennemsnitlige afregningspris for on- og offshore vindkraft at ligge mere end 25 % under den gennemsnitlige spotpris på langt sigt (prispres). Inden 2030 viser modelresultaterne et prispres på under 20%. Det bemærkes dog, at modelværktøjet sandsynligvis undervurderer prispresset, da modellen har fuld information om produktions- og forbrugsforhold (ingen afvigelser mellem planer og faktisk drift). For 2014 viser modellen fx en afvigelse på omkring 8% mod realiserede ca. 12 %.

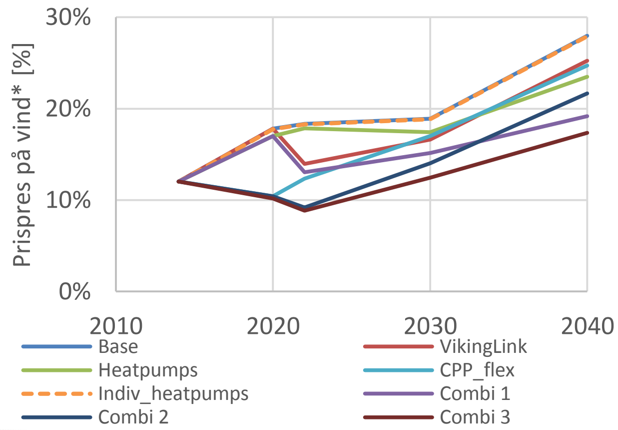


Resultater

Integration af vindkraft

Scenariernes effekt på integrationen af vindkraft vises ved ændringer i prispresset på vind-el. Prispresset er defineret som forskellen imellem vindafregningsprisen og den gennemsnitlige spotpris i Danmark målt i procent. Der fokuseres her på scenariernes effekt for vindintegration, men det understreges, at tiltagene også tjener andre formål. Således anvendes Viking Link ikke kun til eksport og import af vindkraft, og de store varmepumper leverer fjernvarme, hvorved der fortrænges anden varmeproduktion. Viking Link reducerer prispresset med knap 4 %-point ved introduktionen i 2022 samtidig med at den gennemsnitlige spotpris øges . På længere sigt reduceres prispresset med 2-2.5%-point. De store varmepumper får først for alvor effekt på længere sigt (2040), med reduktion af prispresset på mere end 4%-point.

I kombinationsscenarierne svarer reduktionen ca. til summen af de respektive enkelte scenarier (Viking Link, varmepumpescenariet og Fleksibilitet på større kraftvarmeværker) . Elpatroner/turbinebypass på de større kraftværker i Danmark har størst effekt på kort sigt, hvor prispresset på vind reduceres med 7%-point. Små individuelle varmepumper har stort set ingen effekt på prispresset.



*For 2014 vises statistisk data

Scenarierne har indflydelse på produktionsmønstrene i det samlede el- og fjernvarmesystem. De væsentligste effekter er:

Viking Link

- Kort sigt: Reduceret produktion fra naturgas i Storbritannien. Øget produktion fra kulkraft i andre lande.
- Længere sigt: Mindre nedregulering af vindkraft (mindre curtailment)

Varmepumper

- Reduceret produktion fra biomasse KV i Danmark. Øget produktion fra kulkraft og naturgas i andre lande.
- Besparelser på omkostninger til varmeproduktion i DK.
- Længere sigt: Mindre nedregulering af vindkraft

Fleksibilitet på større kraftvarmeværker

- Reduceret produktion fra biomasse KV i Danmark. Øget produktion fra brunkul og naturgas i andre lande. (Mindre udtalt end i varmepumpe scenariet)
- Mindre nedregulering af vindkraft
- Besparelser på omkostninger til varmeproduktion i DK.

Fleksibilitet på individuelle varmepumpe

- Begrænset effekt på det overordnede system.
- Mindre nedregulering af vindkraft

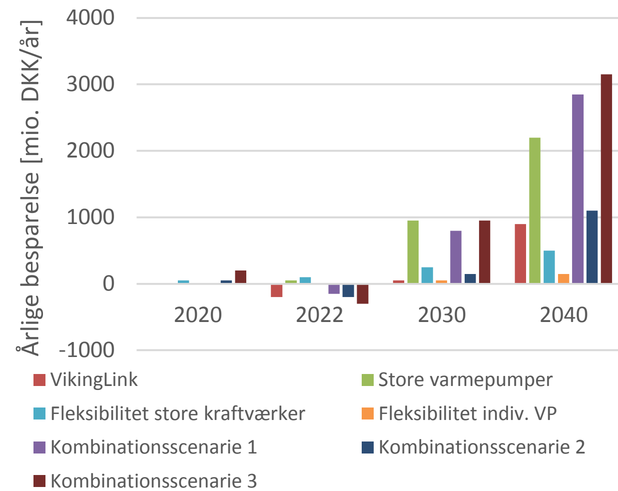
Resultater

Samfundsøkonomi

Scenarierne viser generelt en positiv samfundsøkonomi for det samlede system – set over en længere årrække. De samfundsøkonomiske fordele er ikke alene baseret på forbedret integration af vindkraft, men inkluderer også ændrede produktionsomkostninger i el- og fjernvarmesystemet generelt. Ved at sammenligne de forskellige scenarier kan konkluderes, at en kombination af Viking Link og varmepumper er en økonomisk fordelagtig strategi for at integrere vindkraft på langt sigt. Udbredelsen af varmepumper i Danmark og opførelsen af VikingLink er tiltag der begge virker positivt på vindintegration uden at det ene tiltag forringer økonomien i det andet væsentligt.

For især Viking Link, udbygning med store varmepumper og kombinationen af disse to scenarier, er den samfundsøkonomiske gevinst størst på længere sigt (2030 og frem), mens der på kort sigt kan være et samfundsøkonomisk tab forbundet med scenarierne. Den beregnede samfundsøkonomi gælder dog for den samlede region, og det er forskelligt hvordan enkelte lande påvirkes. Dette gælder især for Viking Link scenariet, da transmissionsudbygning påvirker landende forskelligt. For Danmark er samfundsøkonomien af Viking Link positiv igennem hele perioden, mens der på kort sigt kan opstå et samfundsøkonomisk tab for andre lande. Dette skyldes bl.a. landenes forskellige produktionsmix samt den særlige engelske pris på CO_2-emissioner.

Samfundsøkonomien for scenariet med øget fleksibilitet på individuelle varmepumper afhænger af omkostningen for at realisere scenariet, som især vil omfatte udgifter til individuelle varmelagre og styring. Disse omkostninger er ikke inkluderet her.

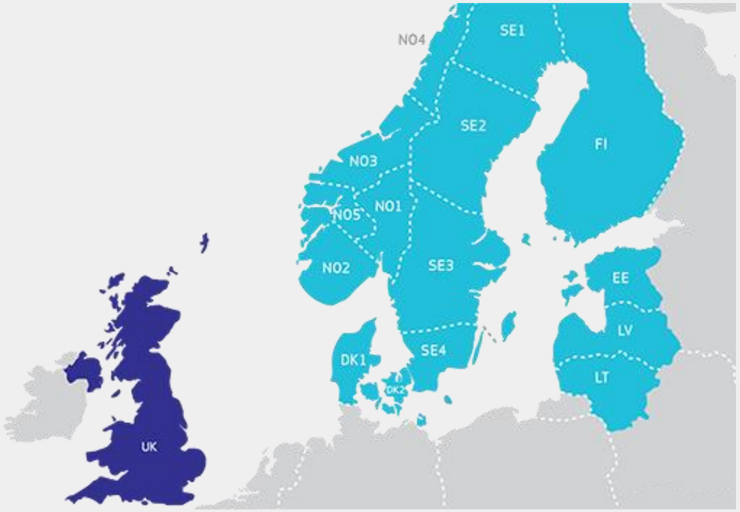


Scenario	Nutidsværdi [mia. DKK]
Viking Link	5.6
Udbygning med store varmepumper	20.2
Øget fleksibilitet på større kraftværker	5.1
Øget fleksibilitet på individuelle varmepumper	1.3
Kombination af Viking Link og udbygning med store varmepumper	22.8
Kombination af Viking Link og øget fleksibilitet på større kraftværker	7.6
Kombination af Viking Link, udbygning med store varmepumper og øget fleksibilitet på større kraftværker	25.3

*Der er ikke inkluderet eventuelle omkostninger til individuelle varmelagre m.m.

BACKGROUND ELECTRICITY PRICES

The Nordic Power Market



Nord Pool Spot Market

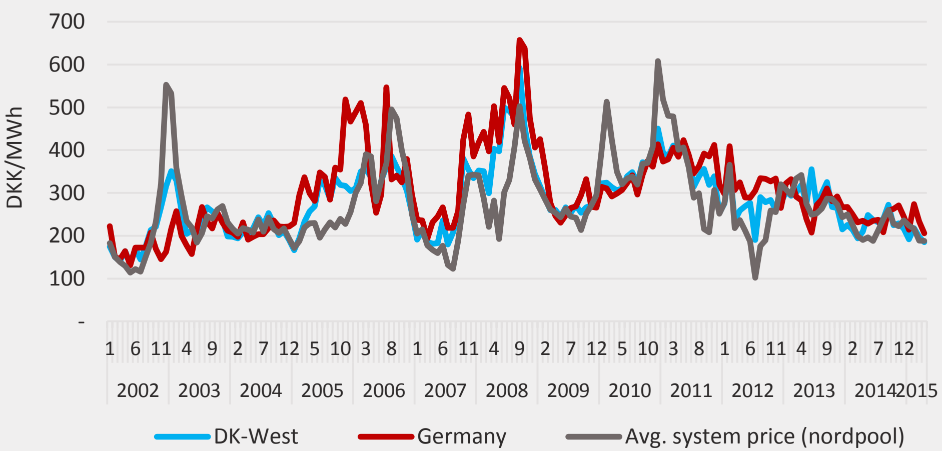
The Nord Pool Spot daily competitive auction at 12:00 establishes a price for each hour of the next day (24 hours). Prices are created for each bidding area, as well as an overall 'system price'.

A bid states prices for each hour and corresponding volumes in a specific area.

Area prices differ from the 'system price' due to congestion of limited transmission capacity. The DK1 area represents Western Denmark.

The system price (SYS) is the market clearing price which disregards transmission capacity. SYS is the basis for financial power derivatives.

Nord Pool covers the Nordic Countries (-Iceland) and the Baltic States.



Data source: Nordpoolspot.com. Nominal prices.

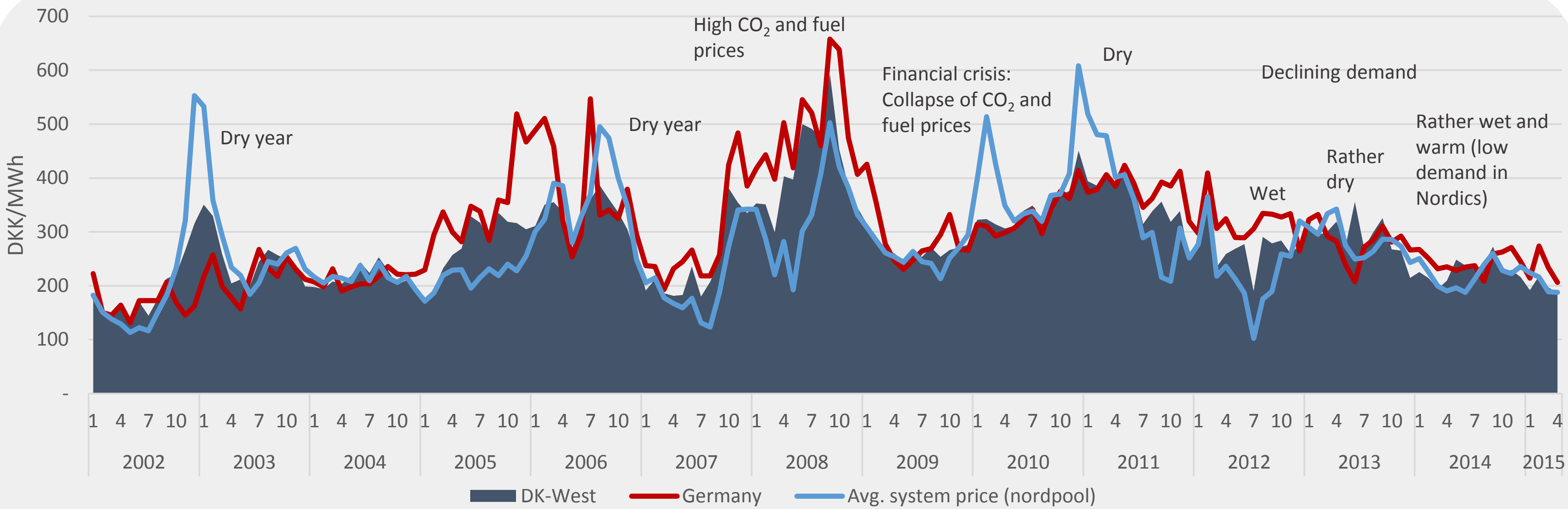
Continental connections

The Nordic power market is interconnected with continental Europe.

Market based flows between Nord Pool and Northwest European markets result from iterative price calculations - market coupling.

Absent of congestion, bids from a generator in Norway essentially compete with bids from a power plant in France.

Historical Western Danish Spot Price

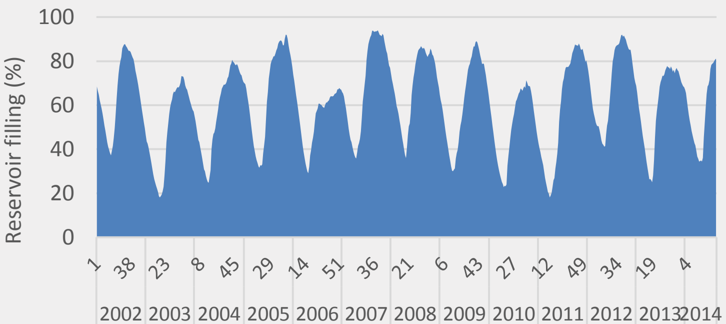


Data source: Nordpoolspot.com. Nominal prices.

Hydrological conditions have a significant impact on the Nordic price formation.

- In dry years, Sweden, Finland and Norway increase net-imports to compensate for lack of hydro generation.
- In wet years abundance of hydro allows plant owners to lower the prices of their supply offers.

Besides the availability of hydro power, the main driver of short-term movements in the power price are fuel prices and the price of CO_2.



Norwegian hydro reservoir storage levels in percent of capacity.

Average Prices by generator type

Captured prices vary by generation technologies

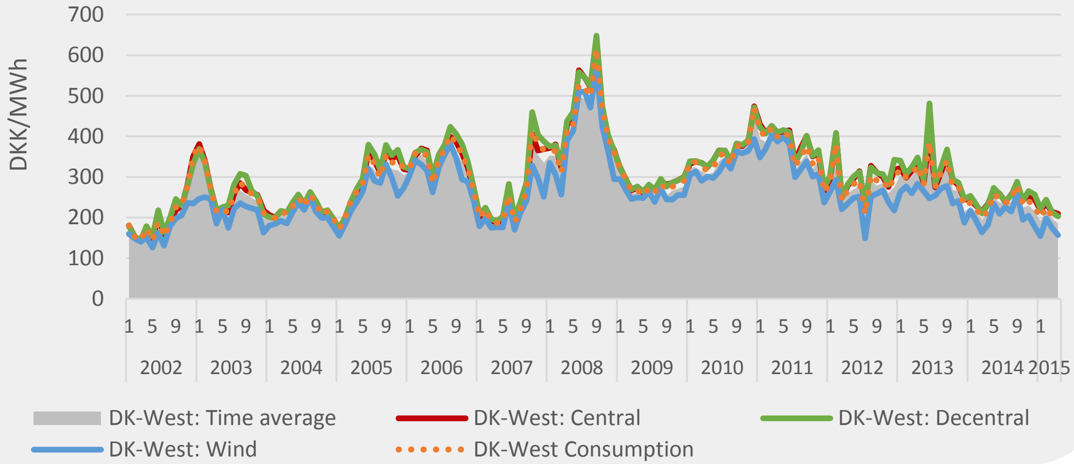
Danish power generators are primarily large power stations, decentralised CHPs and wind turbines. Recent years have also see an increase in distributed solar PV.

Since 2002, prices captured by generators in Western Denmark have in relation to the average hourly price been:

- Central power stations +8%
- Decentralised CHP +9%
- Wind power -10%
- Solar power +5%

Simple time-weighted averages provide a first indication of the market potential for various generation technologies to capture prices, but since wholesale prices vary hour-by-hour, average quarterly and yearly prices differ between technologies.

- Dispatchable generation with high short-run marginal costs capture higher (albeit fewer) prices on average.
- Technologies with low short-run marginal costs capture lower prices, but have more operating hours.
- Intermittent generation generally captures lower prices, particularly when the resource (e.g. wind) is simultaneously abundant across a wide region. Solar power generally has an advantage of coincidence between generation and high demand. This will erode with a significant increase in penetration.



Calculations based on data from Energinet.dk. Nominal prices.

BALMOREL MODEL

The Balmorel Model

Balmorel is used for analysing electricity, CHP and heat in internationally integrated markets. Applications are long-term planning, as well as detailed short-term or operational analysis.

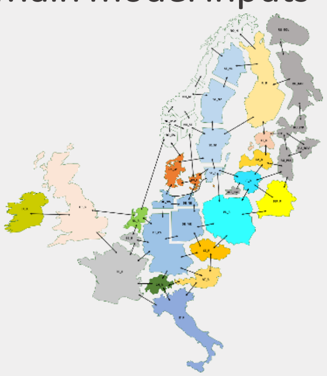
The model can be used to calculate generation, transmission and consumption of power and heating on hourly basis as well as to optimize the electricity, heat and transmission capacity in the system.

Prices are generated from system marginal costs, emulating optimal competitive biding and clearing of the market.

Modelling power and district heating systems

- Hourly dispatch optimisation
- Optimal investments in generation and transmission
- Price formation in partial equilibrium price formation allowing for market and stakeholder analysis.

Main model inputs



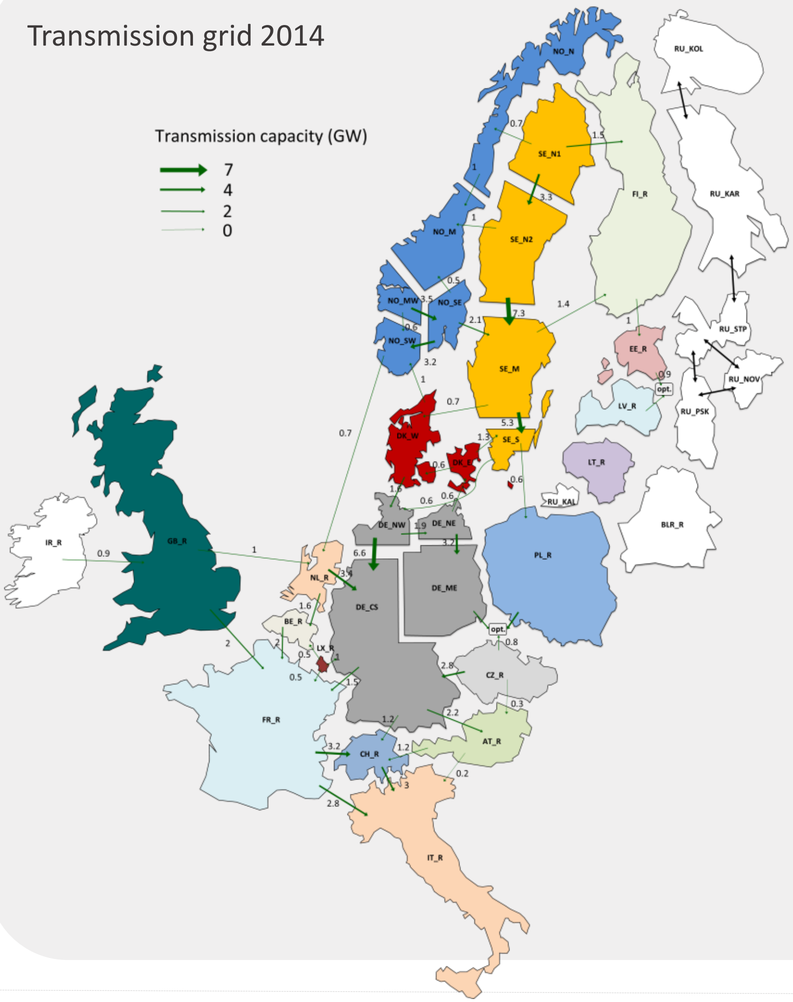
- Existing generation capacities, respective unit's technical and economic data, investment options (incl. refurbishments) and technology development.
- Transmission system infrastructure, and options and costs for capacity expansion.
- Projected demand for power and heating
- Projected fuel and CO_2-prices.
- Policies, taxes and support schemes

Areas of application include:

- International power market development
- Analyses of wind integration
- Security of electricity supply
- The role of demand response
- The role of natural gas
- Expansion of electricity transmission
- Markets for green certificates
- Electric vehicles in the power system
- Environmental policy evaluation

Representation of the international power market

Transmission grid 2014

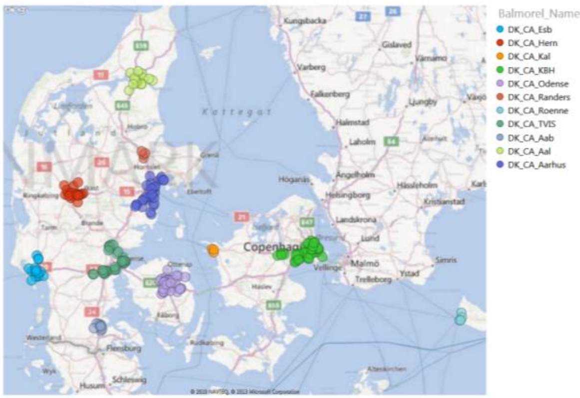


Modelling power transmission and price areas

Development in the international and interconnected power and energy system has significant implications on the development in any singular price area.

- The analysis described in this report includes calculations in the regions shown on the map. Most relevant are Denmark and Great Britain (note that Northern Ireland is included in the Ireland price area and not in Great Britain), the Nordic countries, Germany, France the Netherlands and Belgium.
- Individual countries are subdivided into regions, between which the most significant power transmission congestions occur.
- In the Nordpool countries, these regions coincide with the price zones in Nordpool. Presently, the German power market has only one price zone (together with Austria), in spite of congestion in the internal grid. Modelling Germany as one price region without consideration of internal congestion in Germany would lead to unrealistic power flows and export opportunities, e.g. for Danish power plants however, therefore 4 price regions are modelled for Germany.

Representation of Denmark's district heating and CHP



Units connected to centralised heating areas in DK

Individual and aggregated district heating systems

In Denmark, there are approximately 420 different district heating networks, with numerous plants and heat producing units contained in these systems.

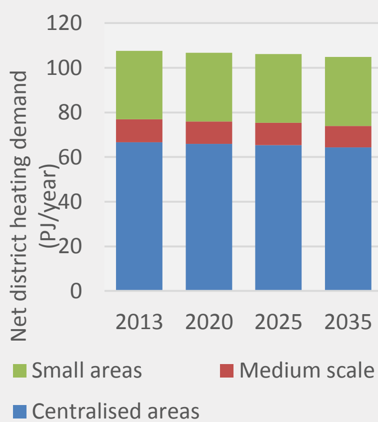
11 centralised areas account for approx. 62% of the total district heating demand, roughly 10% is located in medium scale areas (more than 1 PJ annual heat demand), and 28% are located in small decentralised heating areas.

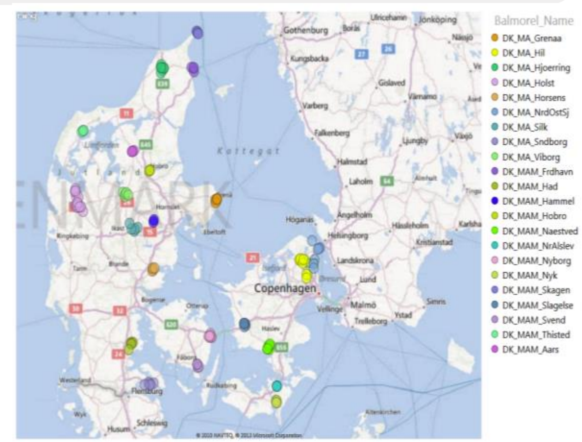
The centralised and medium sized areas are represented individually, while the small areas are aggregated according to the type of supply. However, all areas partially supplied by municipal solid waste are represented individually, regardless of their size.

Apart from district heating units and systems, commercial CHP plants supplying local industry heat demands are also included in two separate areas in Western and Eastern Denmark.

Data for existing power plants and district heating demands are based on annual statistics reported by all producers to the Danish Energy Agency for 2011.

Forecasts for heat demand factor in both energy savings and expansion of the respective district heating networks are based on analyses of the Danish district heating systems by Ea Energy Analyses and COWI for the Danish Energy Agency during 2013.





Units connected to medium scale DH systems individually represented

ASSUMPTIONS AND MODEL SETUP

Power consumption development

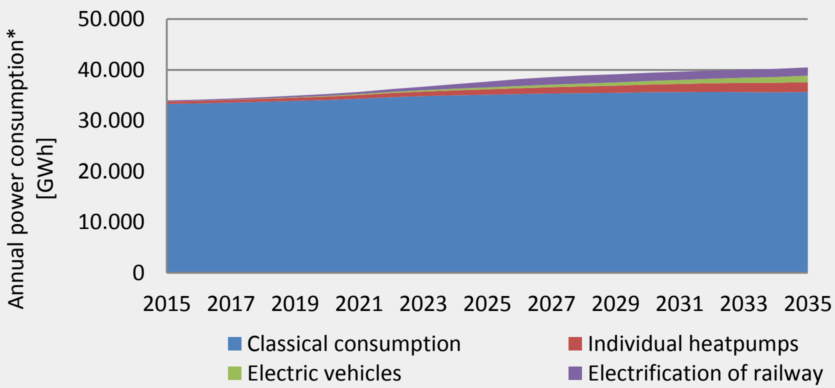
Nordics: Power demand is based on national forecasts where available. Otherwise, forecasts are based on National Renewable Energy Action Plans (NREAPs) until 2020.Development after 2020 is based on a BASREC-study with input from participating countries.

Denmark: Development for Denmark based on assumptions from the Danish TSO Energinet.dk (Includes moderate introduction of EVs and individual heat pumps)

Great Britain: Based on DECC projection (*Updated energy and emissions projections 2014*) excluding Northern Island and Auto-generators. According to the DECC projection electricity usage increases by roughly 23% between 2020 and 2035, mainly due to higher demand in the residential and service and agriculture sector, in parts due to declining impact of current efficiency policies.

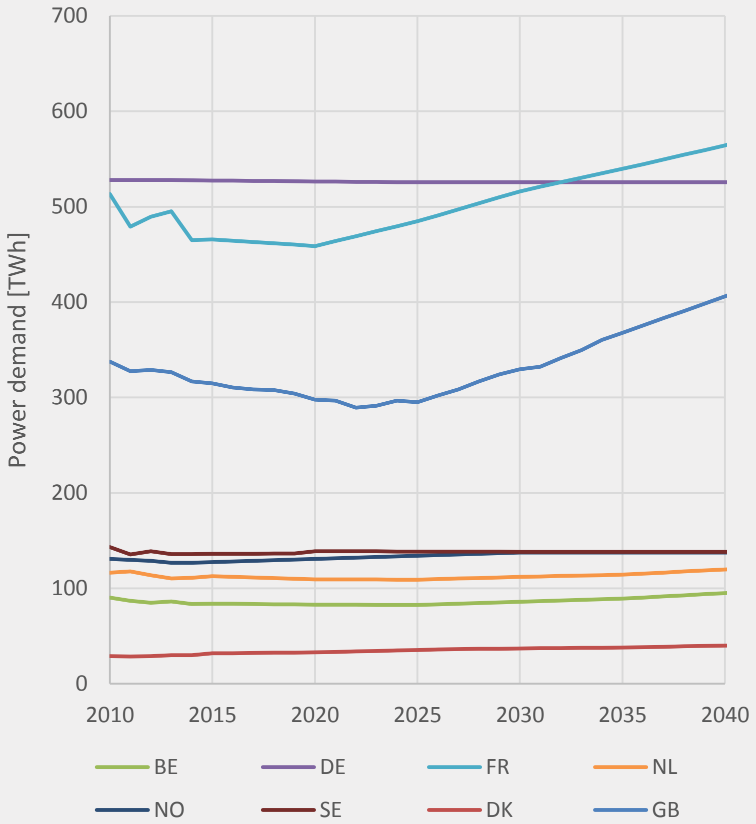
Other EU: Statistic data based on ENTSO-E, forecasts based on statistic data and the trend in *EU Energy, Transport and GHG Emissions – Trends to 2050* by the European Commission

Power demand Denmark



*source: Energinet forudsætninger, May 2015; including losses; excluding demand for large heat pumps and electric boilers (determined endogenously by Balmorel)

Power Demand Nordics and North-West Europe



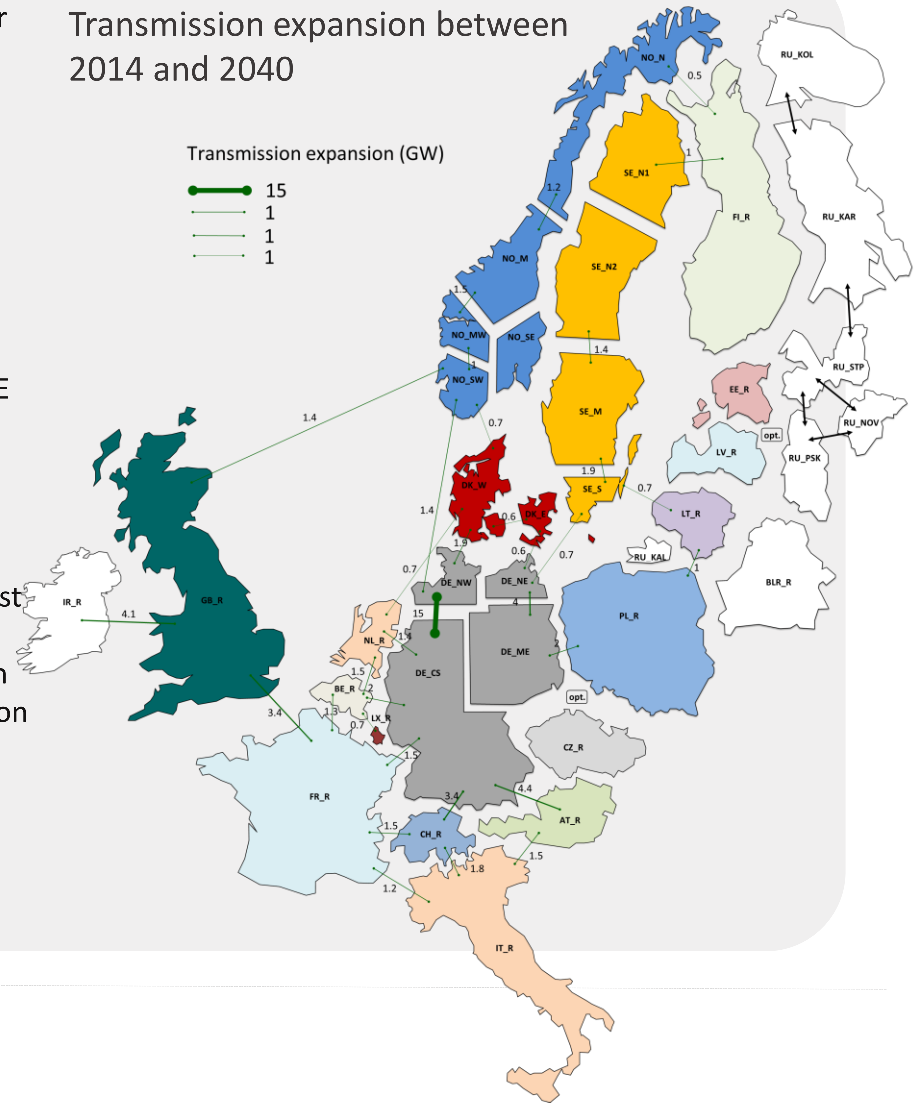
Power transmission capacities

Development of the overall transmission grid is based on the Ten Year Network Development Plan 2014, developed by the transmission system operators within ENTSO-E. The planned capacities are supplemented information by TSOs, where updated information is available.

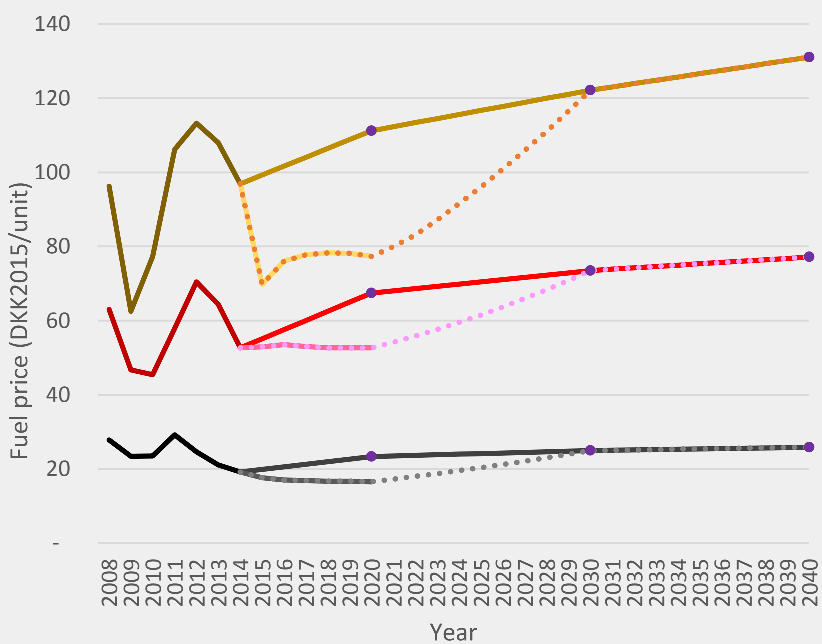
Significant changes for Denmark (excluding the Viking Link).

- **Nordlink** 1.4 GW (DE-NO) by 2020
- **CobraCable** 0.7 GW (DK-NL) by 2020
- **Kriegers Flak** adds transmission option between Eastern DK and DE by 2019 (not shown on map)
- **German internal grid**, based on the TSOs' latest grid development plan (NEP2014), scenario B. Data until 2020 was directly implemented; expansion beyond 2020 appeared optimistic with regards to the controverse ongoing discussions. Therefore, the most controversial expansion corridors were assumed to be delayed to 2025. Transmission capacity between North West DE and Southern DE increases significantly between 2020 and 2025. Futher expansion beyond 2025 between South and North DE
- **Danish internal grid** 0.6 GW (DK East-DK West) by 2030

Transmission expansion between 2014 and 2040



Fossil fuel price development



Note: FWD prices are extended to be constant in real terms beyond observations.

Historical - Coal
FWD - Coal
Historical - Crude oil
FWD - Crude oil
Historical - Natural gas
FWD - Natural gas
IEA price points
IEA - Coal
Convergence - Coal
IEA - Crude oil
Convergence - Crude oil
IEA - Natural gas
Convergence - Natural gas

Oil prices reclining from bottom

The oil market was bottomed out at the beginning of 2015 having reached the lowest level since the onset of the financial crisis. Tight oil plays in the US, OPEC's reluctance (inability) to curb supplies - accompanied with weak demand - created a significant shift in the supply-demand balance. US inventories have only recently started to decline, putting upward pressure on the forward curve, indicating a modest recovery.

Natural gas

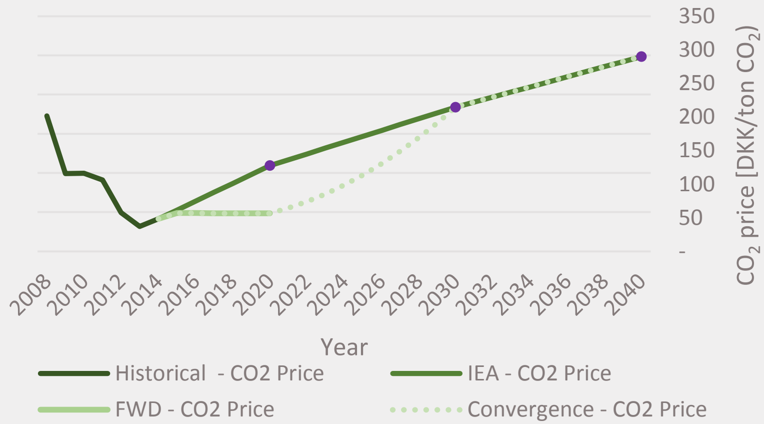
In recent years, shale gas developments, especially in the US, have led to a glut in the LNG markets and a trend towards a decoupling of natural gas and oil prices has depressed natural gas prices on European trading hubs. Replication of the US shale gas has so far not been very successful. In spite of pressure from new technology bringing additional reserves on-stream, and stagnant growth, eventually global competition for access to energy commodities and pricing by scarcity is likely to recur.

Coal prices at historic lows

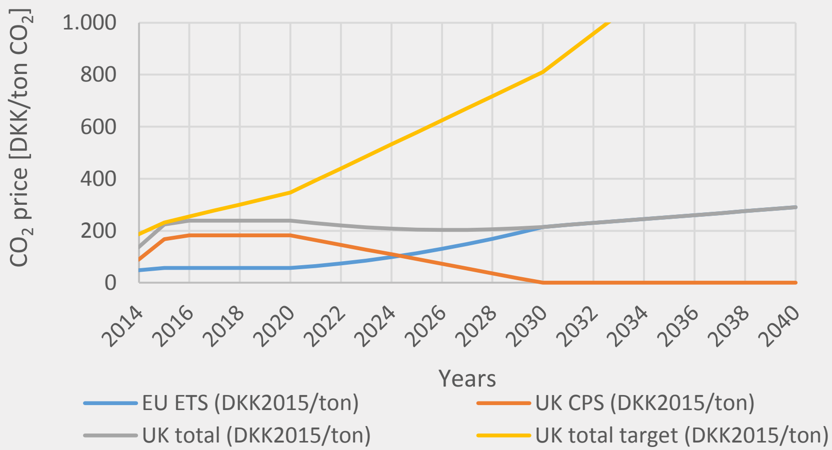
Coal prices are also at historic lows. Cheaper natural gas in the US, increase of renewable energy and weak power demand in the EU and not least a stagnation of Chinese coal consumption growth are key reasons for the slide of coal prices. Coal prices are now lower than at the bottom of the financial crisis.

Prices are projected to converge from today's towards the IEA's main projection between 2020 and 2030.

CO_2-emissions price development (EUA & Denmark)



Note: FWD prices are extended to be constant in real terms beyond observations.



Driving the green transition

At current levels, the CO_2-emission prices alone cannot drive the green transition of the European Energy Systems. CO_2-futures reflect the current price of EUA's (EU emission allowances). These can be banked from year to year (free storage).

The IEA WEO 2014 states CO_2-prices in the EU-ETS of 20 USD/ton in 2020 rising to 40 USD/ton in 2040 (in real 2013 values). By comparison, the EU impact assessment assumes a 40 EUR/ton CO_2-price by 2030 to attain the 40% CO_2 reduction target. Adding energy saving measures reduces the 2030 price to 22 EUR/ton and adding support for RE deployment and EE reduces the price to 11 EUR/ton. In a conservative scenario without enabling polices for technological development the 2030 CO_2-price is 53 EUR/ton if the same reduction target has to be met. The key question is if the CO_2-price will be brought on track, or if the RE-transition will be driven by subsidies.

The base assumption on prices for EUA's in this report follows forward prices to 2020 and after this it is assumed that policy will drive prices to converge towards the IEA WEO 2014 New Policies scenario, with prices intersecting in 2030. This corresponds to assuming a continued mix between supporting RE by subsidies and a driving CO_2-price, with an emerging importance of the CO_2-price.

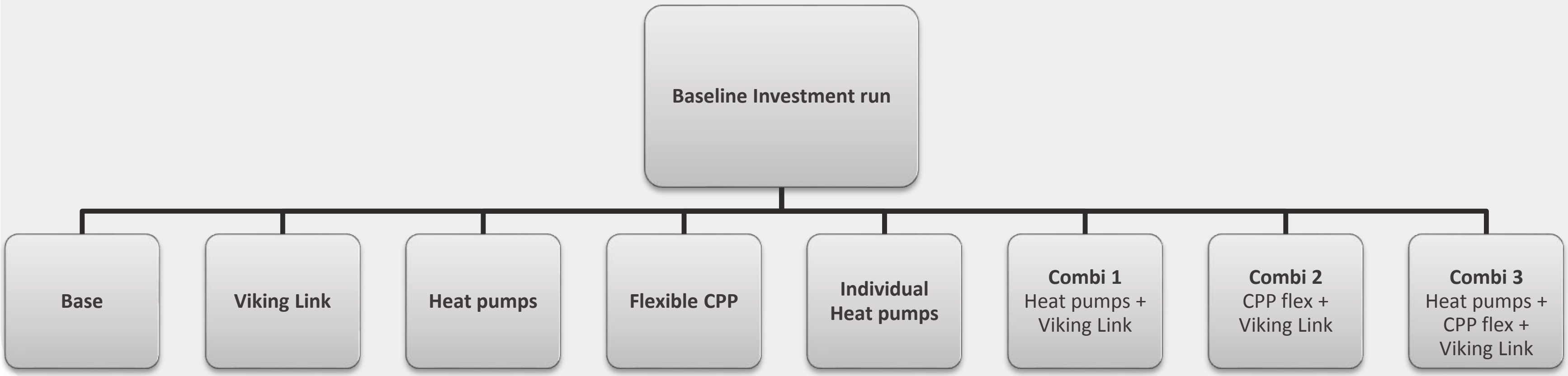
In 2013, the UK introduced a carbon price floor, aiming at ensuring a minimum CO_2-price of £16/tCO_2 in 2013 to £70/tCO_2 in 2030 (2009-prices). The system is implemented by adding a national tax on CO_2 (CPS, Carbon Price Support), which should cover the difference between the EU ETS price and the total target. However, in 2014 the UK introduced a cap on the national tax of £18/tCO_2 for 2016-2019 to limit the difference between the EU ETS price and the total national CO_2-tax. Currently, no policies for such a cap beyond 2019 are in place, and in principal CPS will rise again after 2019. However, in this report it has been assumed, that the national tax will be phased out between 2020 and 2030, and thus the effective carbon price in the UK will be the same as in the rest of Europe as of 2030. The reasoning behind this is twofold: 1) It is not desirable to base the economic value of an interconnector between Denmark and the UK on a difference in the CO2-regulation system, which by its nature is uncertain. 2) With increasing connection of the power systems in the UK and continental Europe, it becomes less likely, that a large difference in the effective CO2-price will be acceptable for power producers in international competition.

Scenario setup

INTEGRATION MEASURES

Scenario setup

- **Baseline investment**: Model opimized power and heat capacity in all modelled countries.
- **Base**: Hourly baseline run, dispatch optimization.
- **Viking Link**: Identical to the Base scenario, but with an added 1.4 GW transmission link between Great Britain and Denmark.
- **Heat pumps**: Generation capacities of the Baseline investment for all countries but Denmark. Capacities in Denmark are optimized by the model after lowering the tariff on electricity for district heat generation to a value of 150 DKK/MWh.
- **Flexible CPP**: Generation capacities from base scenario, but installation of electric boilers at larger CPP plants in Denmark. Some of this effect could be achieved by using turbine bypass.
- **Individual heat pumps**: Generation capacities from base scenario, but increased flexibility of individual heat pumps. Assumed option to move demand by approximately 4 hours.
- **Combi 1**: Identical to the Heat pumps scenario but with added Viking Link.
- **Combi 2**: Identical to Flexible CPP but with added Viking Link
- **Combi 3**: Identical to Heatpumps scenario but with added Flexible CPP and Viking Link



Model results

BASELINE INVESTMENT RUN

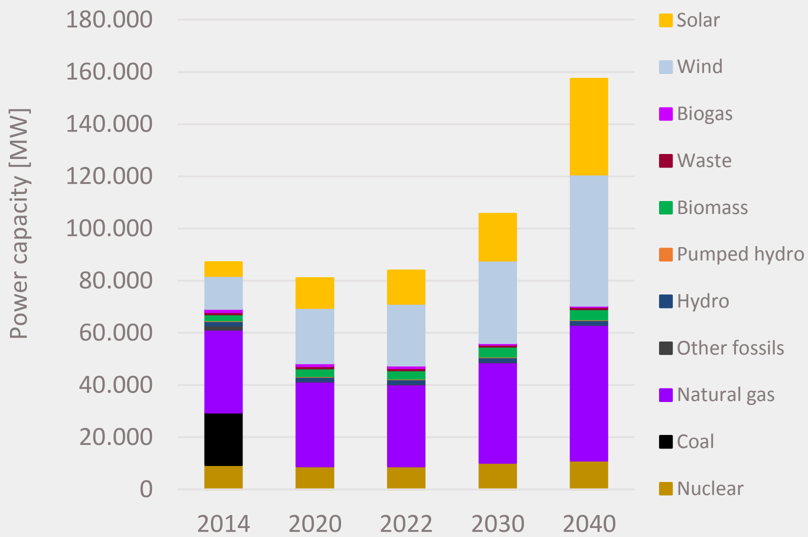
Investment approach

In the Baseline investment run the electricity and heat capacities are optimized by the model. The table below shows the general approach with respect to which generation is included exogenously and which generation capacity is decided on by model optimization.

	Renewable capacity	Other capacity
Denmark	Exogenous until 2035. Investment beyond	Decommissioning + Investments
Nordics	Exogenous until 2030. Investment beyond	Decommissioning + Investments. Nuclear Exogenous
Grat Britain	Exogenous until 2035. Investment beyond	Decommissioning + Investments. Nuclear Exogenous
Germany	Exogenous until 2035. Investment beyond	Decommissioning + Investments. Nuclear Exogenous
Other EU	Exogenous until 2020 (NREAP). Investment beyond	Decommissioning + Investments. Nuclear Exogenous
Transmission	Exogenous until 2030 (TYNDP). Constant beyond	

Capacity development

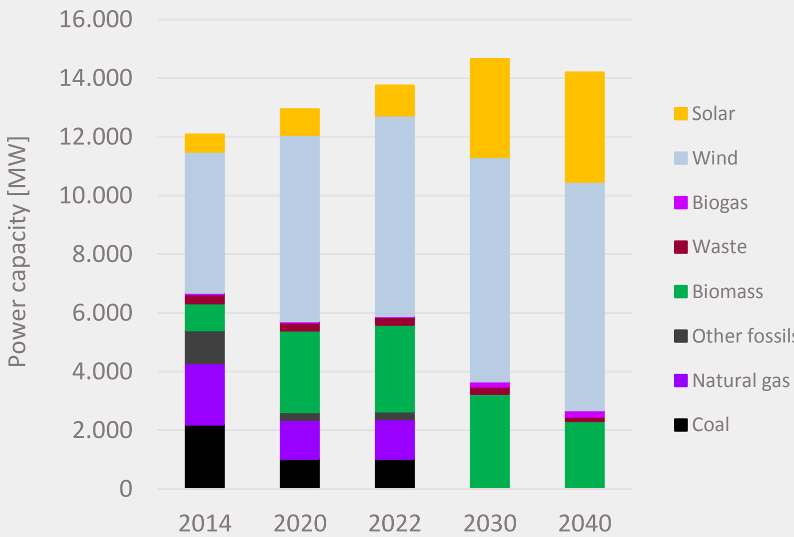
Great Britain



Renewable capacity is modelled exogenously until 2035. Development of nuclear capacity is based on the average of the *Reference* scenario and the *Existing policies* scenario of the Updated Energy and Emission projections 2014 (UEP 2014) by the Department of Energy and Climate Change (DECC). Investment and decommissioning decisions for fossil fuels are modelled endogenously. As a result all coal capacity is decommissioned by 2020.

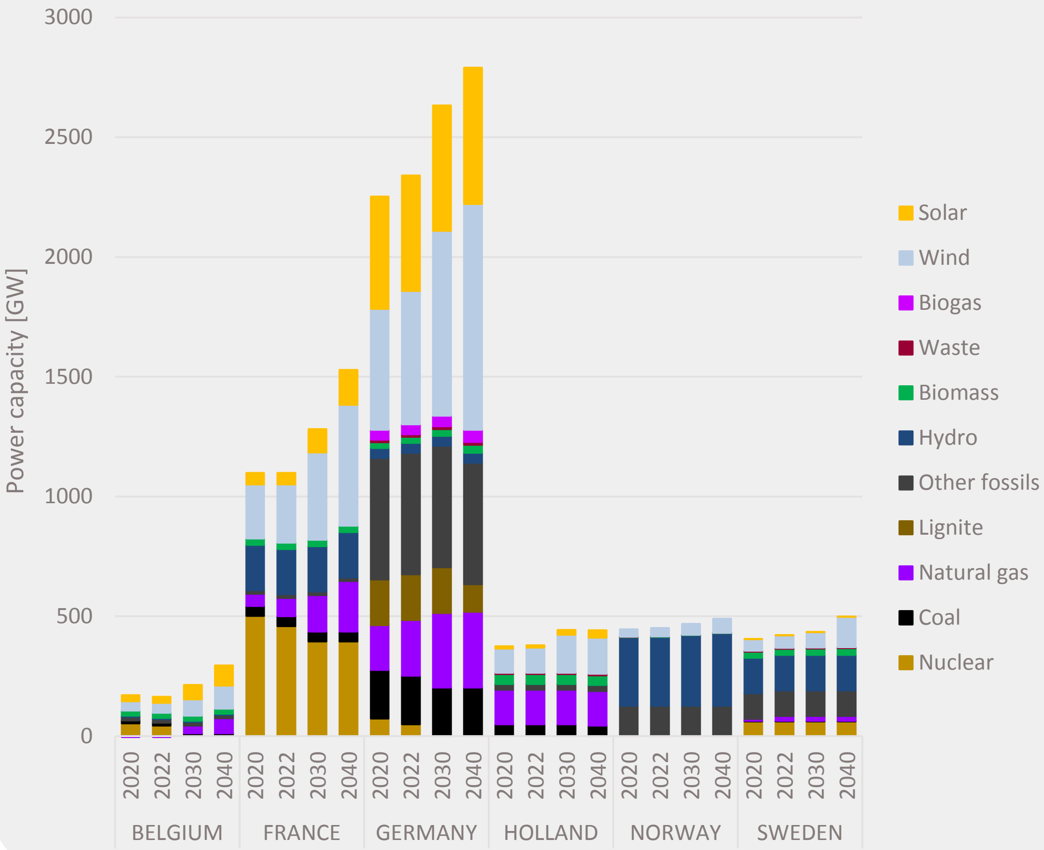
Denmark

In Denmark, investments are made endogenously for thermal capacity based on the current tax and subsidy schemes. Capacities for wind and solar power are given exogenously up to 2035 and based on Energinet.dk forecasts. However, due to the recent price development of solar power, the generation of one larger offshore wind farm has been replaced by solar power.



Capacity development

Nordics and North-West Europe



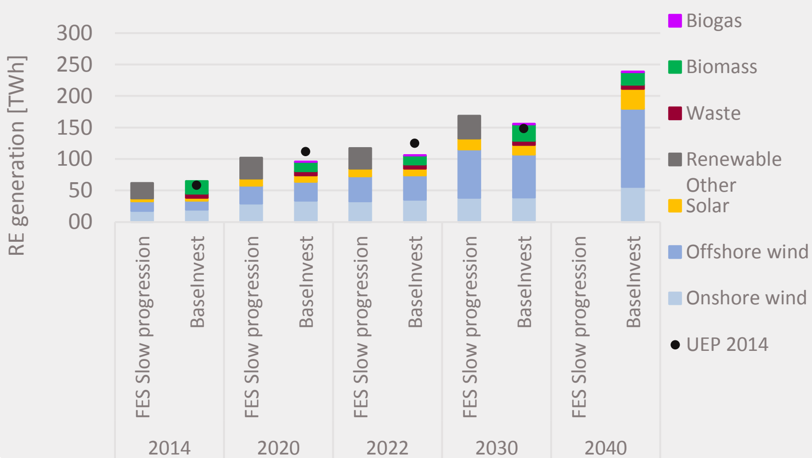
- Nuclear generation for France and Belgium includes plans for phase-out (by 2025 for Belgium) and decrease in capacity (50% of generation by 2025 in France)
- Development in Germany is determined by the so-called Energiewende, which aims for 80% of the generation to be supplied by renewable energy in 2050. The assumptions in the present analysis are based on the analysis framework from the German network development plan for 2015. Nuclear power is phased out by 2023.
- Norway: Build out of wind and expansion of hydro.
- Sweden: Closure of two nuclear blocks at Ringhals and two blocks at Oskarshamn until 2020. Constant nuclear capacity beyond 2020. Increasing capacity of wind.

Generation

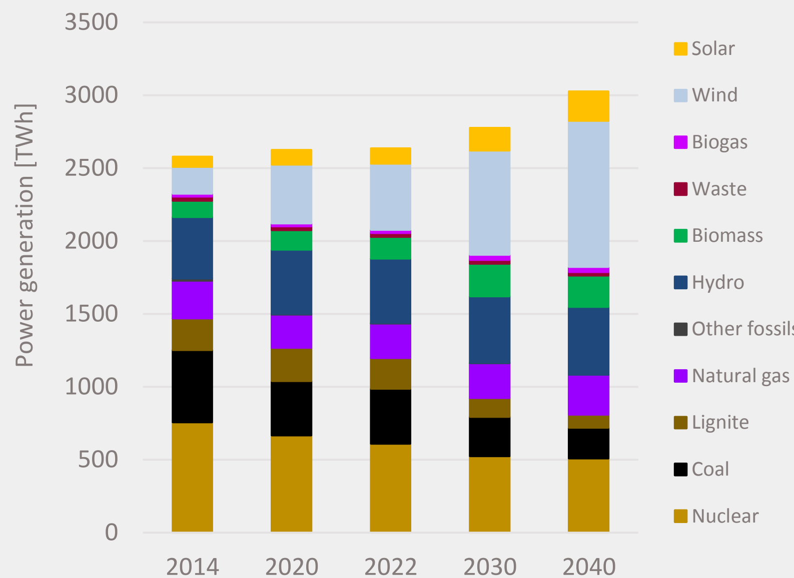
Great Britain renewable generation

Assumptions for solar generation in the UK are based on the National grid's Future Energy Scenario (FES) - Slow progression. The biomass and biogas capacities are based on the Updated Energy and Emissions projections report 2013 (UEP 2013), generation in the actual model runs can be lower than mentioned in the source if applied subsidies aren't high enough to ensure sufficient amount of full load hours. Onshore/Offshore wind capacities are based on the UEP 2013 generation and scaled to fit the total generation of the UEP 2014 . Maximum onshore wind (2040) the model is allowed to invest in is based on FES gone green scenario. All RE capacities have been reduced with a 2,4% factor to account for capacity in Northern Ireland, which is not included in the model runs.

Comparison of sources for development of RE in the UK

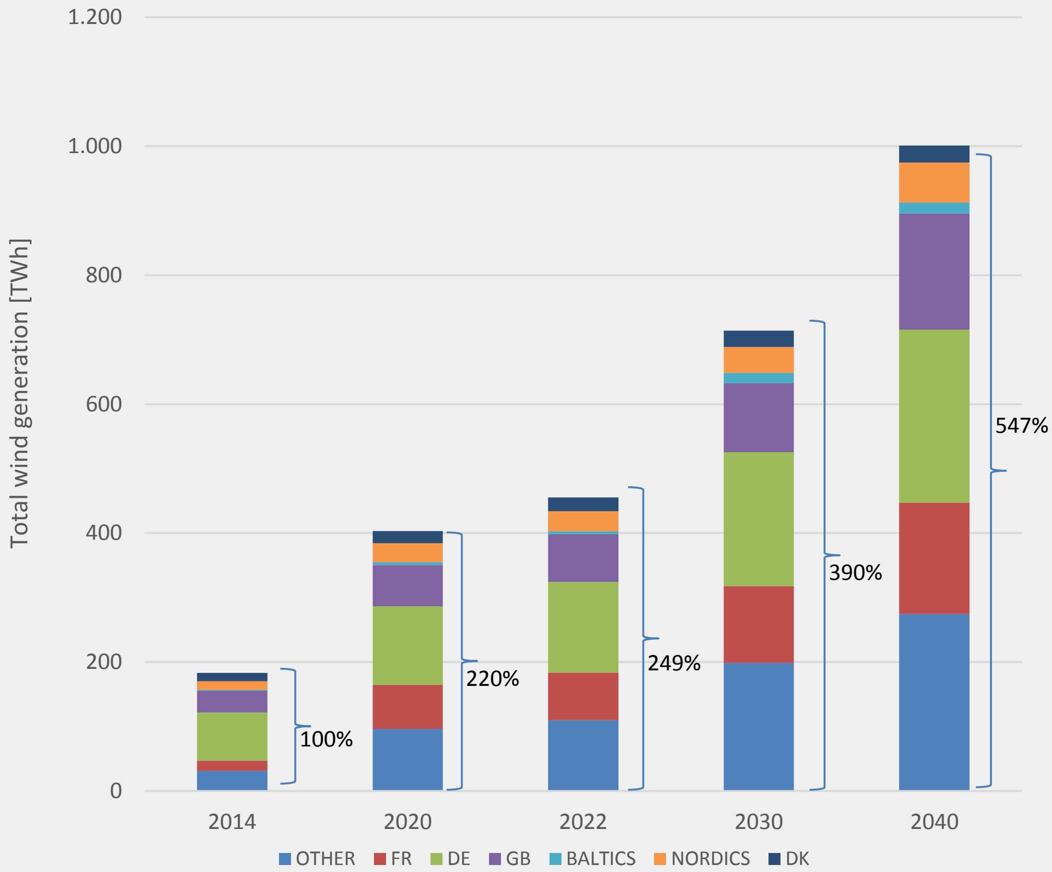


Overall generation



The overall generation in the modelled part of Europe shows a trend of decreasing fossil fuel generation, compensated by a growth in renewable generation - especially wind and solar power.

Wind generation in Europe



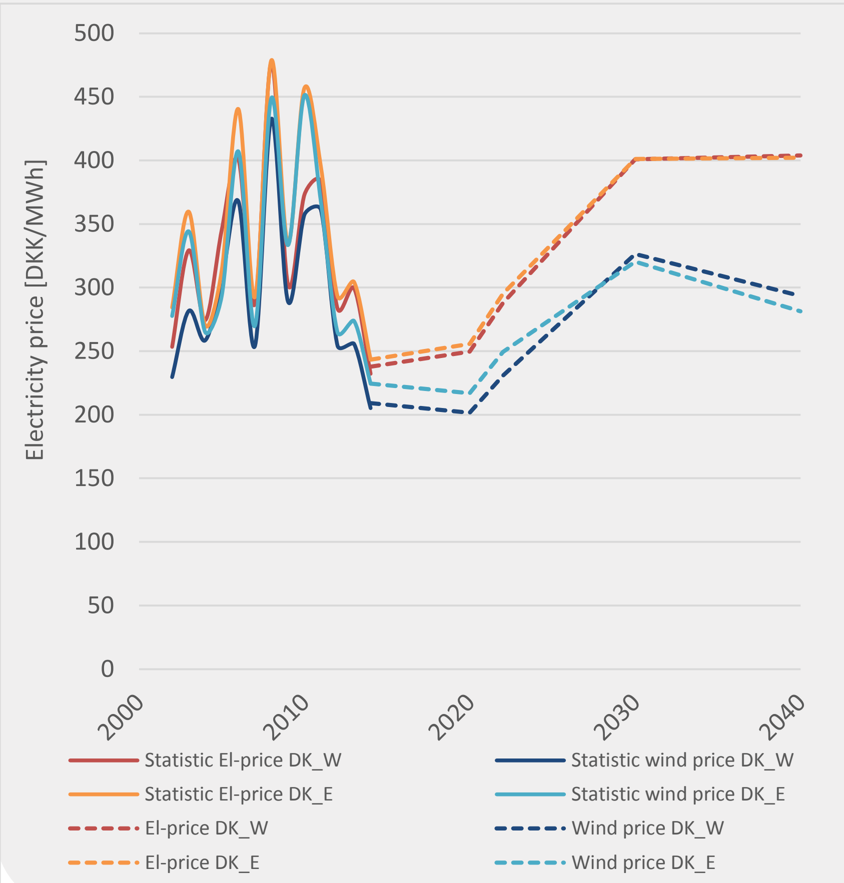
Wind power generation in Europe doubles in the modelled area between 2014 and 2020. By 2040, wind generation as increased to 547% fo the 2014 value. A large share of that is wind power generation in Great Britain, France and Germany. The large share of wind power creates challenges for the system to ensure a high value of the generated wind power. Curtailment of wind power occurs, but is less than 2% by 2040.

Model results

BASE SCENARIO

Electricity prices and prices captured by wind power

Denmark

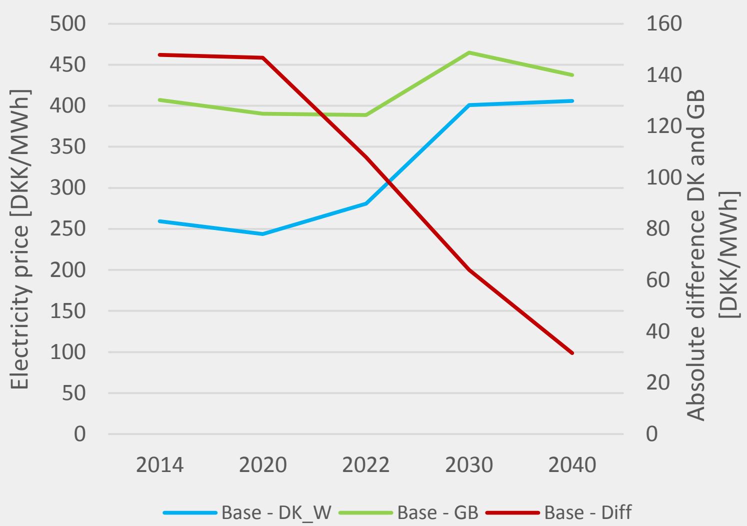


The base scenario shows stable electricity prices until 2020, mainly attributed to the stable fuel and CO_2-prices. After 2020, increasing fuel- and CO_2-prices lead to increasing average electricity prices in Denmark until 2030. After 2040, electricity prices do not increase further, even though fuel and CO_2-prices continue to increase. This is explained by the increased generation from renewable energies, leading to more hours with lower prices, thereby compensating for the higher electricity prices at times, when fossil fuel fired power plants set the market price. Thus, even though average electricity prices stay stable after 2030, the price profile shows more volatile prices.

Prices captured by wind power are approximately 18% below the average electricity price by 2020. This gap increases to almost 29% by 2040, when the share of wind in Denmark and in the overall system is highest. The increasing volatility after 2030 is also reflected by an increasing gap from 2030 to 2040.

Electricity prices

Comparison DK_W and GB

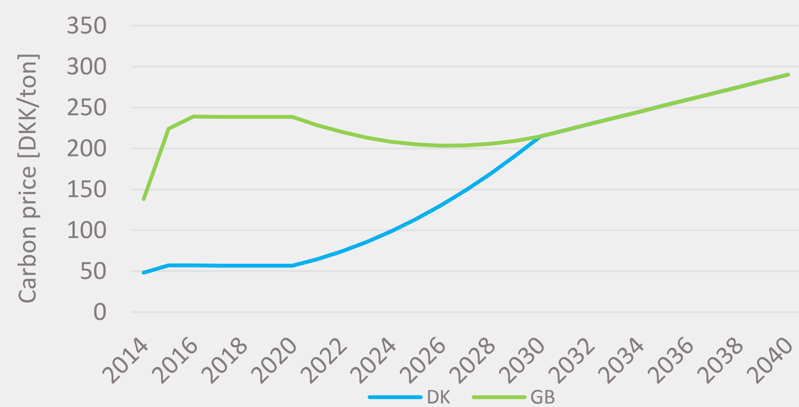


By 2020 the difference between average electricity prices in Denmark and Great Britain is large (about 140 DKK/MWh). As the electricity price in Denmark rises towards 2030 the difference with British prices decreases over the years.

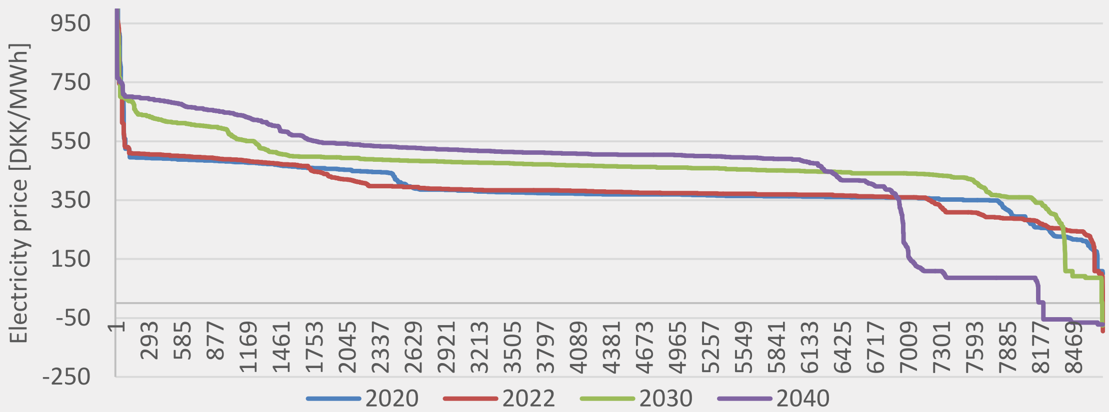
Between 2030 and 2040 the Danish price remains constant while a drop in British prices lowers difference between average electricity prices further.

The decrease in price difference can be partly explained by the decreasing difference in CO_2 prices. The UK has a carbon price support (CPS) of currently £18/ton CO_2 added to the EU-ETS carbon prices. As of 2030, the CPS is assumed to be zero, resulting in the same CO_2 prices for the UK and Europe. A continuation of the current level of the CPS would result in increasing electricity prices in Great Britain, thereby increasing the price difference to Denmark and increasing the value of a link between the two regions for both Denmark and Great Britain from a merchant line perspective.

Depending on the marginal emission factor in continental Europe and Great Britain, the CO_2-price difference of around 200 DKK/ton in 2020 can explain differences in the electricity price of around 85 DKK/MWh. All else equal, the price difference would therefore be reduced by this value by 2030.



Duration curves for electricity prices

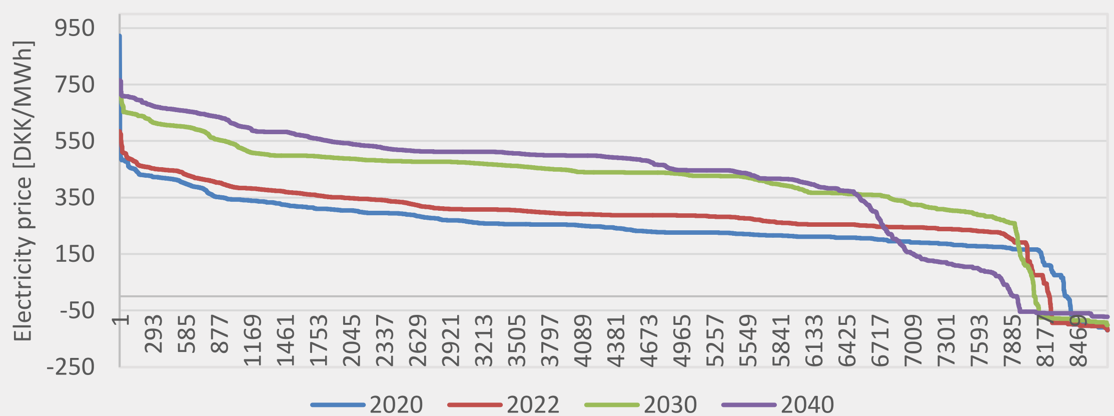


← Great Britain

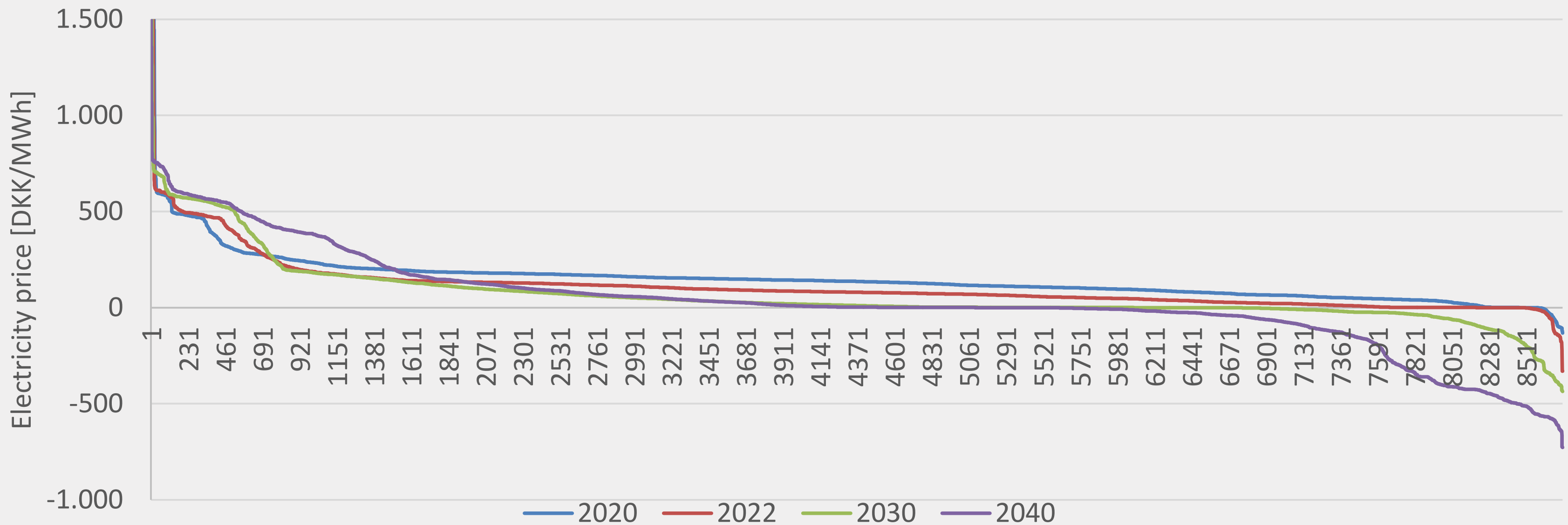
The number of negative prices depends – amongst others – on the subsidy schemes for variable renewable generation. In the model runs, a simplified assumption on a constant RE subsidy has been applied. Subsidy schemes are expected to evolve over the years to not pay a subsidy at times with zero or negative prices (as it is the case for offshore wind power in Denmark already). In this case, fewer hours with negative than shown on the duration curves will occur. However, prices will still be close to zero, as the negative prices reflect situations with excess generation.

West Denmark →

The duration curves for the electricity prices in both Denmark and Great Britain show a trend towards more hours with both higher and lower electricity prices. A difference between average prices can be one important driver for connecting regions. However, since the low and high prices occur at different times in Denmark and Great Britain, connecting the regions can be beneficial even though the price difference between average electricity prices descreases between 2014 and 2040.



Price difference DK West and GB duration curve Base scenario



	Number of hours higher GB price	Number of hours higher DK_W price	Average of absolute price difference
2020	8469	197	148.3
2022	8204	387	110.8
2030	6081	2260	98.4
2040	5109	3356	168.8

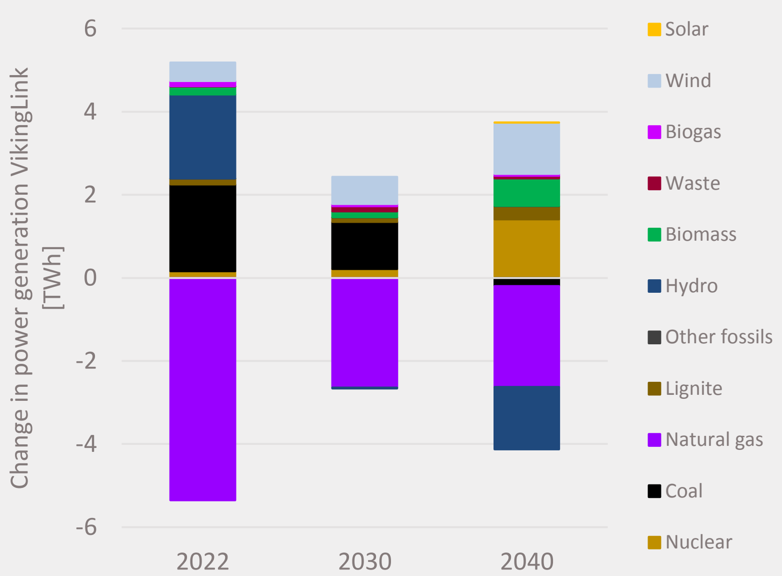
In the base scenario without the Viking Link, the price is initially higher in Great Britain for virtually all the hours of the year. In later years this distribution becomes more balanced. The average of the absolute price difference decreases between 2020 and 2030, then rises drastically in 2040, where Great Britain shows lower prices for more than 3000 hours.

Model results

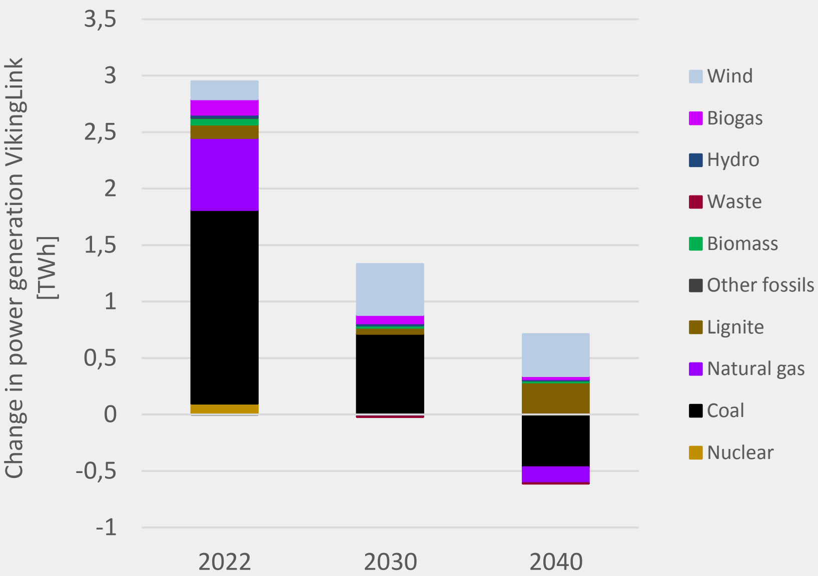
VIKING LINK SCENARIO

Viking Link's generation impact in Europe

Overall changes



Germany

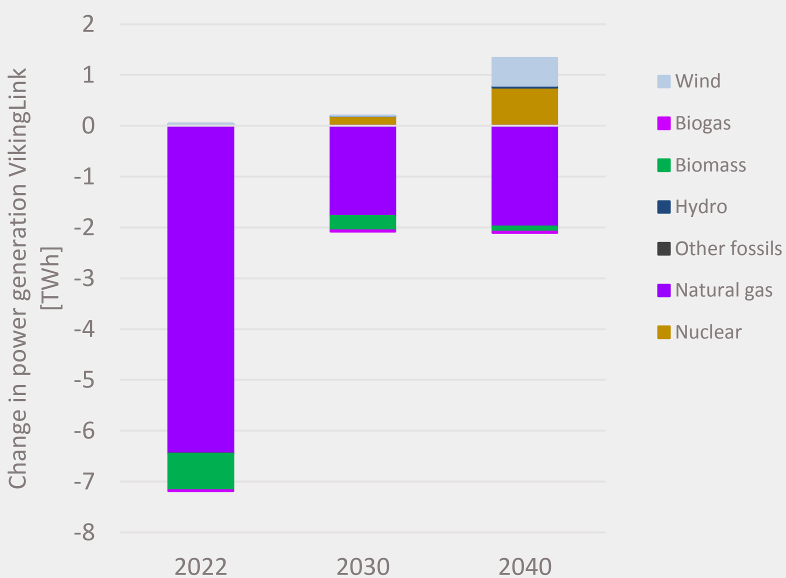


The introduction of the Viking Link in the system has an impact on the generation patterns across Europe. The biggest absolute changes are seen in Great Britain with a reduction in natural gas and biomass, especially in 2022. Initially, the Viking link results in higher coal generation in Germany. This effect is reversed by 2040, where several countries, among which Great Britain, Denmark and Germany show less wind power curtailment due to better integration. Changes in hydro generation are due to the model setup, and are accounted for in the economic calculations.

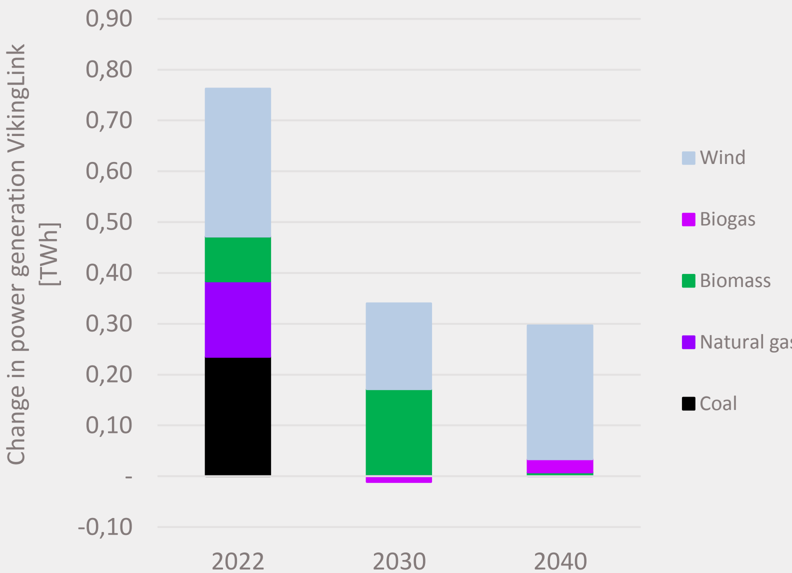
Viking Link's generation impact

Great Britain

Introduction of the Viking Link leads to changes in the overall electricity generation. In Great Britain, a large decrease of natural gas generation is seen especially for the year 2022. Biomass generation decreases to a lesser extent in 2022 and 2030. By 2040, the improved options for electricity export lead to a reduction of wind curtailment and increased generation from nuclear power.



Denmark

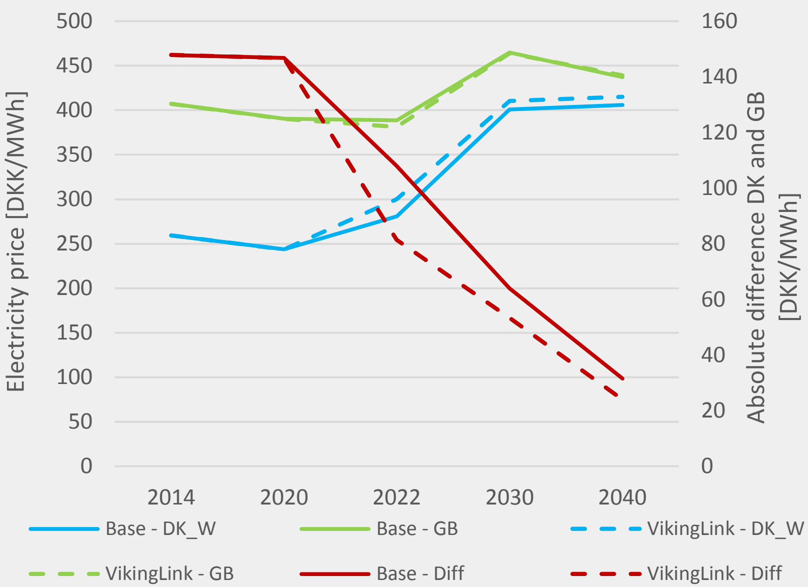


For Denmark, the implementaion of Viking Link leads to reduced curtailment of wind for all years. A rise in natural gas and coal generation can be seen in 2022. In 2022 and 2030 biomass production increases as well.

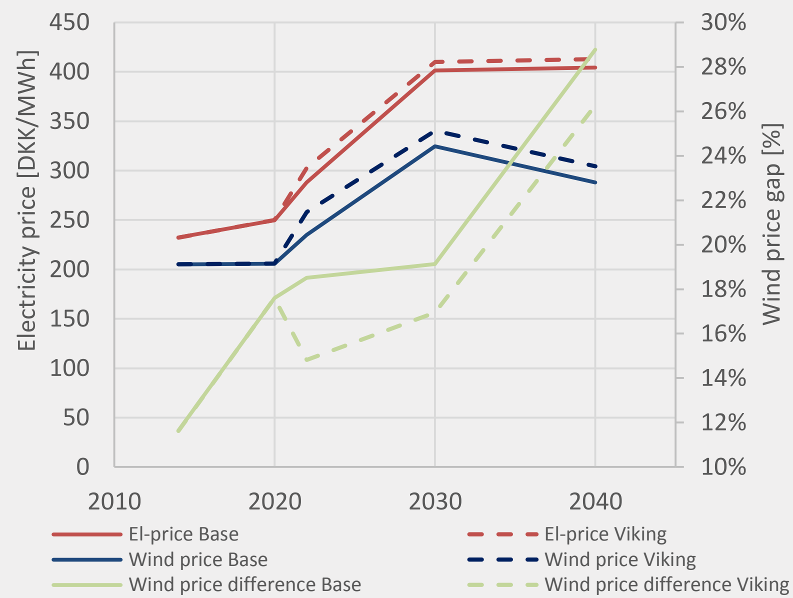
Electricity prices

Comparison DK_W and GB

The inclusion of the Viking Link in the system raises the electricity prices in Denmark by approx. 15 DKK/MWh in 2022 while reducing average prices in Great Britain.

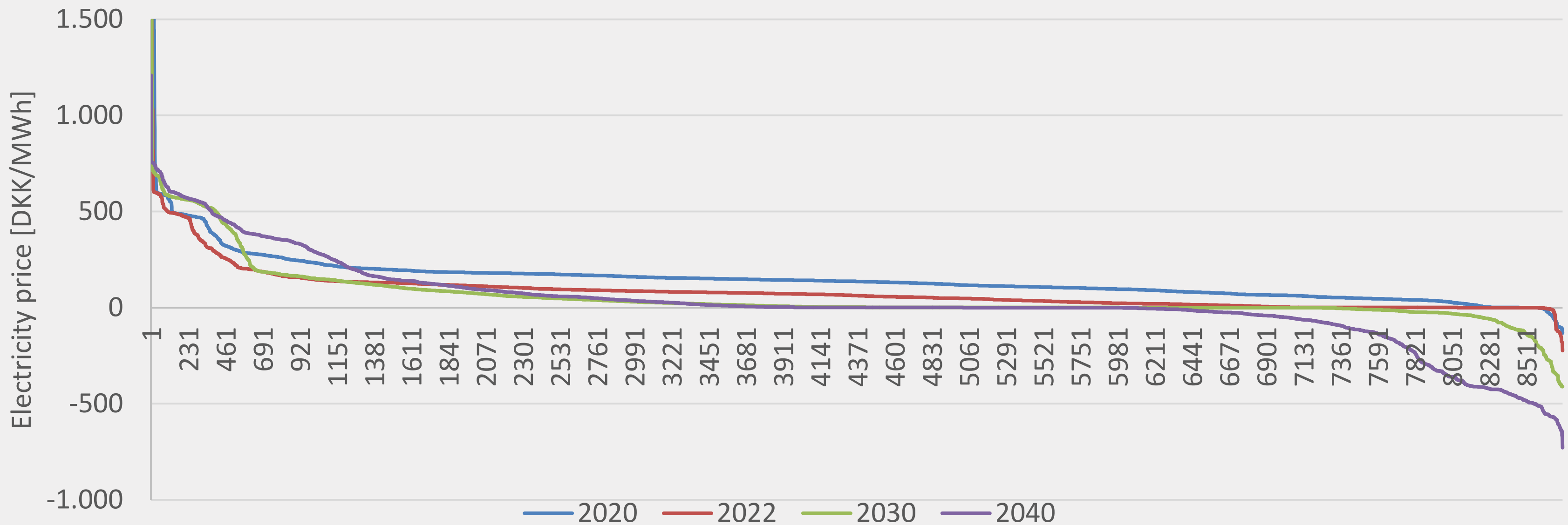


Danish electricity and wind prices



Both the average electricity prices and the wind prices are higher with the Viking Link in operation, the increase in the wind prices is more pronounced however, and the percentage difference between electricity and wind price therefore decreases, showing better integration.

Price difference DK West and GB duration curve Viking Link scenario

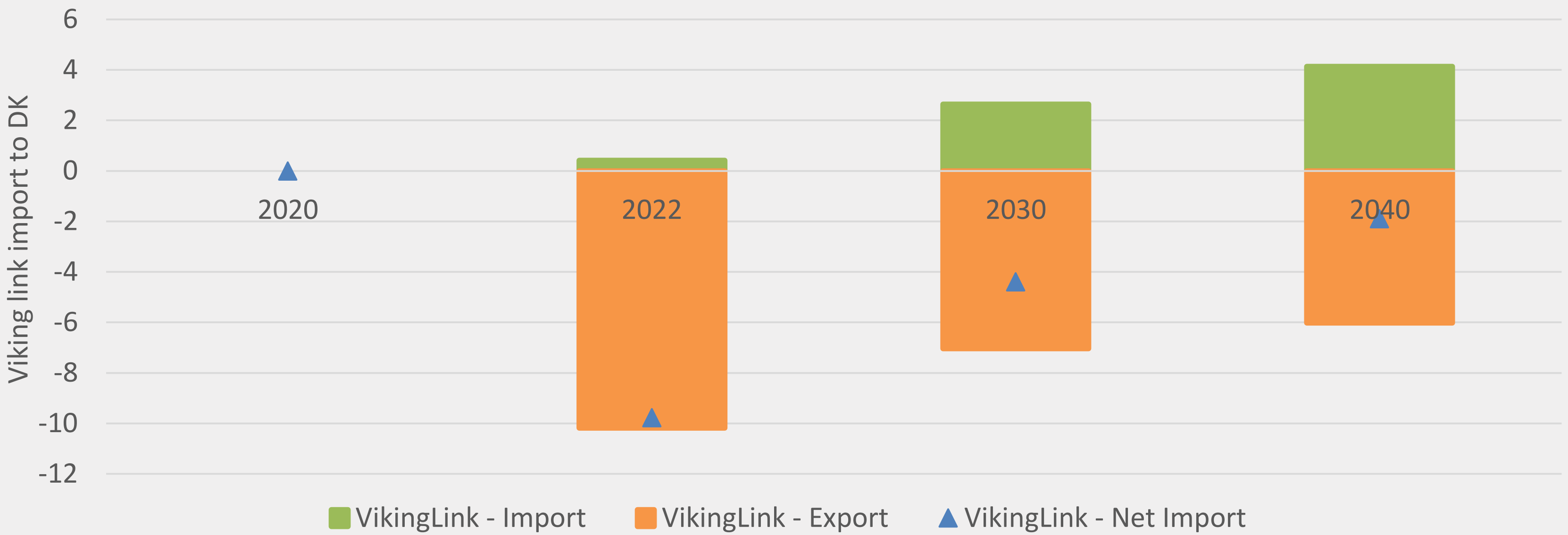


	Number of hours higher GB price	Number of hours higher DK_W price	Average of absolute price difference	Congestion rent [billion DKK]
2020	8469	197	148.3	-
2022	8097	505	83.0	0.9
2030	6017	2317	76.4	0.8
2040	5090	3397	138.7	1.5

The price differences between Denmark and Great Britain are lower when the Viking Link is used. The same trends as in the base scenario remain with a decreasing absolute average until 2030 and a steep increase in 2040.

The sum of all hourly price differences shows the annual congestion rent when multiplied by the flow.

Vikinglink import and export



In the figure above, the green represents the annual transmission from Great Britain to Denmark, where orange shows the transmission in the opposite direction. The blue line represents the sum of the two. In 2022 the transmission in the Viking Link is primarily used for export from Denmark to Great Britain as the electricity prices in Great Britain are higher than in Denmark around the year. Towards 2040 the link is used increasingly for transmission in both directions as more and more hours occur where the electricity prices are higher in Denmark than in Great Britain. This is a result of the increased volatility of the hourly electricity prices and the different generation profiles for wind power in Great Britain and Denmark.

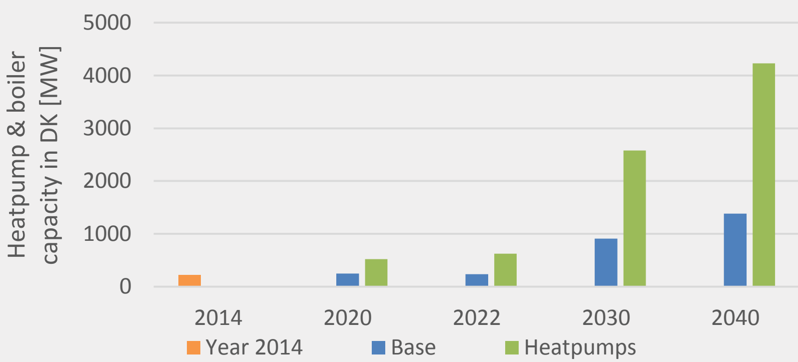
Model results

HEAT PUMPS SCENARIO

Heat pump capacity

Heat pumps scenario

	Installed heat capacity [MW]	Capacity in natural gas areas	FLH
		Heatpumps	
2020	369	96%	6,242
2022	490	97%	5,769
2030	2,299	40%	3,313
2040	3,976	24%	3,271
		Electric boilers	
2020	149	68%	1,210
2022	133	66%	732
2030	281	11%	512
2040	251	0%	752



In the heat pump scenario, the heat pump capacity is found by reducing the total tax and tariff for electricity usage for district heating generation to 150 DKK/MWh and letting the model optimize investments in the power and district heating sector in Denmark. The level of the chosen tariff is meant to reflect the socio-economic tariff of using electricity. However, no detailed analysis on this matter has been carried out in this project, and 150 DKK/MWh is a bit lower, than the socio-economic tariff of around 160 DKK/MWh (excluding losses) the Danish Energy Agency is using for industrial consumers. However, heat pumps can have production patterns better suited for the grid capacity compared to industrial consumers, which might be able to justify even lower socio-economic tariffs.

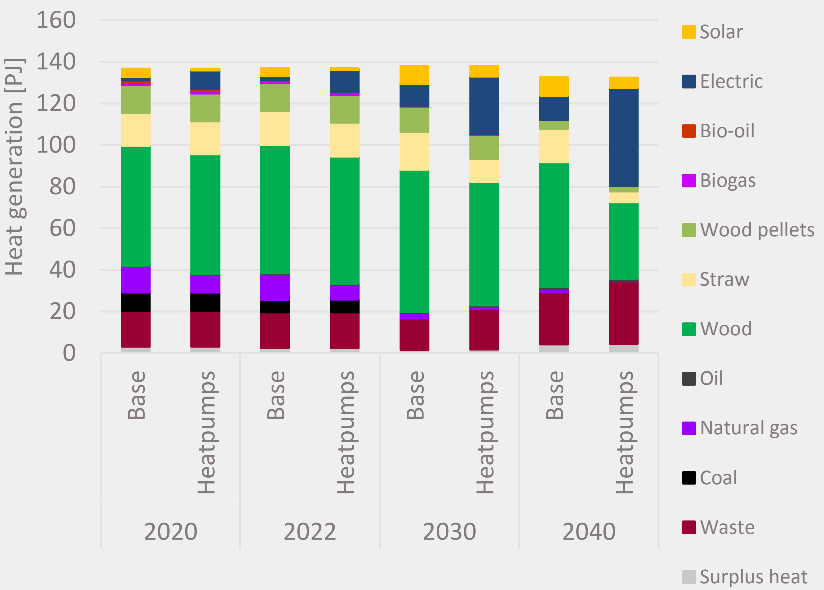
In order to ensure a reasonable pace of introduction of heat pumps and electric boilers, the maximum allowed capacity in 2020 and 2022 is capped at 300 and 500 MW heat capacity, compared to the capacity in 2014. The total heat pump and boiler capacities in the Heatpumps scenario are given in the left table, along with their resulting full load hours.

Technical data for the heat pumps are based on the Technology catalogue by the Danish Energy Agency and Energinet.dk.

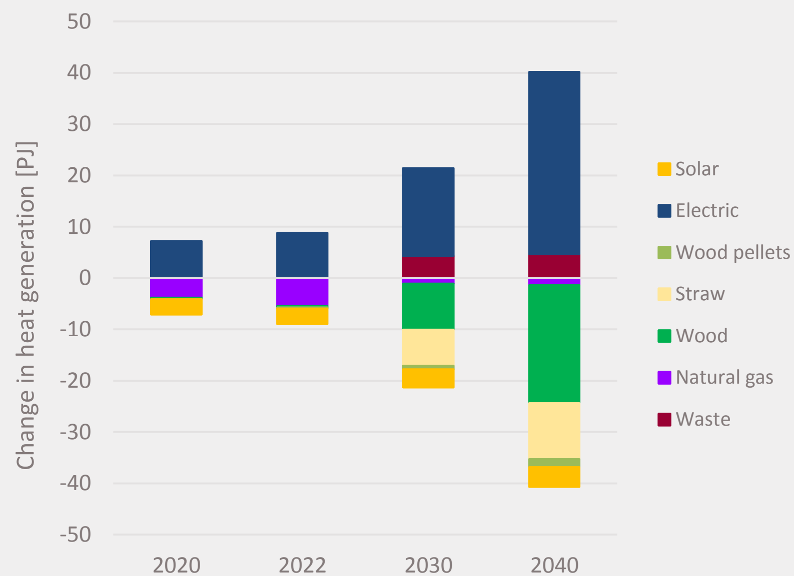
	COP	Investment cost [mio. DKK/MWh heat]	O&M variable [DKK/MWh heat gen.]	O&M Exogenous [DKK/MW heat cap.]
2020	2.9	5.0	2.4	14,500
2030	3.0	4.6	2.4	14,500

Generation

Heat generation



Initially, mainly heat generation by natural gas and solar is replaced by the new heat pumps. From 2030 onwards heat generation from biomass is replaced.

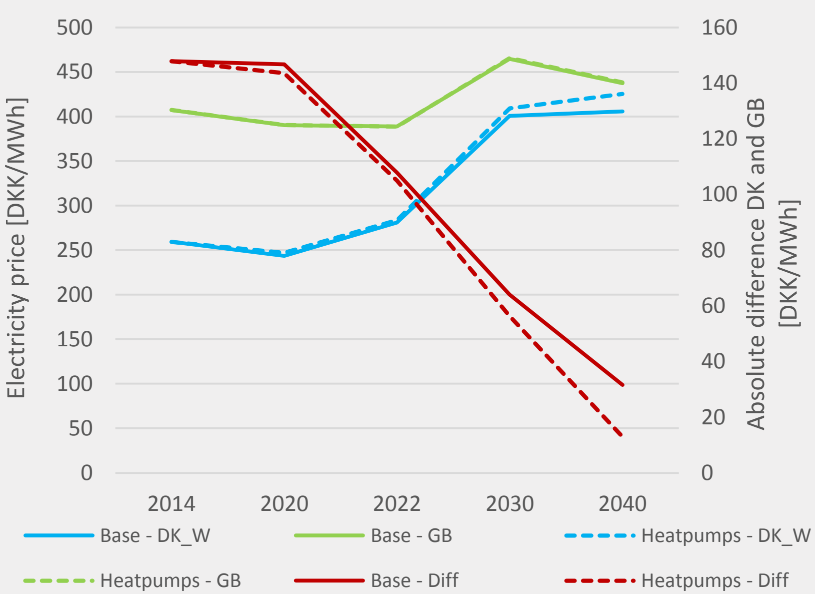


The heat generation in Denmark shows a gradual increase in heat generation by heat pumps in the Heatpumps scenario. In 2020 the heat generation from boilers and heat pumps is only 6.5% of the total heat generation. By 2040 36% of heat generation is from electricity.

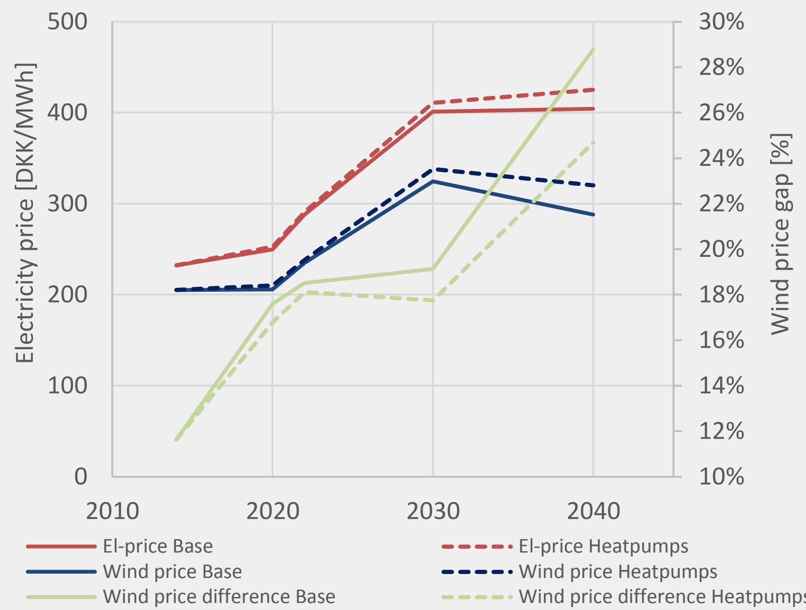
Electricity prices

Comparison DK_W and GB

The Heat pumps scenario raises the electricity prices in Denmark in the longer term with approx. 10-20 DKK/MWh by 2030 and 2040, while prices in Great Britain are largely unaffected. All else equal, the decreasing gap could slightly decrease the potential for connecting the two regions.



Danish electricity and wind prices



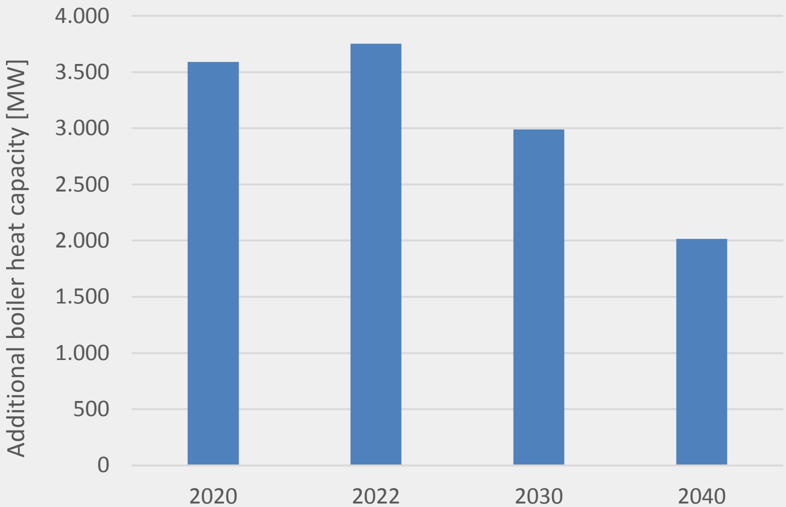
Both electricity and the wind prices are higher in the Heat pumps scenario, the increase in the wind prices is more pronounced however, and the percentage difference between electricity and wind price therefore decreases compared to the base scenario.

Model results

FLEXIBILITY ON LARGER POWER PLANTS SCENARIO

Capacity

Added boiler capacity in Denmark



On the larger power plants in Denmark, additional electric boiler capacity is installed to ensure more flexibility. To some extent, a similar measure can be achieved by adding the option of turbine bypass to the power plants. Therefore, no taxes and tariffs on electricity usage by the electric boilers are assumed. However, it should be noted that the electric boilers can also run when the power plants are not in operation and thus do not only act like turbine bypass.

The boilers that were added to the central areas in Denmark have the following characteristics

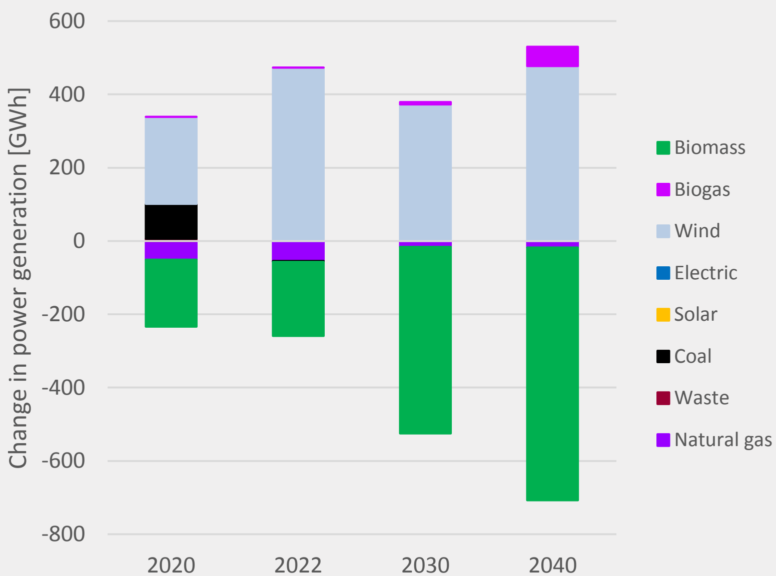
Efficiency	O&M variable [DKK/MWh heat gen.]	Investment [DKK/MW heat cap.]
99%	4.0	0,5

The total heat capacity and the FLH of the boiler are shown for the four years in the table below. In 2040 about 400 MW was already in the system in the base scenario and is added to the additional capacity. The low number of full load hours indicates the limited usage of the electric boilers.

	Total installed heat capacity [MW]	FLH
2020	3,591	269
2022	3,753	262
2030	2,989	444
2040	2,431	818

Change in generation in Denmark

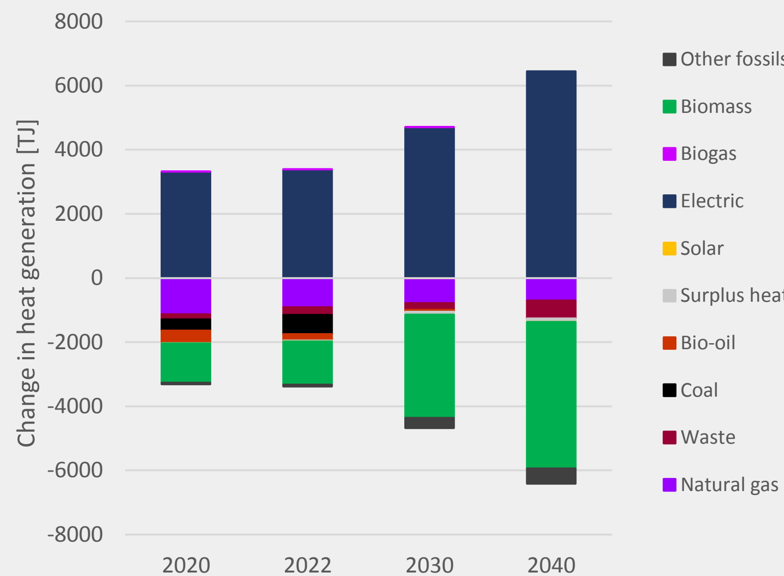
Electricity generation



In Denmark, the changes in the electricity production show a clear trend to less curtailment and a reduction of power generation from biomass CHP. In the earlier years some changes in natural gas and coal are also seen.

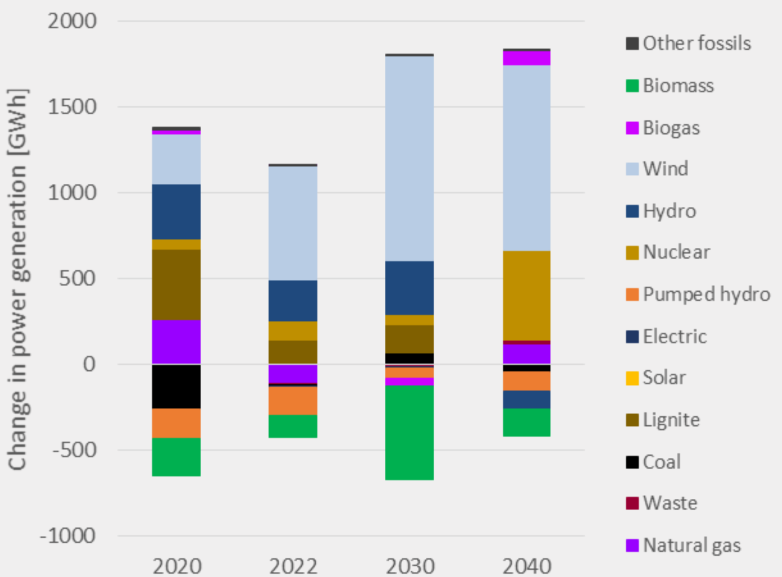
Heat generation

The added boilers generate heat that replaces mainly biomass, natural gas and coal in the system. The displaced biomass is mainly CHP production.



Change in overall electricity generation

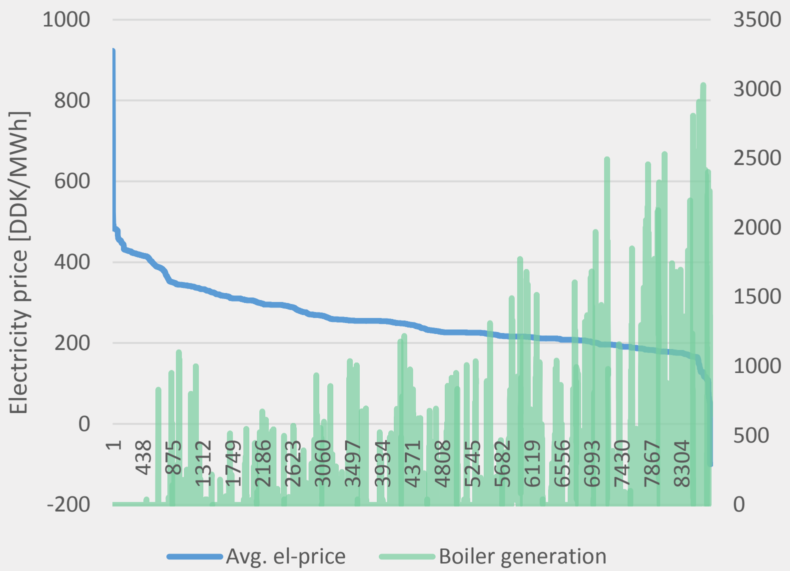
Overall electricity generation



The changes in the electricity generation in the entire model for the increased flexibility on central power plants are for a large part a reduction in curtailment of wind power.

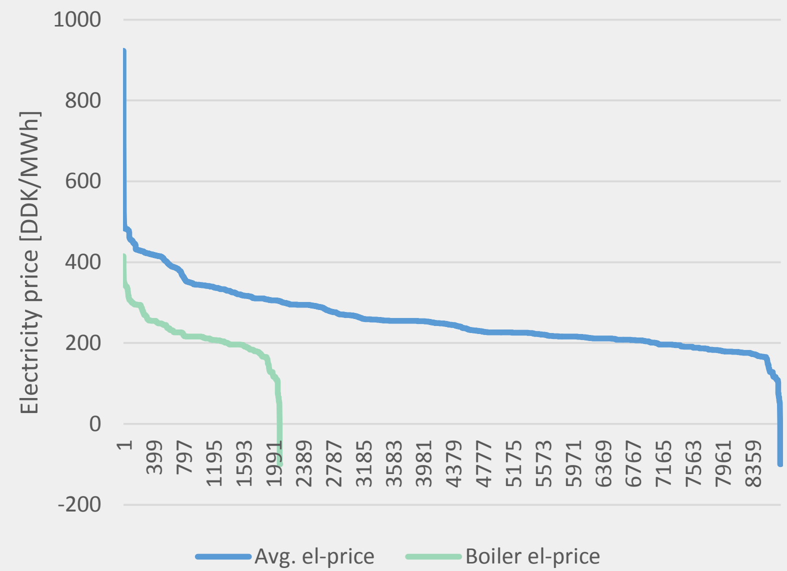
Boiler generation and electricity price

Boiler generation (2020)



The electric boilers generate more heat at low electricity prices, while heat generation is based on CHP at higher electricity prices. Compared to the base scenario, the number of hours with very low or negative electricity prices in Denmark in 2020 is reduced significantly, which leads to a relative large impact on the electricity prices captured by wind power.

Boiler electricity price (2020)

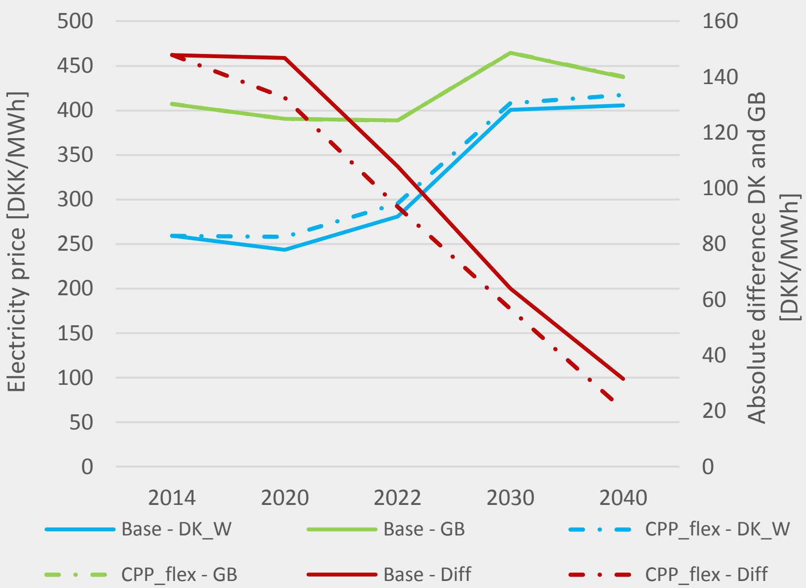


The graph above shows the electricity price duration curve and the duration curve of the electricity price when the electric boilers are in operation. It can be seen that the boilers are only in operation for a maximum of 2000 hours a year at low electricity prices. The graph does not indicate whether boilers run at full capacity all over Denmark, and thus the 2000 hours are not equivalent to the number of full load hours.

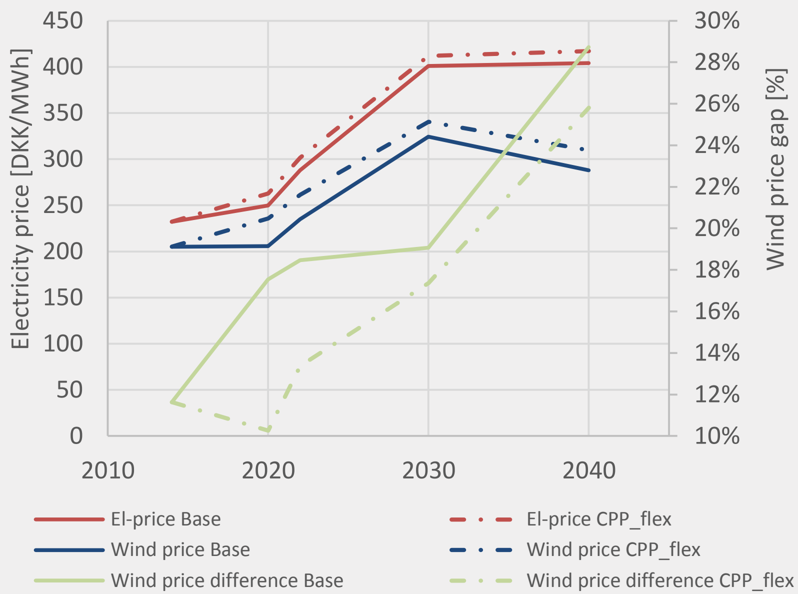
Electricity prices

Comparison DK_W and GB

The flexibility on the central power plants in Denmark raises the electricity prices in Denmark, while prices in Great Britain are unaffected. The gap between the two countries is therefore lowered in the CPP flex scenario.



Danish electricity and wind prices



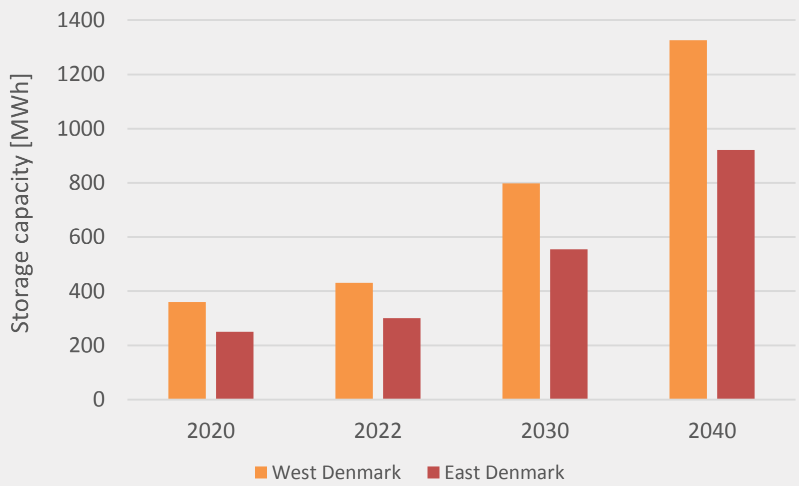
Both electricity and the wind prices are higher in the CPP flex scenario compared to the Base case. The increase in the wind prices is more pronounced, especially in the early years and the percentage difference between electricity and wind price therefore decreases compared to the base scenario.

Model results

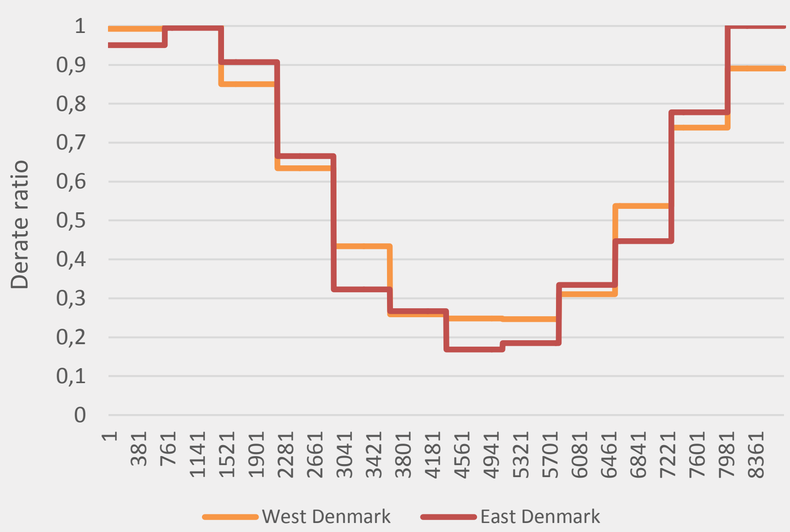
INDIVIDUAL HEAT PUMPS SCENARIO

Capacity

Added storage capacity in Denmark



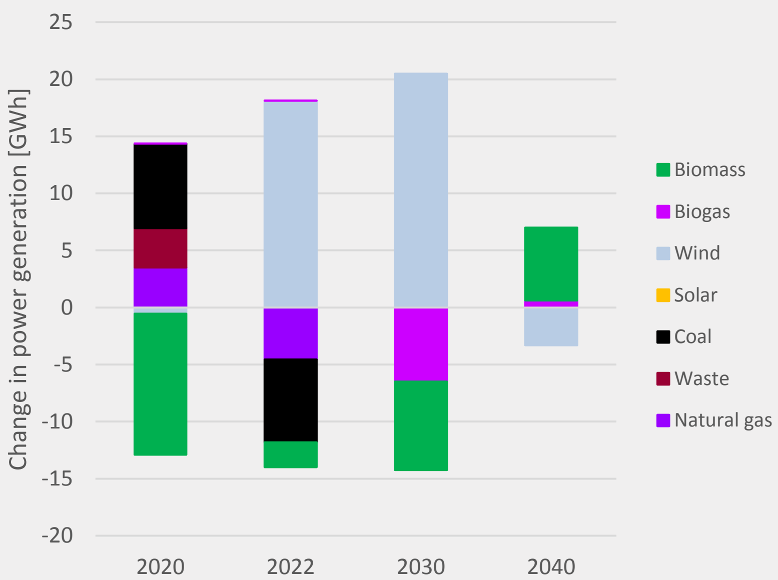
The graph on the left illustrates the amount of electricity, that can be "stored" by using the heat pumps in a more flexible way. During summer, the lower heat demand limits the option to "store" electricity, which is taken into account by using a seasonal variation of the maximum storage capacity, illustrated on the graph below.



In the Individual Heat pumps scenario, electricity usage for individual heat pumps has increased flexibility. While the electricity demand for individual heat pumps follows the heat demand in the base scenario, the model has the option to shift demand around 4 hours in time in the individual heat pump scenario. This represents the option to use local hot water tanks and the heat stored in buildings to use the heat pumps at times with lower power prices.

Change in generation in Denmark

Electricity generation

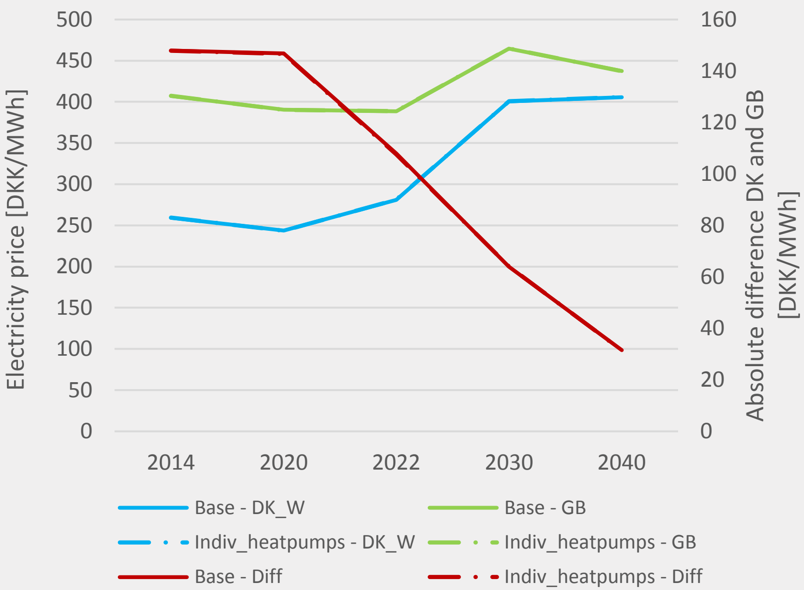


The changes in the electricity generation in Denmark for the Individual heat pumps scenario are limited. In 2022 and 2030 small some reduction in wind curtailment is seen. The limited impact on the overall power system also limits the impact on wind power integration and system economy.

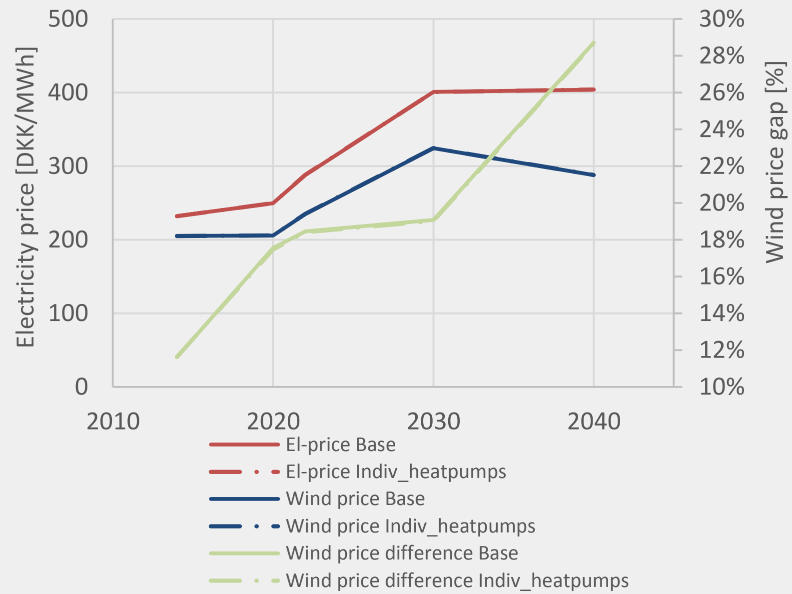
Electricity prices

Comparison DK_W and GB

Negligible changes compared to base scenario



Danish electricity and wind prices



Negligible changes compared to base scenario

Model results

INTEGRATION INDICATORS

Additional power demand, export and flexibility

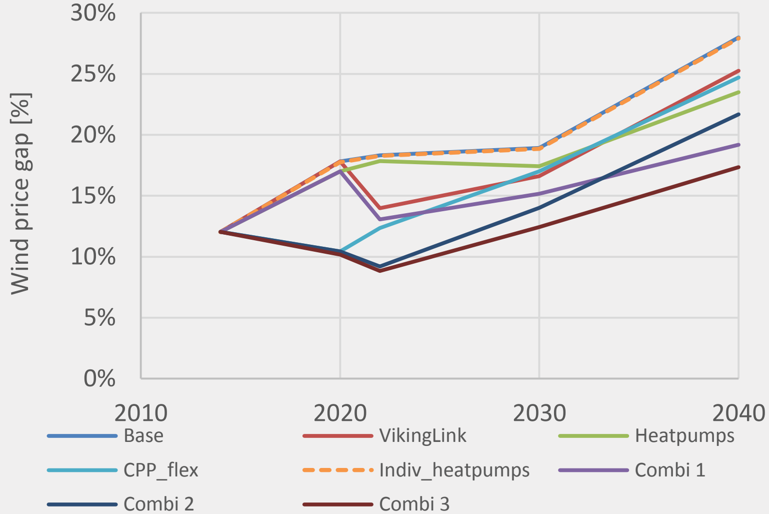
To some extent, the effect of the different scenarios on the overall power system and the integration of wind power is limited by the *size* of the integration measure. The different scenarios do not necessarily compare in terms of size of the integration measure with respect to power capacity, power demand or associated investment costs. The table below gives an overview on the size of the different integration measures from a power system point of view, when compared to the base scenario. Note, that the shown power "demand" is not necessarily additional demand, but an interpretation of the effects for the Danish power system. As an example, export from Denmark through Viking Link is shown as additional demand, even though the total demand in the overall system is unchanged. Please see the notes for further details. The values for power demand are based on the actual model results and not an a priori assumption.

	Additional potential power "demand" [GW]						
	VikingLink	**Heatpumps**	**CPP flex**	**Indiv heatpumps**	**Combi 1**	**Combi 2**	**Combi 3**
2020	0.00	0.09	3.65	0.15	0.09	3.65	3.74
2022	1.40	0.13	3.81	0.18	1.53	5.21	5.34
2030	1.40	0.49	3.04	0.34	1.89	4.44	4.93
2040	1.40	1.00	2.04	0.56	2.40	3.44	4.44
	Additional power "demand" [TWh]						
	VikingLink*	**Heatpumps**	**CPP flex**	**Indiv heatpumps****	**Combi 1*****	**Combi 2******	**Combi 3*******
2020	0.00	0.62	0.97	0.42	0.62	0.97	1.52
2022	9.78	0.81	0.99	0.53	10.49	10.34	10.99
2030	4.40	1.58	1.34	0.99	5.43	5.44	6.29
2040	1.89	3.30	1.76	1.64	4.45	2.96	4.98

*Power demand shows net export from Denmark to Great Britain on an annual basis
**Power demand shows amount of power demand, that is made flexible. Annual power demand does not change.
***Power demand shows combination of net export from Denmark to Great Britain on an annual basis and additional annual power demand for heat pumps.
**** Power demand shows combination of net export from Denmark to Great Britain on an annual basis and additional annual power demand for electric boilers.
*****Power demand shows combination of net export from Denmark to Great Britain on an annual basis and additioanl power demand from heatpumps and electric boilers

Wind weighted prices in Denmark

Relative difference



The wind weighted price is an indicator for wind integration; in a system with good wind integration the wind weighted price does not differ largely from the average electricity price. All analysed integration measures show a positive effect on wind integration in terms of the wind weighted electricity price. (the Individual heat pumps scenario is shown in dotted lines as the effect is small). In the short term, the effect is most pronounced in the CPP_flex scenario. However, also the introduction of Viking Link in 2022 leads to a decreasing gap compared to 2020. In early years, the heat pumps scenario shows very low differences, but by 2040 the values resemble those of the other scenarios. In general, onshore wind has a larger price gap than offshore wind.

Ratio of differences

To validate the wind weighted prices of the integration scenarios compared to the base scenario, the following measure can be used

$$\frac{\Delta\, Wind\ weighted\ price}{\Delta\, Average\ electricity\ price}$$

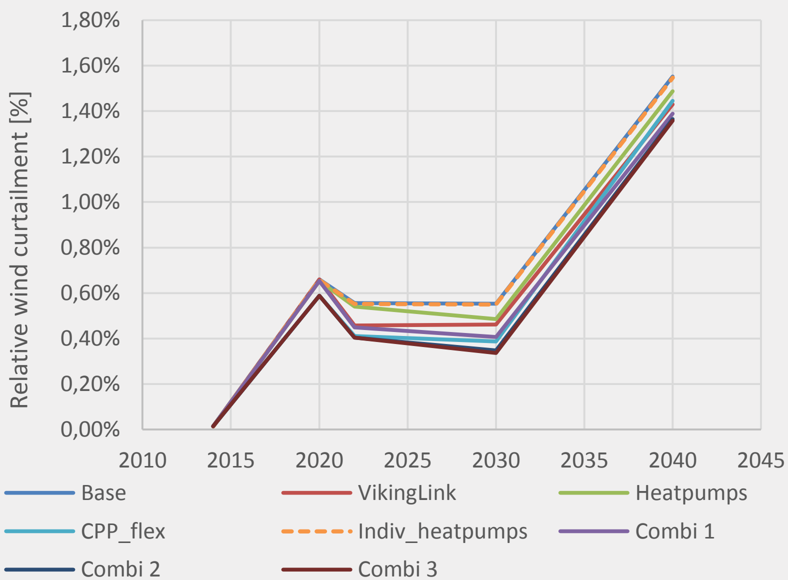
The table below shows the changes of the wind weighted and average electricity price as well as the ratio. A high ratio indicates good wind integration. The ratio is generally higher for the Viking Link scenario compared to the Heat pumps scenario. The CPP_flex scenario shows the highest values for 2020 and 2022.

The combi scenarios show changes in wind weighted and average electricity prices, that are close to the sum of the respective individual scenarios.

	Fraction (diff. Wind weighted price/diff average electricity price)						
	VikingLink	**Heatpumps**	**CPP flex**	**Indiv.Heat-pumps**	**Combi 1**	**Combi 2**	**Combi 3**
2020	0/0	4.5/2.9	29.9/13.1	0.2/0	4.5/2.9	29.9/13.1	32.6/15.3
2022	23.2/14.7	3.6/3	26.6/13.8	0.3/0.2	28.2/17.8	44.6/25.1	47.2/26.9
2030	15.9/8.6	13.5/9.7	15.8/10.8	0.2/-0.1	29/17.6	34.5/19.5	47.5/27.5
2040	16.5/8.7	32.4/21.1	21.6/13.2	0.3/0.1	60.1/35.4	38.9/21	71.9/41.2
	Ratio						
	VikingLink	**Heatpumps**	**CPP flex**	**Indiv.Heat-pumps**	**Combi 1**	**Combi 2**	**Combi 3**
2020	-	1.52	2.29	-	1.52	2.29	2.13
2022	1.58	1.21	1.93	1.52	1.59	1.78	1.75
2030	1.84	1.40	1.46	-1.59	1.64	1.77	1.73
2040	1.90	1.53	1.64	5.75	1.70	1.85	1.75

Overall curtailment

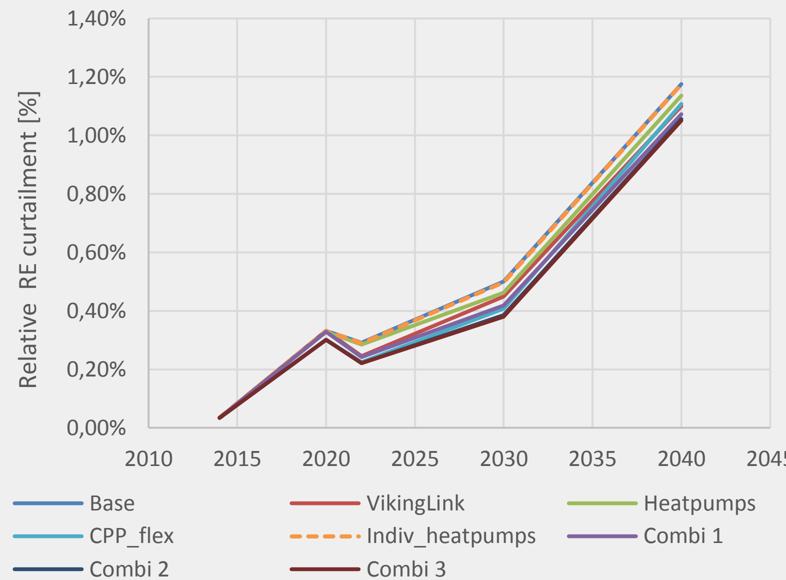
Wind curtailment



Wind curtailment is another indicator to assess wind integration. A drop in overall wind power curtailment is seen for the Viking Link and Combi 1 scenario in 2022. The Heat pumps scenario has a smaller effect in 2020, but is similar in curtailment level to the Viking Link scenario by 2030. The CPP flex scenario shows the largest effect in all years but 2040.

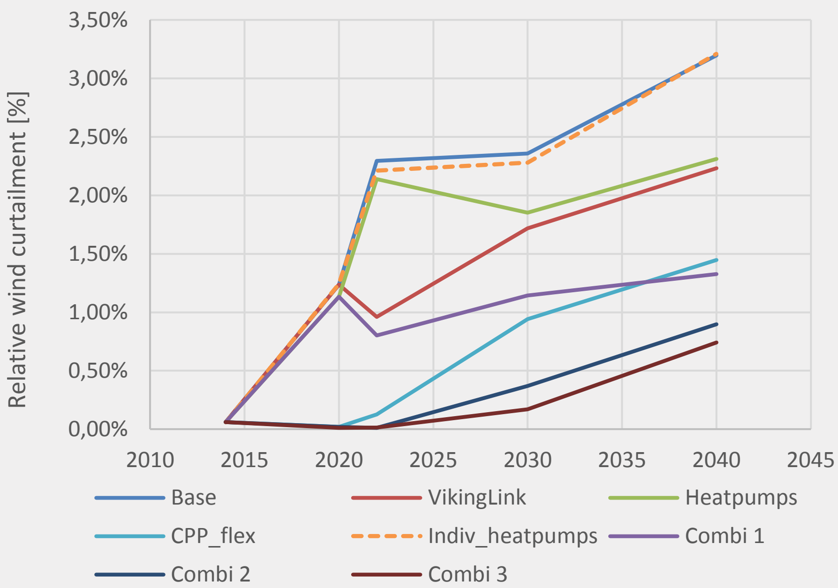
RE curtailment

Similar results are seen for the overall RE curtailment (which also includes wind, solar and hydro run-of-river curtailment).



Curtailment in Denmark

Wind curtailment



A drop in Danish wind power curtailment is seen for the Viking Link and Combi 1 scenario in 2022. The Combi 1 scenario shows a large reduction in curtailment compared to the single integration scenarios. For the scenario with flexibility on Danish power plants, very little curtailment is seen in 2020 and 2022. In later years this scenario shows curtailment in the order of the Combi 1 case. Overall the difference from the base scenario is small. Both combination scenario 2 and 3 show low curtailment for all years.

Geographical distribution of curtailment will in reality to some extent depend on the detailed regulation regimes in different countries, which are not replicated in the model.

Model results

ECONOMY OF WIND INTEGRATION MEASURES

Economy

Socio-economic perspective

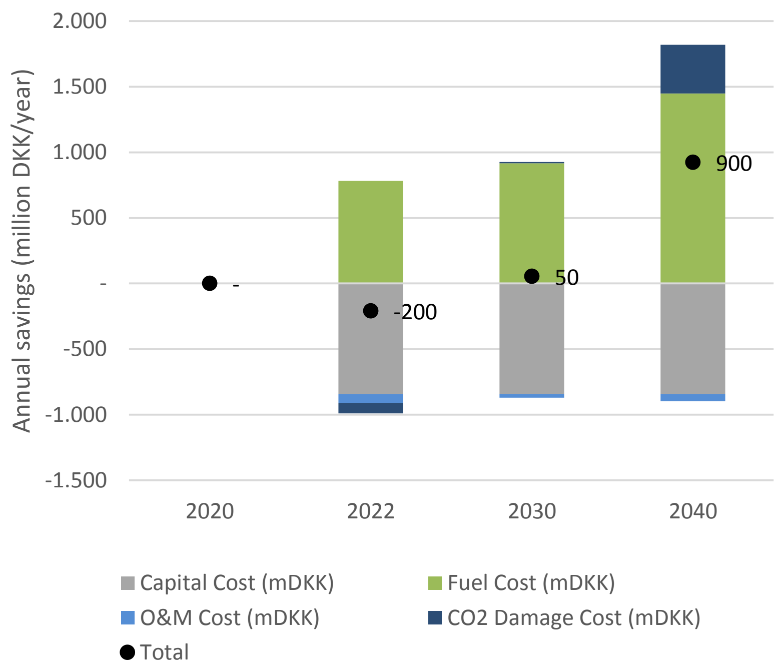
- Evaluation of economic effects based on
  - Comparison to Base scenario
  - Socioeconomic perspective: Changes in system costs for providing heat and electricity
  - All numbers rounded to multiple of 50 million DKK
- Included elements
  - Capital cost on technologies. Based on a socioeconomic interest rate of 4% and a lifetime of 20 years. Including changes in capital cost due to the introduction of heat pumps and replacement of CHP capacity.
  - Fixed and variable O&M
  - Fuel cost
  - CO_2-damage cost (value of CO_2 set equal to ETS price)
    - No socio-economic value of moving emission from the UK (Higher tax on CO_2 before 2030) to continental Europe (lower price on CO_2 before 2030)
  - Value of changes in hydro generation. Recalculated to fuel, O&M and CO_2 savings/cost based on the average emission factor for electricity generation in the overall system excluding hydro, wind, solar and municipal solid waste, a general O&M cost of 30 DKK/MWh and the remaining on fuel cost to match the overall value of changes in hydro generation.
  - For the NPV calculation, the period from 2020 to 2051 is taken into account (30 years lifetime on Viking Link). Since no model calculation has been performed beyond 2040, the same values as for 2040 are assumed for the period 2040-2051.
- Not included elements
  - Cost of establishing flexibility on individual heat pumps
  - Damage costs of changes in other emissions (NO_x and SO_2). This could have a (smaller) impact on the results. However, it is difficult to estimate the emission factors for the existing power plants and a detailed analysis of this matter was not carried out in this project.
  - Cost due to tax distortion

Viking Link scenario

Economy

- Economy includes 13.4 billion DKK investment costs for the Viking Link *(Source: ENTSO-E Ten Year Network Development Plan)* and an estimated 0,5% of the investment for Operation and maintenance/year.
- Main savings from reduced fuel cost
- In the short run, annual operational savings are below the capital and O&M cost for Viking Link and the socio-economic value for 2022 alone is therefore negative.
  - Price difference between Denmark and Great Britain is partly driven by different CO_2-taxes, which do not reflect socioeconomic savings.
- Savings increase, even though average price difference between Denmark and Great Britain decreases
  - Price spread by hour increases
  - In the long run, additional transmissions capacity can reduce wind curtailment
- Socioeconomicy is shown for the entire region. The effect on individual countries will differ. For Denmark the socioeconomic value of Viking Link is positive throughout the entire period, while other countries experience losses in the short run.
- By 2040, the general value of new transmission in the system increases due to higher shares of variable RE generation. Viking Link is the only allowed transmission investment over the period. However, other transmission lines could also show positive economy.
- Higher CO_2-emissions in the short run due to lower generation from gas in the UK and higher generation from coal in continental Europe

Annual savings



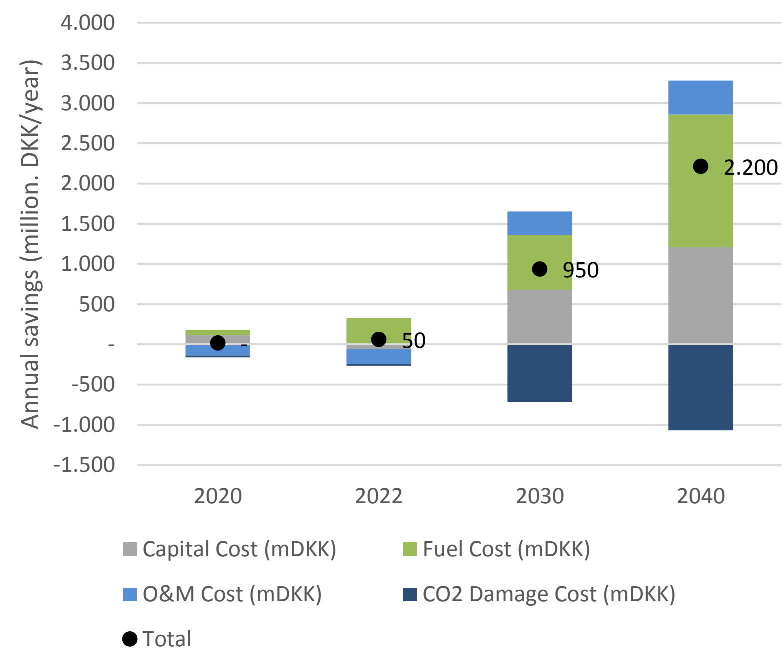
- NPV in 2020: approx 5.6 billion DKK (30 yrs.)

Heat pumps scenario

Economy

- Economy calculations include capital cost and savings in the Danish district heating system.
- Main savings from reduced fuel cost, but also capital cost.
- Positive savings, from first year, although low for 2020 and 2022. Increasing value as a result of higher usage of heat pumps.
- Higher CO_2-emissions due to higher electricity consumption and reduced electricity generation from biomass in Denmark. In a well-functioning CO_2 quota system, one could argue that the short term effect would be rising CO_2-prices and no additional CO_2-emissions, possibly with a similar economic effect.
- The model is not allowed to invest in new capacity in other power production when the heat pumps are introduced and the increased need for electricity therefore comes from existing thermal plants. A different approach where the model would be allowed to invest in wind power could change the results on CO_2-emissions.

Annual savings



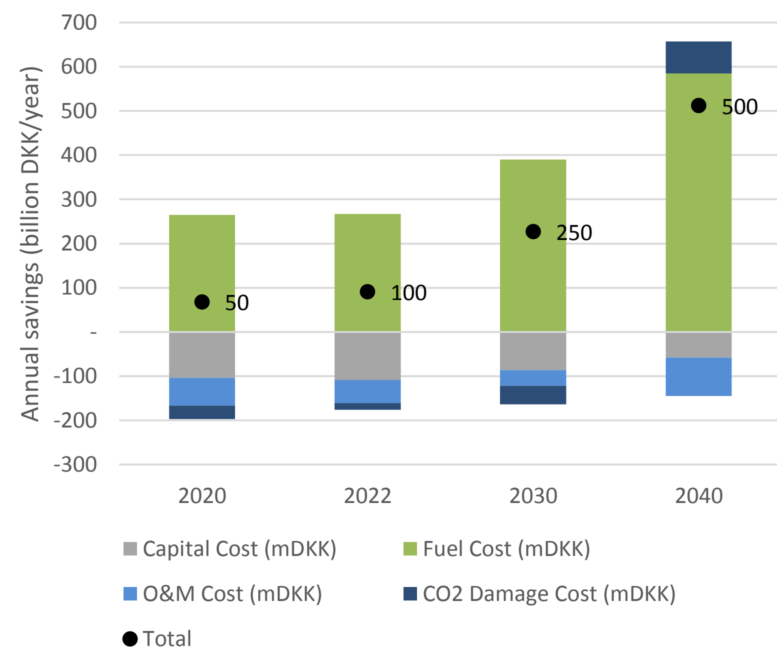
- NPV in 2020: approx. 20.2 billion DKK

Flexibility on Larger Power Plants Scenario

Economy

- Economy calculations include changes in capital cost but not fixed O&M costs connected to introducing flexibility on the power plants.
- Main savings arise from reduced fuel cost.
- Increasing savings as a result of higher number of hours with low electricity prices and subsequently higher number of full load hours for electric boilers.

Annual savings



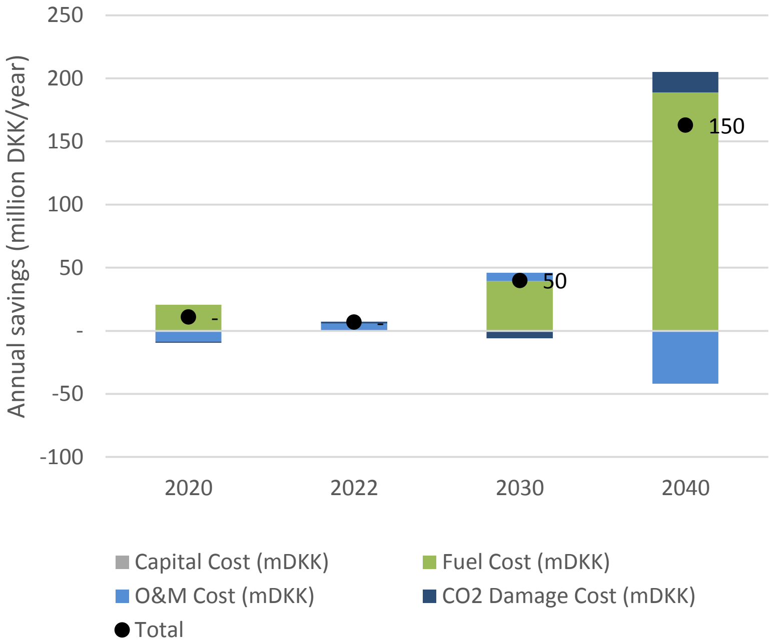
- NPV approx. 5.1 billion DKK

Individual heat pumps scenario

Economy

- Economy calculations do not investment cost arising from flexibilisation of individual heat pumps, such as individual heat storages. This cost has not been estimated within the current project.
- Main savings from reduced fuel cost.
- Small savings in the short run.

Annual savings



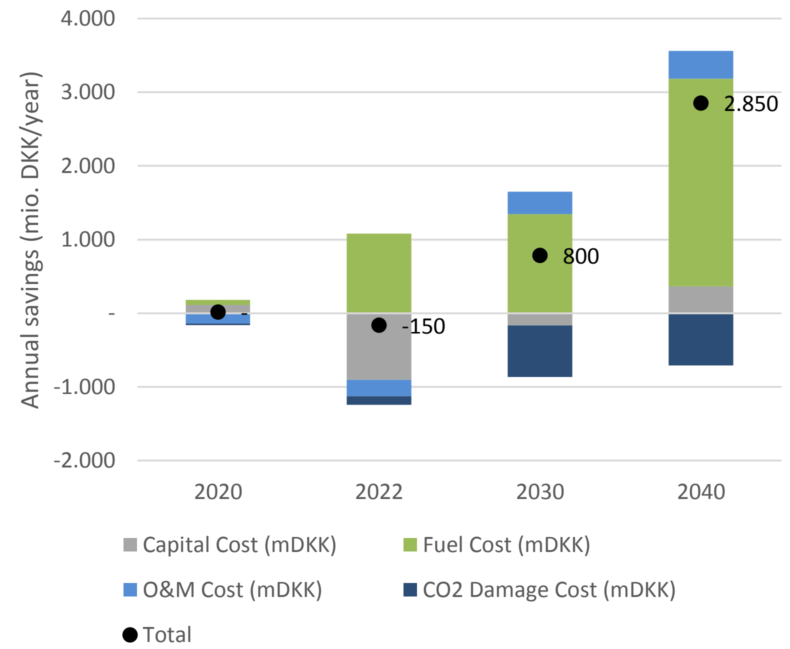
- NPV approx. 1.3 billion DKK

Combined scenario 1 : Heatpumps + Viking Link

Economy

- Economy calculations include capital cost and savings in the Danish district heating system, and capital costs and O&M costs for the Viking Link.
- Main savings from reduced fuel cost
- Low savings in the short run, in parts due to the low savings in the heat pump scenario, and in parts due to the extra cost from the Viking Link scenario for 2022.
- Increasing value towards 2030 and 2040 as a result of higher fluctuations in electricity prices and higher usage of heat pumps.
- Higher CO_2-emissions due to higher electricity consumption and reduced electricity generation from biomass in Denmark

Annual savings



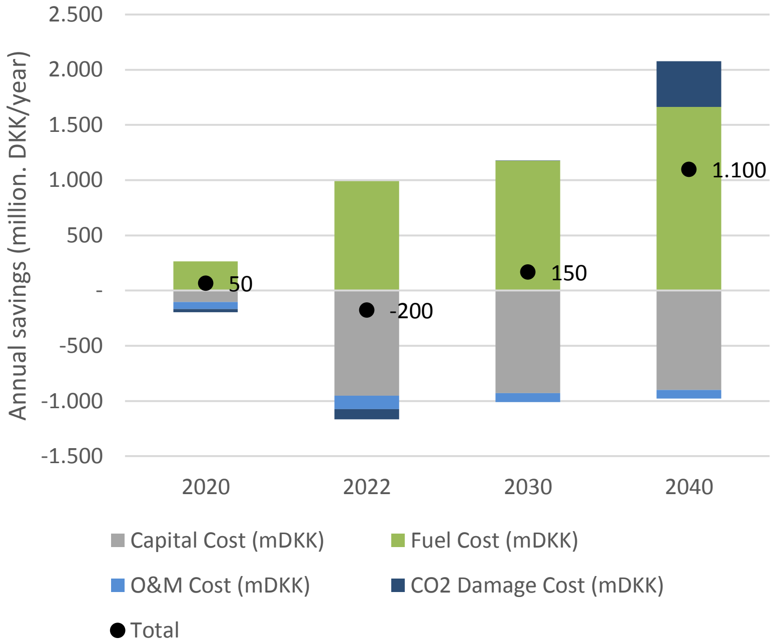
- NPV approx. 22.8 billion DKK
- NPV for Viking Link with heat pump scenario as base: 2.6 billion DKK corresponding to approx 47% of the value of Viking Link compared to the base scenario

Combined scenario 2: CPP flex + Viking Link

Economy

- Economy calculations include changes in capital cost but not fixed O&M costs connected to introducing flexibility on the power plants. Viking Link investment costs and O&M costs are included.
- Main savings from reduced fuel cost
- Low savings in the short term. Increasing value as a result of higher fluctuations in electricity prices and increased usage of electric boilers.

Annual savings



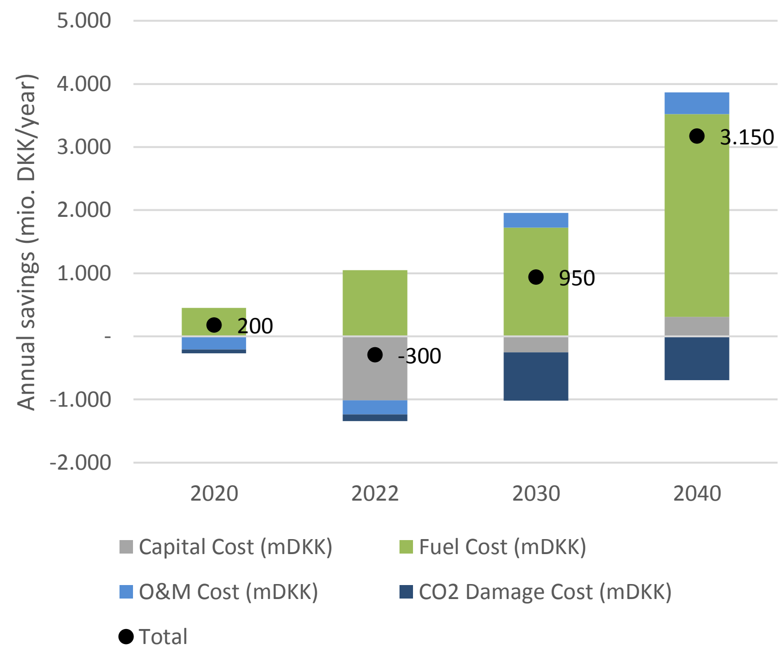
- NPV approx. 7.6 billion DKK
- NPV for Viking Link with CPP flex scenario as base: 2.4 billion DKK corresponding to approx 43% of the value of Viking Link compared to the base scenario

Combined scenario 3: Heatpumps + CPP flex + Viking Link

Economy

- Economy calculations include capital cost and savings in the Danish district heating system including changes in capital cost but not fixed O&M costs connected to introducing flexibility on the power plants. Viking Link investments and O&M costs are included.
- Main savings from reduced fuel cost, but also capital cost
- Low savings in the short term. Increasing value as a result of higher fluctuations in electricity prices and higher usage of heat pumps.
- Higher CO_2-emissions due to higher electricity consumption and reduced electricity generation from biomass in Denmark

Annual savings



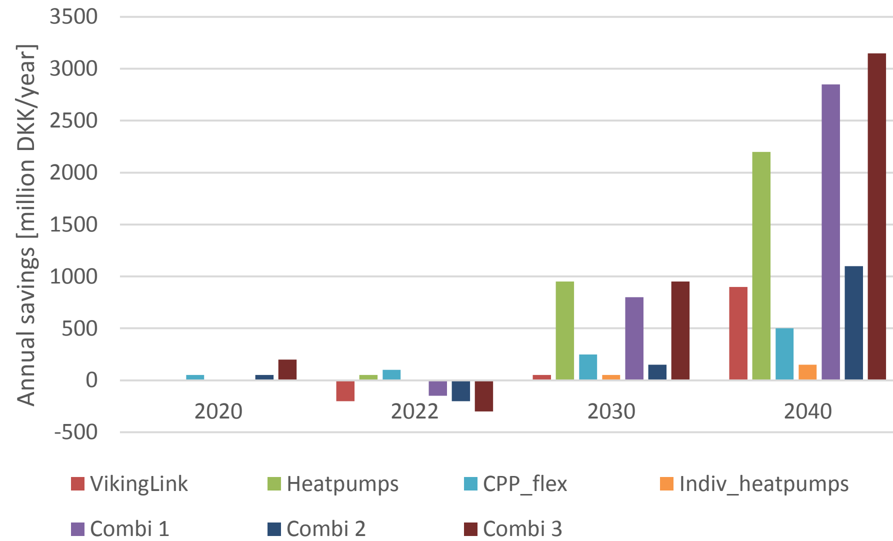
- NPV approx. 25.3 billion DKK
- NPV for Viking Link with heat pump + CPP flex as base: 1.3 billion DKK corresponding to approx 23% of the value of Viking Link compared to the base scenario

Socioeconomic value of different scenarios

The net present value (NPV) of the different scenarios is calculated for 2020 as base year with a discount rate of 4% and over the period from 2020 to 2051, which corresponds to a lifetime of Viking Link of 30 years.

All scenarios show a positive socioeconomic net present value. However, the individual heatpump scenario does not include possible investment cost, which could change this picture. For all scenarios, savings are largest in the long term for 2030 and beyond, while savings are low or negative in the short term.

When comparing the combination scenarios with their respective scenarios without the Viking Link, it is possible to estimate the value of Viking Link with a different base assumption. This comparison show, that the NPV of Viking Link is reduced to between 27% and 47% when all other integration measures would be in place, compared to a situation, where only Viking Link is included. However, this shows the total NPV including the investment and O&M cost for the VikingLink. When only looking at the operational savings in the system, the value of Viking Link is reduced to between 78% and 84%. This means, that a large share of the operational savings from Viking Link can still be achieved, even if all other integration measures are implemented.



Scenario	NPV [billion DKK]	NPV of VikingLink [billion DKK]	NPV of Viking Link compared to Viking Link without other integration measures	NPV of operational savings from Viking Link compared to Viking Link without other integration measures
VikingLink	5.6	5.6	100%	100%
Heatpumps	20.2	-		
CPP_flex	5.1	-		
Indiv_heatpumps	1.3	-		
Combi 1 (Heatpumps+VikingLink)	22.8	2.6	47%	84%
Combi 2 (CPP_flex+VikingLink)	7.6	2.6	45%	84%
Combi 3 (Heatpumps+CPP_flex+VikingLink)	25.3	1.3	27%	78%