Ea Energianalyse

Offshore wind and infrastructure

Development in Europe towards 2050 and related challenges for power system infrastructure

April 2020

Ea Energianalyse a/s

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Content

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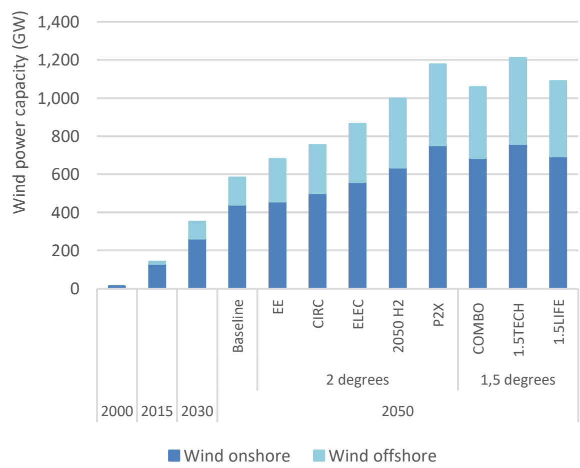
Introduction

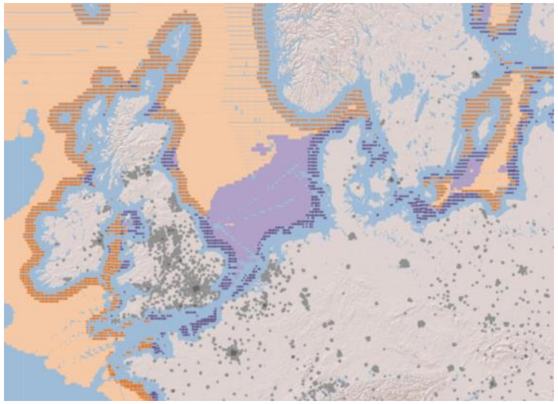
Since the mid-90s, wind power in Denmark has increased from covering just under 5% of the domestic electricity demand to around 47 % in 2019. The trend is expected to continue towards 2030, where the Danish government has set a target for 70% reduction of greenhouse gas emissions compared to 1990. Electrification, and thus green power generation is expected to play a major role in pursuing this target.

With respect to offshore wind, Denmark has also been a frontrunner, being the first country in the world to install wind turbines at sea in 1991. Since then, Danish offshore wind power capacity has grown steadily to about 1,700 MW by end 2019. According to the European Commission's Long-Term Strategy 2018 , the role of offshore wind is expected to grow rapidly in the years to come, both in a global and a European context. Total European offshore wind capacity is expected to reach 143 GW by 2030 and between 223 and 451 GW by 2050. In this development, Denmark can rely on a large offshore wind potential including high wind-resource areas both close to Danish shores and in relatively shallow water .

This study confirms the importance of offshore wind for the long term development of the European Energy system and gives insights to the major importance of the transmission system buildout for an efficient development and operation of the European Power system. A meshed offshore grid connecting both offshore wind and providing transmission capacity between countries can help reducing the total transmission buildout need and improve cost-effectiveness. Further efficiency gains can be obtained from potential synergies between offshore wind and P2X generation, where P2X production can benefit from being located close to offshore wind generation and further reducing power transmission needs and system costs.



European Commission's Long-Term Strategy, 2018



Shallow water (10 - 60 m): Near shore (<60 km) Far shore (60 - 300 km)
Deeper water (60 - 2 000 m): Near shore (<60 km) Far shore (60 - 300 km)

International Energy Agency's Offshore Wind Outlook, 2019

Methodology

Scenario analyses

In this study, synergies between offshore wind power buildout and the growing need for transmission grid are analysed.

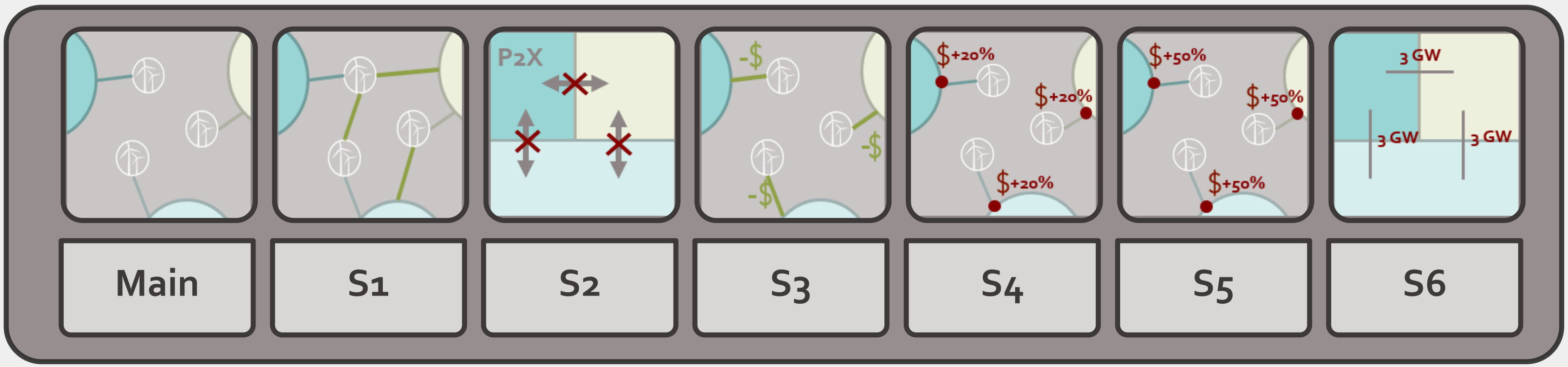
The analysis assumes decarbonization of the European energy system towards 2050. For the power system, this pathway is modelled by a drastic increase in power demand for direct electrification and generation of e-fuels (P2X) as well as high CO_2 cost. Main assumptions for this development are based on the European Commission's 1.5TECH scenario.

One main scenario showing the overall system development and several sensitivities are analysed in the study.

Main scenario: In the main scenario, the power system optimization abides by main assumptions such as

- Increasing power demand to ensure decarbonization of the European energy system
- Optimized power system, based on assumptions for technology development, renewable energy potentials and resources.
- Onshore and offshore transmission buildout is limited to 6 GW per decade per transmission corridor
- Offshore wind transmission consists of single-linked hubs so that each offshore project can only be connected directly to the country of origin and hubs cannot be interconnected.
- Initial regional distribution of P2X production follows the demand for P2X, but generation of P2X can be reallocated across the region at a cost of 30 EUR/MWh

Sensitivity analysis



- **S1 Multi-linked hubs: Sensitivity on the impact of a meshed offshore grid:** The optimization of the offshore grid can utilize multi-linked hubs, meaning that offshore wind farms can be connected to more than 1 country or to each other
- **S2 No P2X redistribution: Sensitivity on the importance of co-optimizing power system development and P2X production:** The production of e-fuels is assumed to be located in the same region as the demand for these fuels.
- **S3 Low DC cost: Sensitivity on the importance of the cost for transmission system buildout:** The costs transmission system expansion are assumed to reduce by 34% between 2020 and 2050 (17% in Main scenarios)
- **Sensitivities on the importance of transmission system planning restrictions and potential difficulties in the planning process and local resistance represented by higher cost or lower absolute buildout potential.**
  - **S4 20% Hit-land cost :** Additional cost related to connecting to land: 20% of the cost of and AC/DC substation
  - **S5 50% Hit-land cost :** Additional cost related to connecting to land: 50% of the cost of and AC/DC substation
  - **S6 Onshore limitations:** Onshore transmission buildout restricted to 3 GW per decade per transmission corridor

Model results

MAIN CONCLUSIONS

Main conclusions

1. Model simulations show **an offshore deployment comparable to 1.5TECH** scenario by the European commission with a total of around 350 GW in 2050 in the modelled area, equalling an annual net buildout of 11 GW in the entire period.

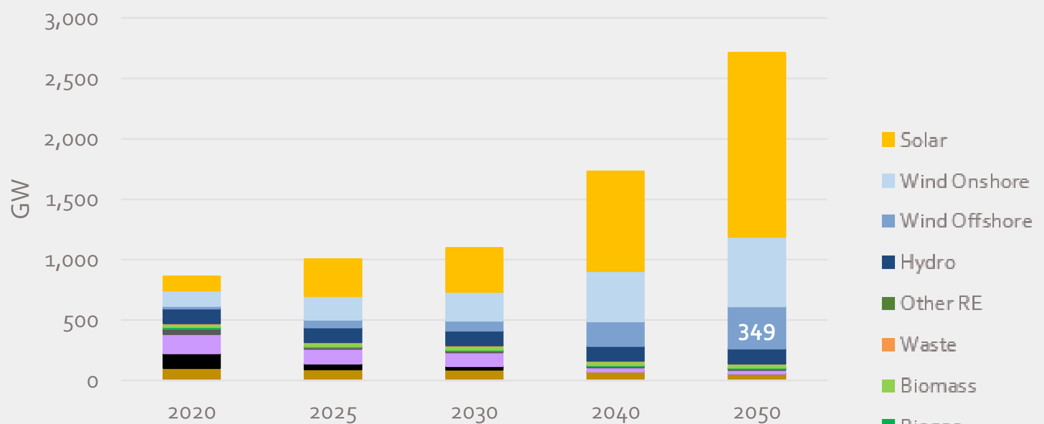
2. Model simulations show that **extensive built-out of transmission** will be neceassary. Towards 2050, total transmission capacity increases by a factor of 5.

3. Meshed offshore transmission can substantially **reduce the need for direct transmission connections** between zones. Direct offshore transmission is reduced by 25%, and total transmission capacity is reduced by 5%.

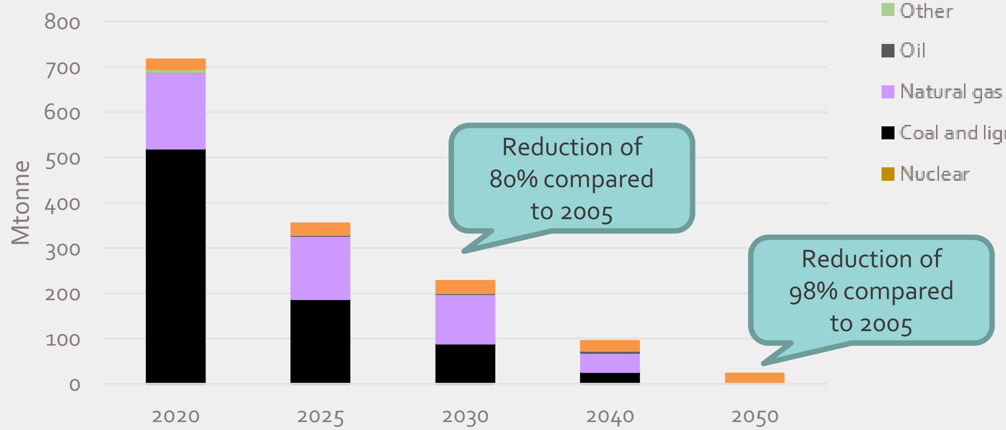
4. There is a potential **synergy between offshore wind and P2X generation** – co-optimization of the location of P2X-plants with offshore wind buildout leads to system benefits and substantially reduced transmission needs, showing a total transmission capacity reduction by 15%

1. Model simulations show an offshore deployment comparable to 1.5TECH scenario by the European commission

Power generation capacity in the modelled area



CO_2 emissions in the modelled area



Offshore wind capacity (2050)

- 1.5TECH: 451 GW
  - For the entire EU
- Scaled: 385 GW
  - Scaled with demand to model area
- Main scenario: 349 GW

Offshore wind generation (2050)

- Scaled estimate 1.5 TECH: 1,734 TWh*
- Main scenario: 1,520 TWh

CO_2 emissions (2050)

98% reduction compared to 2005

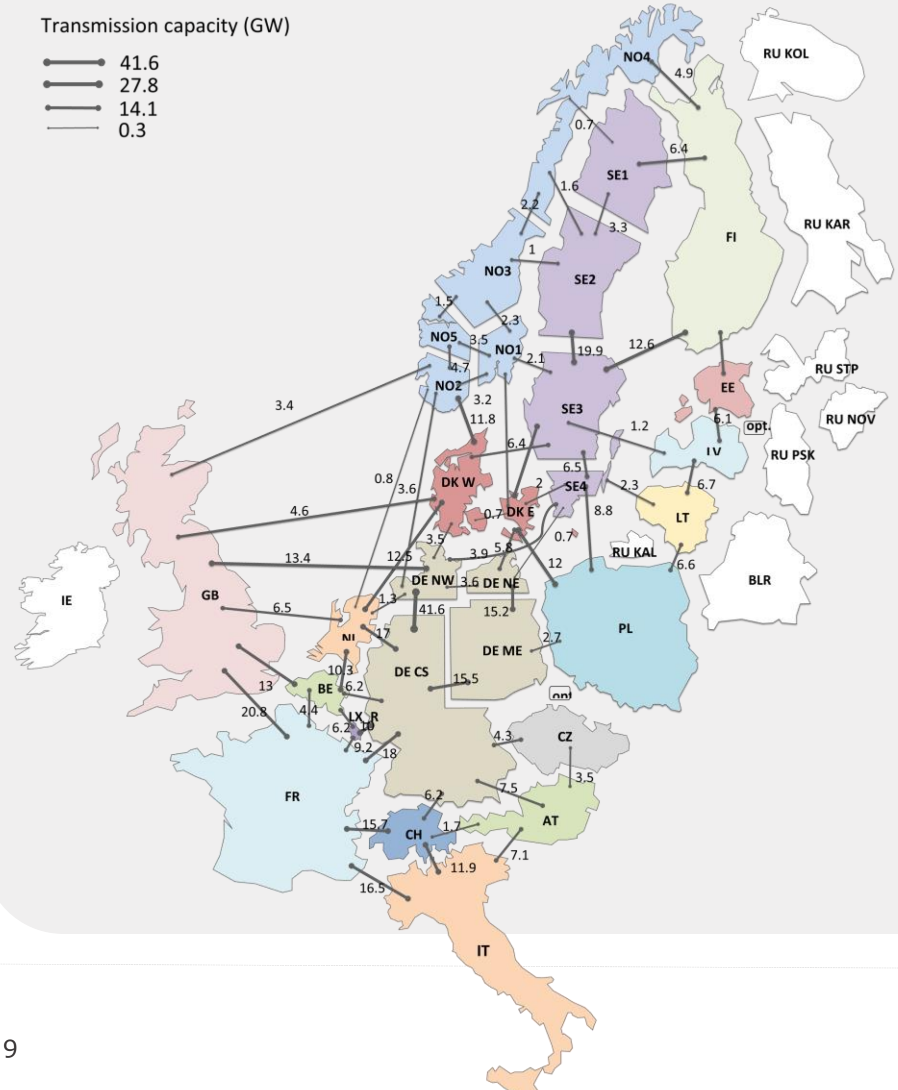
- Only waste-incineration-related emissions left**

* Onshore/offshore split based on assumptions for respective full load hours

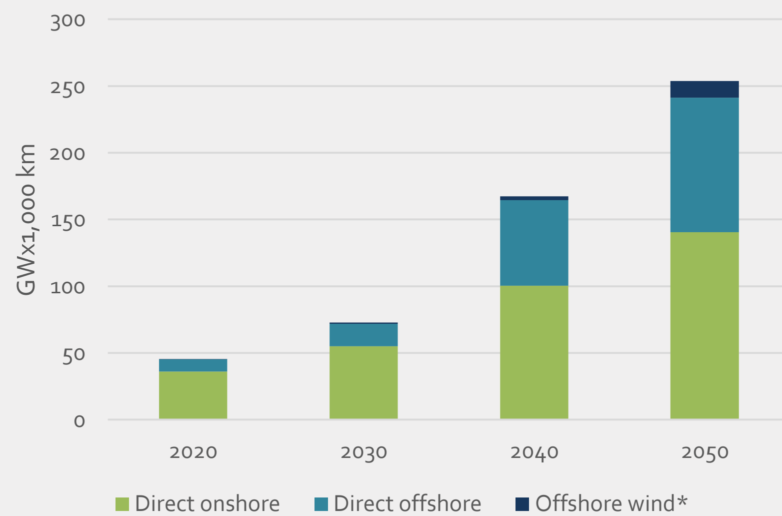
**Reduction of emission of waste-inceration requires waste-management strategies, that have not been analysed in this project.

2. Model simulations show that extensive built-out of transmission will be neceassary

Transmission capacity in the modelled area (2050)



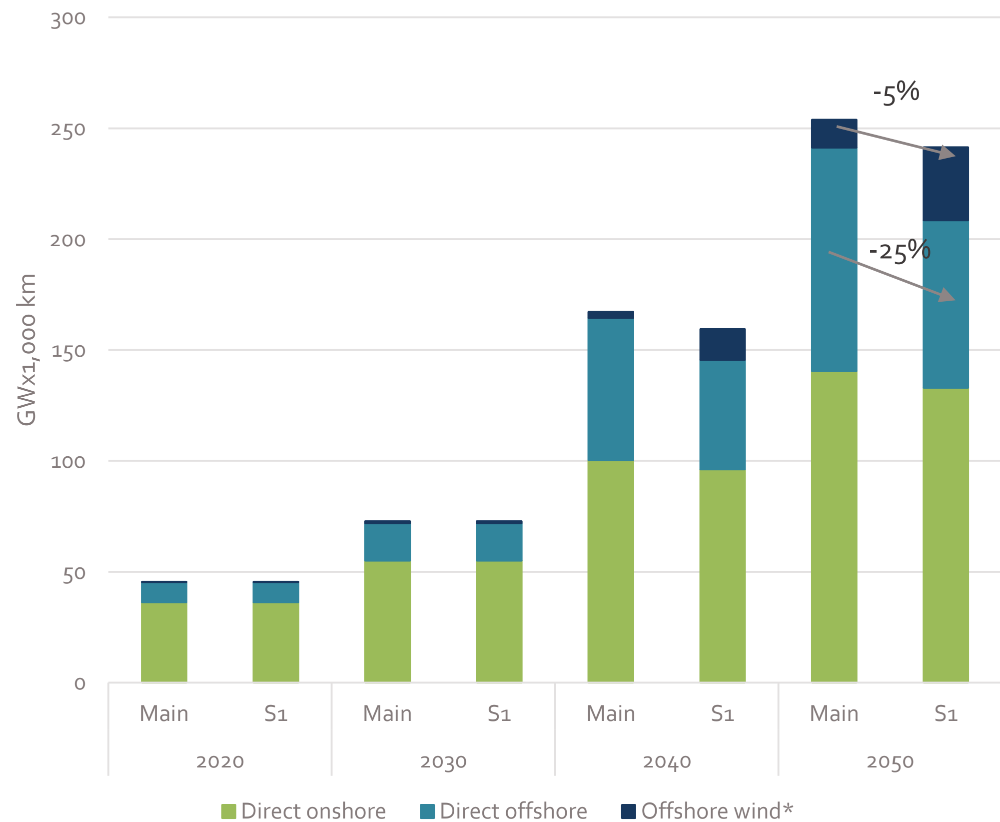
Between 2020 and 2050, total transmission capacity expressed in GWx1,000km grows five-fold. An increasingly large share of the total transmission consist of direct offshore connections (transmission between two bidding zones that crosses open waters).



* Offshore wind includes all connections to offshore windfarms which are not "near-shore"

3. Meshed offshore transmission can reduce the need for direct transmission connections between zones

Transmission capacity x distance



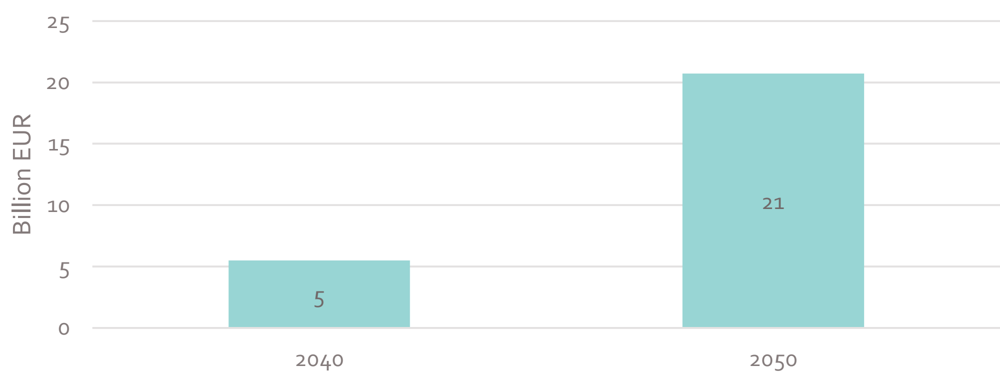
* Offshore wind includes all connections to offshore windfarms which are not "near-shore". In the S1 Multi-linked hubs sensitivity, this category includes all shore-to-wind site and wind site-to-wind site connections

Direct offshore transmission (transmission capacity connecting two countries across open sea) can be reduced by 25% when allowing for meshed offshore transmission. This is about 25 GWx1,000km.

Despite an increase in hub connected transmission capacity (country to wind site or wind site to wind site) the total infrastructure size reduces by 5%.

4. There is a potential synergy between offshore wind and P2X generation

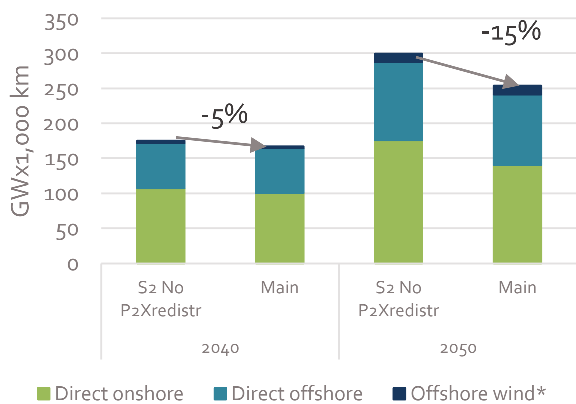
Combined system cost savings* by enabling P2X demand redistribution

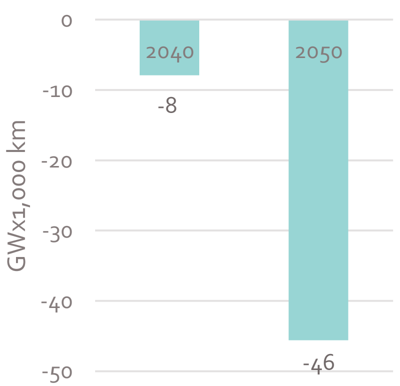


Comparing *Main* to *S2 No P2X redistribution*, shows that by 2050, 21 billion EUR/year can be saved in the modelled area by enabling redistribution of P2X production. This saving accounts for the cost of redistributing P2X.

By 2050, the total transmission capacity is decreased by 46 GWx1,000 km, corresponding to 15% by allowing P2X redistribution in the *Main* scenario compared to the sensitivity without the redistribution option

Combined descrease in transmission capacity x distrance





* The decrease in total system costs by enabling P2X demand redistribution: Costs include capital costs, O&M and fuel costs as well as P2X redistribution costs, CO_2 externality costs

POLICY RECOMMENDATIONS

Reducing barriers for infrastructure buildout is essential

This study shows a build-out of offshore wind of above 350 GW, in line with the 1.5TECH scenario by the European Commission, which will require a buildout of transmission by a factor of 5.

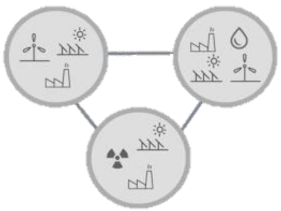
1. Power system infrastructure projects in Europe are generally complicated and time intensive due to political process, regulatory process and local resistance.
2. International coordination across more than two countries needed to enable multiconnected offshore hubs can reduce total transmission buildout and thereby overall need for approval processes but requires strengthening of international grid planning, coordination of regulatory processes, licensing processes and joint financing models.
3. Reducing the barriers will require focus on regional and international rather than national planning and regulation. This focus might challenge the current setup, where national TSOs are responsible for the entire process based on national criteria regarding capacity and costs

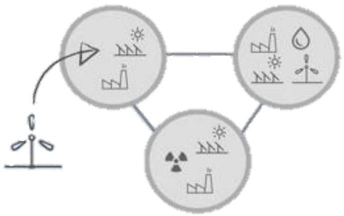
METHODOLOGY – BALMOREL MODEL

Method

Description of the Balmorel energy system modelling tool

The analysis in this study is mainly based on calculations made with the power and district heating market model, Balmorel. The Balmorel model finds a least-cost solution based on a set of assumptions such as the development of fuel prices, requirements on renewable energy deployment and other essential parameters. The model is capable of both **investment** and **dispatch** optimisation, where a solution in terms of among others, generation and interconnector capacity, dispatch, transmission flow and electricity prices is found while satisfying the power demand and heating demand. Prices are generated from system marginal costs, emulating optimal competitive bidding and clearing of the market.



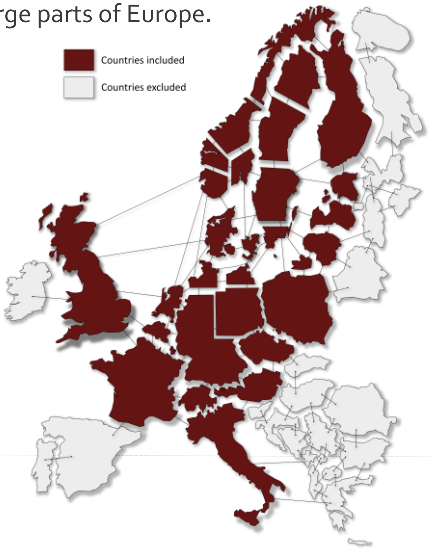


Balmorel is used for analysing electricity, CHP and heat in an internationally integrated market and can be used both for long-term planning, as in detailed short-term or operational analyses.

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

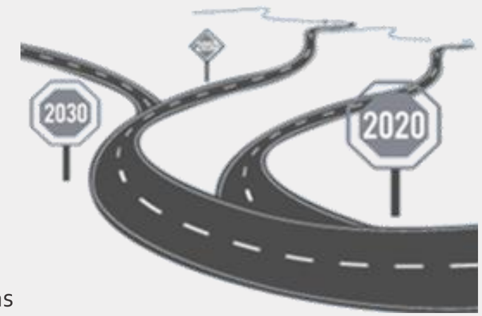
The model includes a representation of the power and district heating system in Denmark, Scandinavia and large parts of Europe.



Balmorel model inputs and results

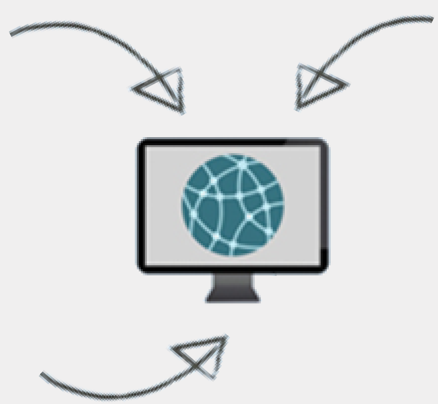
Main model results

- Optimal investments in generation, transmission and storage.
- Dispatch optimisation
- Power and heat price formation in partial equilibrium allowing for market and stakeholder analysis of costs and revenues.
- Generation mix, fuel use and emissions such as CO_2



Main model inputs

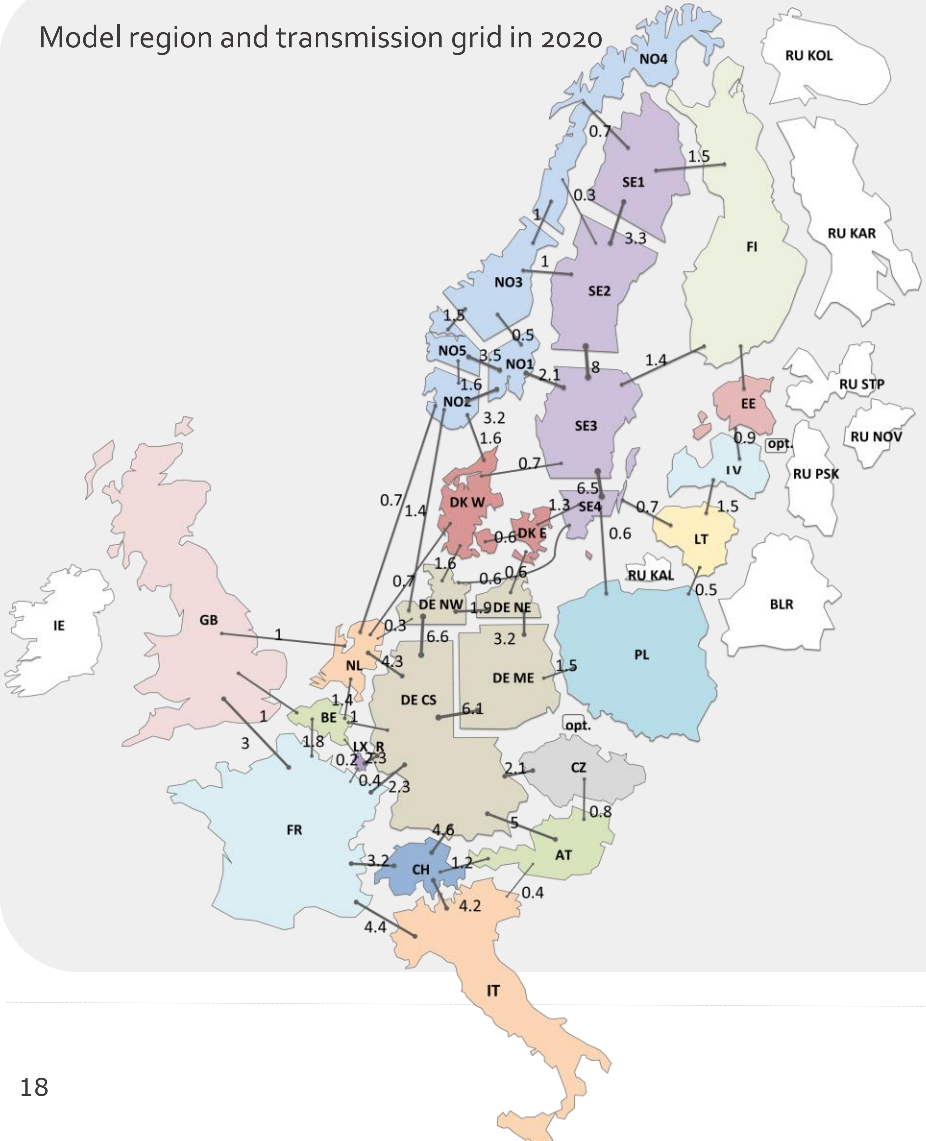
- Existing generation capacities, respective unit's technical and economic data, investment options (incl. refurbishments) and technology development.
- Transmission system infrastructure, and options and costs for capacity expansion.
- Projected demand for power and heating (incl. marginal willingness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



MAIN ASSUMPTIONS

Representation of the international power market

Model region and transmission grid in 2020



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 colored on the map. Most relevant are Denmark, the Nordic countries, Poland and Germany.
- Individual countries are subdivided into regions, where 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 Luxembourg), 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, therefore 4 price regions are modelled for Germany.

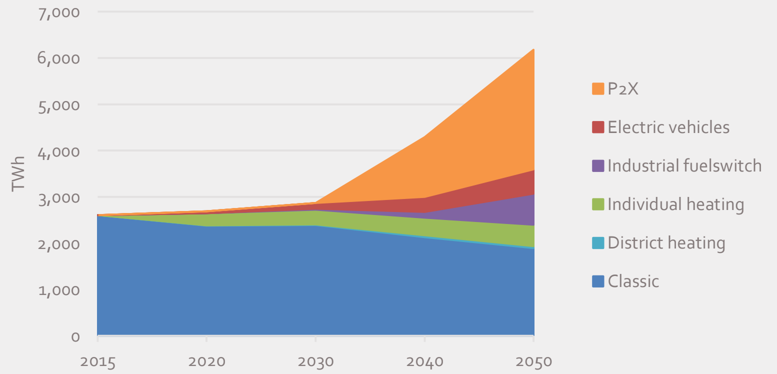
Power consumption development

Statistics for 2015 are based on ENTSO-E data

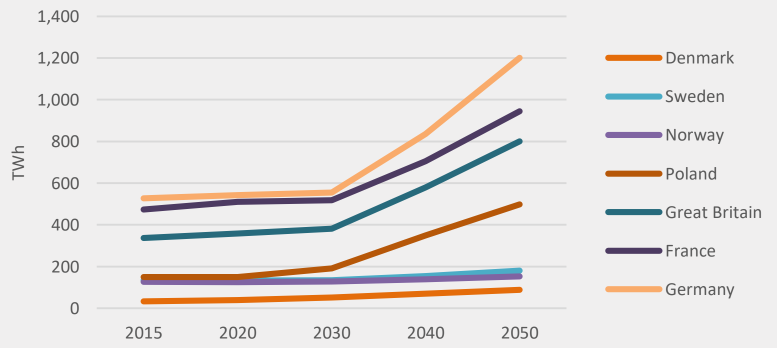
Demand projections for future years are in this project are based on the European Commission's 2050 Long-Term Strategy, 2018 (LTS18), following the 1.5TECH scenario in 2050. The 1.5TECH scenario is a scenario with 100% GHG reductions in 2050. While the total power demand in the 1.5TECH scenario more than doubles (123% increase) between 2015 and 2050, it does not project very high levels of direct electrification of the transport, heating and industrial sector. Rather, the 1.5TECH scenario sees clean fuels such as hydrogen as a main strategy to transform and store energy. Following the importance of clean fuels in the 1.5TECH scenario, 70% of the power demand increase (2015-2050) comes from P2X.

- **Classic demand** contains all demand which does not fall under the other categories. The demand is mainly modelled with demand profiles based on the consumption in 2014.
- **Electric vehicles demand** includes all electricity for road transport. This demand is flexible, and an increasing share can be moved for 4 hours.
- **Electricity for individual heating** includes electricity consumption for space heating in buildings, which is included as heat demand. The demand is supplied by heat pumps and electric boilers. All of the individual heat demand is flexible and can be moved 4 hours.
- **Electricity for electrification of industrial energy demand** (industrial fuel switch) is included as the growth in electricity use in the industrial sector (compared to 2015), considering increasing energy efficiency. The demand is included as heat demand which can be fully supplied by coal, natural gas and oil boilers. When advantageous, additional electric boilers can be installed to supply the heat demand.
- **Electricity for district heating** is based on model. Heat pumps and electric boilers are among the options to supply the district heating demand. Other options are fuel based district heating generation from heat only boilers or CHP.
- **Electricity for P2X** is included based on the consumption of e-gasses, e-liquids and hydrogen. A P2X efficiency of 70% is assumed for hydrogen and 60% for e-gasses and e- liquids. If profitable, storages can be installed to move portions of the demand.

Power demand in the modelled area



Power demand Nordics and North-West Europe



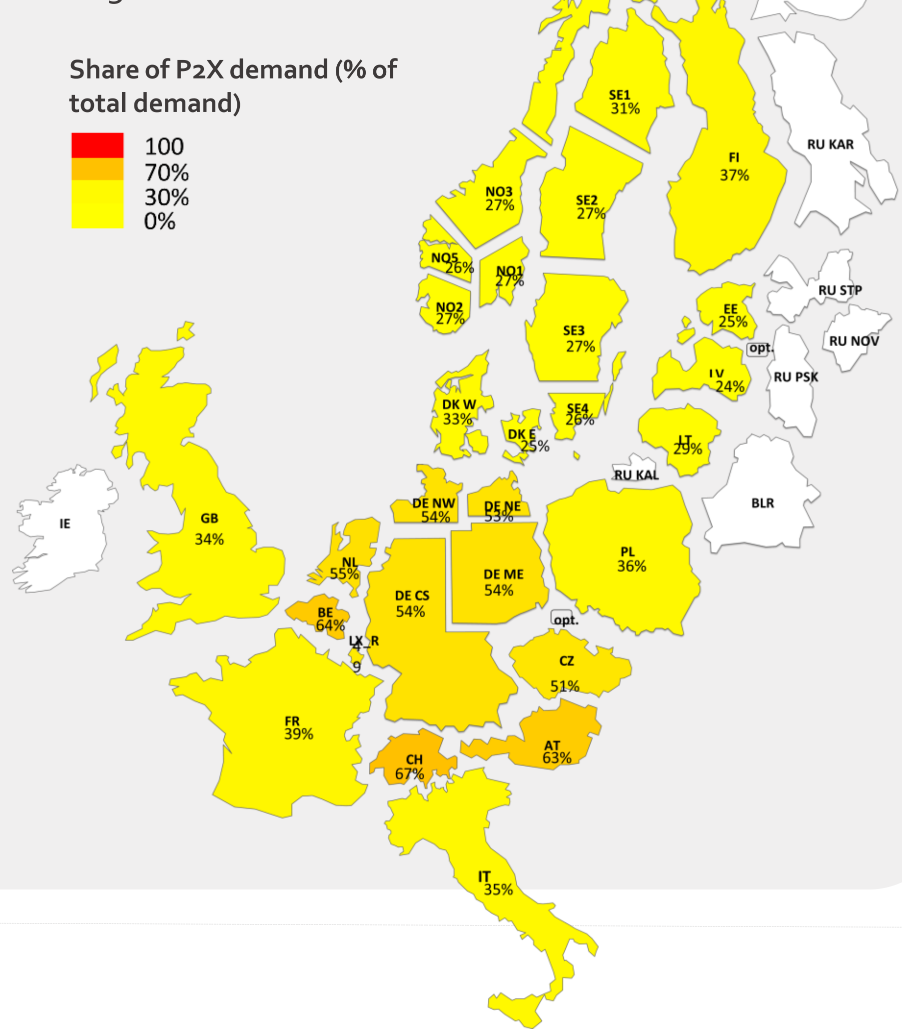
P2X demand allocation

On average, power demand for power-to-X (P2X) constitutes about 42% of total power demand in the modelled area in 2050.

As a starting point, the demand for e-fuels and H2 is allocated across the European regions in the modelled area according to their current energy demand for transport and industrial uses. If all regions were to produce their consumed e-fuels, this would results in a higher share of power demand for P2X in industry/transport intensive countries as shown on the map to the right.

As part of the optimization process, the model can move the supply of P2X to another region (with lower electricity prices) or in time at a cost of 30 EUR/MWh e-fuel.

Share of P2X power demand in 2050



Power transmission capacities

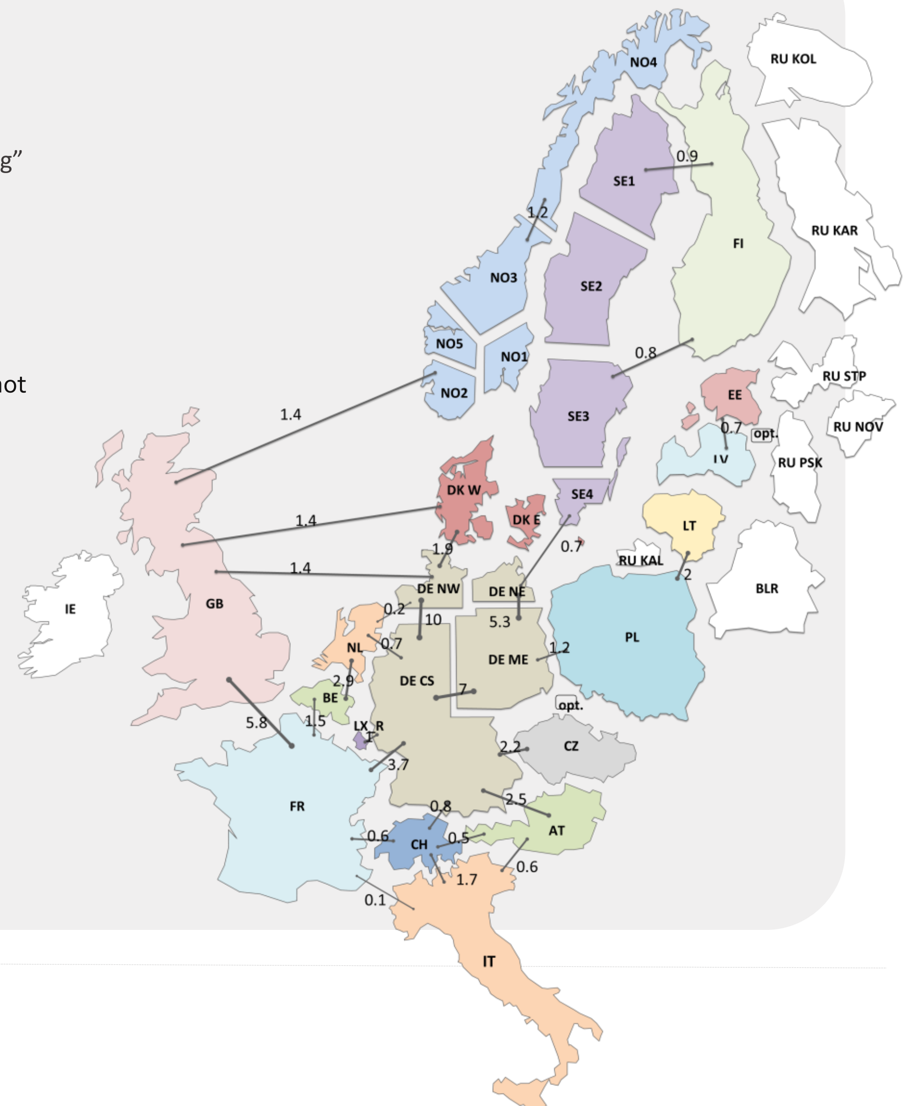
Development of the overall transmission grid is based on the Ten Year Network Development Plan 2018 (TYNDP18), developed by the transmission system operators within ENTSO-E.

- The transmission capacity of current lines are included with NTC (net transfer capacity).
- Future interconnector projects with status “under construction” and “permitting” as detailed in the TYNDP18 are included until 2030.

Significant updates for Denmark:

- **CobraCable** 0.7 GW (DK-NL) by 2019
- **Kriegers Flak** adds transmission option between Eastern DK and DE by 2019 (not shown on map)
- **Nordlink** 1.4 GW (DE-NO) by 2020
- **Viking link** 1.4 GW (DK-GB) by 2023
- **German internal grid**, based on the TSOs’ latest grid development plan (first draft NEP2019), scenario B, including delays of earlier expansion plans. Transmission capacity between North West Germany and South Germany increases significantly between 2020 and 2025. Futher expansion beyond 2025 between South and North Germany.

Input transmission expansion between 2020-2030



Power transmission investments

Future transmission capacity expansion beyond 2030 is based on model optimization.

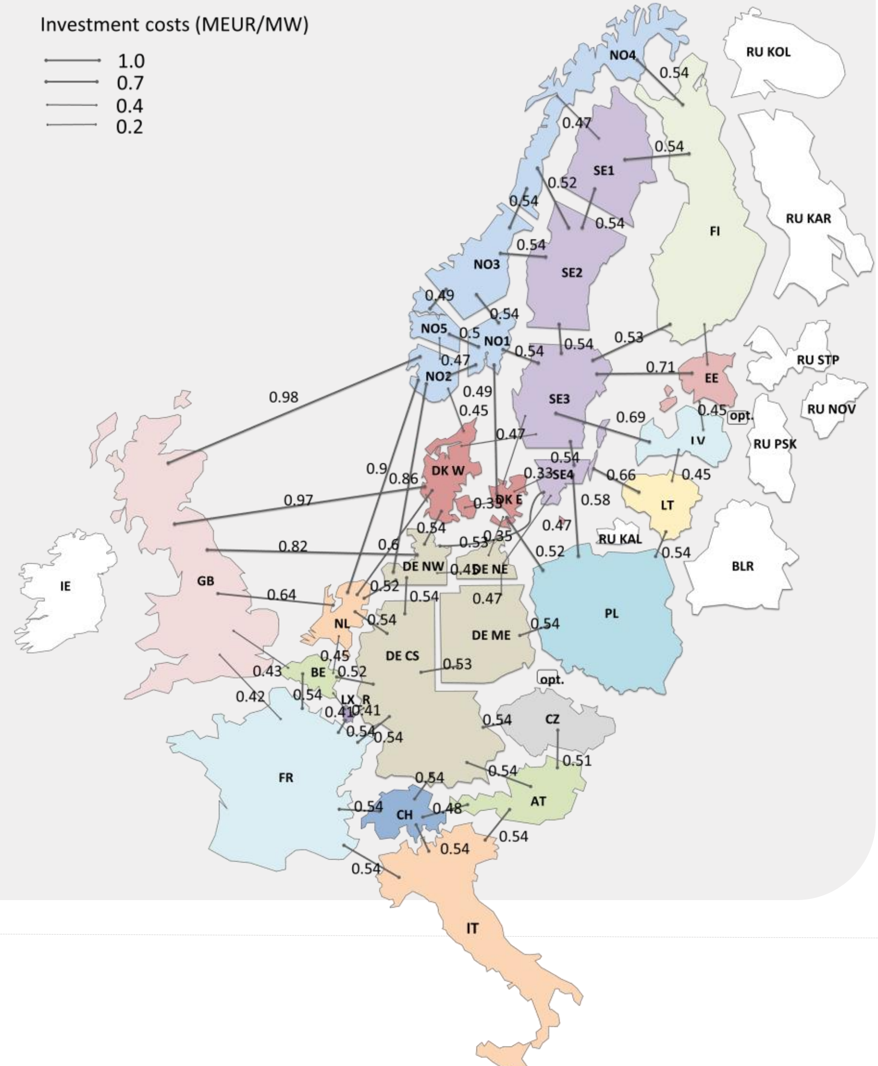
Unit cost for transmission expansion are shown below and are applied to the individual options based on distance estimates, taking into account internal reinforcement needs. The component costs are based on the Electricity Ten Year Statement 2015

		2020	2030	2040	2050
Offshore connection M€/km DC	€/MW/km	1,288	1,187	1,122	1,067
Offshore connection M€/km AC	€/MW/km	1,780	1,640	1,550	1,475
Onshore connection M€/km	€/MW/km	1,053	970	917	872
Substations AC (x2)	M€/MW	0.08	0.07	0.07	0.07
Substations DC (x2)	M€/MW	0.29	0.26	0.25	0.24
Offshore platform AC	M€/MW	0.14	0.13	0.12	0.11
Offshore platform DC	M€/MW	0.43	0.39	0.37	0.35

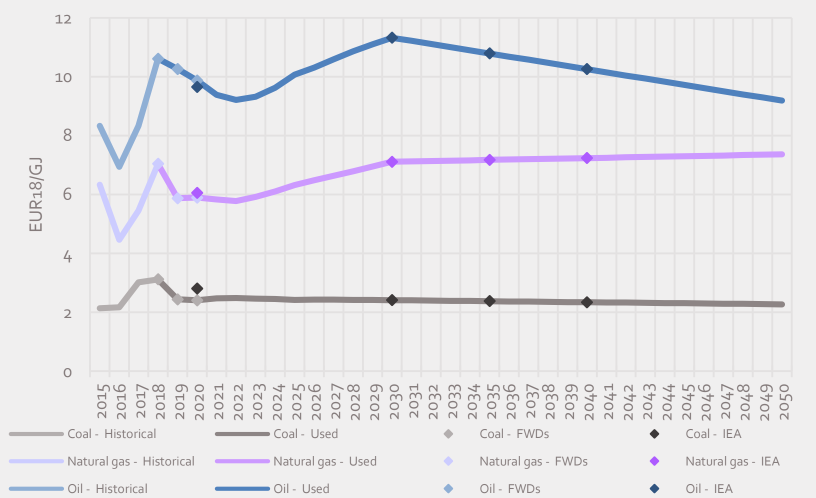
Internal German reinforcements are limited to 12 GW per corridor per decade.

For all other interconnectors, investments in transmission lines are limited to 6 GW per corridor per 10 years.

Investment costs for transmission expansion (2040)

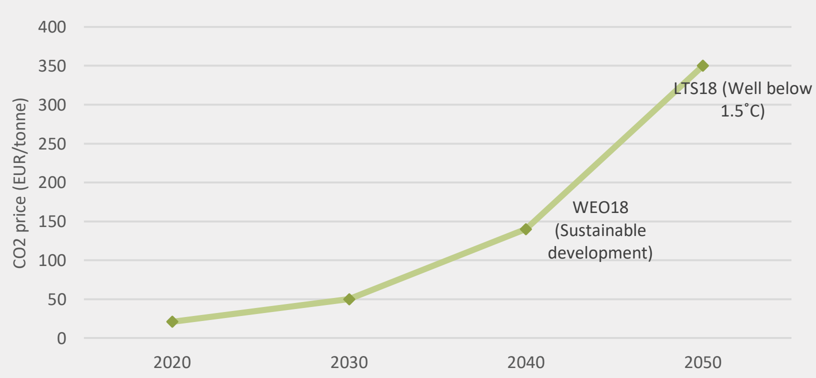


Fossil fuel price and CO_2-emissions price development



Fossil fuel prices

Fossil fuel prices are based on the sustainable transition scenario from the International Energy Agency's World Energy Outlook 2018 (Sustainable development) for 2030, 2035 and 2040, and extrapolated hereafter. For 2020, forward prices are used as a best guess. Between 2020 and 2030 prices are projected to converge from futures to the IEA's projections.



CO_2-emissions price

As one of the drivers for the green transition, the CO_2 price is assumed to grow rapidly in the coming 30 years. In 2040, the Sustainable development scenario from the WEO18 is used where in 2050 the EU Commissions assumptions in the well below 1.5˚C scenario are assumed (LTS18).

Offshore wind resource and potential

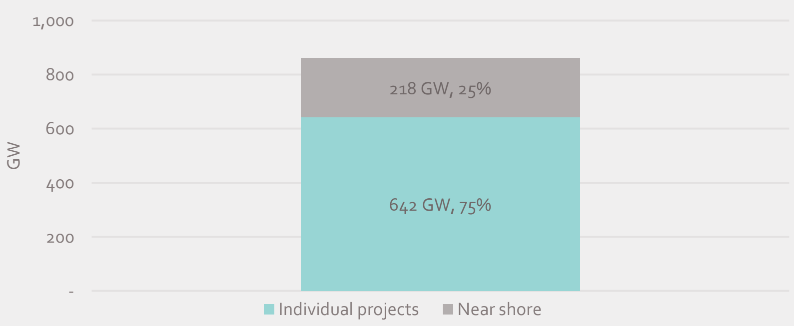
Offshore wind potential is modelled based on the 4C offshore wind database[I], offshore potentials from the BEMIP[II] project and the ENSPRESSO offshore wind energy potentials (low restriction scenario)[III].

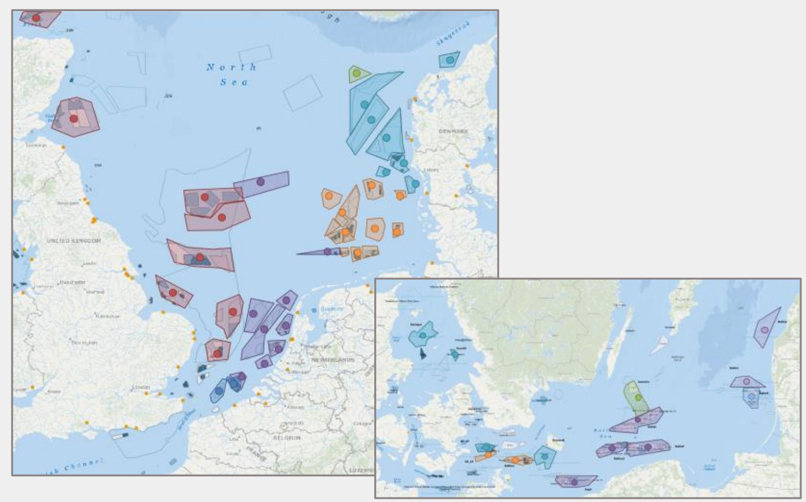
All offshore wind projects in the modelled area are included at sea depth <60m, totalling at 860 GW. Two representations are used:

- **Aggregated near-shore areas:** Smaller near-shore projects (<22 km) are modelled in an aggregated manner and are always directly connected to the country which owns the waters and therefore do not have any part in the hubs. The potential is set to 10% of the estimates in the ENSPRESSO database for areas less than 22 km from shore = 218 GW in total.
- **Individual projects:** Projects further out in sea are modelled as distinct offshore potentials with respective offshore connection point. The detailed site conditions are based on the 4C offshore wind database and the BEMIP project, scaled by country to match the total ENSPRESSO potentials for areas further out than 22 km = 642 GW in total.

Wind speed time series for each of the areas are based on MERRA-2 re-analysis data for 2014.

Offshore wind potential in modelled area





I https://www.4coffshore.com/offshorewind/
II https://ec.europa.eu/energy/en/topics/infrastructure/high-level-groups/baltic-energy-market-interconnection-plan
III https://data.jrc.ec.europa.eu/collection/id-00138

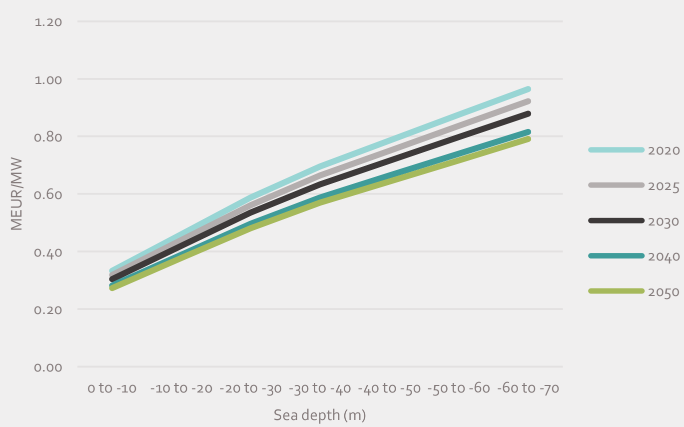
Offshore wind technologies

Offshore wind costs assumptions are based on the Danish Technology catalogue (TC) (Update from June 2019)[I].

- Investment costs (base investments)
- O&M costs

Connection costs are based on assumptions from British electricity grid operator national grid ESO in the Electricity Ten Year Statement 2015 (ETYS15)[II]

Foundation costs estimates are based input from COWI and the Danish Technology Catalogue. For a doubling of sea depth, costs are assumed to increase with a factor √2



			2020	2025	2030	2040	2050
	Windfarm costs						
TC	Base investment	M€/MW	1.44	1.38	1.31	1.21	1.18
TC + COWI	Foundation						
	0 m to -10 m	M€/MW	0.33	0.32	0.30	0.28	0.27
	-10 m to -20 m	M€/MW	0.46	0.44	0.42	0.39	0.38
	-20 m to -30 m	M€/MW	0.59	0.56	0.53	0.50	0.48
	-30 m to -40 m	M€/MW	0.70	0.66	0.63	0.59	0.57
	-40 m to -50 m	M€/MW	0.79	0.75	0.72	0.66	0.64
	-50 m to -60 m	M€/MW	0.88	0.84	0.80	0.74	0.72
	-60 m to -70 m	M€/MW	0.96	0.92	0.88	0.82	0.79
	Connection costs						
ETYS15	Offshore connection M€/km DC	€/MW/km	1,288	1,237	1,187	1,122	1,067
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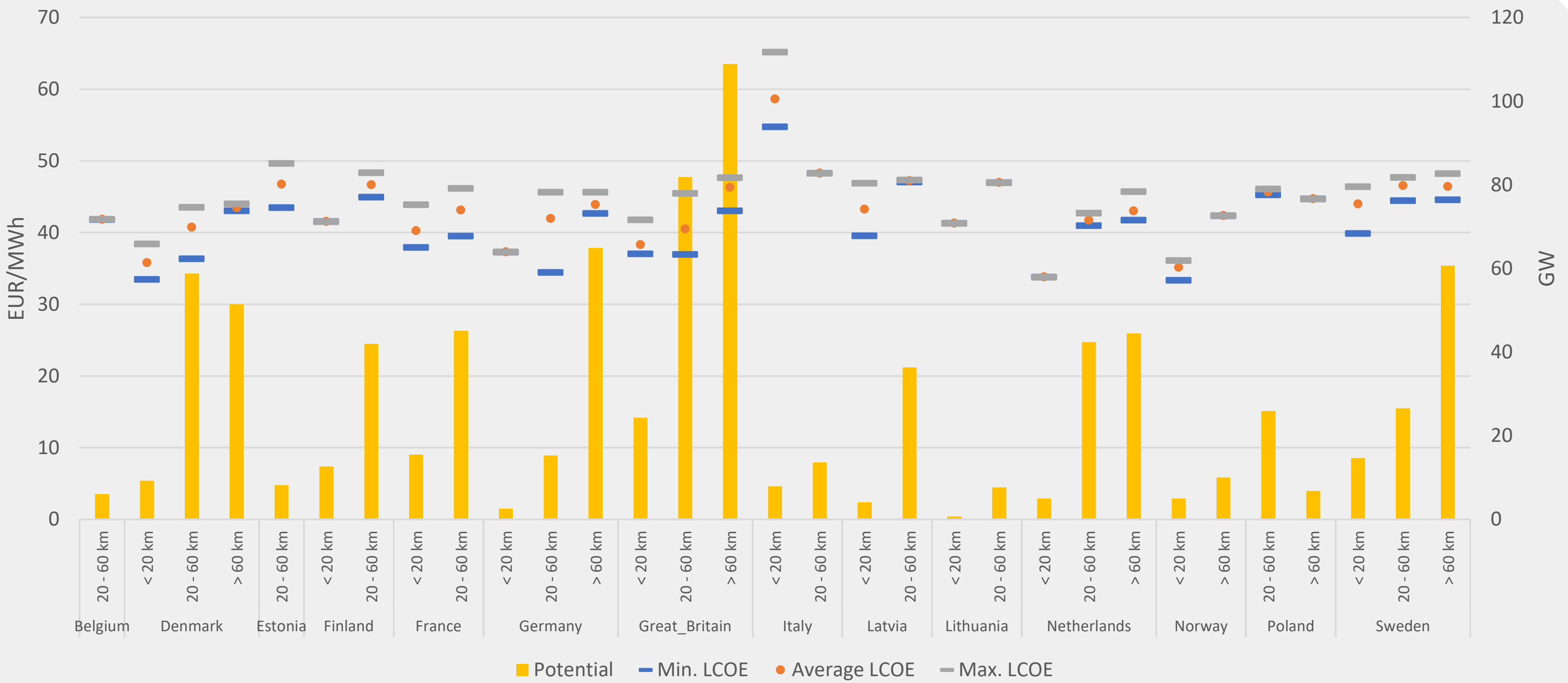
	Substations AC (x2)	M€/MW	0.08	0.08	0.07	0.07	0.07
	Substations DC (x2)	M€/MW	0.29	0.27	0.26	0.25	0.24
	Offshore platform AC	M€/MW	0.14	0.13	0.13	0.12	0.11
	Offshore platform DC	M€/MW	0.43	0.41	0.39	0.37	0.35
	Operation and maintenance costs						
TC	Fixed O&M	€/kW	41.33	39.06	37.05	33.89	32.59
	Variable O&M	€/MWh	3.06	2.91	2.76	2.53	2.43

[I] https://ens.dk/en/our-services/projections-and-models/technology-data
[II] https://www.nationalgrideso.com/publications/electricity-ten-year-statement-etys

Offshore wind potentials and LCOE by country



- Levelized Costs of Electricty for 2050 shown on left axis
- Offshore wind capacity potential shown on right axis

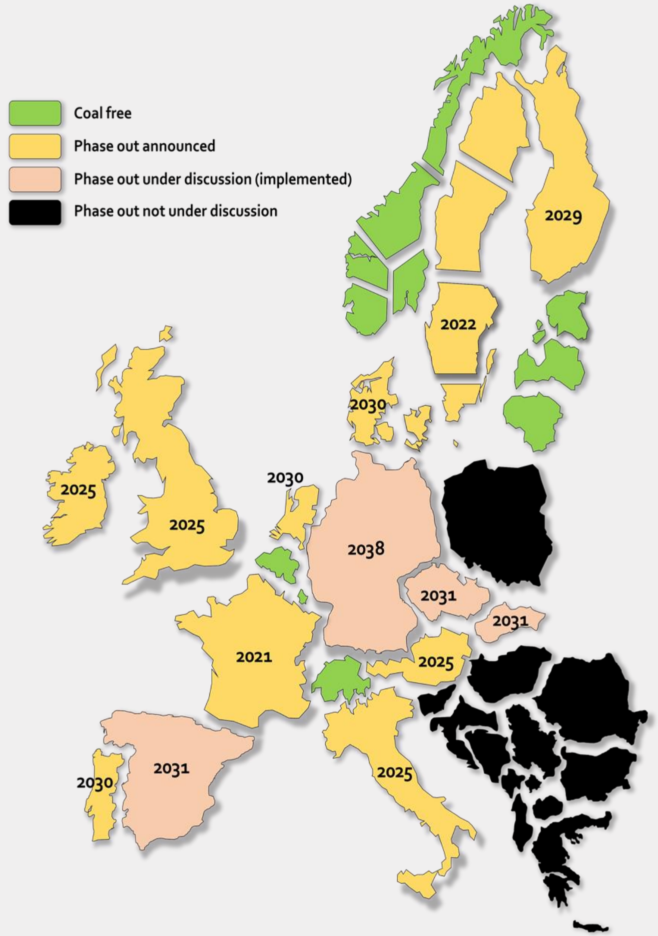
Investment approach

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. Model-optimized investments are assessed one year at a time, considering an annuity factor of 7.10% for generation (e.g. corresponding to a discount value of 5% and an economic lifetime of 25 years – representing an investors perspective) and 5.83% for transmission investments (lifetime of 40 year).

	Renewable capacity	Other capacity
Denmark	Minimum requirements until 2030 (AF18[I] adjusted to represent Energiaftalen) Model-based investment beyond	Model-based decommissioning + investments.
Germany	Minimum requirements until 2030 (NEP16[II]) Model-based investment beyond	Model-based decommissioning + investments. Nuclear Exogenous
Great Britain	Minimum requirements until 2030 (FES15[III]). Investment beyond Model-based investment beyond	Model-based decommissioning + investments. Nuclear Exogenous
Other EU	Minimum requirements until 2030 (TYNDP18 –Sustainable transition). Model-based investment beyond	Model-based decommissioning + investments. Nuclear Exogenous
Transmission	/	Exogenous until 2030 (TYNDP18). Model-based investments beyond
Batteries	/	Model-based investments. Optimized in volume and inverter capacity independently

[I] AF18: Analyseforudsætninger 2018, Energinet
[II] NEP16: Netzentwicklungsplan 2016, FNB
[III] FES15: Future Energy Scenarios 2015, National Grid

Coal phase-out



Europe Beyond Coal

National plans for coal phase-out in Europe have been implemented in the Balmorel model. Political announcements have been gathered from Europe Beyond Coal*

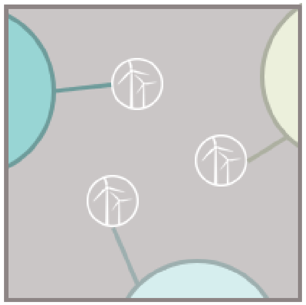
The graph on the left shows countries affected by the agreement in yellow and salmon (more countries shown than modelled in the simulation). Both countries with officially announced coal phase-outs and countries where a phase-out is still under discussion have been implemented.

In the following countries, the coal capacity cannot be used in the a spot market but can be used as strategic reserve:

- Germany
- Great Britain
- France
- Italy

The other phase-out countries will decommission all coal capacity by indicated target year. The phase-out has been assumed linear.

* https://beyond-coal.eu/wp-content/uploads/2018/06/Overview-of-national-coal-phase-out-announcements-Europe-Beyond-Coal-June-2018.pdf

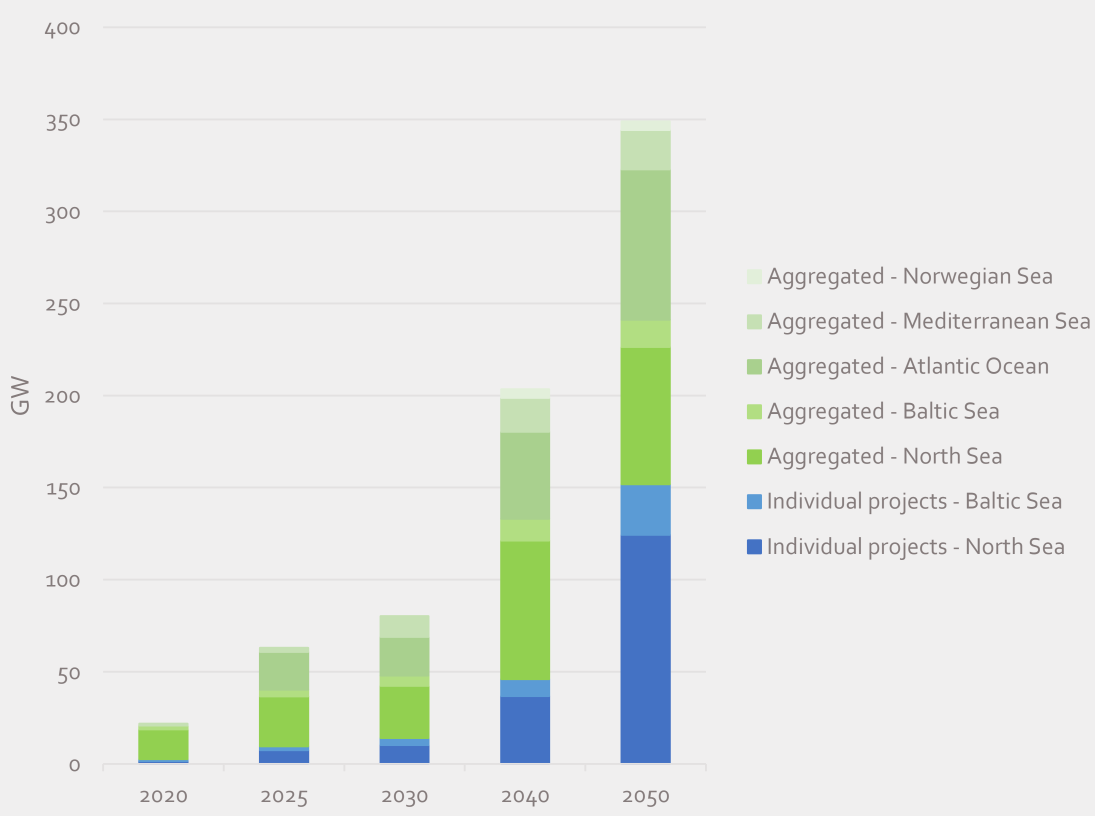


MAIN SCENARIO

Model results

Offshore wind capacity build-out

Offshore wind power capacity in 2050 by sea and representation type



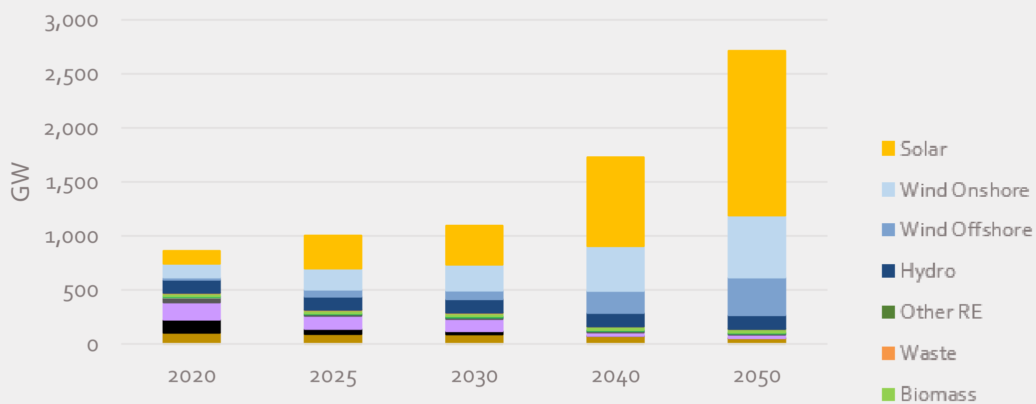
The figure to the left shows the offshore wind capacity for the *Main* scenario by year, divided over the seas inwhich they're located and the represenation in the model. **Aggregated:** near-shore wind farms in the North and Balic Sea and all windfarms int he Atlantic, Medditerranean and Norwegian Sea. **Individual project:** wind farms modelled as specific sites.

In the *Main* scenario, offshore wind sees an enormous expansion between 2020 and 2050, increasing the total installed capacity sixteen-fold, ending with a total capacity of 349 GW by 2050.

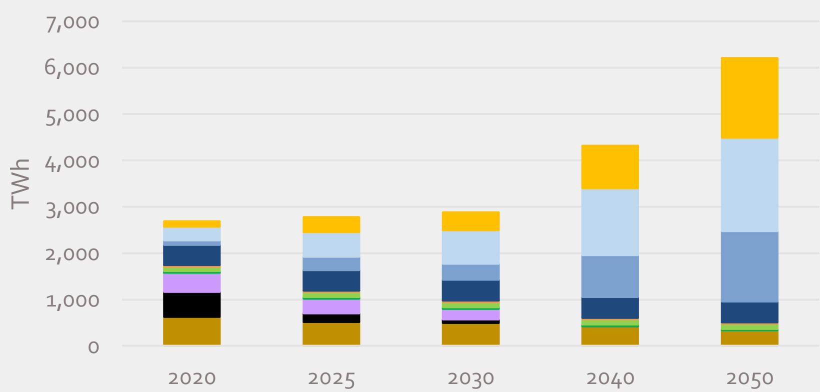
Most of the offshore wind capacity (57%) is found in the North Sea with about 200 GW by 2050 . The Baltic Sea capacity is 42 GW.

Generation results in the modelled area

Power generation capacity in the modelled area



Annual generation in the modelled area

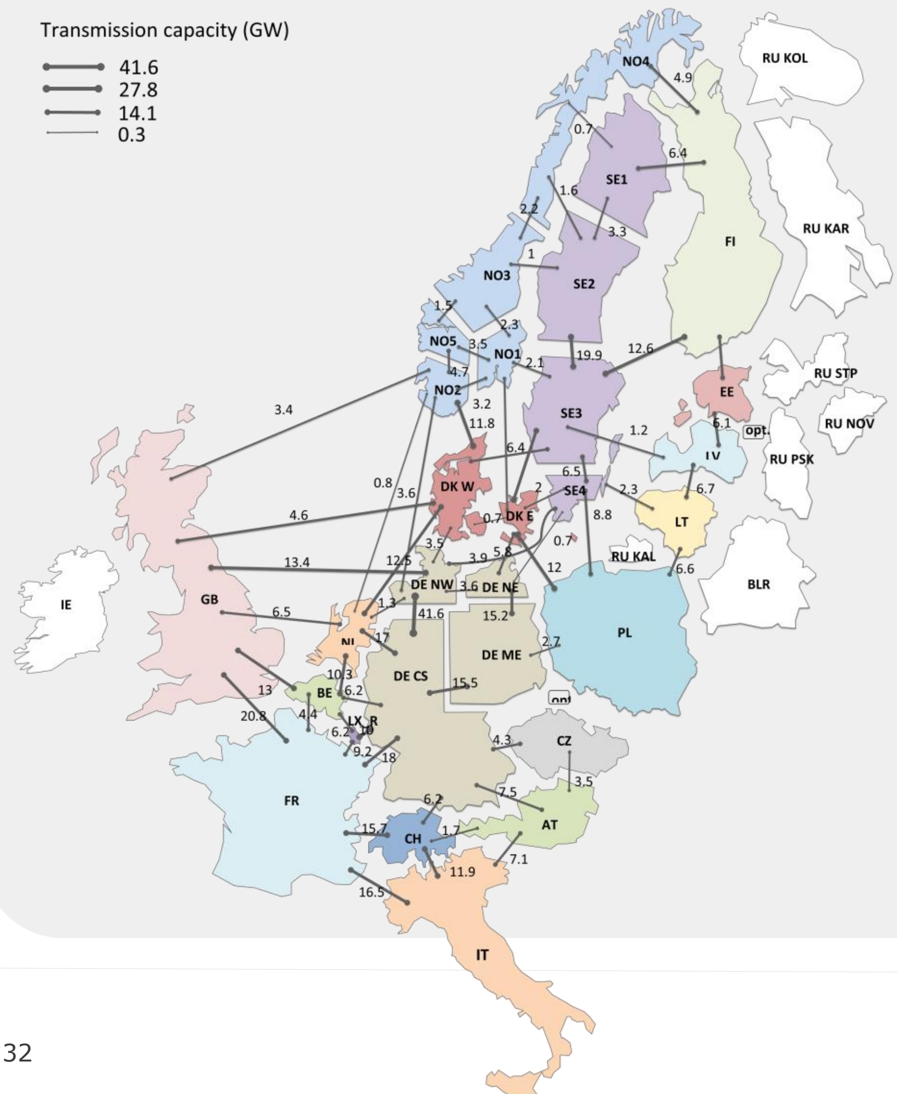


Between 2020 and 2050, power capacity expansions consists of a large amount of solar capacity, onshore wind as well as offshore wind.

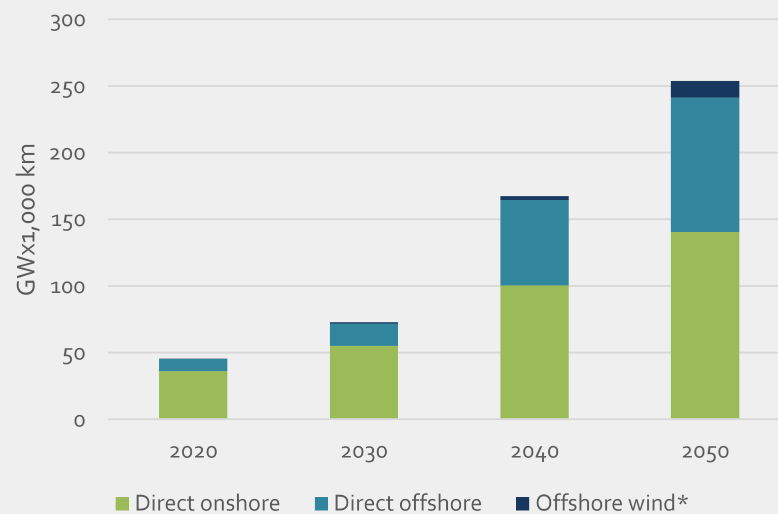
By 2050, solar power accounts for 28% of generation, onshore wind for 32% and offshore wind for 24%, totalling at 85% of the generation produced by variable renewable energy

Transmission expansion results

Transmission capacity in the modelled area (2050)



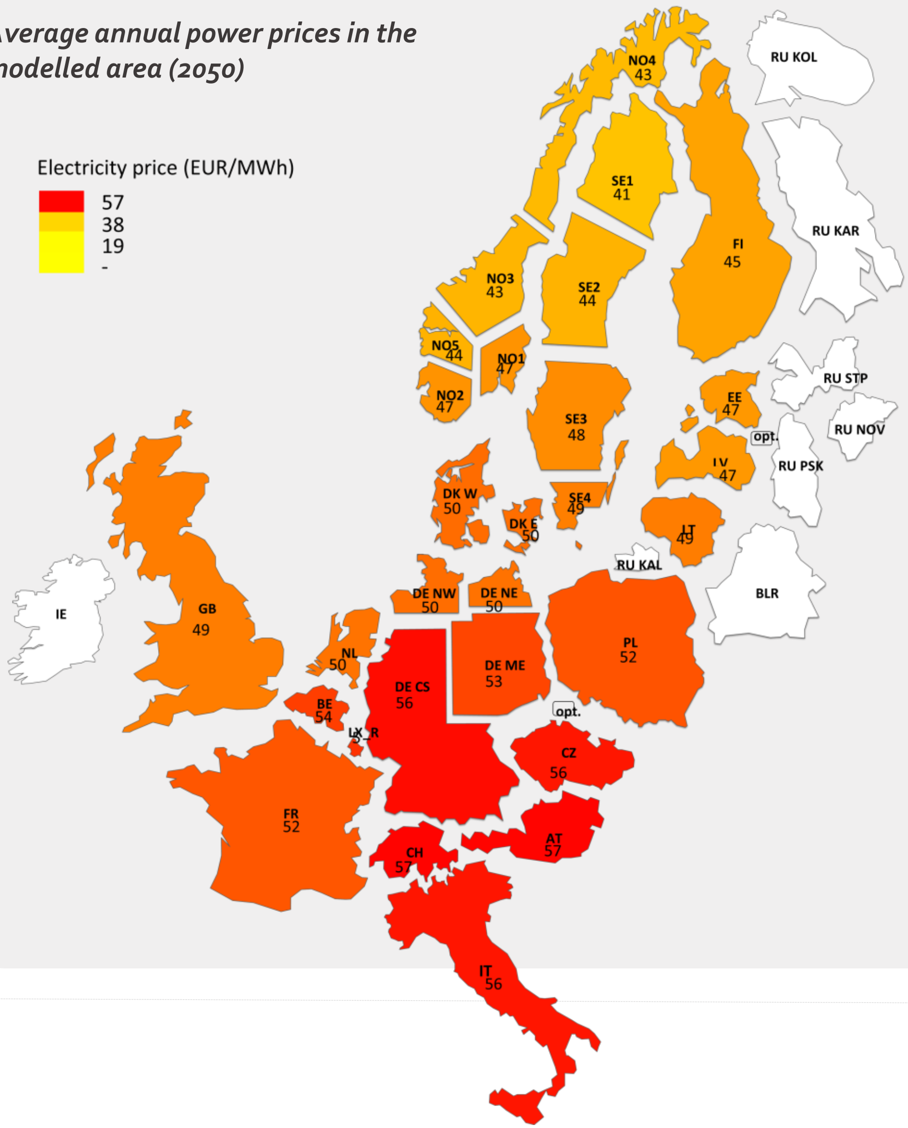
Between 2020 and 2050, total transmission capacity expressed in GWx1,000km grows five-fold. An increasingly large share of the total transmission consist of direct offshore connections.



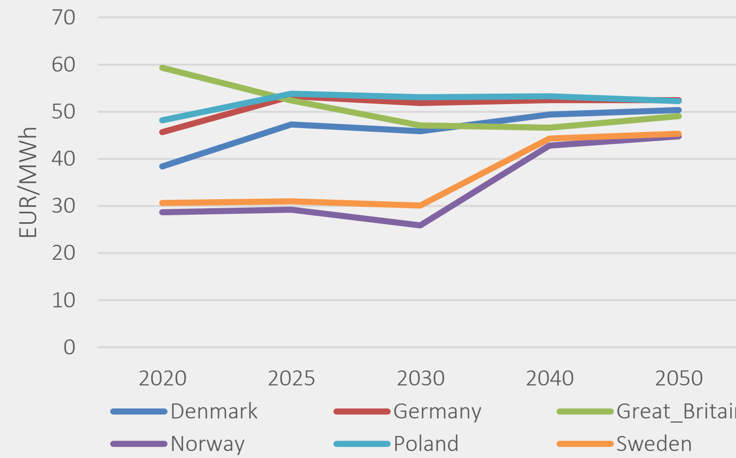
* Offshore wind includes all connections to offshore windfarms which are not "near-shore"

Power prices

Average annual power prices in the modelled area (2050)



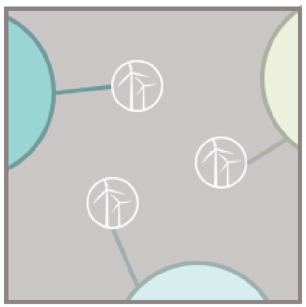
Developement of average annual power prices for selected countries



The power prices in the modelled area show particular developements per counrty. Better interconnection between the price regions results in less differentiated power prices by 2050, compared to 2020.

Danish prices increase gradually between 2020 and 2050, where the prices of the Nordics are rise more steeply.

As Great Britain becomes increasingly integrated in the European power system, its power prices show a declining trend.

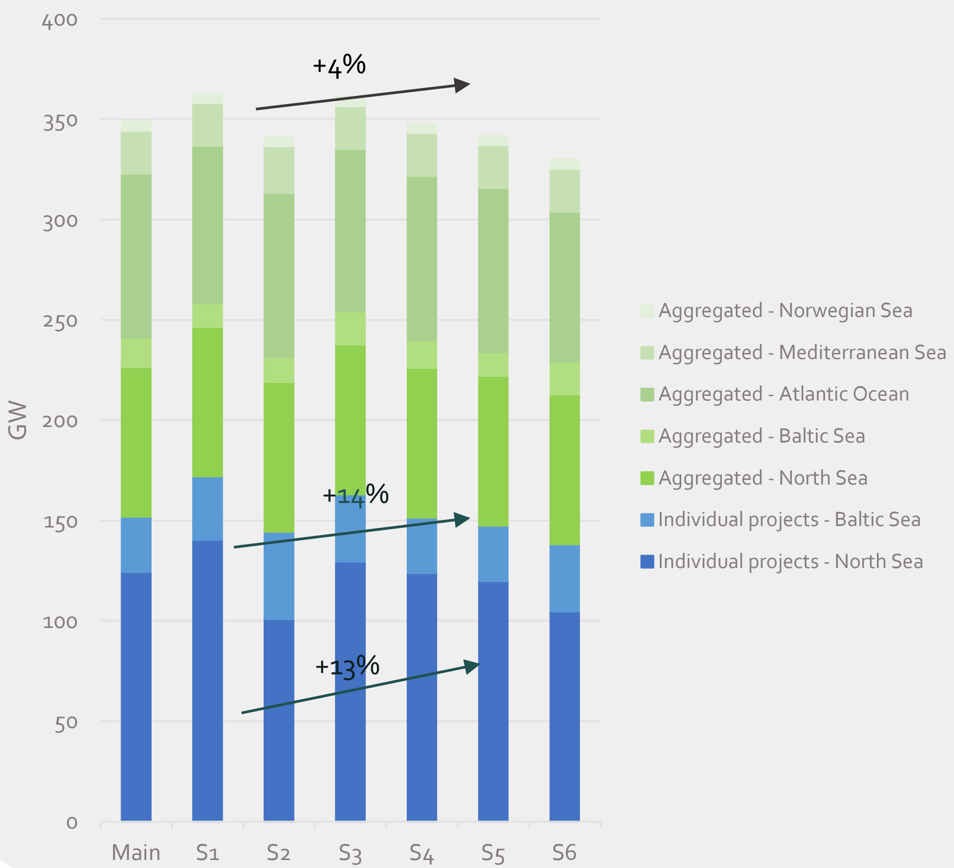


SENSITIVITY ANALYSIS

Multi-linked hubs

Offshore wind capacity build-out

Offshore wind power capacity in 2050 by sea and representation type



In the *S1 Multi-linked hubs* sensitivity, total offshore build-out increases with 4% compared to the *Main* scenario, due to meshed offshore transmission.

The increase of offshore capacity by sea is:

- North Sea: +8%
- Baltic Sea: +3%

The offshore wind capacity increase at hubs (modelled as individual projects) is 13%, or by sea:

- North Sea: +13%
- Baltic Sea: +14%

In the *S1* sensititvity, the option to interlink hubs with several connections is used at almost all hubs, whereby almost 45% of the offshore wind capacity in the modelled area is multi-linked.

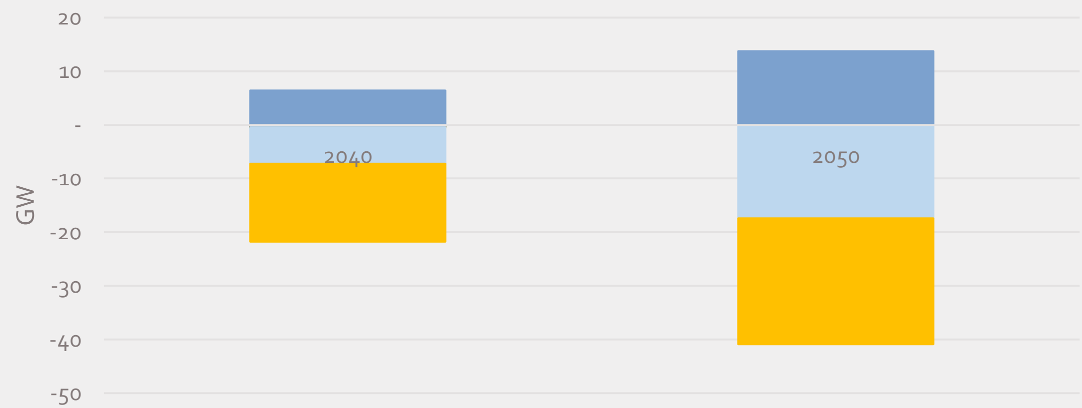
Electricity generation and power capacity changes

Allowing meshed offshore transmission in the *S1 Multi-linked hubs* scenario, results in an increase in offshore wind capacity of about 14 GW in 2050. At the same time, onshore land-use can be reduced due to a decrease of onshore variable renewable capacity:

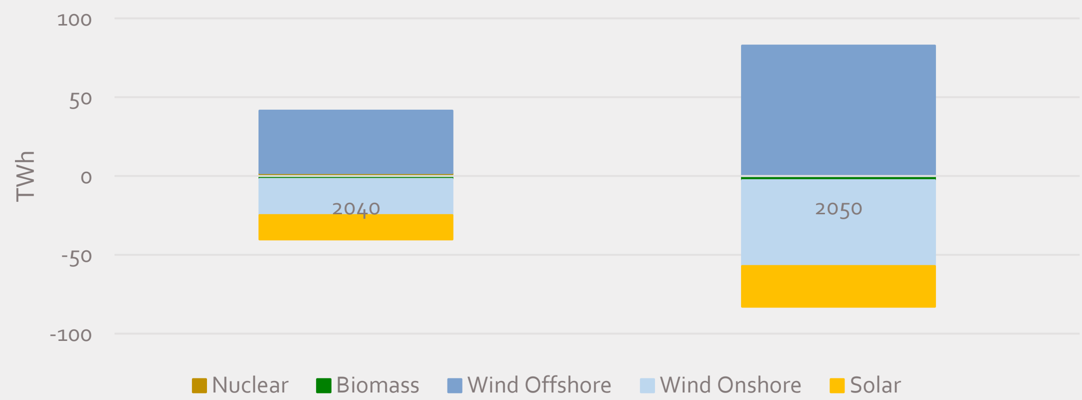
- 17 GW for onshore wind
- 23 GW for solar

In energy terms, the increase in offshore wind generation in the *S1 Multi-linked hubs* scenario is 83 TWh in 2050 or about 5.4%

Changes in power capacity*



Changes in electricity generation*



** Graph shows difference in generation between M1 Single-linked hubs and M2 Multi-linked hubs scenario.*

Transmission build-out

[GWx1000km*]		2020	2030	2040	2050	Increase (2020-2050)
Main	Onshore	36	55	100	140	x 4
	Offshore total	9	18	67	113	x 12
	Shores to shore	9	17	64	101	x 11
	Wind farm to shore/hub to hub	0	1	3	13	x 75
	Sum	**45**	**73**	**167**	**254**	**x 6**
S1 Multi-linked hubs	Onshore	36	55	96	133	x 4
	Offshore total	9	18	63	108	x 12
	Shores to shore	9	17	49	75	x 8
	Wind farm to shore/hub to hub	0	1	14	33	x 196
	Sum	**45**	**73**	**159**	**241**	**x 5**

*To quantify infrastructure build-out, the unit *GWx1,000 km* was used, calculated as the Net Transfer Capacity of the interconnection multiplied by the cable length.

Meshed offshore transmission in the *S1 Multi-linked hubs* sensitivity can reduce the total transmission in GWx1,000km* build-out by 5% compared to the *Main* scenario.

Direct offshore transmission between countries is reduced by 25% (25 GWx1,000km).

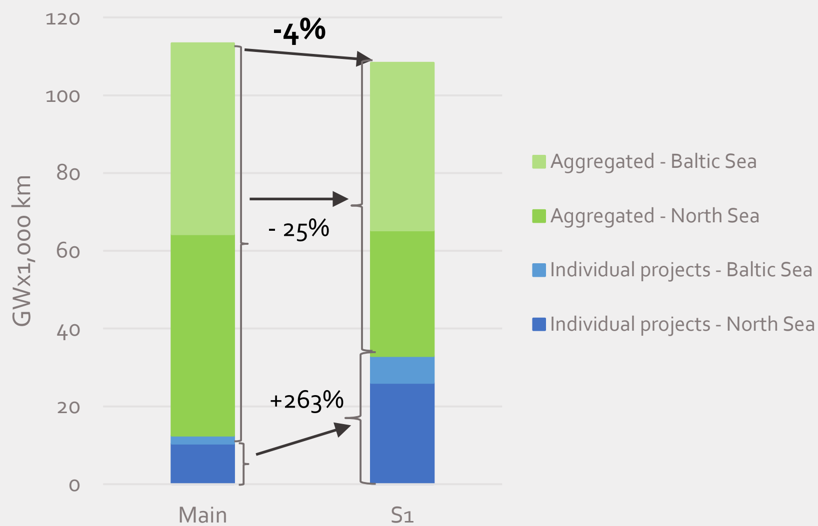
When allowing multi-linked hubs, the need for transmission per offshore wind capacity decreases, meaning offshore wind is more efficiently connected to demand centres.

In the *Main* scenario, offshore transmission is 0.32 GWx1,000km per GW offshore capacity. In the *S1 Multi-linked hubs* sensitivity, this reduces to 0.3

Comparing total transmissions, the values become 0.73 and 0.67 GWx1,000km per GW in the *Main* and *S1 Multi-linked hubs* sensitivity respectively.

Transmission build-out (2)

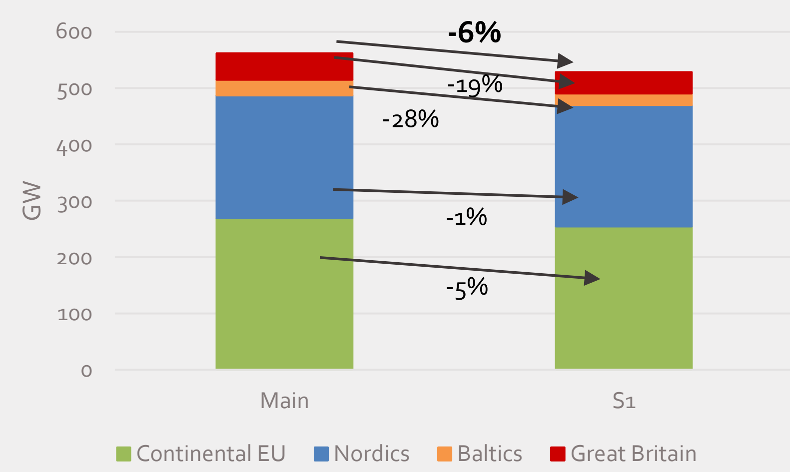
Offshore transmission capacity in 2050 by sea/hub-connection



The offshore transmission capacity in the modelled area measured as the NTC multiplied with cable length decreases with about 4% in the *S1 Multi-linked hubs* sensitivity compared to the *Main* scenario. Out of those offshore connections, an increasing amount are connections through hubs (at wind farm projects), and a decreasing share are direct connections.

The total 'Hit-land' capacity* is reduced by 5% in the *S1 Multi-linked hubs* sensitivity compared to the *Main* scenario. This is due to increased meshed offshore transmission, allowing for both interconnection between countries and connection of offshore wind farms to shore. This optimization decreases lines connected to land.

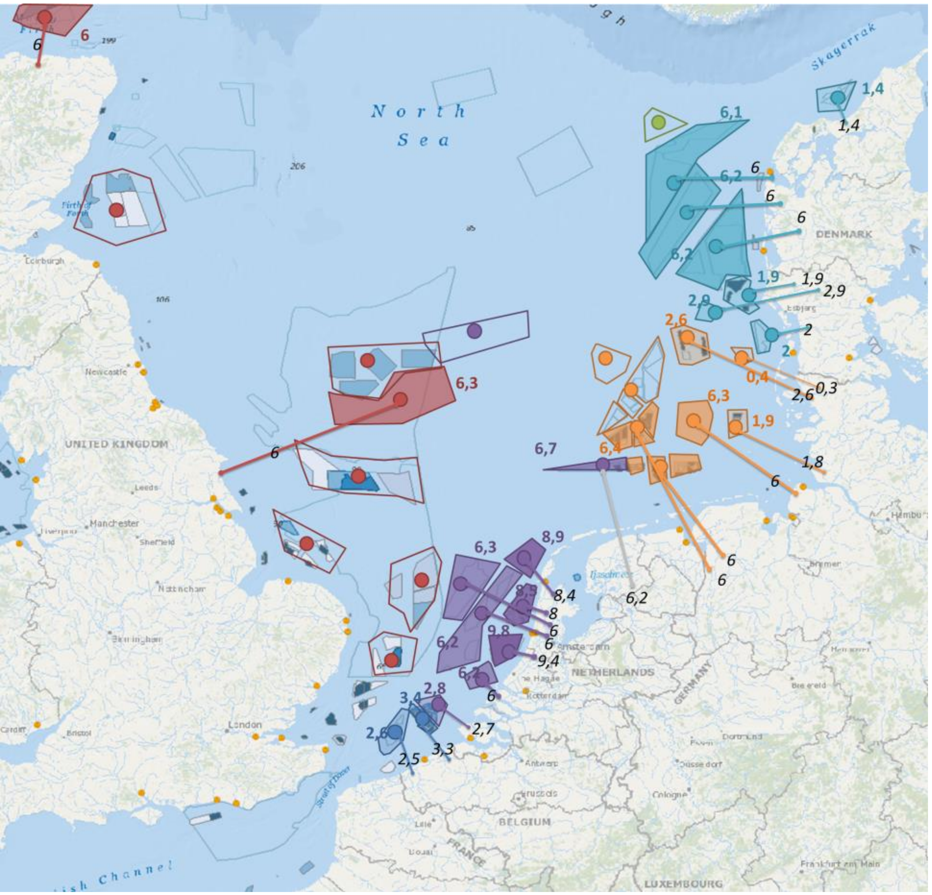
Hit-land capacity*



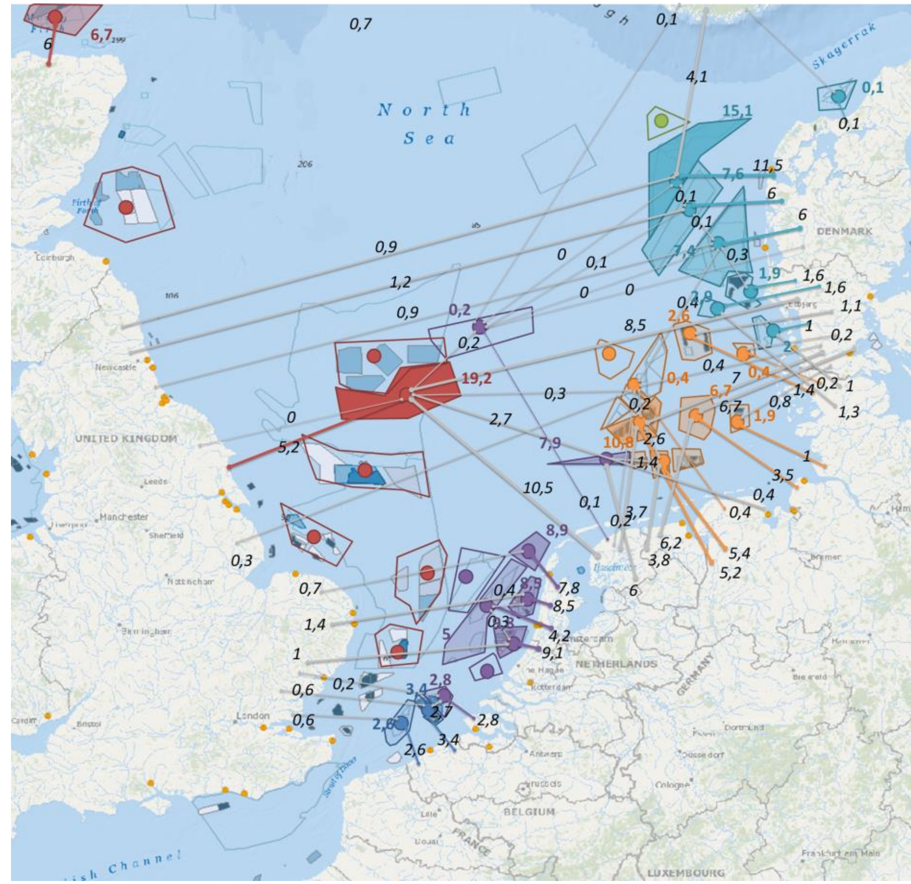
** Total cable capacity connected to land: Direct onshore or offshore connection between countries, direct offshore wind connections and hub-to-shore connections*
Only countries with offshore wind potential in the North sea or Baltic sea are included in the figure

North Sea 2050 – illustrative maps

Main



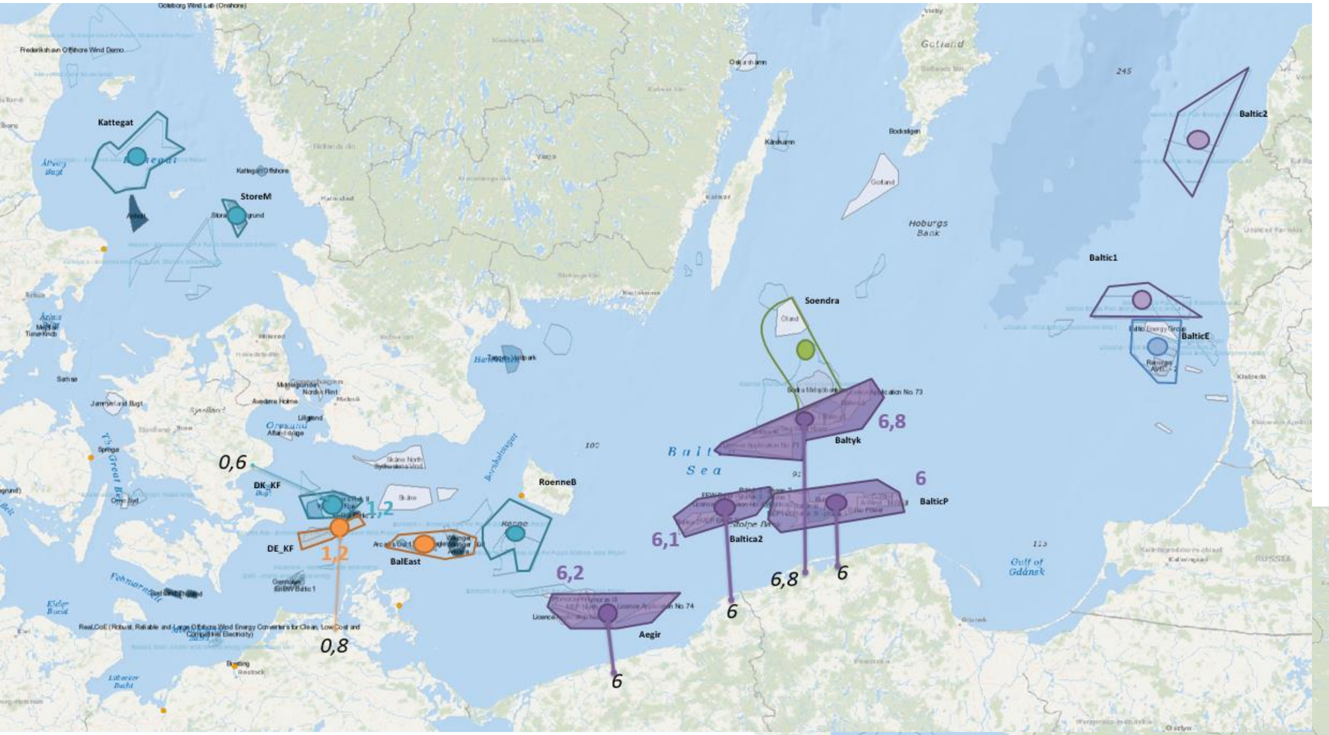
S1 Multi-linked hubs



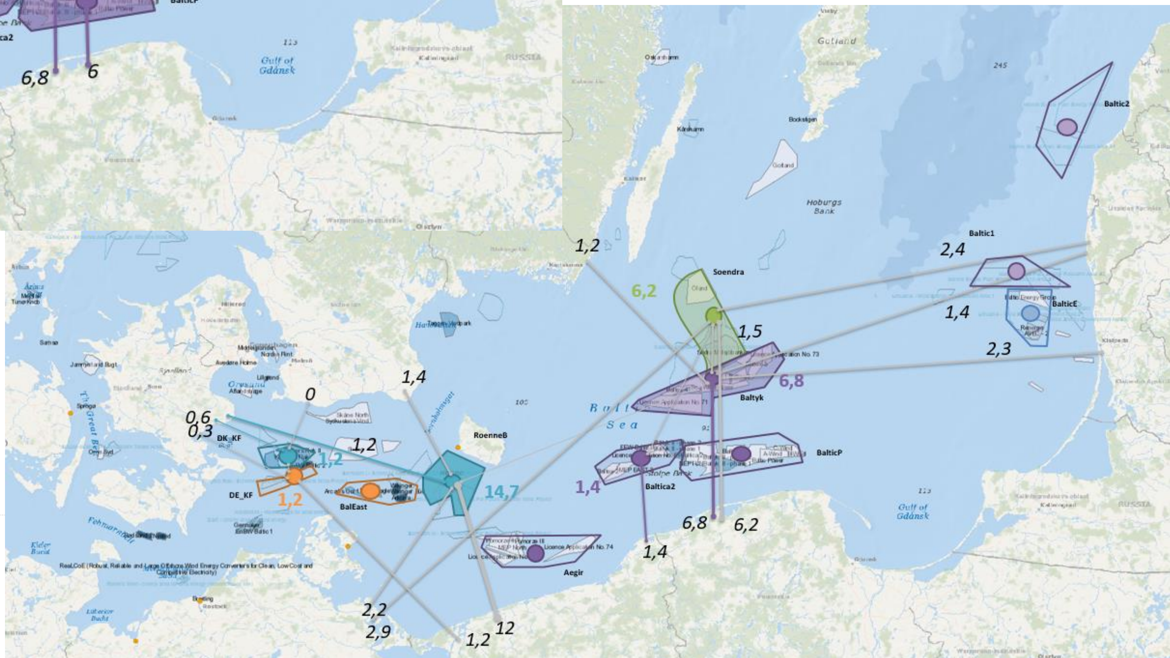
The maps are illustrative for the benefit of connecting hubs to more than one country and do not show actually expected transmission build-out. In reality, transmission cables and smaller hubs might be merged to form larger meshed offshore corridors

Baltic Sea 2050 – illustrative maps

Main



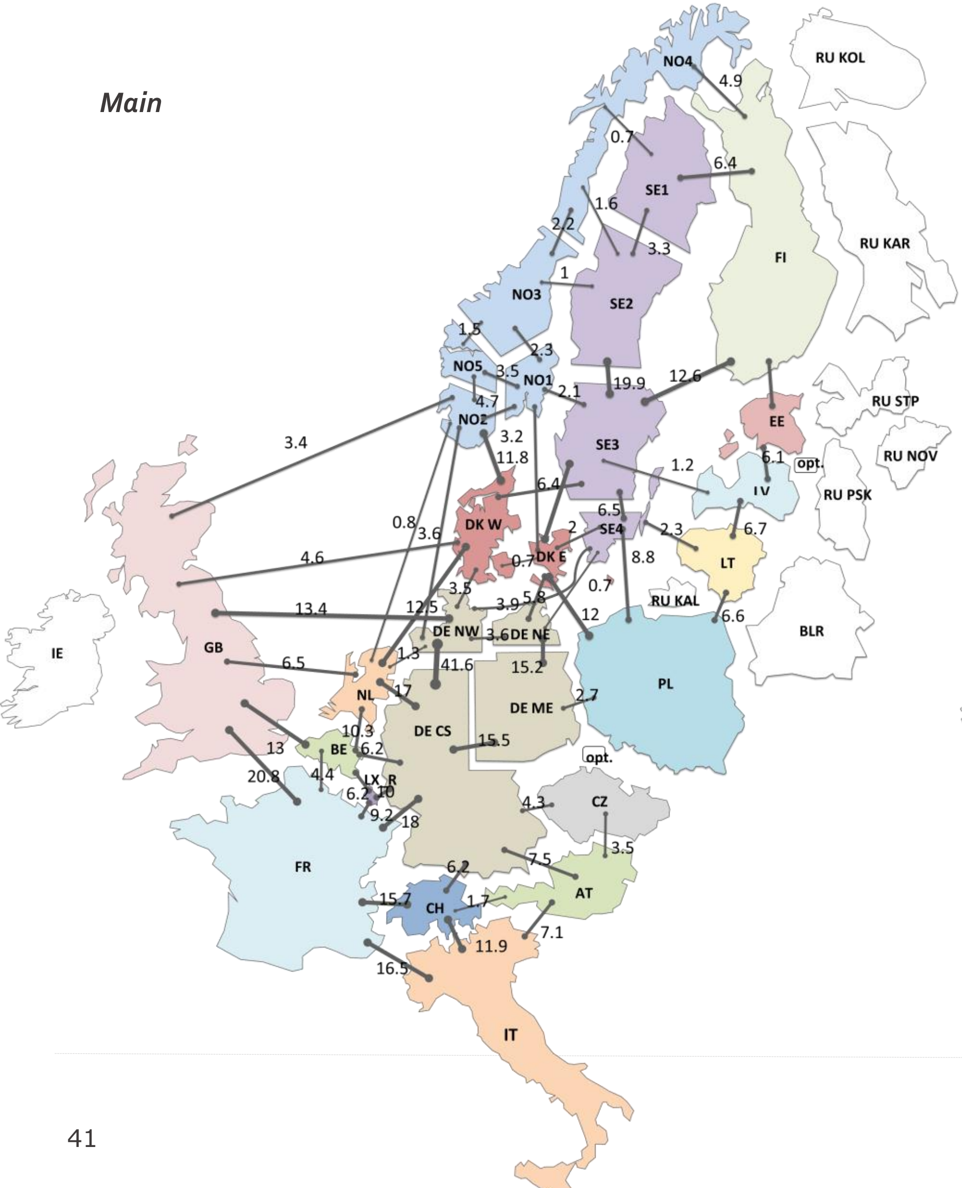
S1 Multi-linked hubs



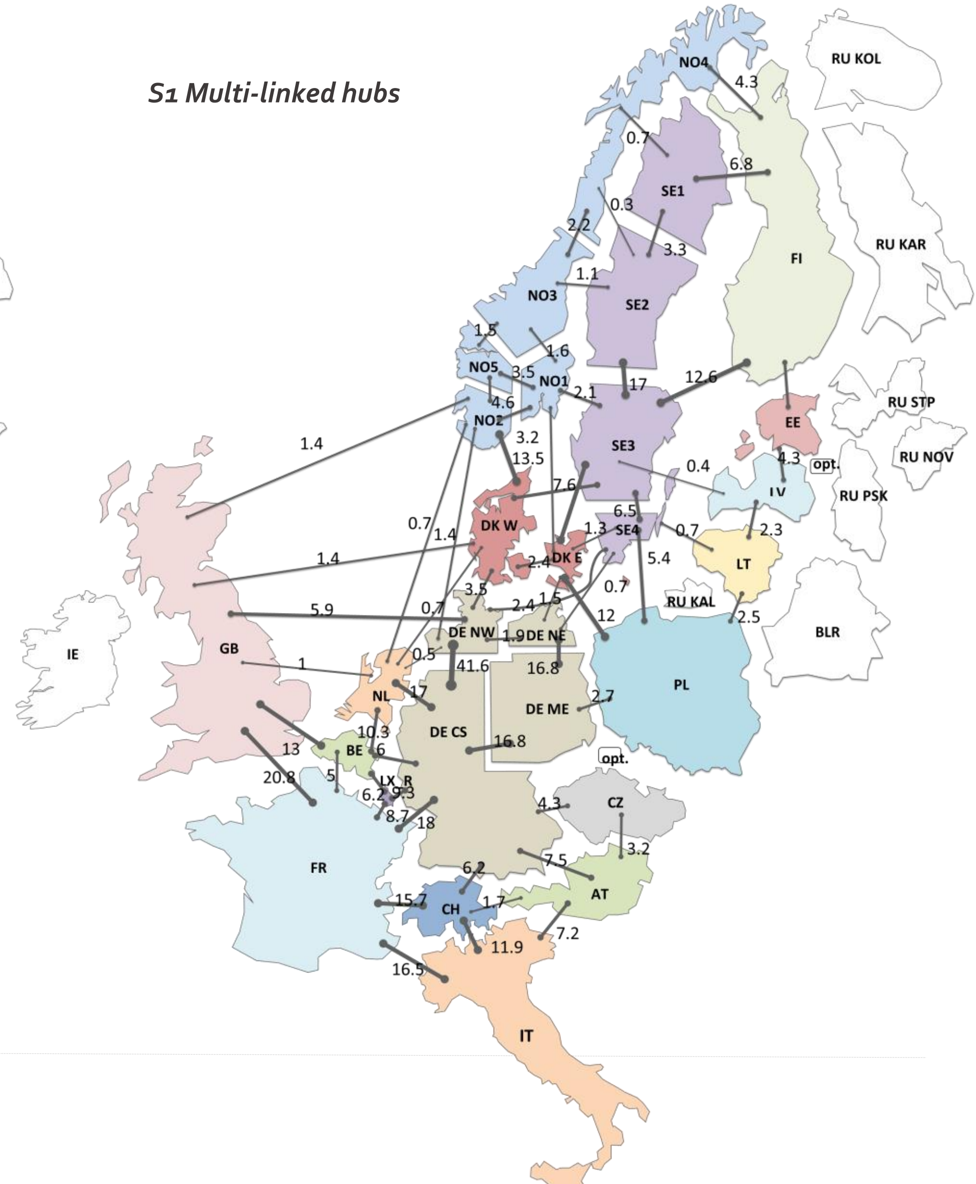
The maps are illustrative for the benefit of connecting hubs to more than one country and do not show actually expected transmission build-out. In reality, transmission cables and smaller hubs might be merged to form larger meshed offshore corridors.

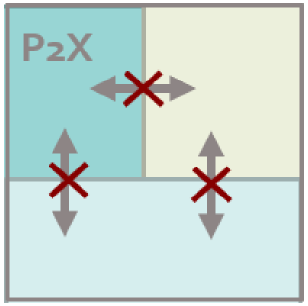
Direct transmission capacity between countries in 2050

Main



S1 Multi-linked hubs



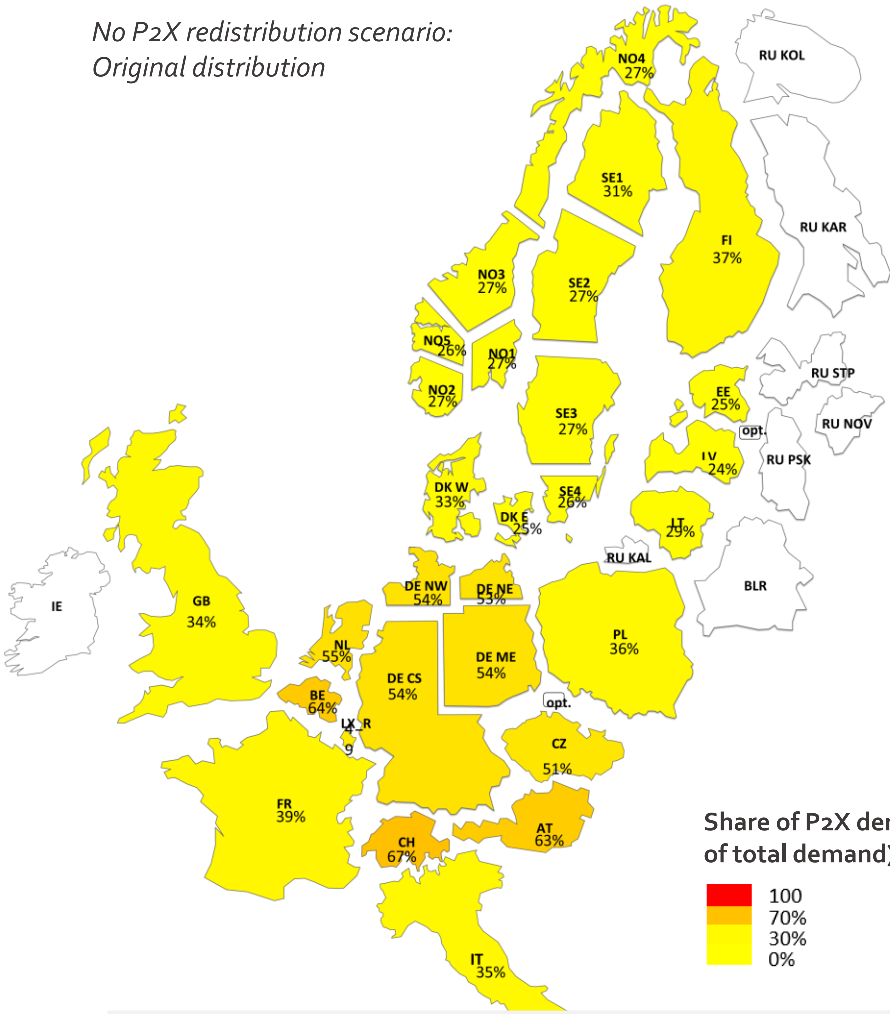


SENSITIVITY ANALYSIS

No P2X redistribution

P2X redistribution

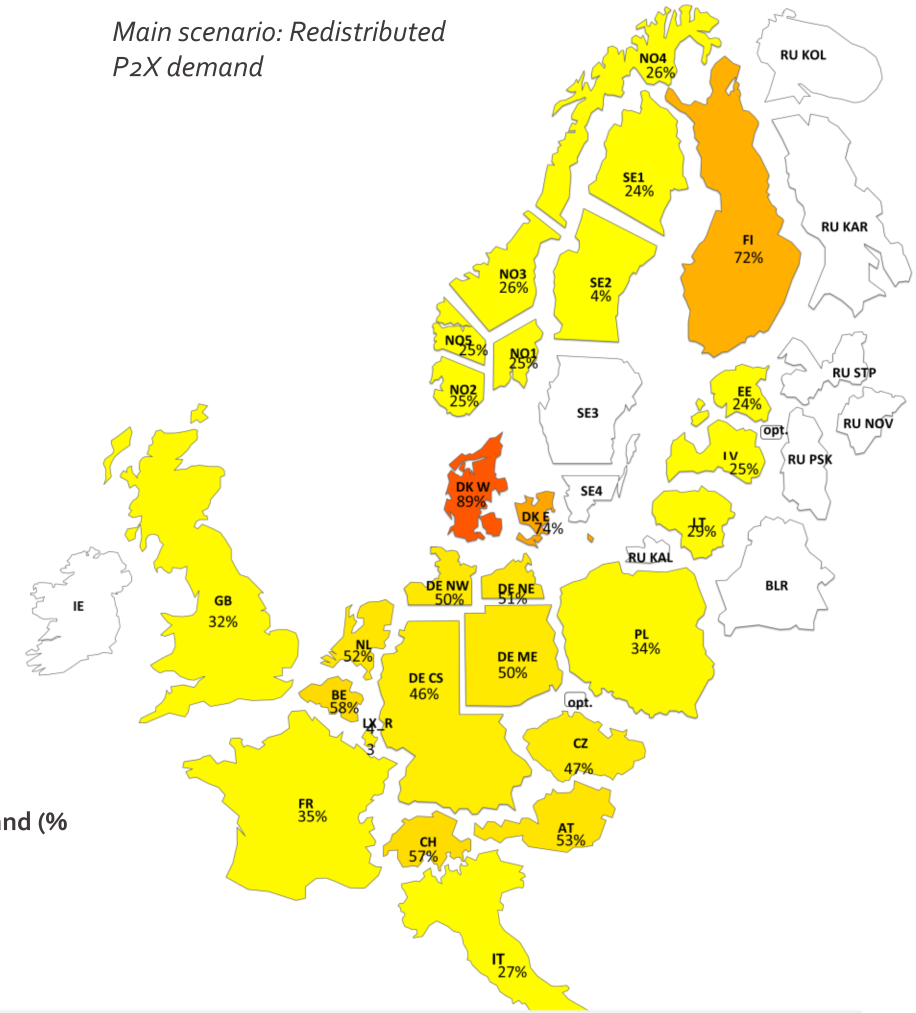
No P2X redistribution scenario: Original distribution



Share of P2X demand (% of total demand)

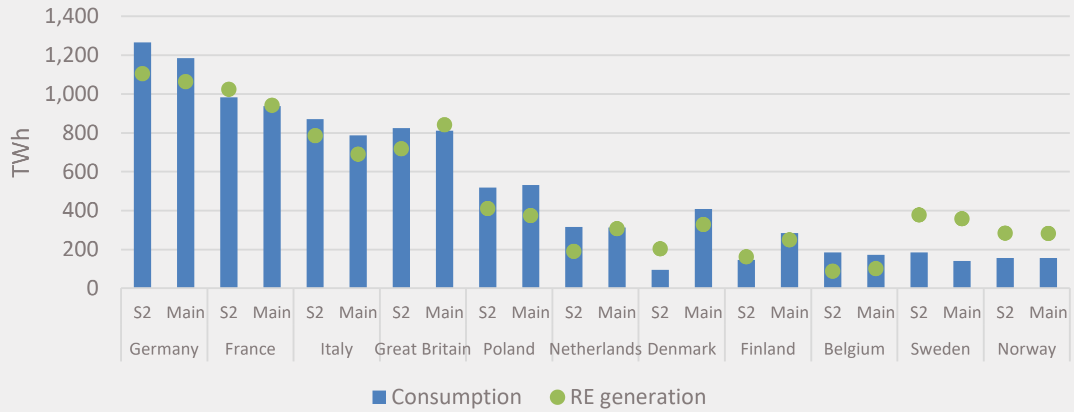
100
70%
30%
0%

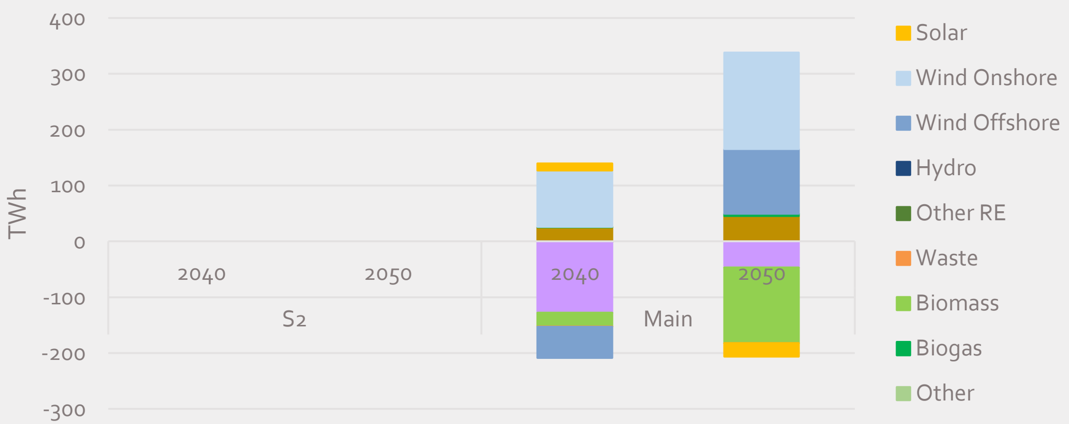
Main scenario: Redistributed P2X demand



Optimized allocation of P2X production, shows that Denmark and Finland could become major e-fuel production countries. Power prices in these countries are low due to high shares of wind generation (offshore in Denmark, onshore in Finland).

Power to X

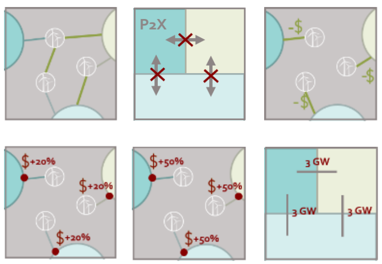




Power-to-X demand is moved from the region consuming e-fuels to regions with good renewable resources, namley onshore and offshore wind power.

Mainly Denmark and Finland become P2X producers.

Natural gas, biomass and solar power reduce in the *Main* scenario compared to the sensitivity without P2X redistribution, while onshore and offshore wind increase.

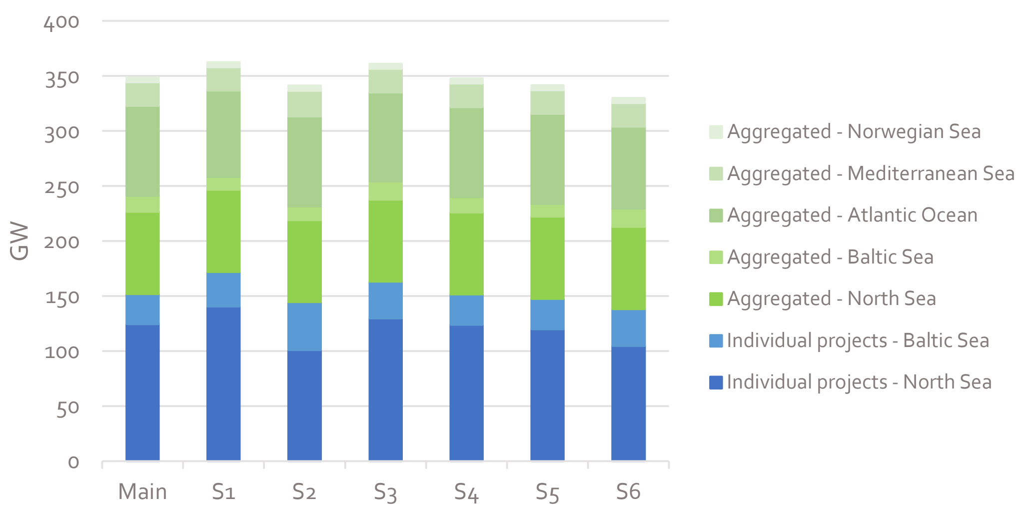


SENSITIVITY ANALYSIS

Overview of all sensitivities

Offshore wind capacity buildout

Offshore capacity in 2050 by sea and representation



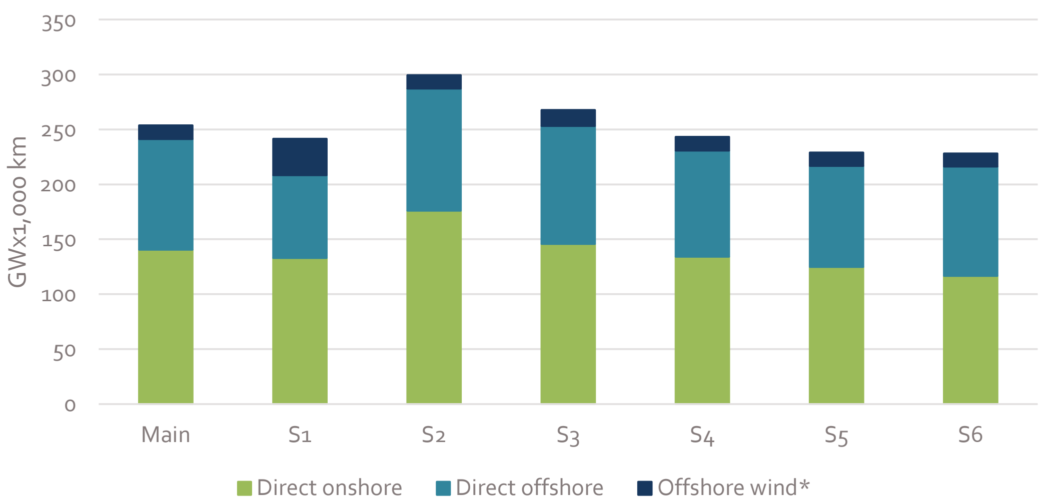
(GW)	Total capacity		North Sea hub capacity		Baltic Sea hub capacity	
	GW	% incr.	GW	% incr.	GW	% incr.
Main	349	-	124	-	28	-
S1 Multi-linked hubs	363	4%	140	13%	32	14%
S2 No P2X redistr.	341	-2%	101	-19%	44	58%
S3 Low DC cost	361	3%	130	4%	34	22%
S4 20% HLC	348	0%	124	0%	28	0%
S5 50% HLC	342	-2%	120	-4%	28	0%
S6 Onshore lim	330	-5%	105	-16%	34	22%

Sensitivities compared to the main scenarios:

- Without P2X redistributionoffshore wind capacity is moved from the North Sea (-19%) to the Baltic Sea (+58%)
- Lower DC transmission costs improves competiveness of offshore wind especially at the hubs in the North Sea
- Additional 'Hit land costs' only result in small decreases in total offshore wind capacity
- Reducing the expansion rate of onshore transmission lines, reduces overall offshore wind capacity

Transmission capacity buildout

Offshore transmission capacity in 2050



(GWx1,000 km)	Total capacity GWx 1,000 km	Total capacity % incr.	Onshore capacity GWx 1,000 km	Onshore capacity % incr.	Offshore capacity GWx 1,000 km	Offshore capacity % incr.
Main	254	-	140	-	113	-
S1 Multi-linked hubs	241	-5%	133	-5%	108	-4%
S2 No P2X redistr.	299	18%	176	25%	123	9%
S3 Low DC cost	281	5%	156	4%	125	8%
S4 20% HLC	268	-4%	146	-5%	122	-4%
S5 50% HLC	243	-10%	134	-11%	109	-8%
S6 Onshore lim	229	-10%	125	-17%	104	-2%

Compared to the Main scenarios,

- No P2X redistribution results in higher total transmission capacity.
- Lower DC transmission costs result in higher infrastructure build-out.
- Hit land costs result in decreased total transmission, though hub connected transmission remains constant or slightly increased.
- Reducing the expansion rate of onshore transmission lines reduces overall infrastructure capacity. Offshore transmission remain similar to the Main scenarios.