Co-financed by the European Union
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Analysing Utilisation Behaviour of Interconnection and Hub Internal Connection Capacity

A study commissioned by the North Sea Wind Power Hub consortium

Final Report

3 DECEMBER 2020

North Sea Wind Power Hub Programme

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Analysing Utilisation Behaviour of Interconnection and Hub Internal Connection Capacity

- **Earlier work of the North Sea Wind Power Hub (NSWPH) consortium has led into the hub-and-spoke concept: a modular 12GW hub consisting of six 2GW modules connected by hub internal connectors. The modules connect 12GW of offshore wind (OWF) capacity and are connected to multiple countries via either interconnectors (ICs) or hybrid assets, depending on the market setup. These transmission assets have the function to both transport OWF energy onshore and facilitate IC flows.**

- **Whereas multiple configurations have been considered, which cover the connected countries and IC capacities, the required hub internal connector capacities have not been analysed before.**

- **This study, entitled 'Analysing Utilisation Behaviour of Interconnection and Hub Internal Connection Capacity', is based on power market and load flow modelling and it aims to quantify the flows on the ICs and the hub internal connectors which connect the 2GW blocks given certain IC capacities between the hub and certain countries. This provides an indication of the level of hub internal connection capacity that is required between the 2GW building blocks to facilitate a "copper plate" setup.**

- **This study functions as reference material for the technical concept papers funded by the 'Connecting Europe Facility' of the European Union.**

- **The contents of this publication are the sole responsibility of North Sea Wind Power Hub and do not necessarily reflect the opinion of the European Union.**

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Foreword

The North Sea has an enormous potential to contribute to the decarbonised energy system of the future through the vast potential of offshore wind as a variable renewable energy source. Hub-and-spoke projects, see figure 1, which combine wind connection and interconnection capacity result in i) reduction of costs of infrastructure, ii) reduction of emissions by increased offshore wind deployment, and iii) increased system stability by the smoothening effect of interconnection on wind energy generation and enlarged exchange possibilities of balancing energy.

This study focusses on understanding the utilisation and the utilisation drivers of the interconnection capacity and the hub internal connection capacity of three hub-and-spoke configurations, see figure 2. The study analyses the years 2030 and 2040 to get a deeper understanding of the impact of demand and supply developments on the value of interconnection by conducting a power market modelling. The end goal of this study is to create a first insight into transmission capacity utilisation, thereby enabling the optimisation of interconnector and hub internal connector capacities between the 2GW-modules of a hub-and-spoke project. This study does not intend to give insight in total project costs and benefits for a hub-and-spoke project, but only looks at the coupled Day-ahead energy market and what capacities between the envisioned 2GW-modules enables a copper plate functionality between all (inter-)connected 2GW-modules. Other (intra-day) markets are out of scope for this study.

Wider work on this topic shows us that combining cross-zonal interconnection and wind connection results in increased utilisation of electrical infrastructure in comparison to radial wind projects. The benefits are increased when more diverse electricity markets are connected to the hub-and-spoke project and when electricity prices become more volatile due to increased electricity demand and intermittent electricity generation. In such cases, the results indicate that hub-and-spoke projects allow (wind) energy to flow from markets with oversupply to markets where it can provide most socio-economic benefit and hence increasing socio-economic welfare and system stability. This effect is enlarged under the offshore bidding zone setup. This study highlights the role of the hub internal connectors in transporting wind energy towards the high-price bidding zone (e.g. 6GW of wind production is transported from all offshore wind farms through the 2-GW modules, via the hub internal connectors towards Germany in case Germany has the highest electricity price).

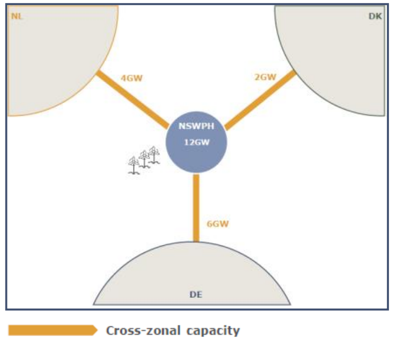

Figure 1. In hybrid projects, as the Hub-and-Spoke projects, offshore wind grid connection and interconnection are combined. In the future, offshore load in the form of PtX can be added to the hubs and connected to the offshore gas grids.

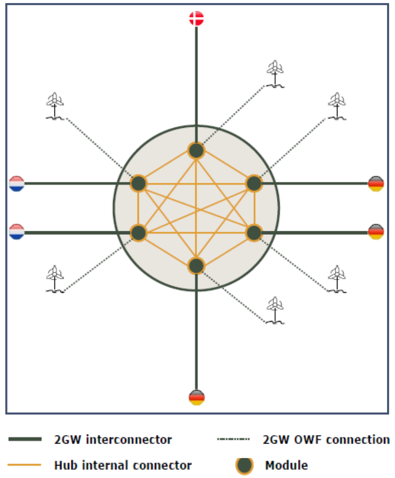

Figure 2. The study focusses on the usage of transmission capacity for the possible connections between the 2GW-modules, thereby creating a first step to analyse the optimal transmission capacity between the 2GW-modules, which in most configurations are also connected to 2GW offshore wind farms, and the onshore markets via 2GW interconnectors.

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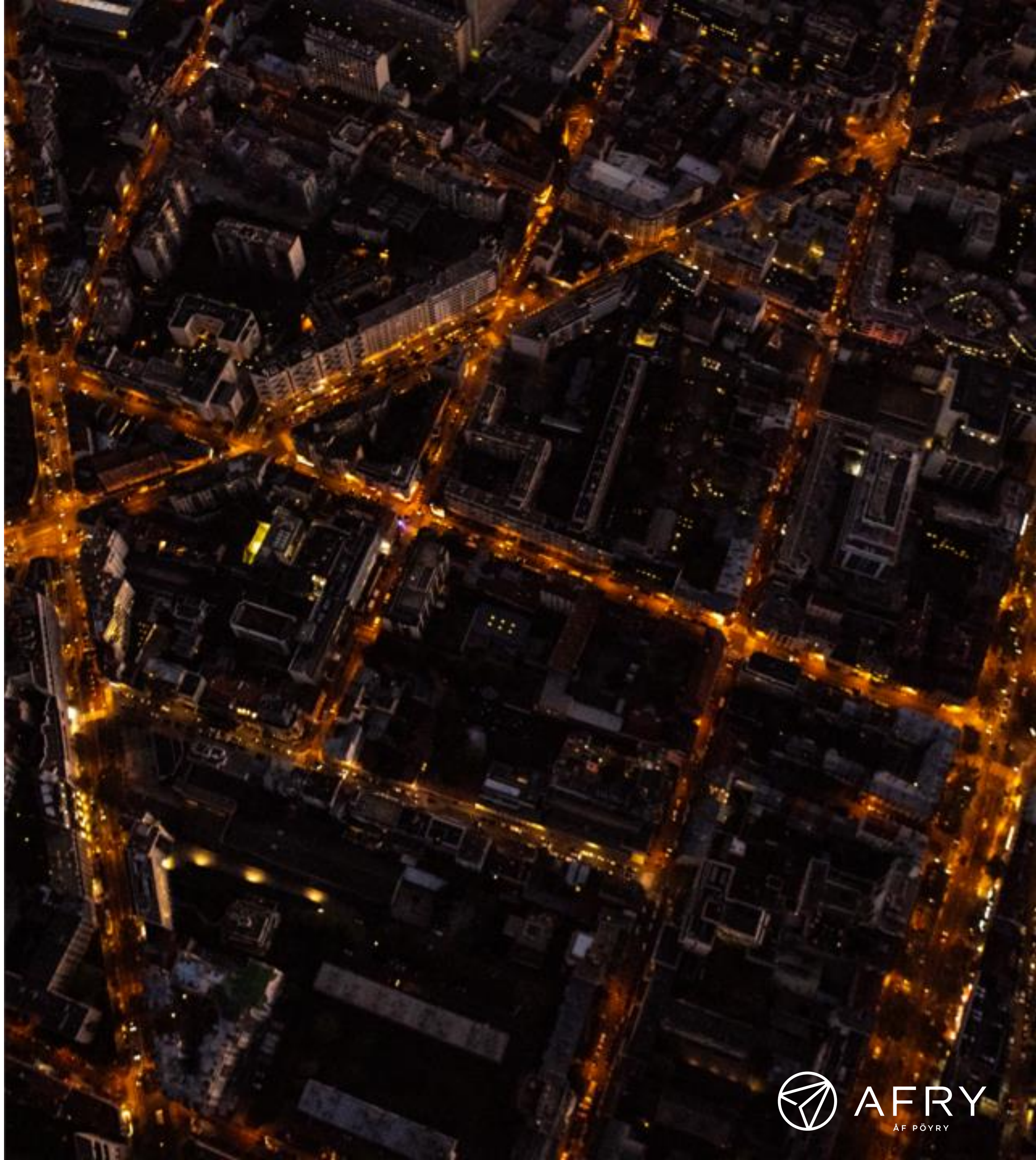

Study Authors:

Rafael Maldonado, Gauthier Le Traon, Asimina Karakyriakou and Simon Bradbury

Focus is on the utilisation and the utilisation drivers of the IC capacity and the hub internal connection capacity between the 2GW modules

BACKGROUND

- Following AFRY's October 2020 'Market Setup Impact on Price Dynamics and Income Distribution' study, the North Sea Wind Power Hub (NSWPH) consortium (1) commissioned AFRY to analyse the within-hub internal connector utilisation and required capacities to achieve a 'copper plate' setup.
- Earlier work of the NSWPH consortium has led into the hub-and-spoke concept: a modular 12GW hub consisting of six 2GW modules connected by hub internal connectors. The modules connect 12GW of offshore wind (OWF) capacity and are connected to multiple countries via either interconnectors (ICs) or hybrid assets, depending on the market setup. These transmission assets have the function to both transport OWF energy onshore and facilitate IC flows. Whereas multiple configurations have been considered, which cover the connected countries and IC capacities, the required hub internal connector capacities have not been analysed before.

STUDY OBJECTIVES

- This study, based on power market and load flow modelling, aims to quantify the **flows on the ICs and the hub internal connectors which connect the 2GW blocks given certain IC capacities between the hub and certain countries**. This provides us with an indication of what level of hub internal connection capacity is required between the 2GW building blocks to **facilitate a "copper plate" setup**.
- The overall goal of the study is to:
  - understand the utilisation and the utilisation drivers of the IC capacity and the hub internal connection capacity between the 2GW modules which are connected to Denmark, Germany and the Netherlands (i.e. core markets) of a 12GW Hub and Spoke project;
  - understand the utilisation and the utilisation drivers of the IC capacity and the hub internal connection capacity between the 2GW modules – considering additional IC capacity on the Hub and Spoke project, maintaining the same core markets; and
  - understand the utilisation and the utilisation drivers of the IC and the hub internal connection capacity between the 2GW modules of the Hub and Spoke project additionally connected to Belgium, Great Britain and Norway (i.e. core+ markets).
- The market setup, assumptions and physical configurations considered in the study are set out below.

1. TenneT Netherlands, TenneT Germany, Energinet and Gasunie

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Testing four physical configurations under one market setup

4 PHYSICAL CONFIGURATIONS	– Wind Radial (connection to home markets) – Core – Core Increased IC – Core Plus (+)
1 MARKET SETUP	– Offshore Bidding Zone
1 MARKET SCENARIO	– TYNDP20 'National Trends' for 2030 and 2040 – under a range of weather years
HM SENSITIVITY	– Investigating the outputs from the Market Setup Impact study to asses differences of within-hub flows for the Core case under the Home Market (HM) and Offshore Bidding Zone (OBZ) market setups.

Four different configurations tested, with three of them reflecting different hub and spoke arrangements

	Hub size	Offshore Wind Farms (OWF)						Interconnection from onshore systems to hub					
		DE	DK	NL	GB	NO	BE	DE	DK	NL	GB	NO	BE
01 Wind Radial	n.a.	6GW	2GW	4GW	n.a.			n.a.					
02 Core	12GW	6GW	2GW	4GW	n.a.			6GW	2GW	4GW	n.a.	n.a.	n.a.
03 Core Increased IC	18GW	6GW	2GW	4GW	n.a.			8GW [+2GW]	4GW [+2GW]	6GW [+2GW]	n.a.	n.a.	n.a.
04 Core+	18GW	6GW	2GW	4GW	n.a.			6GW	2GW	4GW	2GW [+2GW]	2GW [+2GW]	2GW [+2GW]

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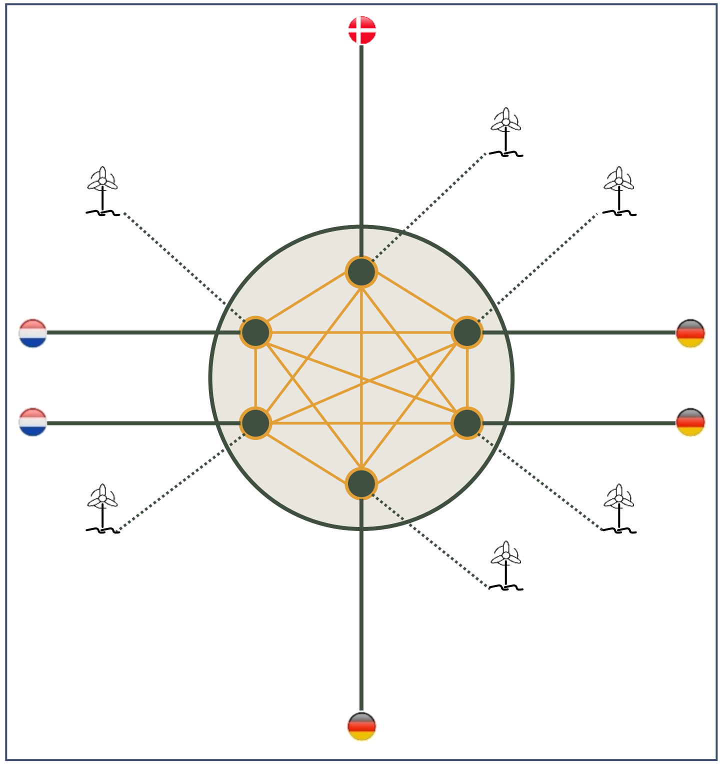
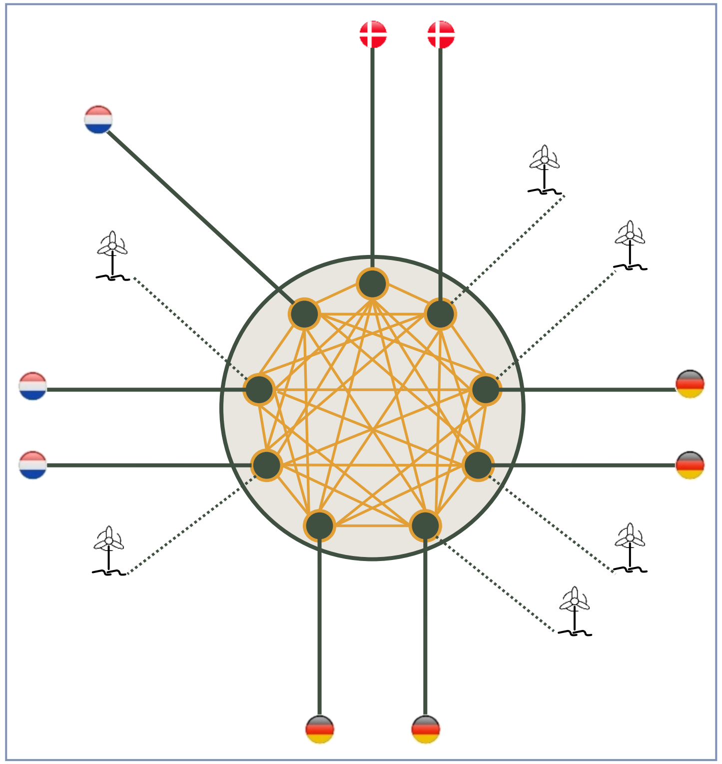
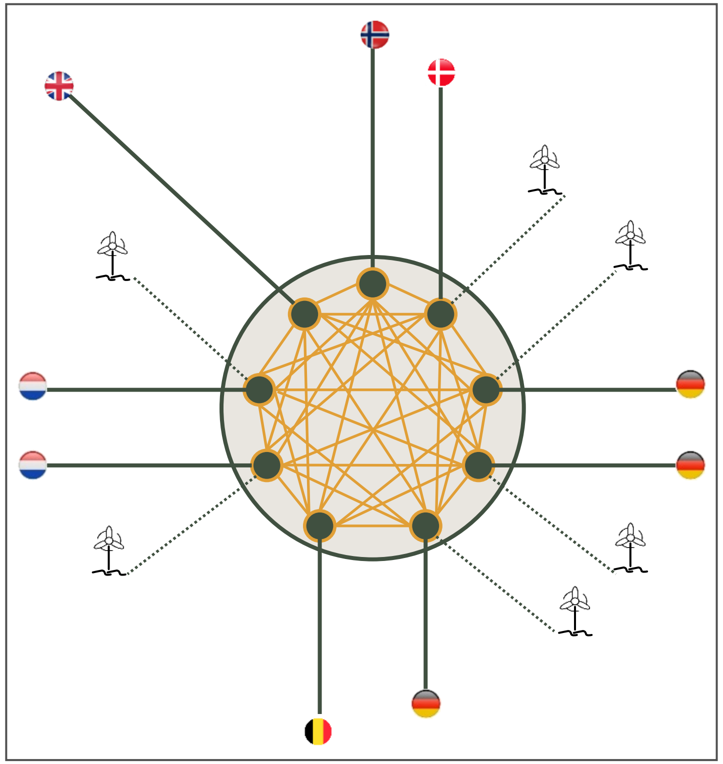
Focus on DE, DK & NL as the core markets, with BE, GB & NO (core+ markets) also included in one configuration

Core	Core Increased IC	Core+
		

2GW interconnector · 2GW OWF connection · Hub internal connector · Module

Two-step approach followed

Power Market modelling

Step A

BID3 market modelling.

Market-wide results.

Hourly flows in and out of the hub via the different spokes – i.e. utilisation of interconnectors and OWF connections.

Load Flow modelling

Step B

BID3 (nodal) functionality to assess load flow between the within-hub transmission modules.

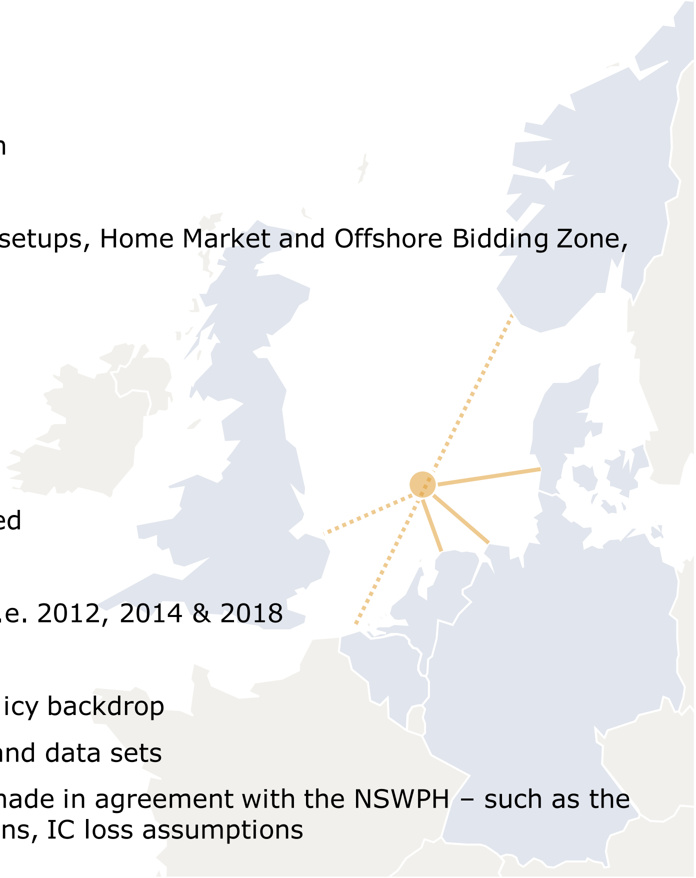
Utilisation of hub internal connectors.

BID3 Electricity Market Model

Supporting information

STRUCTURE

- **Section 1**: Executive Summary, including the main messages of this study
- **Section 2**: Market results of the Wind Radial
- **Section 3**: Market modelling and load flow modelling results of the Core configuration
- **Section 4**: Market modelling and load flow modelling results of the Core Increased IC configuration
- **Section 5**: Market modelling and load flow modelling results of the Core+ configuration
- **Section 6**: High-level comparison of the hub-internal connectors' utilisation under the two market setups, Home Market and Offshore Bidding Zone, under the Core configuration – based on the results of AFRY's October 2020 study for the NSWPH
- **Annex**: Supporting Information, such as modelling background and additional results



CONVENTIONS & ASSUMPTIONS

- All monetary values quoted in this report are in Euros in real 2019 prices , unless otherwise specified
- Annual data relates to the calendar year running from 1 January to 31 December 2030 & 2040
- Unless otherwise specified, results are presented as an average of three historical weather-years, i.e. 2012, 2014 & 2018
- The source for all tables, figures and charts is AFRY Management Consulting
- This study takes the TYNDP20 'National Trends' scenario as its basis in terms of the market and policy backdrop
- Modelling-specific and other technical parameters are based on AFRY's in-house modelling (BID3) and data sets
- Results and messages are sensitive to the underlying assumptions for the Hub and Spoke project made in agreement with the NSWPH – such as the single OWF generation profile, the connectors' technical characteristics and symmetry of assumptions, IC loss assumptions

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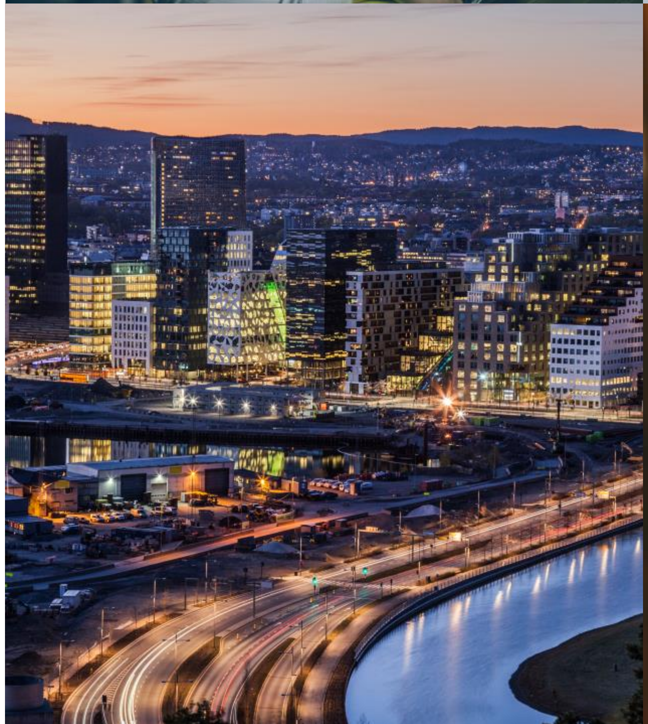
Agenda

1. **Executive Summary**
2. Wind Radial
3. Core
4. Core Increased IC
5. Core Plus
6. Home Market sensitivity






Low use of transmission assets beyond the transfer of hub-connected OWF generation means that maximum within-hub flows also remain limited

TRANSMISSION ASSETS
i.e. ICs or hybrid assets depending on market setup

1. **Overall flows and utilisation rates of hub related transmission assets are low**
   a. If the hub includes Denmark, Germany and the Netherlands then the transmission assets are mainly used to transfer the hub-connected OWF generation to the various onshore connection points, with limited use associated with flows from the onshore national systems.
   b. Increasing the IC capacity between the hub and the three markets has limited value overall, unless Great Britain and Norway are added to the hub. The addition of Great Britain and Norway to the hub adds greater diversity which leads to an increase in the overall utilisation of the hub transmission assets driven by flows from these two national systems.

HUB-INTERNAL CONNECTORS
i.e. lines between the modules

2. **Copper plate setup is achieved when all hub-internal connectors have a capacity of 675MW or less – depending on the configuration**
   a. The maximum flows on a single hub-internal connector either never reach this threshold or reach it only for a few hours in a year.
   b. When the hub acts purely as a 'generation centre' (i.e. with no flows triggered from the national systems – this can occur for more than 90% of the time when the hub includes Denmark, Germany and the Netherlands), copper plate setup is achieved with hub-internal connectors of 453MW or less – depending on the configuration. This threshold is, in most cases, surpassed for less than 300 hours in a year.
   c. Outages on any of the hub-internal connectors lead to an increase in the flows on the remaining lines as power is redirected via the remaining operating lines. In this case, the N-1 secure copper plate setup requires line capacities of 844MW or less – depending on the configuration.

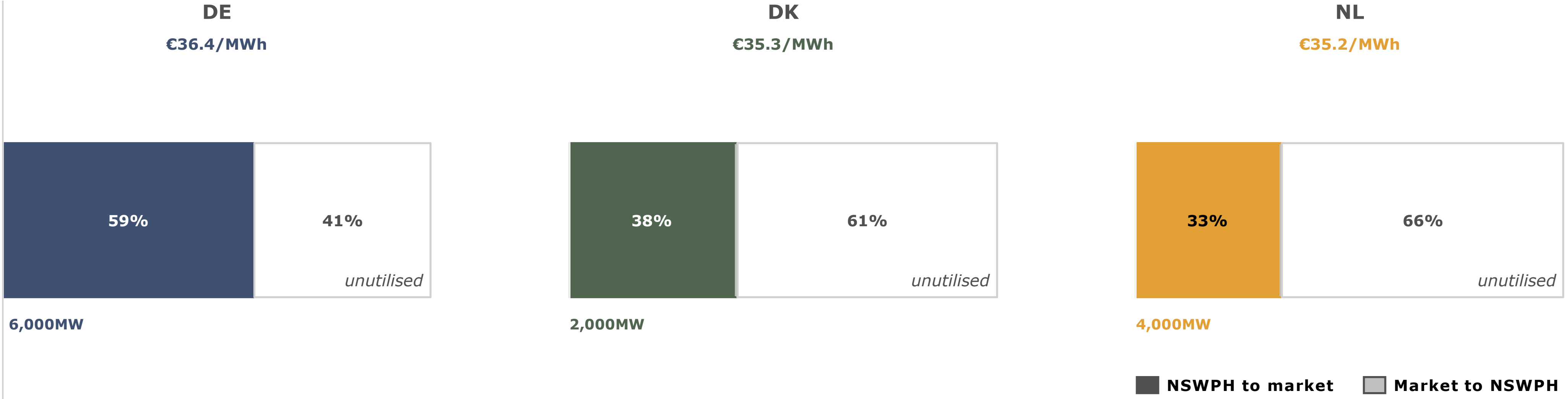
Note: Our analysis assumes that all OWFs share the same generation profile, and that all hub-internal connectors have the same technical characteristics.

MAIN MESSAGE #1A

Overall flows and utilisation rates of hub related transmission assets are low

Average electricity price and utilisation rates on each IC by direction of flow, 2030

CORE
DE, DK & NL



NOTES

- The charts show the utilisation rates of the transmission assets by direction, defined as the physical flow accounting for losses divided by the capacity of each spoke – for the year 2030. The 2030 average electricity price per market is also provided for reference.
- With electricity prices among the three core markets fairly correlated and price spreads limited, total utilisation remains low. However, utilisation varies for the different ICs connecting the onshore systems to the hub. For example, the German IC is used at a rate of 59% in 2030, primarily to transfer the hub-connected OWF generation to the German market where the price signal is stronger. This leads to a significantly lower utilisation on the Danish and Dutch ICs. Overall, utilisation from the national systems to the NSWPH is less than 1% across all ICs.
- **If the hub includes Denmark, Germany and the Netherlands then the transmission assets are mainly used to transfer the hub-connected OWF generation to the various onshore connection points, with limited use associated with flows from the onshore national systems.**

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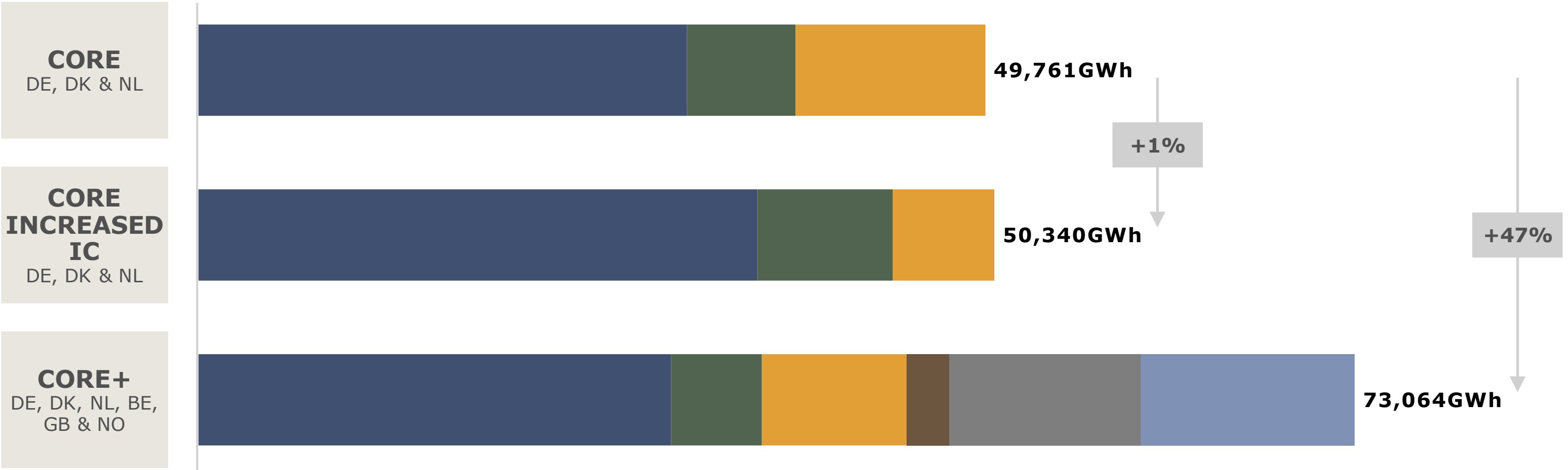
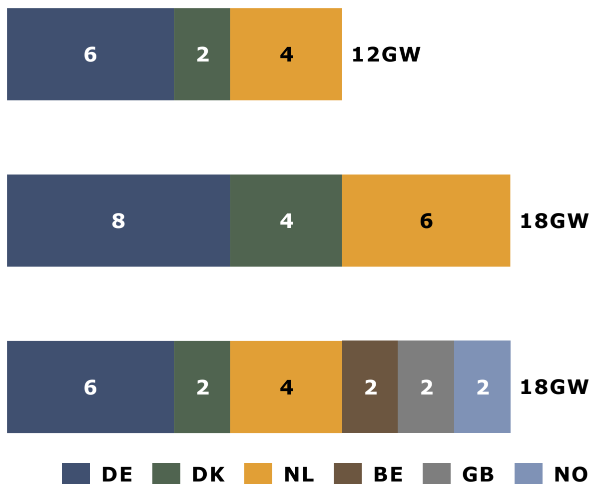
Overall flows and utilisation rates of hub related transmission assets are low – unless GB and Norway are added to the hub

Annual physical cross-zonal flows in GWh, incl. losses, 2030



IC capacity in GW



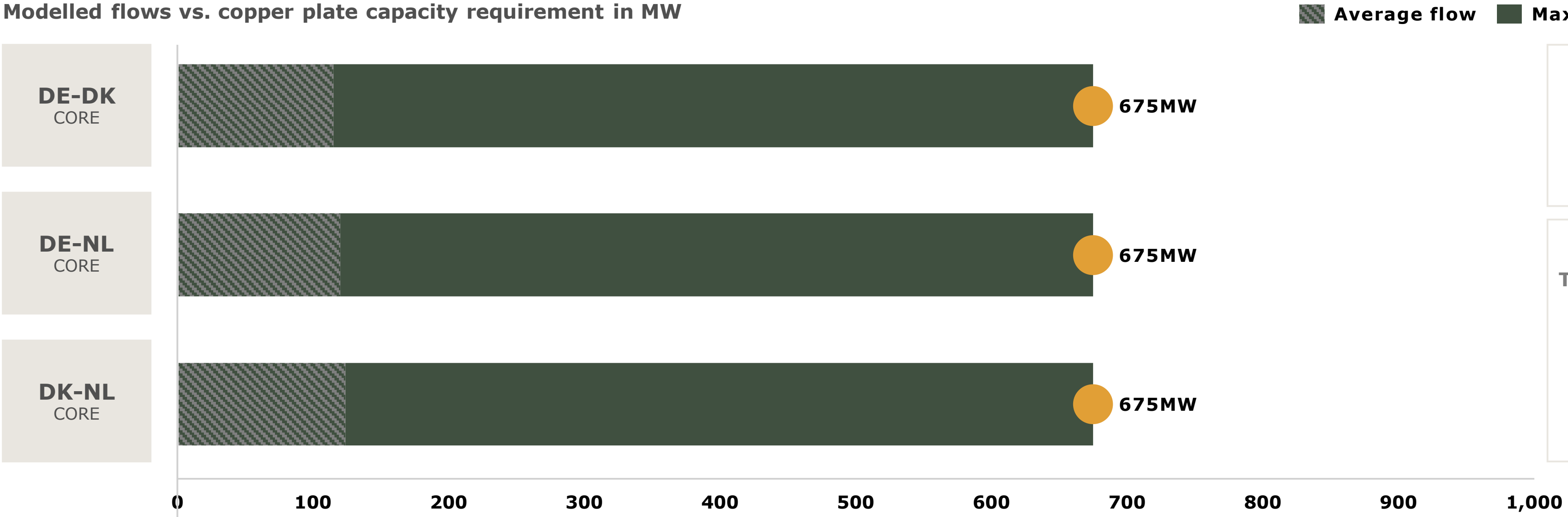
NOTES

- The chart shows the hub related transmission assets' physical flows accounting for losses, as triggered by commercial signals, i.e. electricity price spreads, at the day-ahead stage.
- Overall flows remain practically the same between the two first configurations, despite the hub capacity increasing by 6GW. This is due to the price signals being generally low among the three core markets. When GB and Norway are added to the hub setup, total flows increase by 47% (with Belgium having limited impact). On the Norway IC, this is mainly driven by flows from Norway's system towards the hub. On the GB IC, flows are more balanced in terms of direction.
- **Increasing the IC capacity between the hub and the three markets has limited value overall, unless Great Britain and Norway are added to the hub. The addition of Great Britain and Norway to the hub adds greater diversity which leads to an increase in the overall utilisation of the hub transmission assets driven by flows from these two national systems.**

MAIN MESSAGE #2A

Copper plate setup is achieved when all hub-internal connectors have a capacity of 675MW or less – depending on the configuration

Modelled flows vs. copper plate capacity requirement in MW



Total number of lines: 15

DE-DK: 3
DE-NL: 6
DK-NL: 2
Between modules of the same market: 4

Total coper plate capacity of 10,125MW assuming all hub-internal connectors are commissioned.

Removal of the lines between modules of the same market can decrease total coper plate capacity to 7,425MW (1).

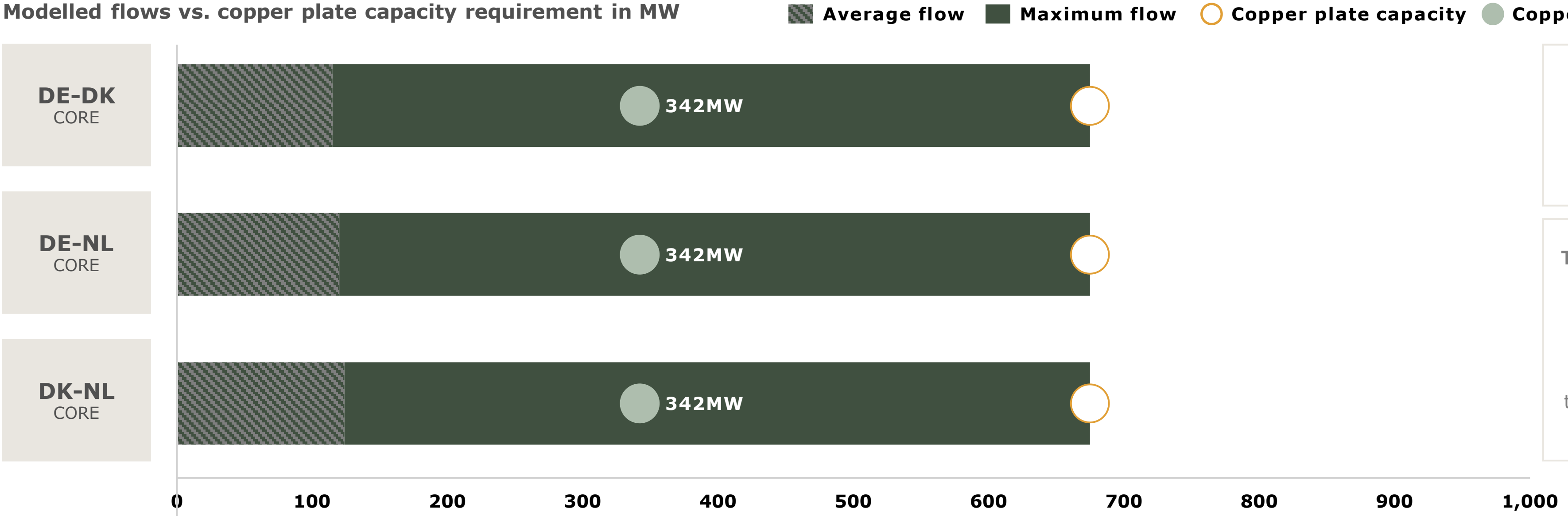
NOTES

- The chart plots for each hub-internal connector (or line) (2), under the Core configuration: i) the outputs of the load flow modelling in terms of average hourly flow (patterned bars) and maximum hourly flow (green bars) on each within-hub connector – regardless of direction, over the two modelled years 2030/40; and ii) the calculated theoretical maximum flow on each hub-internal connector (orange circle) – i.e. 'copper plate' capacity requirement.
- The 675MW threshold is reached 5 times in 2030 and 24 times in 2040. Under the other configurations, maximum hourly flows never reach their respective threshold (e.g. under the Core Increased IC, while copper plate setup is achieved when all hub-internal connectors have a capacity of 642MW, maximum utilisation on a single line is only 592MW).
- **The maximum flows on a single hub-internal connector either never reach this threshold or reach it only for a few hours in a year.**

1. Lines between modules of the same market (e.g. DE-DE) have zero flows, and thus removing them does not change the utilisation of the other lines. | 2. Flows are for each line, e.g. 'DE-DK' is the flow on each of the three lines connecting the three DE modules with the DK module.

Copper plate setup is achieved when all hub-internal connectors have a capacity of 675MW or less – in most periods a lower threshold can be sufficient

Modelled flows vs. copper plate capacity requirement in MW



Total number of lines: 15

DE-DK: 3
DE-NL: 6
DK-NL: 2
Between modules of the same market: 4

Total coper plate capacity of 5,130MW – when assets act purely as a generation centre and assuming all hub-internal connectors are commissioned.

Removal of the lines between modules of the same market can decrease total coper plate capacity to 3,762MW (1).

NOTES

- Building on the chart presented on the previous slide, this chart plots: the calculated theoretical maximum flow on each hub-internal connector (green circle) – i.e. 'copper plate' capacity requirement – when the assets act purely as a 'generation centre' (i.e. no flow originating from the onshore systems).
- Under the configurations that include Denmark, Germany and the Netherlands, the hub acts for the majority of time – i.e. more than 90% – purely as a 'generation centre'. In fact, flows surpassing the 342MW threshold only occur on a few occasions – i.e. around 300 times in 2030 (Core configuration).
- **When the hub acts purely as a 'generation centre' (i.e. with no flows triggered from the national systems – this can occur for more than 90% of the time when the hub includes Denmark, Germany and the Netherlands), copper plate setup is achieved with hub-internal connectors of 453MW or less – depending on the configuration. This threshold is, in most cases, surpassed for less than 300 hours in a year.**

1. Lines between modules of the same market (e.g. DE-DE) have zero flows, and thus removing them does not change the utilisation of the other lines.

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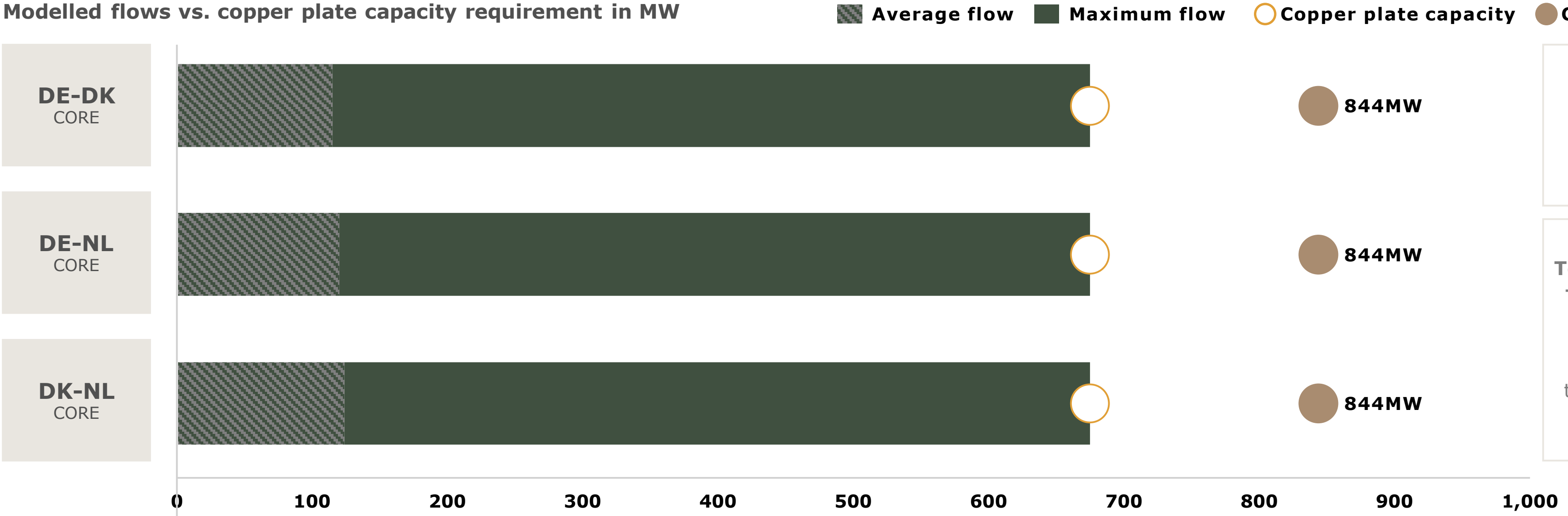
MAIN MESSAGE #2C

Copper plate setup is achieved when all hub-internal connectors have a capacity of 675MW or less – a higher threshold is needed for N-1 compliant

Modelled flows vs. copper plate capacity requirement in MW



Total number of lines: 15

DE-DK: 3
DE-NL: 6
DK-NL: 2
Between modules of the same market: 4

Total coper plate capacity of 12,660MW – for N-1 compliant and assuming all hub-internal connectors are commissioned.

Removal of the lines between modules of the same market can decrease total coper plate capacity to 11,440MW (1).

NOTES

- Building on the chart presented on the previous slide, this chart plots: the calculated theoretical maximum flow on each hub-internal connector (brown circle) – i.e. 'copper plate' capacity requirement – when considering outages on any of the hub-internal connectors, under a 'worst case scenario' (i.e. resulting from the outage which has the greatest impact on the particular line).
- **Outages on any of the hub-internal connectors lead to an increase in the flows on the remaining lines as power is redirected via the remaining operating lines. In this case, the N-1 secure copper plate setup requires line capacities of 844MW or less – depending on the configuration.**

1. Removing lines between modules of the same market increases the required line capacity for N-1 security to 1,040MW (per remaining line) as the possibility for redirecting flows is further reduced.

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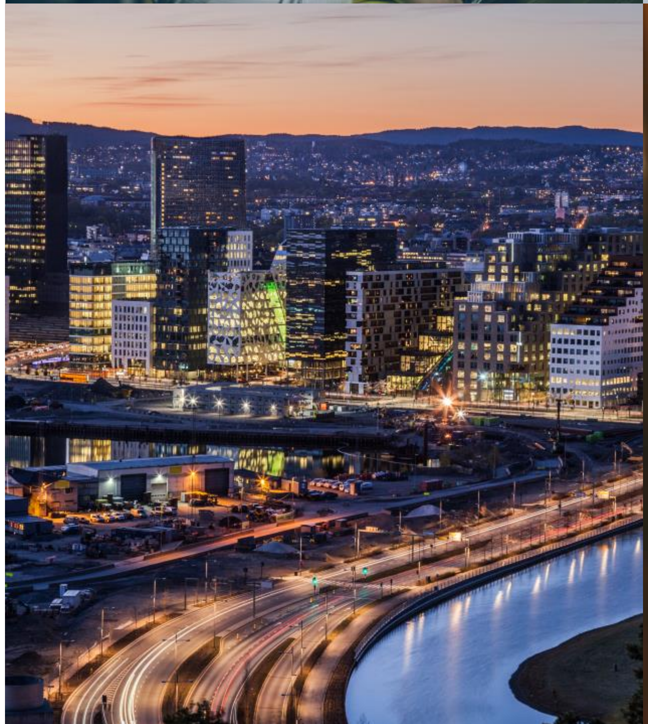


SUPPORTING INFORMATION

Introduction to the Wind Radial results

Market-wide results

- The TYNDP scenario assumes a significant increase in renewable capacities between 2030 and 2040, counterbalanced by higher commodity prices and a tighter system. This has the following impact on wholesale electricity prices:
  - it leads overall to an increase in prices in the Core markets and Belgium, which have high interconnection between them, with prices remaining well-correlated; and
  - among the Core+ markets, Great Britain and Norway follow a different trend, with a decrease in prices between 2030 and 2040 and less correlated prices compared to the rest of the region.

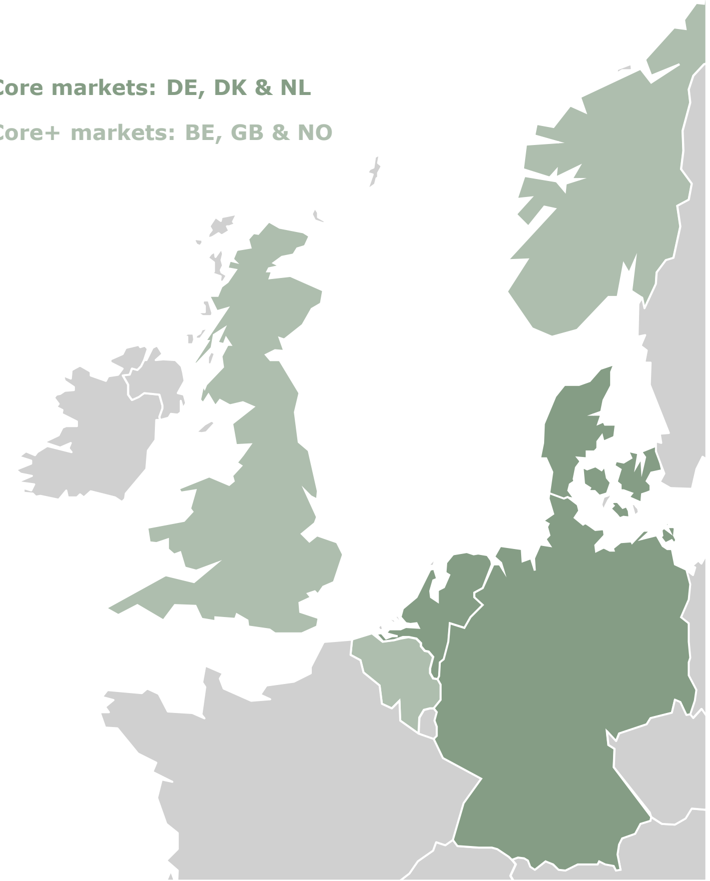
OWF operation

- Despite an increase in average wholesale electricity prices in the Core markets, capture prices for the 12GW of hub-connected OWFs drop from €24-28/MWh to €22-27/MWh between 2030 and 2040. This is because:
  - increasing levels of offshore wind generation in the systems in 2040 compared to 2030 put downwards pressure on prices at times when there is more generation from wind.
- The 12GW of hub-connected OWFs are expected to operate at a load factor of around 45-47%.

GEOGRAPHICAL SCOPE

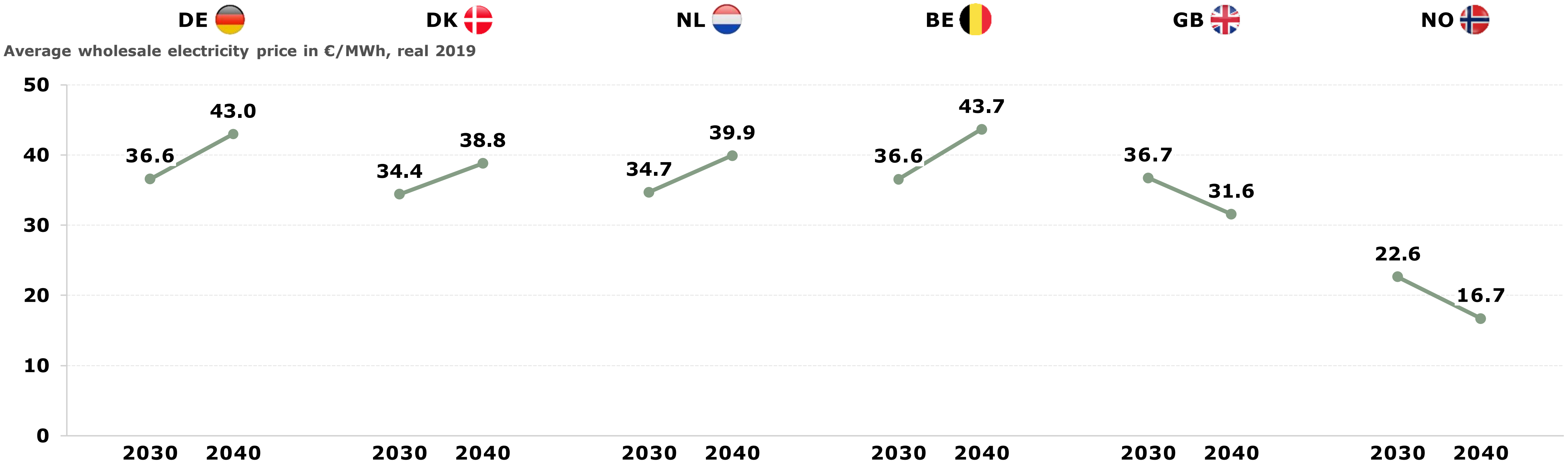
Core markets: DE, DK & NL

Core+ markets: BE, GB & NO



ANNUAL AVERAGE DAY-AHEAD WHOLESALE ELECTRICITY PRICES

Electricity prices increase between 2030 and 2040 across all Core markets and Belgium, while in Great Britain and Norway prices decrease



COMMENTS

- The chart shows the average wholesale electricity price for the Core/Core+ markets for 2030 and 2040 – based on the assumptions of the TYNDP National Trends scenario.
- The annual average electricity price in the German market remains the highest among the Core markets. This is primarily driven by remaining thermal capacity on the system combined with increasing commodity prices, pushing the German electricity prices upwards.
- Prices increase between 2030 and 2040 in the Core markets and Belgium mostly due to higher gas and carbon prices, and a tighter system in 2040 across a number of periods. GB has a more isolated system and a higher penetration of low carbon technologies, with offshore wind and nuclear increasing their share by 2040, resulting in low prices overall which decrease further by 2040. Norway, with its generation mainly based on hydro, has the lowest price, decreasing further by 2040. This is due to an increase in RES generation, a fairly stable electricity demand and a decrease in prices in connected markets e.g. GB.

Note: For the remainder of this report when we refer to the Danish price, we will be using the zonal price for DK1 also referred to as Jutland; when we refer to the Norwegian price, we will be using the zonal price for the most southern zone NO2.

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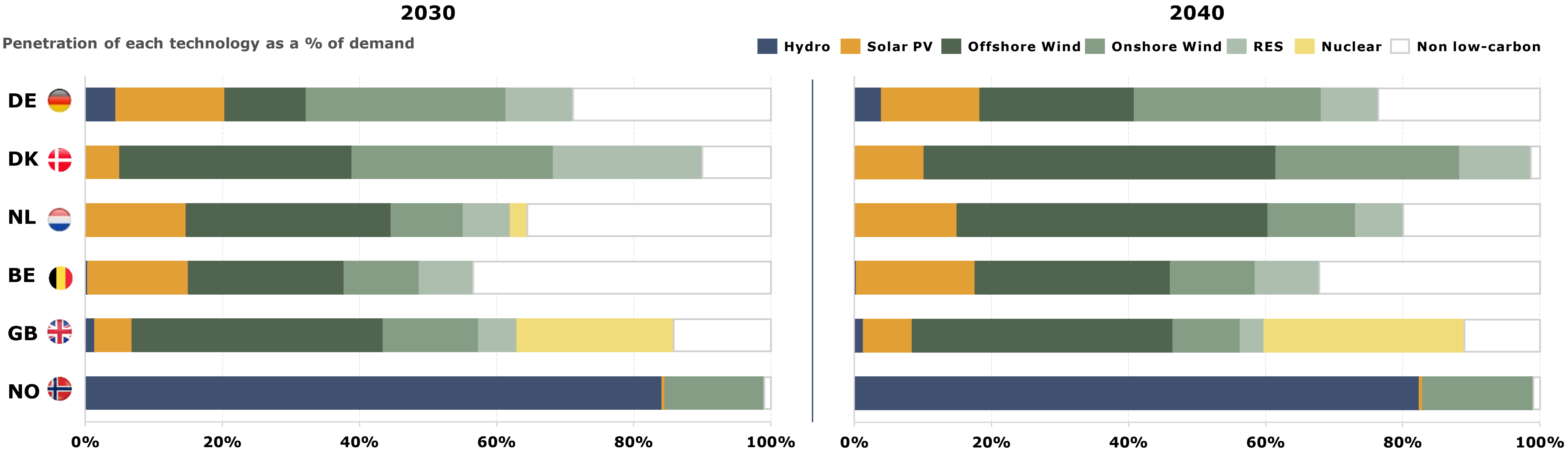
PENETRATION OF LOW CARBON TECHNOLOGY AS A % OF DEMAND

Higher penetration of low carbon technologies across all markets, largely driven by increasing levels of offshore wind capacity

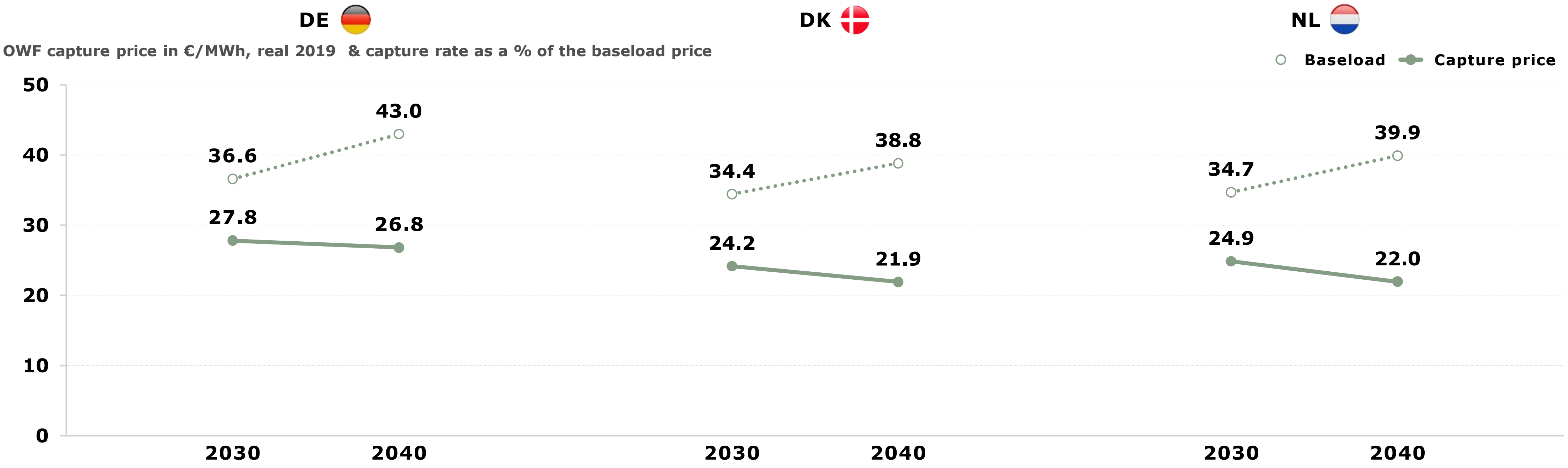


COMMENTS

- The figures show the penetration of each low-carbon technology as a % of overall national demand within each market for 2030 and 2040.
- According to modelling results based on TYNDP20 National Trends input assumptions, among the Core/ Core+ markets, Norway has the highest levels of low-carbon penetration (exceeding its domestic demand and thus exporting to the rest of the markets), followed by Denmark and GB. Germany, Netherlands and Belgium have a lower low carbon penetration due to higher levels of thermal generation left in the system.
- Overall, low carbon penetration levels increase across all markets between 2030 and 2040, primarily driven by a rapid increase in offshore wind (with the exception of Norway in terms of offshore wind levels).

OWF CAPTURE PRICES AND RATES

Despite increasing average prices, capture prices decrease as more offshore wind comes onto the system putting downward pressure on capture rates



	DE 2030	DE 2040	DK 2030	DK 2040	NL 2030	NL 2040
Capture rates	**76.0%**	**62.4%**	**70.2%**	**56.5%**	**71.6%**	**55.0%**

COMMENTS

- The capture price is defined as the unit wholesale electricity revenue of the OWF per MWh accounting for the hourly profile and shape of prices and generation; the baseload price is defined as the annual time-weighed average wholesale electricity price representative for a ‘baseload’ generator.
- The (radially connected) OWFs are expected to capture around 70-75% of the baseload price in 2030. With increasing levels of offshore wind generation in the national systems, which generally puts a downwards pressure on prices at times when wind is generating, this capture rate is expected to drop to as low as 55% for the Dutch and Danish markets (and 62% for Germany) by 2040. This pushes capture prices downwards – despite an increase in the baseload price.

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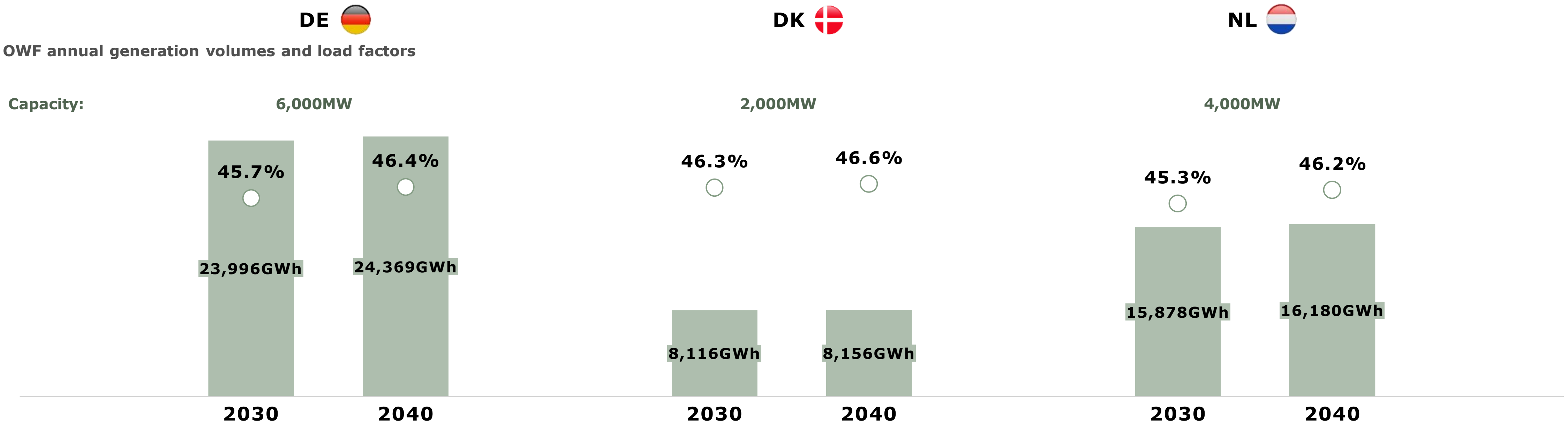
OWF GENERATION VOLUMES

Load factors for the hub-connected OWFs are c. 45-47%

OWF annual generation volumes and load factors



	DE 2030	DE 2040	DK 2030	DK 2040	NL 2030	NL 2040
Curtailment (1) (% of generation)	**473GWh** (2.0%)	**99GWh** (0.4%)	**41GWh** (0.5%)	**0GWh** (0.0%)	**435GWh** (2.7%)	**132GWh** (0.8%)

COMMENTS

- The chart shows the hub-connected OWF generation volumes and load factors, as well as an indication of the volumes that are expected to be curtailed on the basis of merit order effects only. The generation corresponds to the final generation post economic curtailment of the OWF per bidding zone taking into account the losses from the OWF to the national shores.
- Marginally increased load factors in 2040 compared to 2030, and marginally reduced curtailment levels for the OWFs are observed. This is because: i) demand increases rapidly between 2030 and 2040; and ii) more offshore wind comes onto the three systems thus making the specific OWFs less correlated compared to the national average wind production. Both drivers have a relative positive impact on the OWF curtailment levels.

1. Resulting from rational economic dispatch of renewable generation, rather than driven by onshore transmission system issues and / or local constraints.

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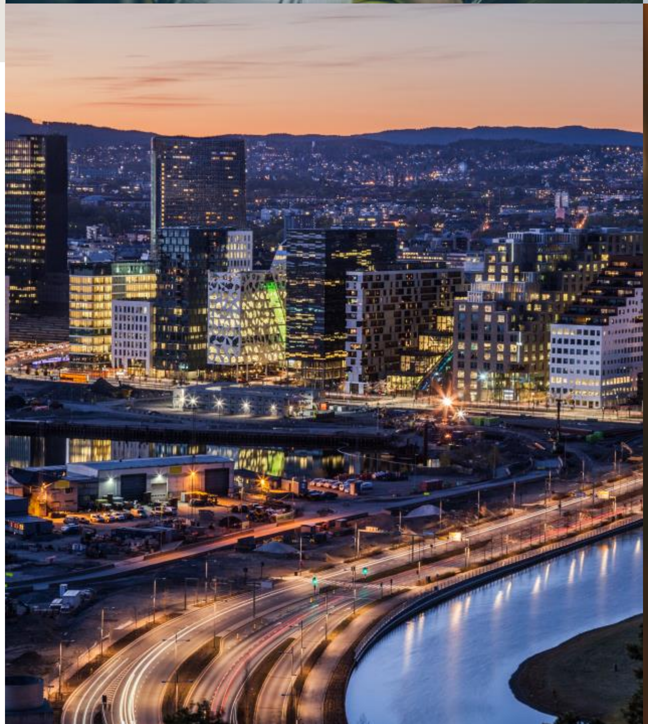
Agenda

1. Executive Summary
2. Wind Radial
3. **Core**
   - Load flow modelling results
4. Core Increased IC
5. Core Plus
6. Home Market sensitivity



SUPPORTING INFORMATION

Introduction to the Core configuration results

I. Market-wide results

- This section focuses on a range of market indicators and provides comparisons of the Core configuration against the Wind Radial. This background information supports and helps explain NSWPH specific operation patterns and outcomes.
- Summary of findings:
  - Baseload electricity prices at similar levels between the two configurations; with a marginal increase of the DK & NL prices, and a marginal decrease of the DE prices under the Core.

II. Hub-connected OWF operation

- This section provides an assessment of the generation and capture revenue of the hub-connected OWFs.
- Summary of findings:
  - The Core configuration results in lower capture revenues for the OWF of around 4-6% compared to the Wind Radial due to the NSWPH capture price being significantly lower compared to the onshore market prices (and mainly compared to the German prices).

III. IC operation

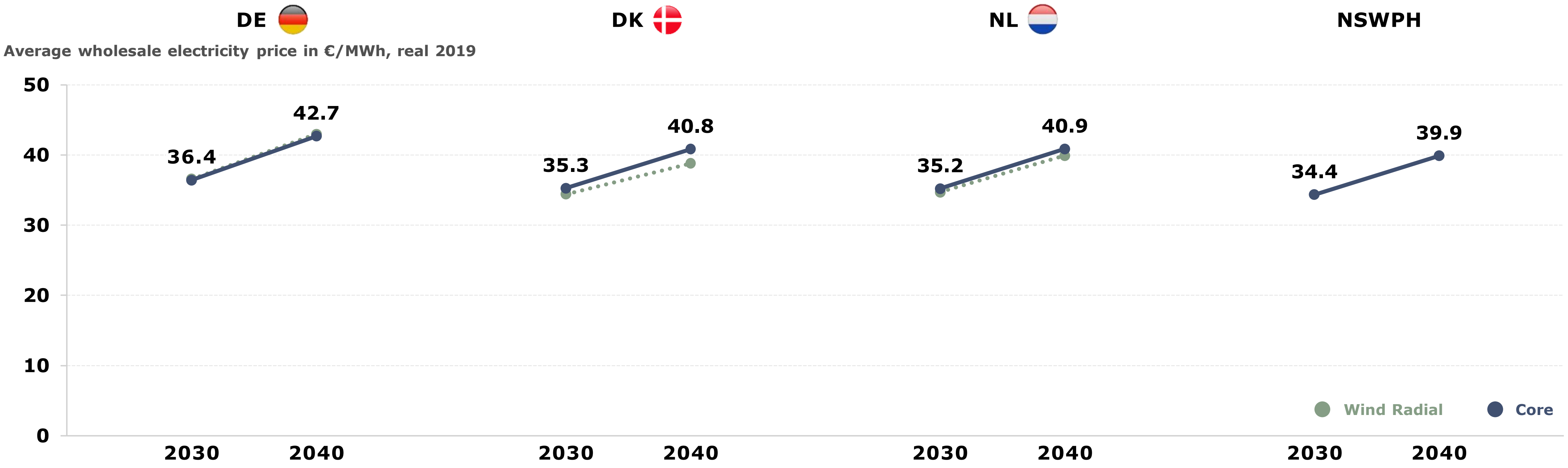
- This section provides an assessment of the operation of the NSWPH IC assets. Given the symmetry of the spokes between the hub and each market, which results in the same flow between the spokes connecting the same market, we present results for the total IC capacity.
- Summary of findings:
  - The ICs are primarily used to transport the hub-connected OWF generation to the national shores with the imports from the various national systems being a negligible part of the overall flows (i.e. less than 2% of the total flow).
  - Utilisation varies for the different spokes connecting the onshore systems to the hub – with the DE spoke used the most.

IV. Operation of within-hub connectors

- The section provides our assessment of the within-hub utilisation, presenting flow duration curves for all connectors and the required capacity of the internal lines to achieve copper plate operation. It also provides our analysis of the system stability to N-1 contingencies.
- Summary of findings:
  - Utilisation remains low across all connectors, in line with the market modelling results.
  - Required capacity on each line is 675MW, but the lines only reach this threshold for a limited number of periods. The system is stable to all internal transmission contingencies if line capacity is above 844MW.

ANNUAL AVERAGE DAY-AHEAD WHOLESALE ELECTRICITY PRICES

National prices are more or less the same under the Core and Wind Radial cases, with the NSWPH (OBZ) price generally below onshore market prices



COMMENTS

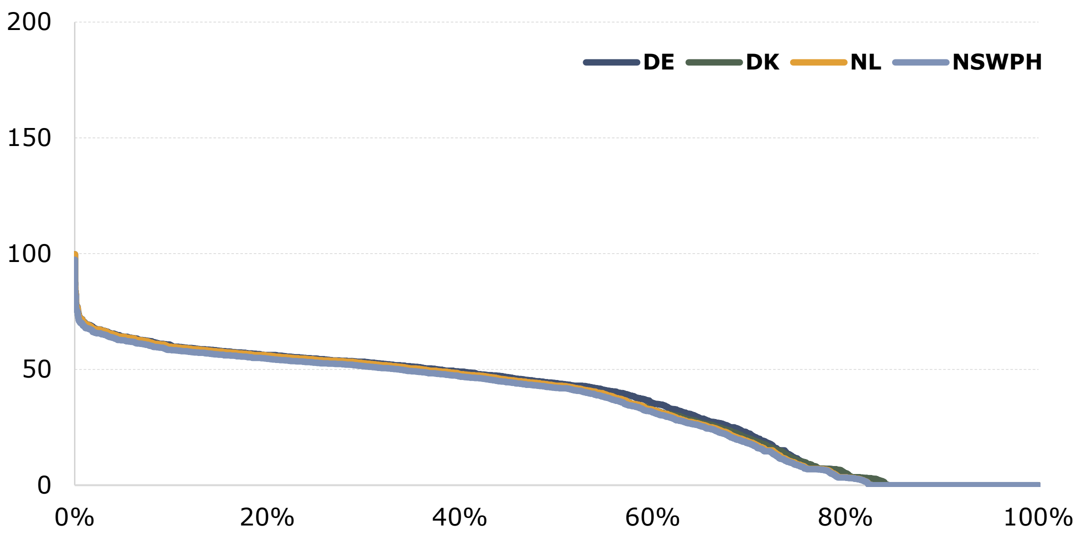
- The chart shows the average wholesale electricity price for the Core markets and the NSWPH for 2030 and 2040, comparing them against the Wind Radial case.
- With increased cross-zonal capacity under the Core configuration (compared to the Wind Radial), German wholesale prices are expected to (marginally) decrease as more flows go towards the German market. Conversely, Dutch and Danish prices are expected to (marginally) increase in the Core configuration.
- The NSWPH electricity prices are determined – at an hourly level – by the prices in its neighbouring markets. The average annual price that results for the NSWPH is lower than prices in the three Core markets.

PRICE DURATION CURVE (PDC) OF DAY-AHEAD WHOLESALE ELECTRICITY PRICES

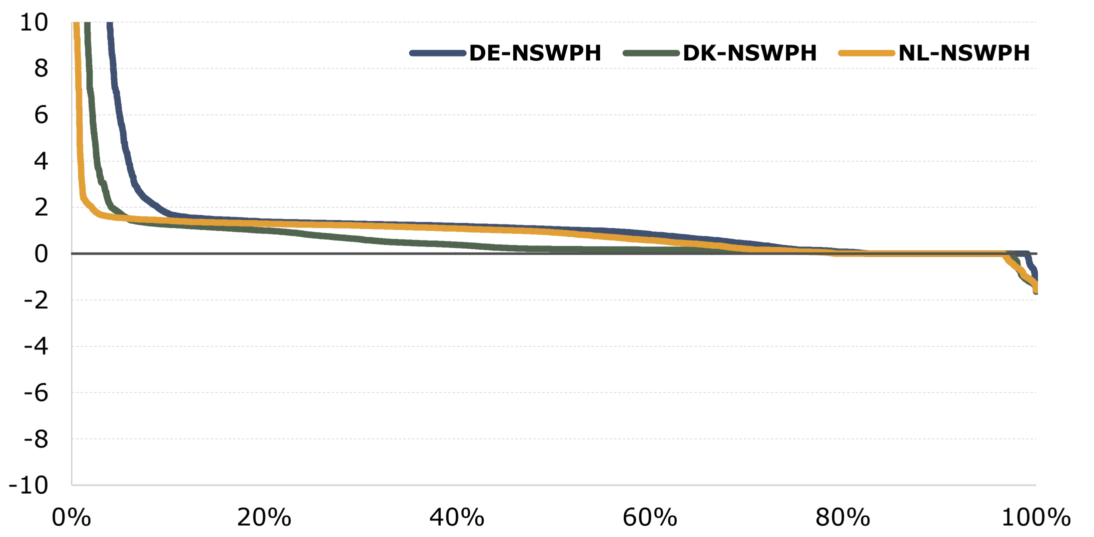
Hourly prices are very similar between the three Core markets with limited price spreads in 2030

PRICE DURATION CURVES IN 2030

€/MWh, real 2019 – incl. all weather years (i.e. 26,280 hours)



DURATION CURVES OF PRICE SPREADS IN 2030



	DE	DK	NL
% of low-priced periods (1)	17%	16%	18%
% of high-priced periods (1)	0%	0%	0%
% of time spreads lower than €2/MWh	91%	96%	98%

COMMENTS

- Price shapes are very similar between the three Core markets with very limited spreads between these markets.
- Electricity prices remain below €2/MWh for around 17% of the time for all three markets with prices almost never reaching €100/MWh.

1. Here, prices below €2/MWh are considered as low-priced periods and prices over €100/MWh are considered as high-priced periods

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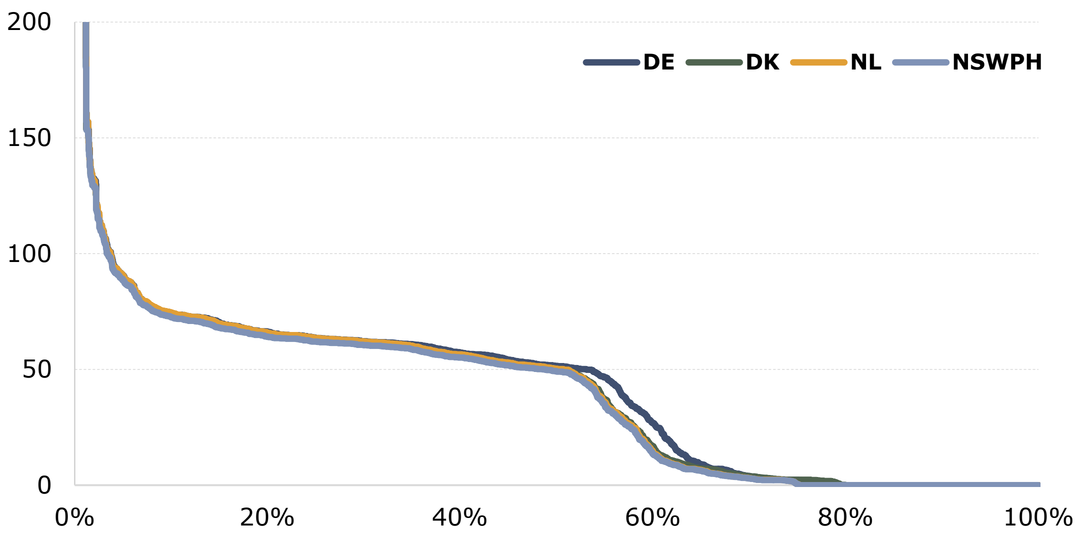
PRICE DURATION CURVE (PDC) OF DAY-AHEAD WHOLESALE ELECTRICITY PRICES

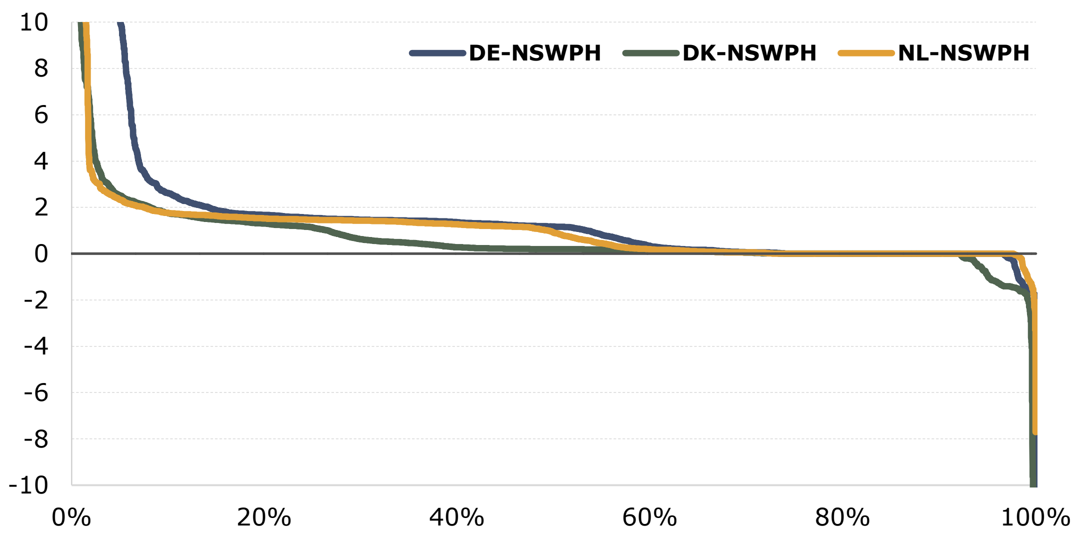
Hourly prices are similar between the three Core markets in 2040, with spreads increasing compared to 2030 – although remaining limited overall

PRICE DURATION CURVES IN 2040

€/MWh, real 2019 – incl. all weather years (i.e. 26,280 hours)



DURATION CURVES OF PRICE SPREADS IN 2040



	DE	DK	NL
% of low-priced periods (1)	**24%**	**23%**	**26%**
% of high-priced periods (1)	**4%**	**3%**	**4%**
% of time spreads lower than €2/MWh	**86%**	**91%**	**92%**

COMMENTS

- Price shapes are very similar between the three Core markets with spreads increasing between the markets; although remaining still somewhat limited.
- Electricity prices remain below €2/MWh for around 24% of the time for all three markets – driven by the higher RES penetration levels as explained previously. However, prices rise above €100/MWh around 4% of the time.

1. Here, prices below €2/MWh are considered as low-priced periods and prices over €100/MWh are considered as high-priced periods

OPERATION OF HUB-CONNECTED OWF

OWF capture revenues are 4% lower under the Core versus the Wind Radial operation in 2030

		Core	Wind Radial		
		NSWPH	DE	DK	NL
Volumes	**Available generation at the respective bidding zones** i.e. accounting for the losses on the transmission cables	50.10 TWh	24.47	8.16	16.31
			48.94 TWh		
Volumes	**Generation post economic curtailment, at the respective bidding zones** i.e. accounting for the volumes that need to be curtailed in each bidding zone	48.67 TWh (46.30%)	24.00	8.12	15.88
			47.99 TWh (45.65%)		
Volumes	**Curtailment volume at the respective bidding zones** i.e. resulting from rational economic dispatch of renewable generation, rather than driven by onshore transmission system issues and / or local constraints	1.43 TWh	0.47	0.04	0.43
			0.94 TWh		
Revenue	**Capture price in €/MWh, real 2019**	€24.70/MWh	€27.81/MWh	€24.16/MWh	€24.86/MWh
Revenue	**Overall hub-connected OWF capture revenue in million Euros, real 2019**	€1,202m	€1,258m		

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OPERATION OF HUB-CONNECTED OWF

OWF capture revenues are 6% lower under the Core versus the Wind Radial operation in 2040

		Core	Wind Radial		
		NSWPH	DE	DK	NL
Volumes	**Available generation at the respective bidding zones** i.e. accounting for the losses on the transmission cables	50.10 TWh	24.47	8.16	16.31
			48.94 TWh		
Volumes	**Generation post economic curtailment, at the respective bidding zones** i.e. accounting for the volumes that need to be curtailed in each bidding zone	49.54 TWh (47.13%)	24.37	8.16	16.18
			48.71 TWh (46.33%)		
Volumes	**Curtailment volume at the respective bidding zones** i.e. resulting from rational economic dispatch of renewable generation, rather than driven by onshore transmission system issues and / or local constraints	0.55 TWh	0.10	0.00	0.13
			0.23 TWh		
Revenue	**Capture price in €/MWh, real 2019**	€22.45/MWh	€26.82/MWh	€21.91/MWh	€21.95/MWh
Revenue	**Overall hub-connected OWF capture revenue in million Euros, real 2019**	€1,112m	€1,188m		

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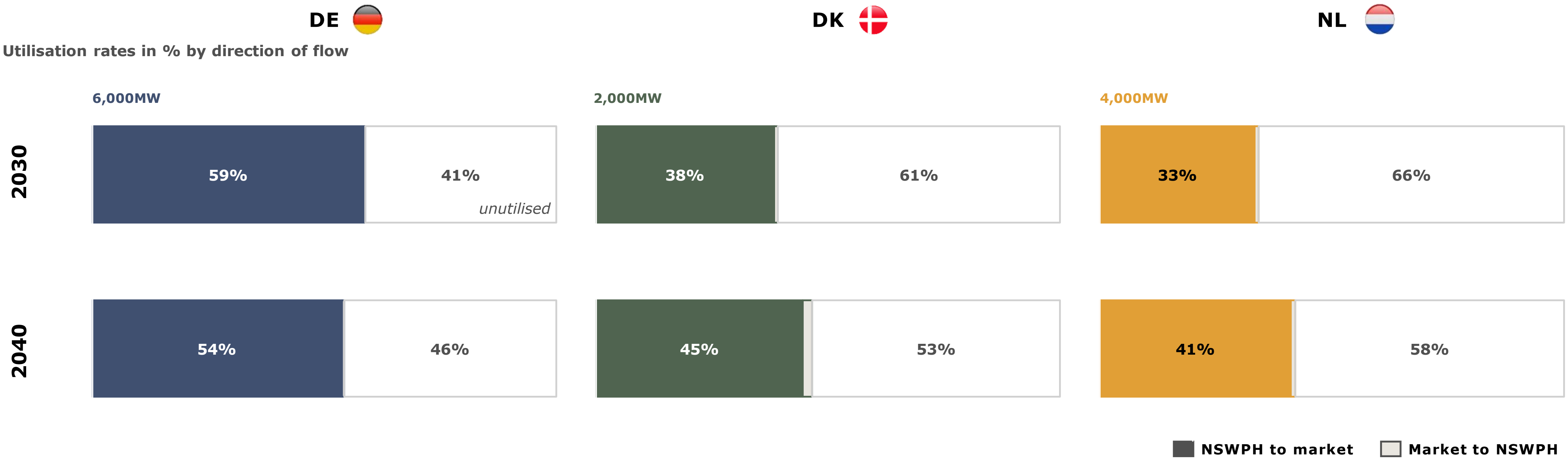
USAGE OF TRANSMISSION ASSETS

Higher utilisation on the German spoke generally in response to relatively higher German prices, with more balanced use across spokes in 2040



COMMENTS

- The charts show the utilisation rates of the transmission assets by direction, defined as the physical flow accounting for losses divided by the capacity of each spoke.
- Utilisation varies for the different spokes connecting the onshore systems to the hub. For example, the NSWPH-DE spoke is used for c. 59% of the time in 2030, primarily to transfer the hub-connected OWF generation to the German shore where the price signal is stronger. This leads to lower utilisation on the Danish and Dutch spokes.
- The trend is more balanced in 2040 where we see more use of the Danish and Dutch spokes due to more price convergence in the Core markets especially in periods of low prices and some tighter periods where Netherlands and Denmark set the price higher than Germany.

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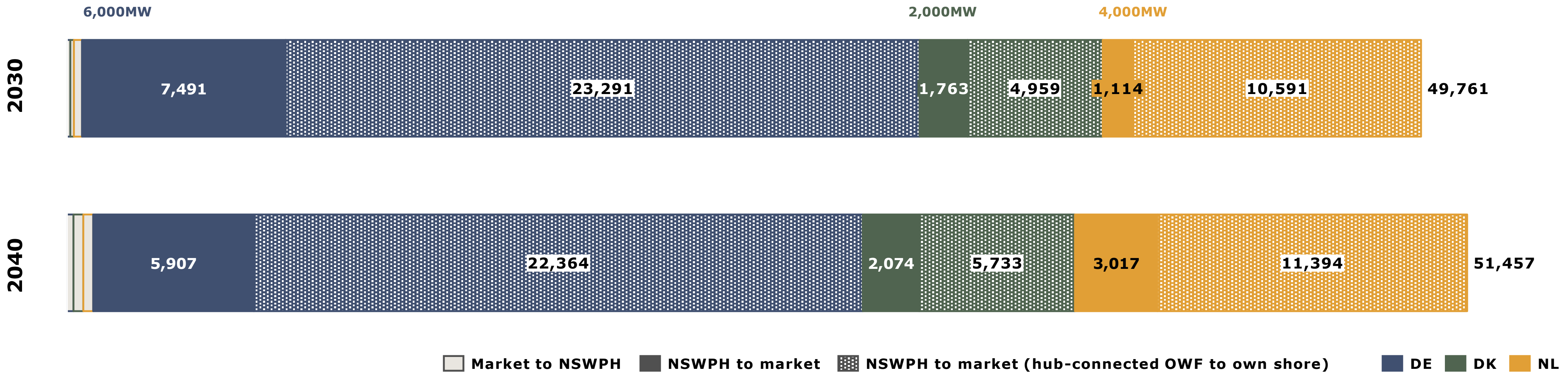
USAGE OF TRANSMISSION ASSETS

Transmission of hub-connected OWF to the onshore systems is the main source of flow, with negligible flows from the various markets to the hub

Annual physical cross-zonal flows in GWh, incl. losses, by direction



COMMENTS

- The chart shows the physical flows accounting for losses on the transmission assets, as triggered by electricity price spreads, at the day-ahead stage.
- Please refer to section 'Utilisation of IC assets based on the market modelling' in the Annex for an explanation and an example of how to read this chart.
- The majority of the flows (c. 80% of the overall flows) are related to the hub-connected OWF generation flowing to each respective onshore systems and mainly to Germany, i.e. without flowing via the hub-internal connectors (i.e. pattern-filled areas).
- The flows originating from the national markets to the hub on the left part of the chart are negligible (less than 2% of the overall flow) due to the limited spreads between the markets and therefore a relatively weak price signal.

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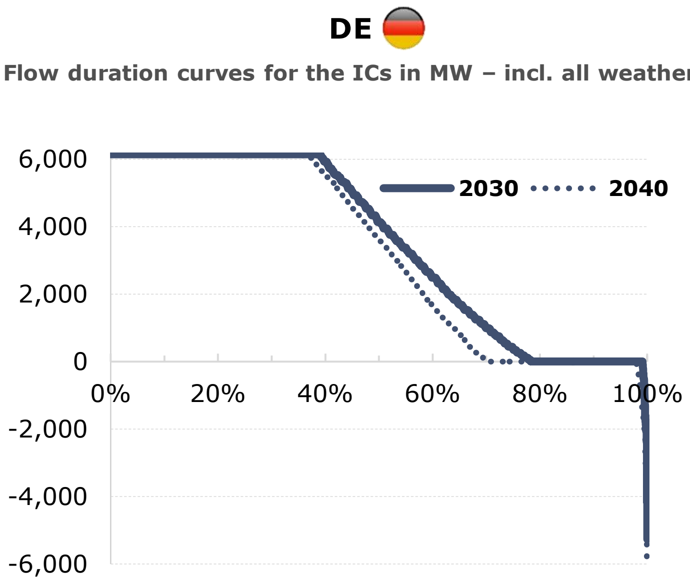
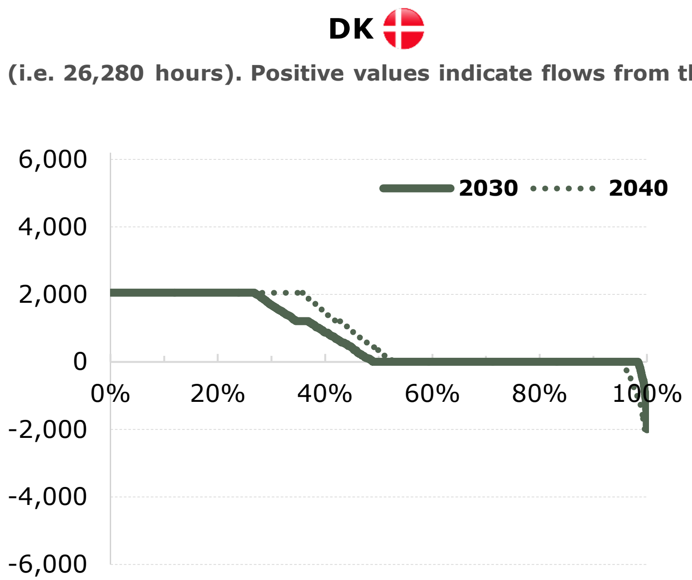
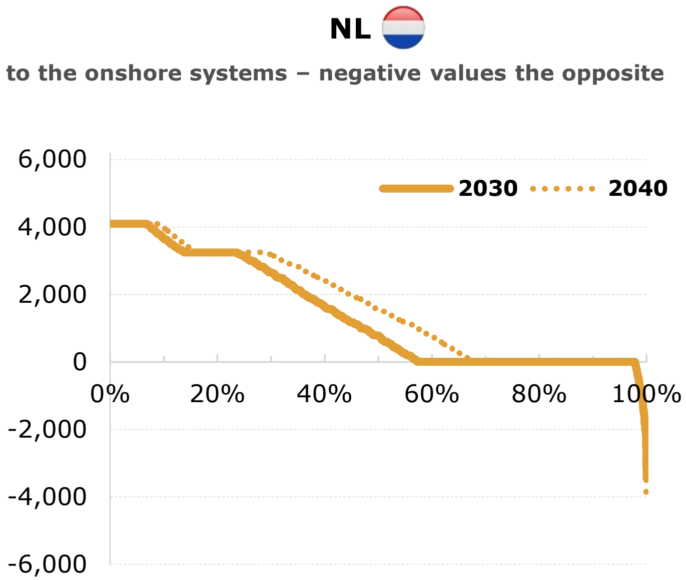
USAGE OF TRANSMISSION ASSETS

German spokes are used for a significant amount of time at their full capacity while the Danish and Dutch spokes have a lower usage

Flow duration curves for the ICs in MW – incl. all weather years (i.e. 26,280 hours). Positive values indicate flows from the hub to the onshore systems – negative values the opposite







COMMENTS

- The charts show the flow duration curve of the total interconnection between the hub and the Core markets in the direction from the hub to the national shores i.e. positive numbers represent flows going from the hub to the national systems and negative numbers represent flows going from the national systems to the hub.
- As seen previously, there are very limited flows in the direction from the national shores to the hub. The ICs are mainly used to transfer the hub-connected OWF to the national systems.
- The German spokes are used for around 40% at their full capacity. The Danish and Dutch spokes are used at full capacity for around 30% and 10% respectively. The Danish and Dutch spokes remain unutilised for a longer period of time – i.e. around 40% compared to 20% for the German spokes.
- As explained above, utilisation among the different spokes is more balanced in 2040 where we expect to see more use of the Danish and Dutch spokes.

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1. Executive Summary
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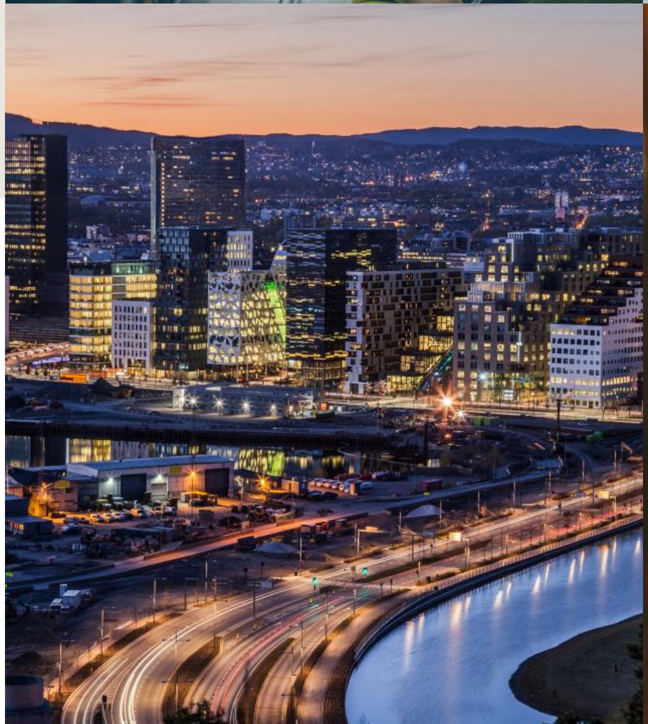
4. Core Increased IC
5. Core Plus
6. Home Market sensitivity



SUPPORTING INFORMATION

Introduction to the load flow results of the Core configuration

SUMMARY

Focus

- To describe the expected pattern of flows within the hub and identify key drivers and trends in utilisation;
- To obtain an expectation for the required capacity of the internal connecting lines to achieve copper plate operation and to identify any internal connectors which may be removed; and
- To understand the stability of the system to N-1 contingencies.

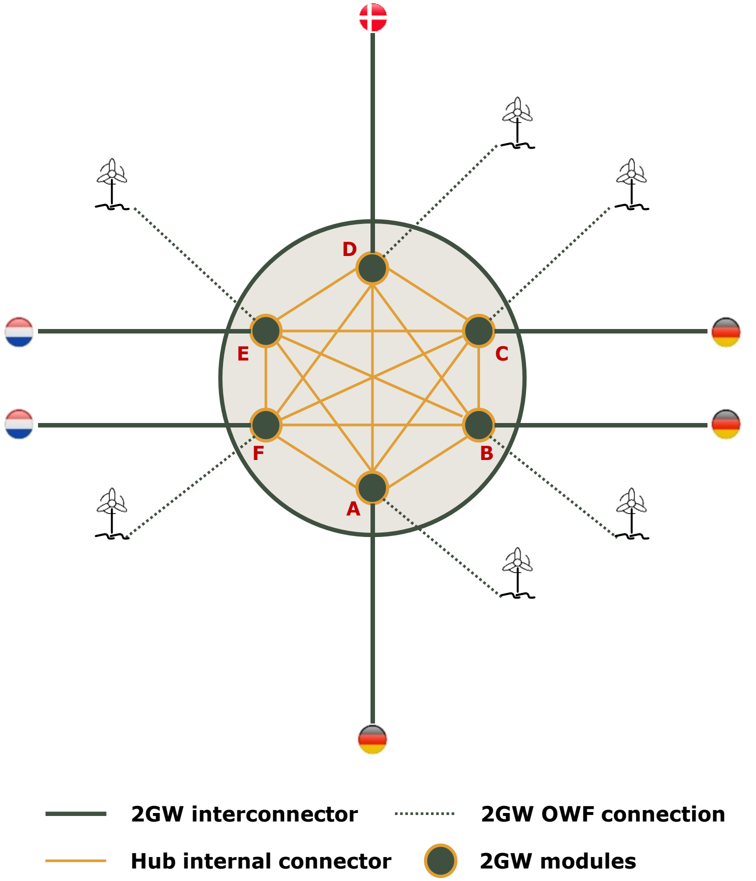
Approach & Assumptions

- Net position of the hourly flow at each 2GW module is based on the market modelling presented in the previous section.
- Hourly power flows within the hub have been determined using load flow modelling in BID3 via a calculated PTDF matrix.
- All hub-internal connectors are assumed to have identical physical characteristics; this results in equal flows on lines between same pairs of markets.

Messages

- Utilisation remains low across all connectors, in line with the market modelling results showing little use outside the transfer of wind to the connected markets.
- Required capacity on each line is 675MW, but the lines only reach this threshold for a limited number of periods. This required capacity is reduced to 342MW at times when the system acts purely as a generator (which happens more than 90% of the time).
- The system is stable to all internal transmission contingencies if line capacity is above 844MW. Lines between the same home markets always have zero flows however they enhance stability of the system.

SETUP USED FOR LOAD FLOW MODELLING

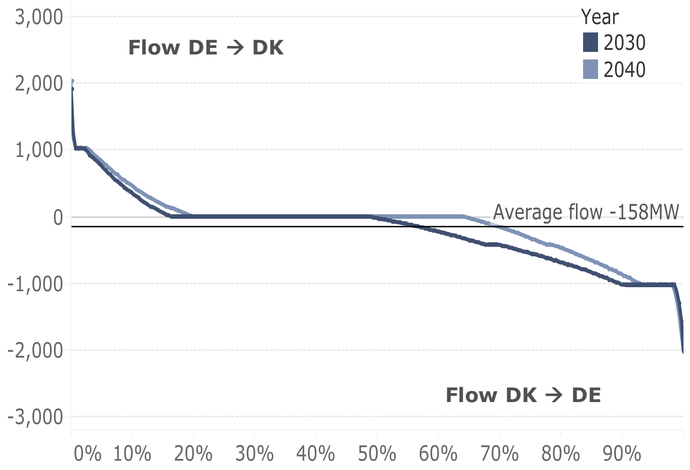


HUB INTERNAL FLOW DURATION CURVES

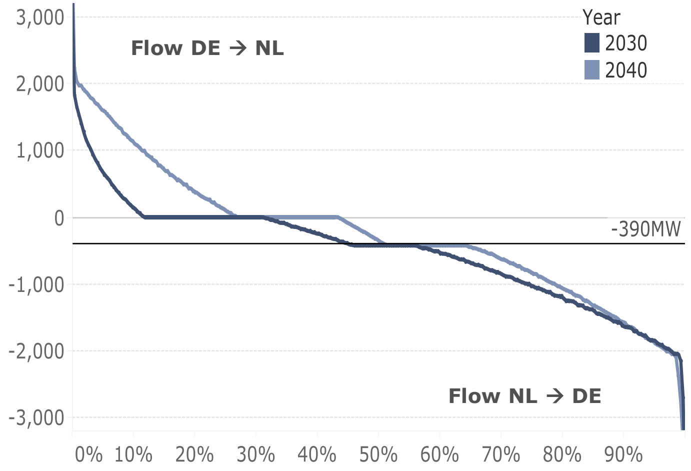
Low utilisation overall of the within-hub assets in line with the market modelling results

Flow duration curves for the hub-internal connectors in MW – incl. all weather years (i.e. 26,280 hours)

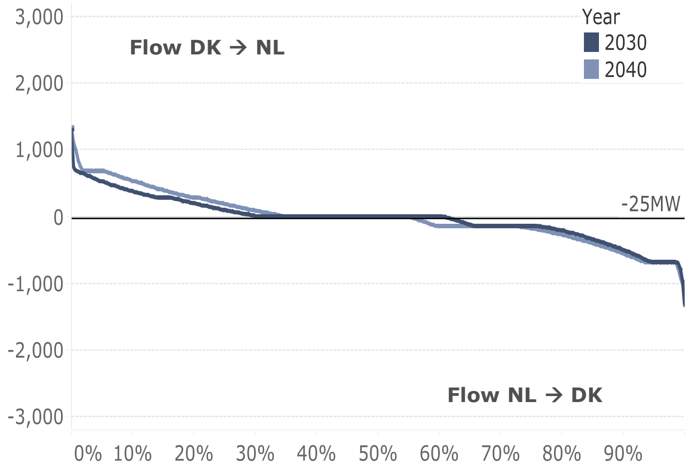
3 DE-DK CONNECTORS



6 DE-NL CONNECTORS



2 DK-NL CONNECTORS



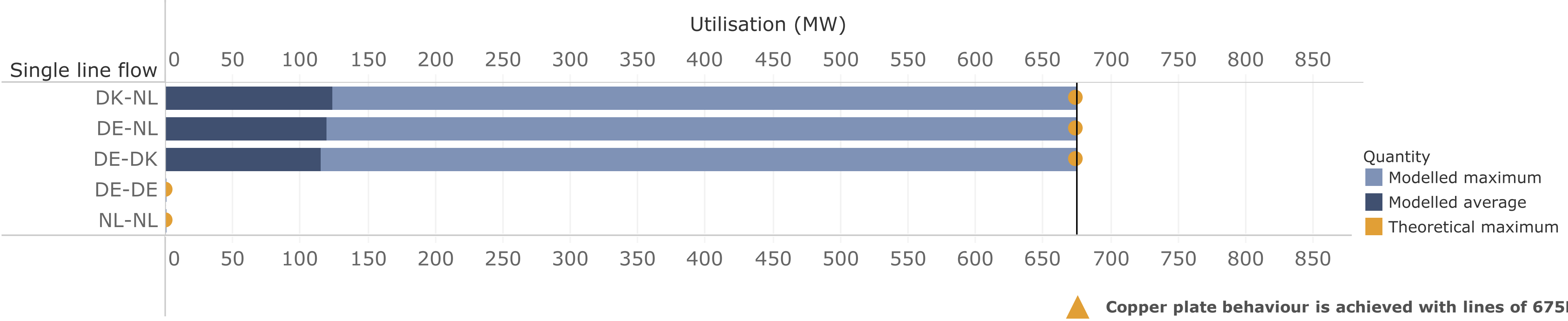
COMMENTS

- The charts show:
  - The total flow for all hub-internal connectors (1) connecting any two modules of the different Core markets, for 2030 (dark blue) and 2040 (light blue); and
  - The average flow over the two modelled years (black line).
- Utilisation remains generally low across all connectors. For example, the total flow on the DE-DK connectors is close to zero for more than 30% of the time in 2030; while the total flow on the DE-NL connectors remains zero for c. 20% of the time in 2030. This is in line with the market modelling results showing little use outside the transfer of wind to the connected markets.
- 2040 sees a transition to higher flows towards the NL modules (mainly from the DE modules). This is in line with the market modelling suggesting higher flows towards the NL shore (and lower flows towards the DE shore) in 2040 – driven by a more balanced IC use resulting from a stronger price convergence among the Core markets.

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-DK, they need to be divided by three.

MODELLED & THEORETICAL WITHIN HUB UTILISATION

All lines between modules of different markets are expected to reach the maximum theoretical flow of 675MW but only for a limited number of times



Copper plate behaviour is achieved with lines of 675MW capacity

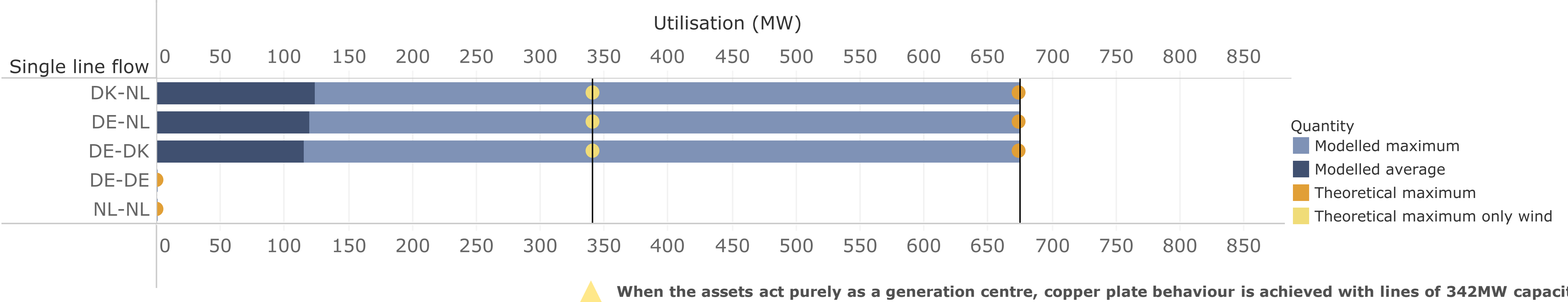
COMMENTS

- The chart plots two sets of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - The outputs of the load flow modelling in terms of average hourly flow on each within-hub connector (dark blue) and the maximum hourly flow on each within-hub connector (light blue) – regardless of direction (i.e. the absolute value of flow) over the two modelled years 2030/40.
  - With the orange marks, the calculated theoretical maximum flow on each hub-internal connector, as described in more detail in the 'Background to the load flow modelling & results' section in the Annex.
- Summary of findings:
  - All lines between modules of different markets reach the maximum theoretical flow of 675MW within the modelling. Maximum flows are only attained when the hub is used simultaneously as a wind generation asset and as a transmission asset, i.e. with both exports and imports to the different onshore systems (see Annex).
  - However, this happens rarely (i.e. around 4-6% of the time), leading to the threshold being reached 5 times in 2030 and 24 times by 2040 (average across weather years). 62% of the time this occurs when DK exports to the hub at full capacity.
  - All lines are assumed to be of the same capacity. This means that if the capacity of one connector were to be scaled down then the usage of all other connectors could be impacted.
  - Lines between modules of the same market (e.g. DE-DE) always have zero flows. Removing these lines does not change the utilisation of other lines. However, this can impact on N-1 security of the system (see 'Background to the load flow modelling & results' section in the Annex).

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

MODELLED & THEORETICAL WITHIN HUB UTILISATION

When the hub acts purely as a generation centre (i.e. no flows from any of the national shores), the maximum flow is at 342MW



When the assets act purely as a generation centre, copper plate behaviour is achieved with lines of 342MW capacity

COMMENTS

- Building on the analysis and the chart presented on the previous slide, this chart plots an additional set of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - With the yellow marks, the calculated theoretical maximum flow on each hub-internal connector when the assets act purely as a generation centre (i.e. no flow originating from the onshore systems), as described in more detail in the 'Background to the load flow modelling & results' section in the Annex. The market modelling suggests that this operation happens for 93% of the time.
- Summary of findings:
  - When the assets act purely as a generation centre, copper plate behaviour is achieved with lines of 342MW capacity.
  - Given that the hub acts for the majority of time purely as a generation centre (with flows from the national systems only appearing during a limited number of periods), it is worth exploring the impact of scaling down the capacity of the hub-internal connectors to this theoretical threshold of 342MW capacity.
  - In fact, flows surpassing the 342MW limit only occur on a minority of occasions. According to the market modelling a 342MW limit would be surpassed 317 times in 2030 and 469 times in 2040 (weather year average).

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

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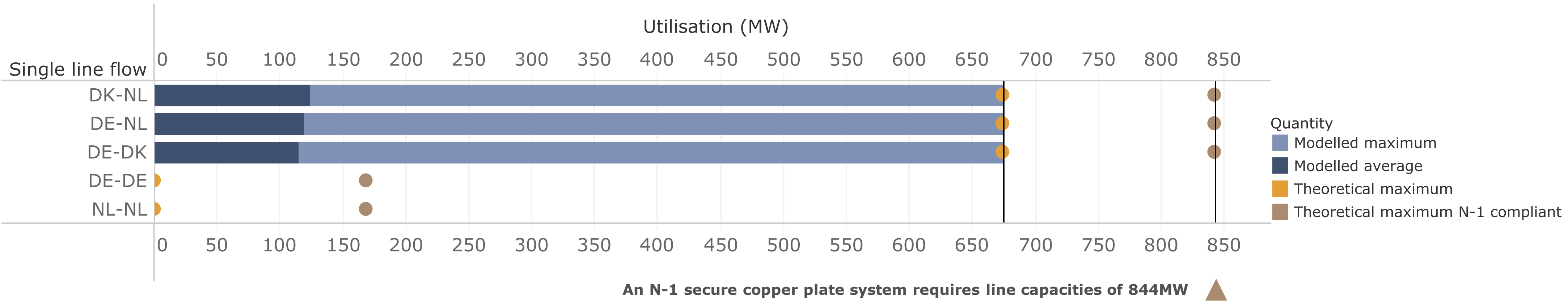
MODELLED & THEORETICAL WITHIN HUB UTILISATION & N-1 COMPLIANT

An N-1 secure copper plate system requires line capacities of 844MW



COMMENTS

- Building on the analysis and the chart presented on the previous slide, this chart plots an additional set of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - With the brown marks, the calculated theoretical maximum flow on each line when considering outages on any of the hub-internal connectors – under a "worst case scenario", i.e. resulting from the outage which has the greatest impact on the particular line.
- Summary of findings:
  - Considering outages on any of the hub-internal connectors increases the flow on the remaining lines as power would need to be redirected via the remaining operating lines.
  - An N-1 secure copper plate system requires line capacities of 844MW.
  - (Although not shown on the chart), removing the lines between modules associated to the same markets (e.g. a line between the NL-NL modules) increases the required line capacity for N-1 security to 1,040MW as the possibility for redirecting flows is further reduced.
- Additional N-1 contingency analysis for the Core configuration is provided in the Annex – 'Background to the load flow modelling & results' section.

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

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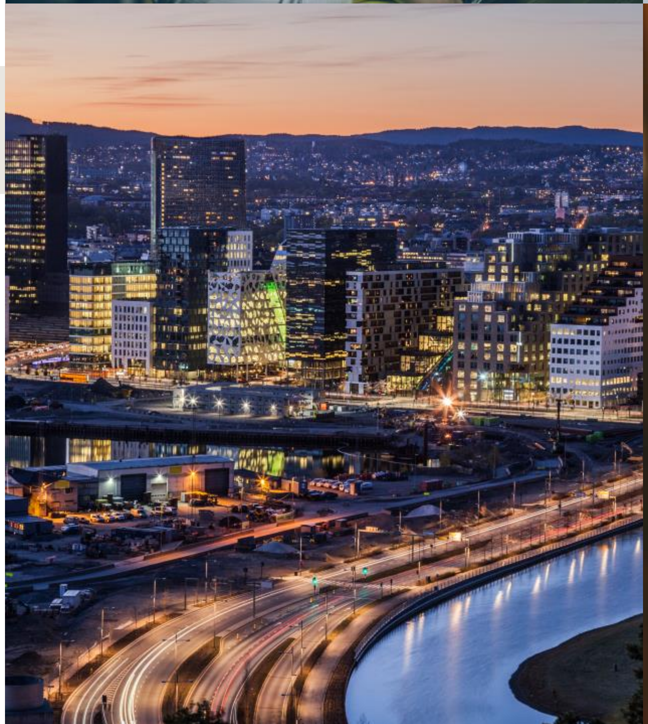


SUPPORTING INFORMATION

Introduction to the Core Increased IC configuration results

I. Market-wide results

- This section focuses on a range of market indicators and provides comparisons of the Core Increased IC configuration against the Wind Radial. This background information supports and helps explain NSWPH specific operation patterns and outcomes.
- Summary of findings:
  - Baseload electricity prices remain at similar levels between the two configurations; with a marginal increase of the DK & NL prices, and a marginal decrease of the DE prices under the Core Increased IC.

II. Hub-connected OWF operation

- This section provides an assessment of the generation and capture revenue of the hub-connected OWFs.
- Summary of findings:
  - The Core Increased IC configuration results in similar capture revenues for the OWF compared to the Wind Radial (with the difference being less than 0.5%). While the NSWPH capture price is lower than the German prices, it remains higher than the Danish and Dutch capture prices – these two effects counterbalance each other resulting in similar overall revenues.

III. IC operation

- This section provides an assessment of the operation of the NSWPH IC assets – with results presented for the total IC capacity between the hub and each of the Core markets.
- Summary of findings:
  - The ICs are primarily used to transport the hub-connected OWF generation to the national shores with the imports from the various national systems being a negligible part of the overall flows (i.e. close to 2% of the total flow).
  - Utilisation varies for the different spokes connecting the onshore systems to the hub – with the DK & NL rates significantly low.

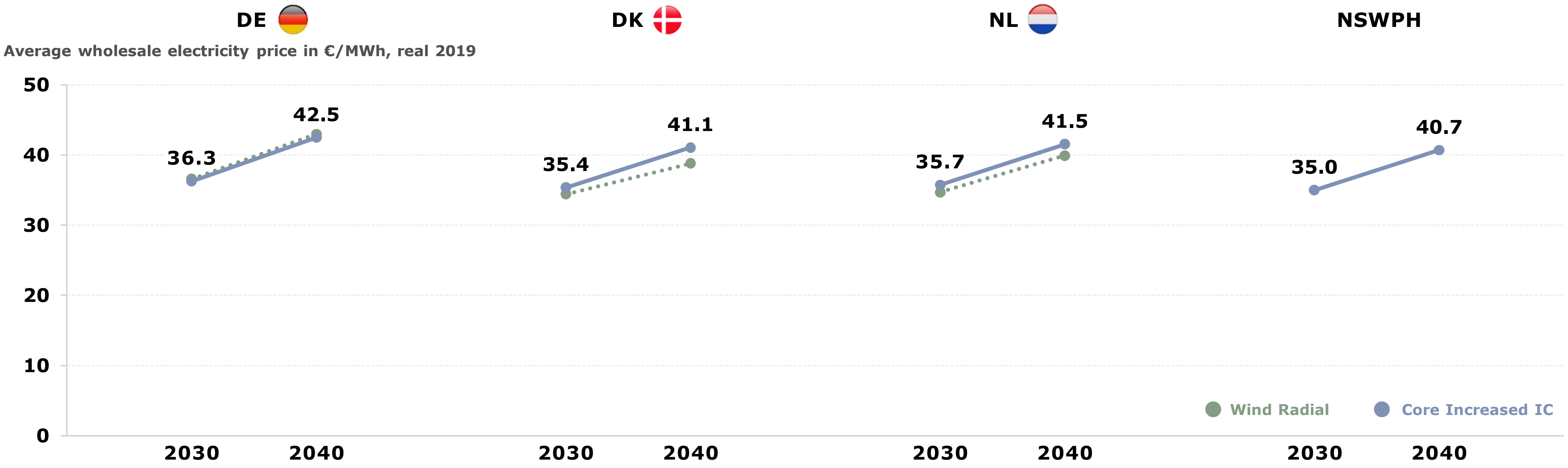
IV. Operation of within-hub connectors

- The section provides our assessment of the within-hub utilisation, presenting flow duration curves for all connectors and the required capacity of the internal lines to achieve copper plate operation. It also provides our analysis of the system stability to N-1 contingencies.
- Summary of findings:
  - Utilisation remains low across all connectors, in line with the market modelling results.
  - Required capacity on each line is 642MW, but the lines never reach this threshold. The system is stable to all internal transmission contingencies if line capacity is above 733MW.

AFRY ÅF PÖYRY

ANNUAL AVERAGE DAY-AHEAD WHOLESALE ELECTRICITY PRICES

Impact on national electricity prices remains limited, with the NSWPH (OBZ) price generally below onshore market prices



COMMENTS

- The chart shows the average wholesale electricity price for the Core markets and the NSWPH for 2030 and 2040 – comparing them against the Wind Radial case.
- With increased cross-zonal capacity under the Core Increased IC configuration (compared to the Wind Radial), German wholesale prices are expected to (marginally) decrease as more flows go towards the German market. Conversely, Dutch and Danish prices are expected to (marginally) increase in this configuration.
- The NSWPH electricity prices are determined – at an hourly level – by the prices in its neighbouring markets. The average annual price that results for the NSWPH is lower than prices in the three Core markets.

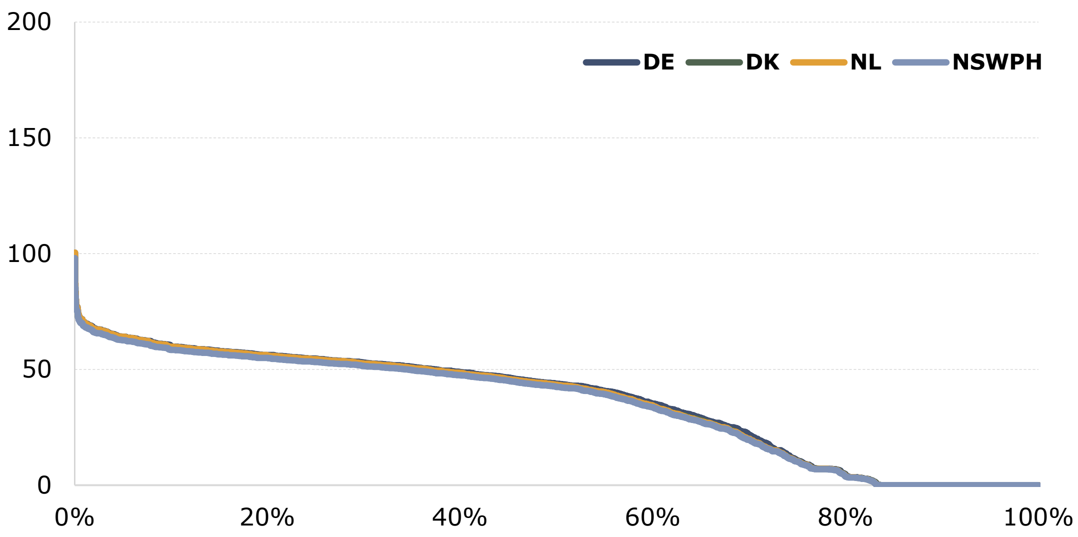
AFRY ÅF PÖYRY

PRICE DURATION CURVE (PDC) OF DAY-AHEAD WHOLESALE ELECTRICITY PRICES

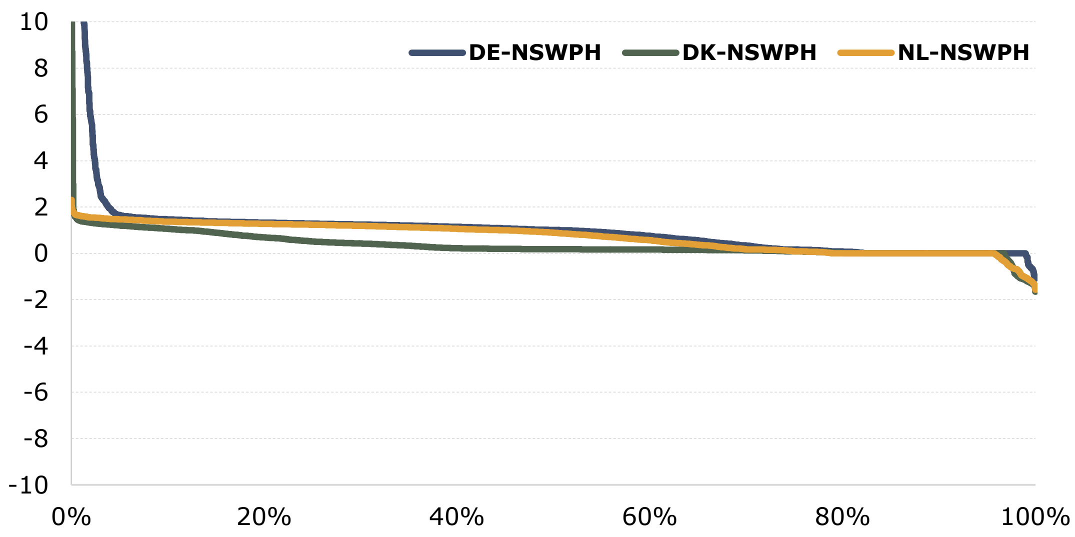
Hourly prices are very similar between the three Core markets with limited price spreads in 2030

PRICE DURATION CURVES IN 2030

€/MWh, real 2019 – incl. all weather years (i.e. 26,280 hours)



DURATION CURVES OF PRICE SPREADS IN 2030



	DE	DK	NL
% of low-priced periods (1)	17%	17%	17%
% of high-priced periods (1)	0%	0%	0%
% of time spreads lower than €2/MWh	100%	96%	100%

COMMENTS

- Price shapes are very similar between the three Core markets with very limited spreads between these markets.
- Electricity prices remain below €2/MWh for around 17% of the time for all three markets with prices almost never reaching €100/MWh.

1. Here, prices below €2/MWh are considered as low-priced periods and prices over €100/MWh are considered as high-priced periods.

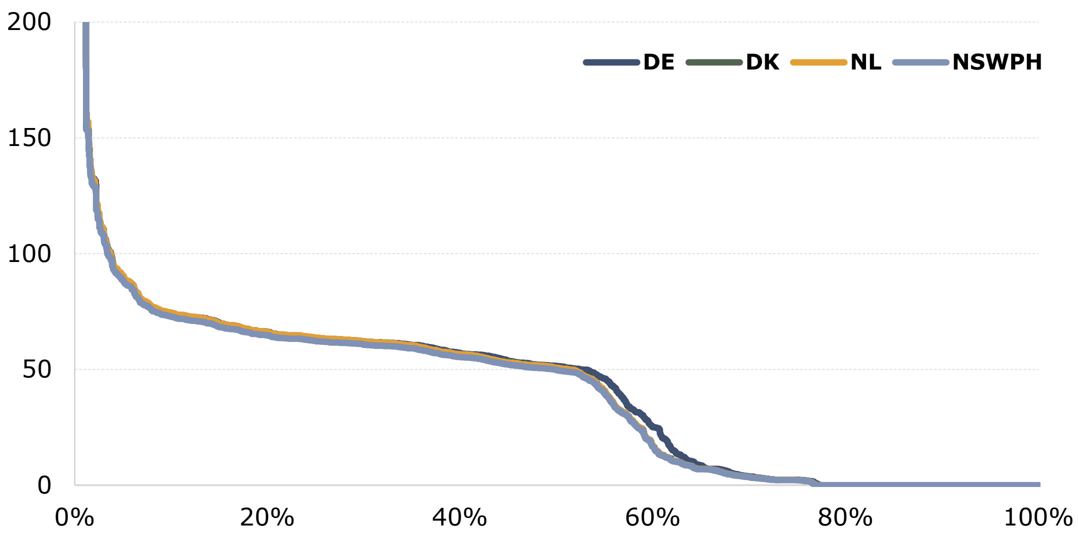
AFRY ÅF PÖYRY

PRICE DURATION CURVE (PDC) OF DAY-AHEAD WHOLESALE ELECTRICITY PRICES

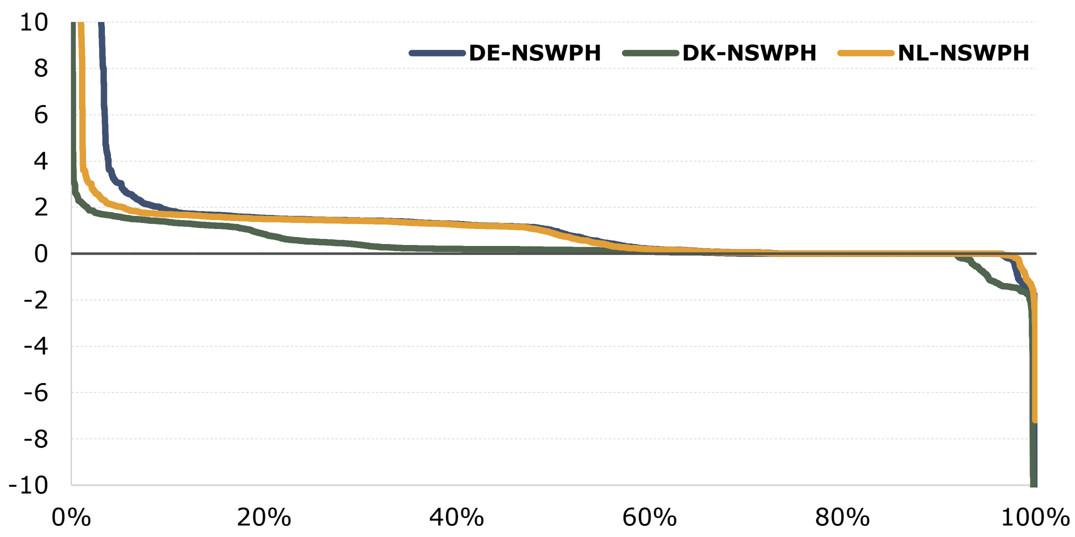
Hourly prices are similar between the three Core markets in 2040, with spreads marginally increasing compared to 2030 – but remaining limited

PRICE DURATION CURVES IN 2040

€/MWh, real 2019 – incl. all weather years (i.e. 26,280 hours)



DURATION CURVES OF PRICE SPREADS IN 2040



	DE	DK	NL
% of low-priced periods (1)	24%	24%	24%
% of high-priced periods (1)	3%	3%	4%
% of time spreads lower than €2/MWh	98%	91%	95%

COMMENTS

- Price shapes are very similar between the three Core markets with spreads increasing between the markets; although remaining still somewhat limited.
- Electricity prices remain below €2/MWh for around 24% of the time for all three markets – driven by the higher RES penetration levels as explained previously. However, prices rise above €100/MWh around 3% of the time.

1. Here, prices below €2/MWh are considered as low-priced periods and prices over €100/MWh are considered as high-priced periods.

OPERATION OF HUB-CONNECTED OWF

OWF capture revenues are similar under the Core Increased IC versus the Wind Radial operation in 2030 (impact is smaller than 0.5%)

		Core Increased IC	Wind Radial		
		NSWPH	DE	DK	NL
Volumes	**Available generation at the respective bidding zones** i.e. accounting for the losses on the transmission cables	50.10 TWh	24.47	8.16	16.31
			48.94 TWh		
Volumes	**Generation post economic curtailment, at the respective bidding zones** i.e. accounting for the volumes that need to be curtailed in each bidding zone	48.76 TWh (46.38%)	24.00	8.12	15.88
			47.99 TWh (45.65%)		
Volumes	**Curtailment volume at the respective bidding zones** i.e. resulting from rational economic dispatch of renewable generation, rather than driven by onshore transmission system issues and / or local constraints	1.34 TWh	0.47	0.04	0.43
			0.94 TWh		
Revenue	**Capture price in €/MWh, real 2019**	€25.92/MWh	€27.81/MWh	€24.16/MWh	€24.86/MWh
Revenue	**Overall hub-connected OWF capture revenue in million Euros, real 2019**	€1,264m	€1,258m		

AFRY ÅF PÖYRY

OPERATION OF HUB-CONNECTED OWF

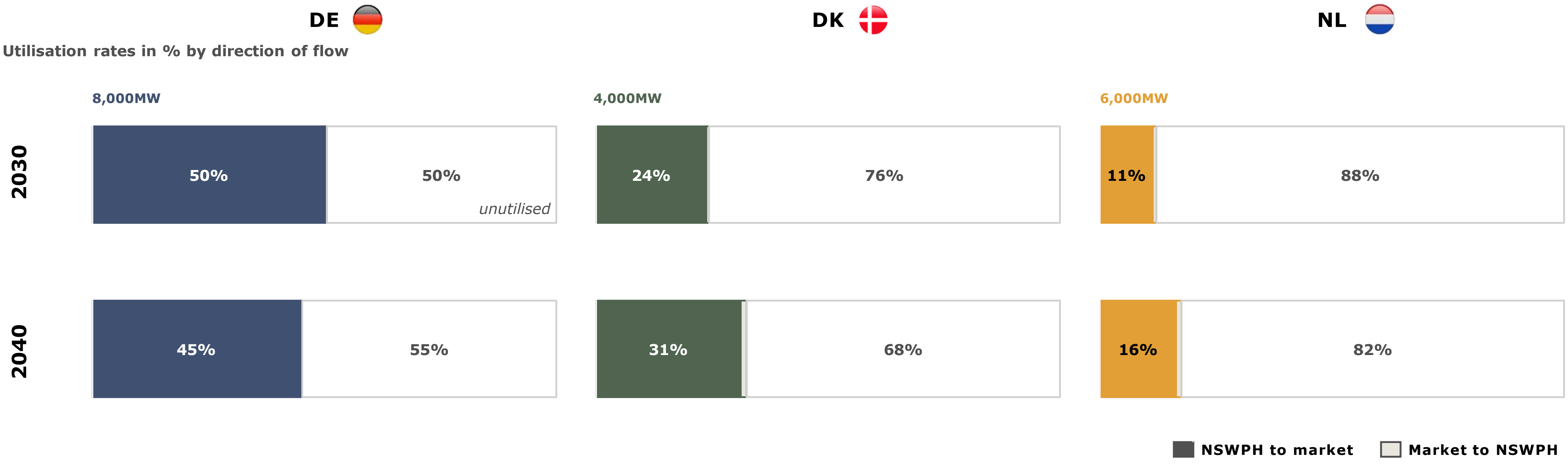
OWF capture revenues are similar under the Core Increased IC versus the Wind Radial operation in 2040 (impact is smaller than 0.2%)

		Core Increased IC	Wind Radial		
		NSWPH	DE	DK	NL
Volumes	**Available generation at the respective bidding zones** i.e. accounting for the losses on the transmission cables	50.10 TWh	24.47	8.16	16.31
			48.94 TWh		
Volumes	**Generation post economic curtailment, at the respective bidding zones** i.e. accounting for the volumes that need to be curtailed in each bidding zone	49.71 TWh (47.29%)	24.37	8.16	16.18
			48.71 TWh (46.33%)		
Volumes	**Curtailment volume at the respective bidding zones** i.e. resulting from rational economic dispatch of renewable generation, rather than driven by onshore transmission system issues and / or local constraints	0.39 TWh	0.10	0.00	0.13
			0.23 TWh		
Revenue	**Capture price in €/MWh, real 2019**	€23.85/MWh	€26.82/MWh	€21.91/MWh	€21.95/MWh
Revenue	**Overall hub-connected OWF capture revenue in million Euros, real 2019**	€1,186m	€1,188m		

AFRY
ÅF PÖYRY

USAGE OF TRANSMISSION ASSETS

Higher utilisation on the German spoke generally in response to relatively higher German prices, with much lower use of the Danish and Dutch spokes



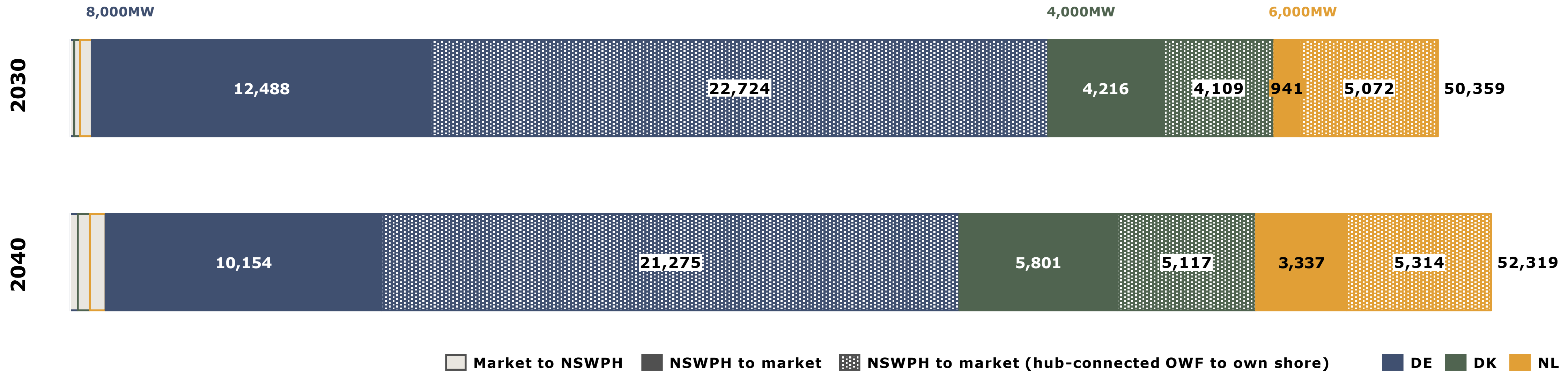
COMMENTS

- The charts show the utilisation rates of the transmission assets by direction, defined as the physical flow accounting for losses divided by the capacity of each spoke.
- Utilisation varies for the different spokes connecting the onshore systems to the hub. For example, the NSWPH-DE spoke (8GW) is used for c. 50% of the time in 2030, primarily to transfer the hub-connected OWFs generation to the German shore where the price signal is stronger. The greater use of the German spoke leads to a significantly lower utilisation on the Danish and Dutch spokes, as the limited price spreads between the Core markets do not justify the increase in IC capacity. Overall, there is very limited use linked to flows from the national systems to the hub.
- The trend is more balanced in 2040 when we see more use of the Danish and Dutch spokes due to more price convergence in the Core markets, especially in periods of low prices and some tighter periods where Netherlands and Denmark have a higher price than Germany.

USAGE OF TRANSMISSION ASSETS

Transmission of hub-connected OWF to the onshore systems is the main source of flow; with negligible flows from the various markets to the hub

Annual physical cross-zonal flows in GWh, incl. losses, by direction



COMMENTS

- The chart shows the physical flows accounting for losses on the transmission assets, as triggered by electricity price spreads, at the day-ahead stage.
- Please refer to section 'Utilisation of IC assets based on the market modelling' in the Annex for an explanation and an example of how to read this chart.
- The majority of the flows (c. 60% of the overall flows) are related to the hub-connected OWF generation flowing to each respective onshore systems and mainly to Germany, i.e. without flowing via the hub-internal connectors (i.e. pattern-filled areas).
- The flows originating from the national markets to the hub on the left part of the chart are negligible (c. 2% of the overall flow) due to the limited spreads between the markets and therefore a relatively weak price signal.

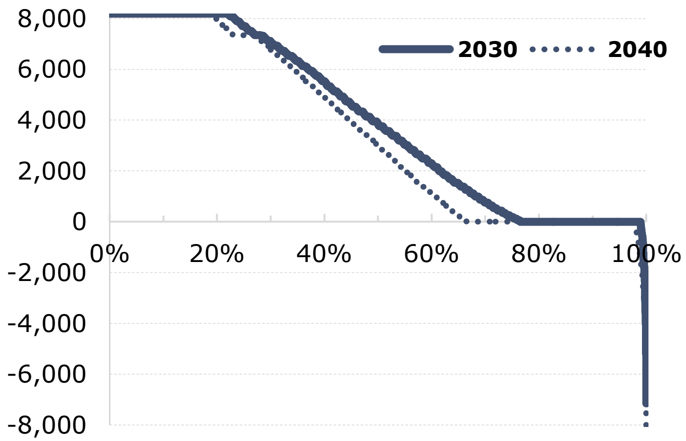
AFRY ÅF PÖYRY

USAGE OF TRANSMISSION ASSETS

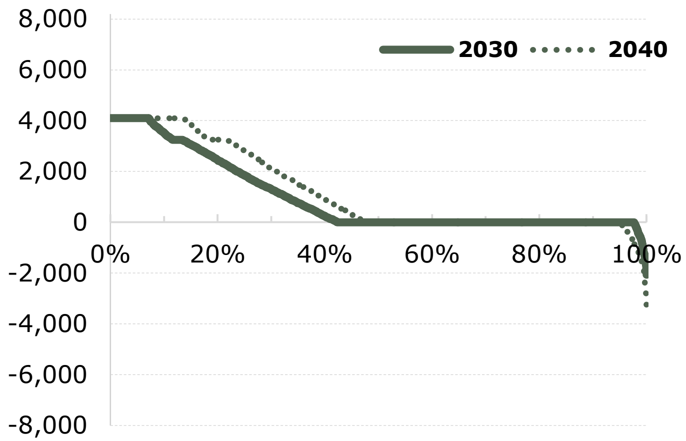
The DE spokes are used at their full capacity for c. 20% of the time, while the DK & NL spokes have a reduced use with the flow being zero for c. 50% of the time

Flow duration curves for the ICs in MW – incl. all weather years (i.e. 26,280 hours). Positive values indicate flows from the hub to the onshore systems – negative values the opposite

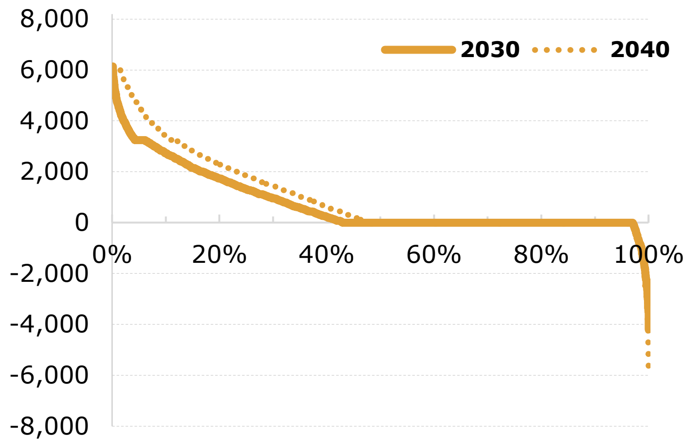
DE



DK



NL



COMMENTS

- The charts show the flow duration curve of the total interconnection between the hub and the Core markets in the direction from the hub to the national shores i.e. positive numbers represent flows going from the hub to the national systems and negative numbers represent flows going from the national systems to the hub.
- As seen previously, very limited flows in the direction from the national shores to the hub. The ICs are mainly used to transfer the hub-connected OWF to the national systems.
- The German spokes are used for around 20% at their full capacity. The Danish and Dutch spokes are used at full capacity for a very limited time. The Danish and Dutch spokes remain unutilised for a longer period of time – i.e. around 50% compared to 20% for the German spokes.
- As explained above, utilisation among the different spokes is more balanced in 2040, when we expect to see more use of the Danish and Dutch spokes.

Agenda

1. Executive Summary

2. Wind Radial

3. Core

4. **Core Increased IC**

   - **Load flow modelling results**

5. Core Plus

6. Home Market sensitivity

SUPPORTING INFORMATION

Introduction to the load flow results of the Core Increased IC configuration

SUMMARY

Focus

- To describe the expected pattern of flows within the hub and identify key drivers and trends in utilisation;
- To obtain an expectation for the required capacity of the internal connecting lines to achieve copper plate operation and to identify any internal connectors which may be removed; and
- To understand the stability of the system to N-1 contingencies.

Approach & Assumptions

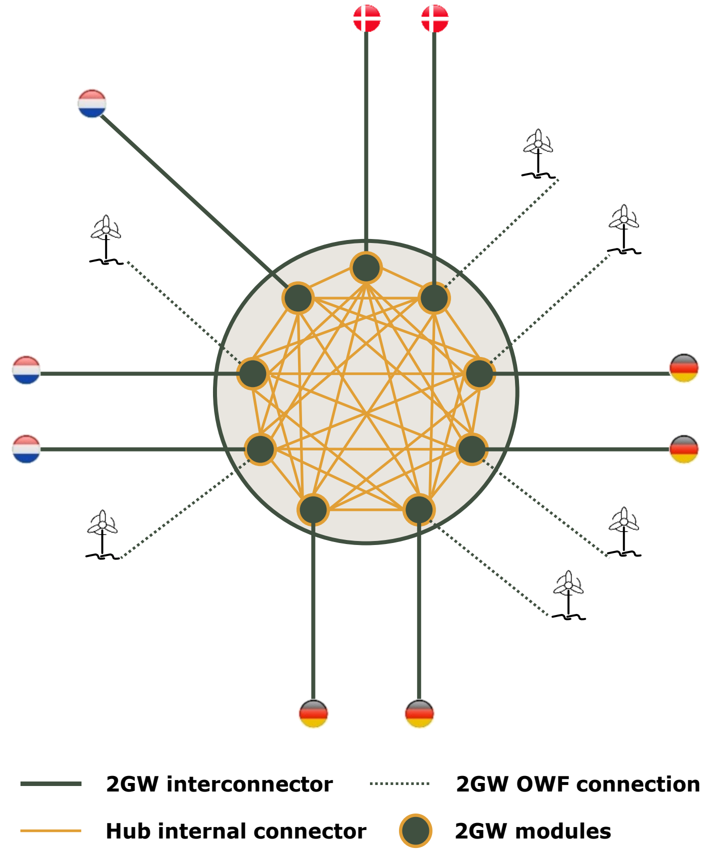
- Net position of the hourly flow at each 2GW module is based on the market modelling presented in the previous section. All ICs from the hub to the same shore have the same hourly flow – given that they have the same technical assumptions.
- Hourly power flows within the hub have been determined using load flow modelling in BID3 via a calculated PTDF matrix.
- All hub-internal connectors are assumed to have identical physical characteristics.

Messages

- Utilisation remains low across all connectors, in line with the market modelling results showing little use outside the transfer of wind to the connected markets.
- Required capacity on each line is 642MW, but the lines never reach this threshold (with maximum flow being 592MW). This required capacity is reduced to 450MW at times when the system acts purely as a generator (which happens more than 90% of the time).
- The system is stable to all internal transmission contingencies if line capacity is above 733MW.

SETUP USED FOR LOAD FLOW MODELLING

Note: the additional DE, DK & NL modules are not connected to an OWF

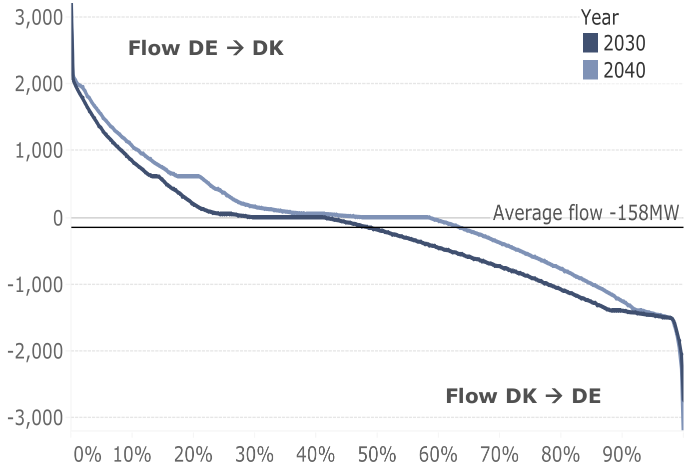


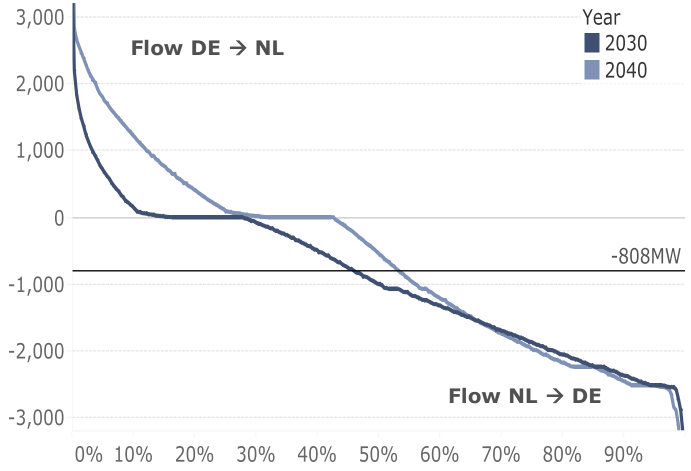
HUB INTERNAL FLOW DURATION CURVES

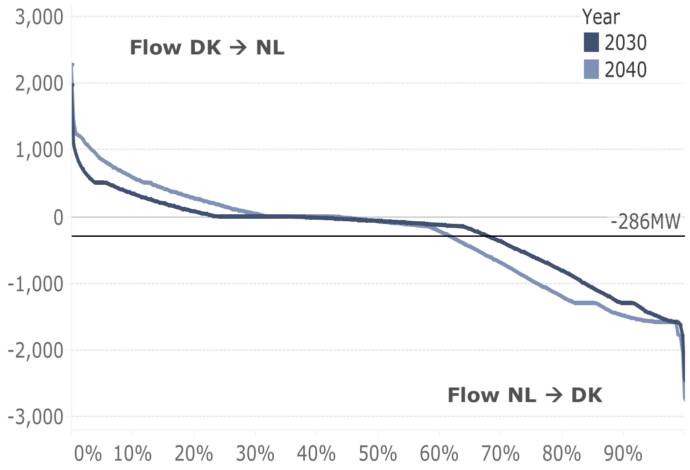
Low utilisation overall of the within-hub assets in line with the market modelling results

8 DE-DK CONNECTORS | **12 DE-NL CONNECTORS** | **6 DK-NL CONNECTORS**

Flow duration curves for the hub-internal connectors in MW – incl. all weather years (i.e. 26,280 hours)







COMMENTS

- The charts show:
  - The total flow for all hub-internal connectors (1) connecting any two modules of the different Core markets, for 2030 (dark blue) and 2040 (light blue); and
  - The average flow over the two modelled years (black line).
- Utilisation remains generally low across all connectors. For example, the total flow on the DE-DK connectors is close to zero for more than 20% of the time in 2030 and 30% by 2040. The total flow on the DE-NL connectors remains zero for c. 20% of the time in 2030 & 2040. This is in line with the market modelling results showing little use outside the transfer of wind to the connected markets (i.e. low use of the assets for transmission between markets).
- 2040 sees a transition to higher flows towards the NL modules (mainly from the DE modules). This is in line with the market modelling suggesting higher flows towards the NL shore (and lower flows towards the DE shore) in 2040 – driven by a more balanced IC use resulting from a stronger price convergence among the Core markets.

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-DK, they need to be divided by eight.

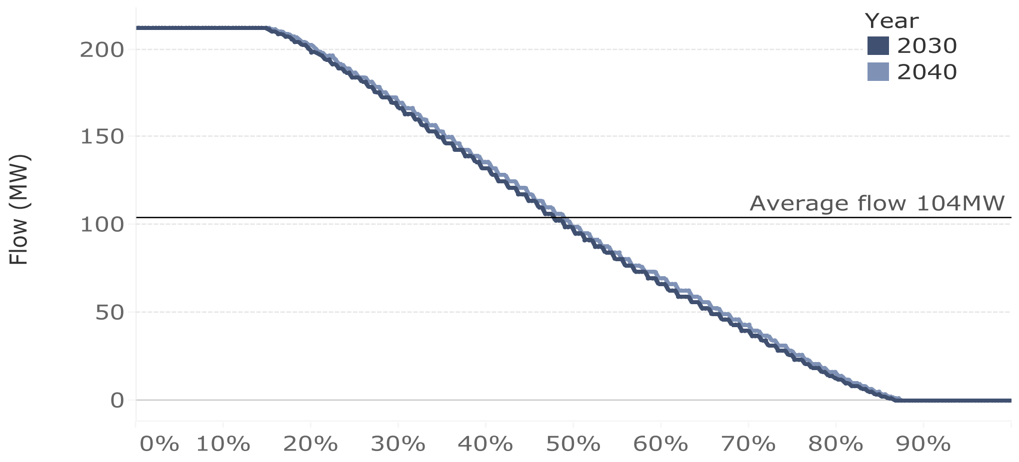
HUB INTERNAL FLOW DURATION CURVES

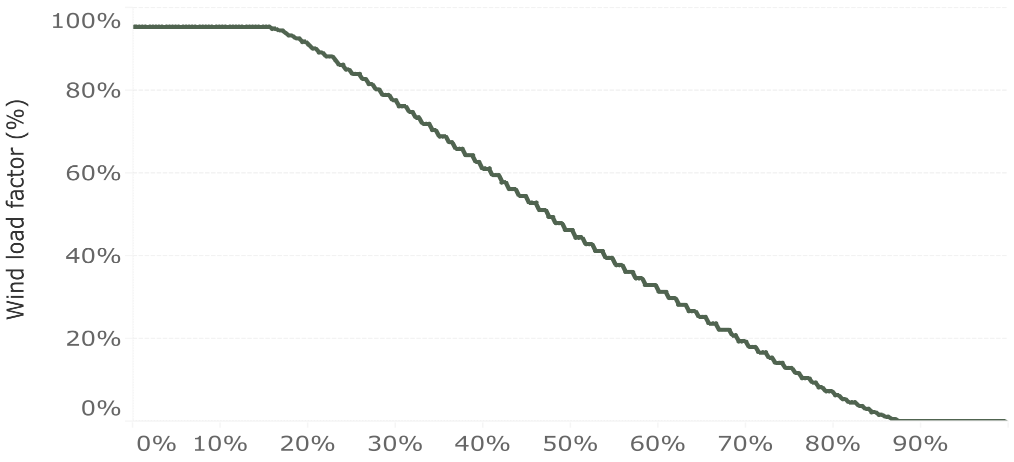
Flows on the lines between modules with and without wind farms associated to the same Core market are in proportion to the wind generation

EXAMPLE: DK (WIND)-DK (NO WIND) CONNECTORS

EXAMPLE: OWF LOAD FACTORS

Flow duration curves for the hub-internal connectors in MW – incl. all weather years (i.e. 26,280 hours) & OWF load factors in %





COMMENTS

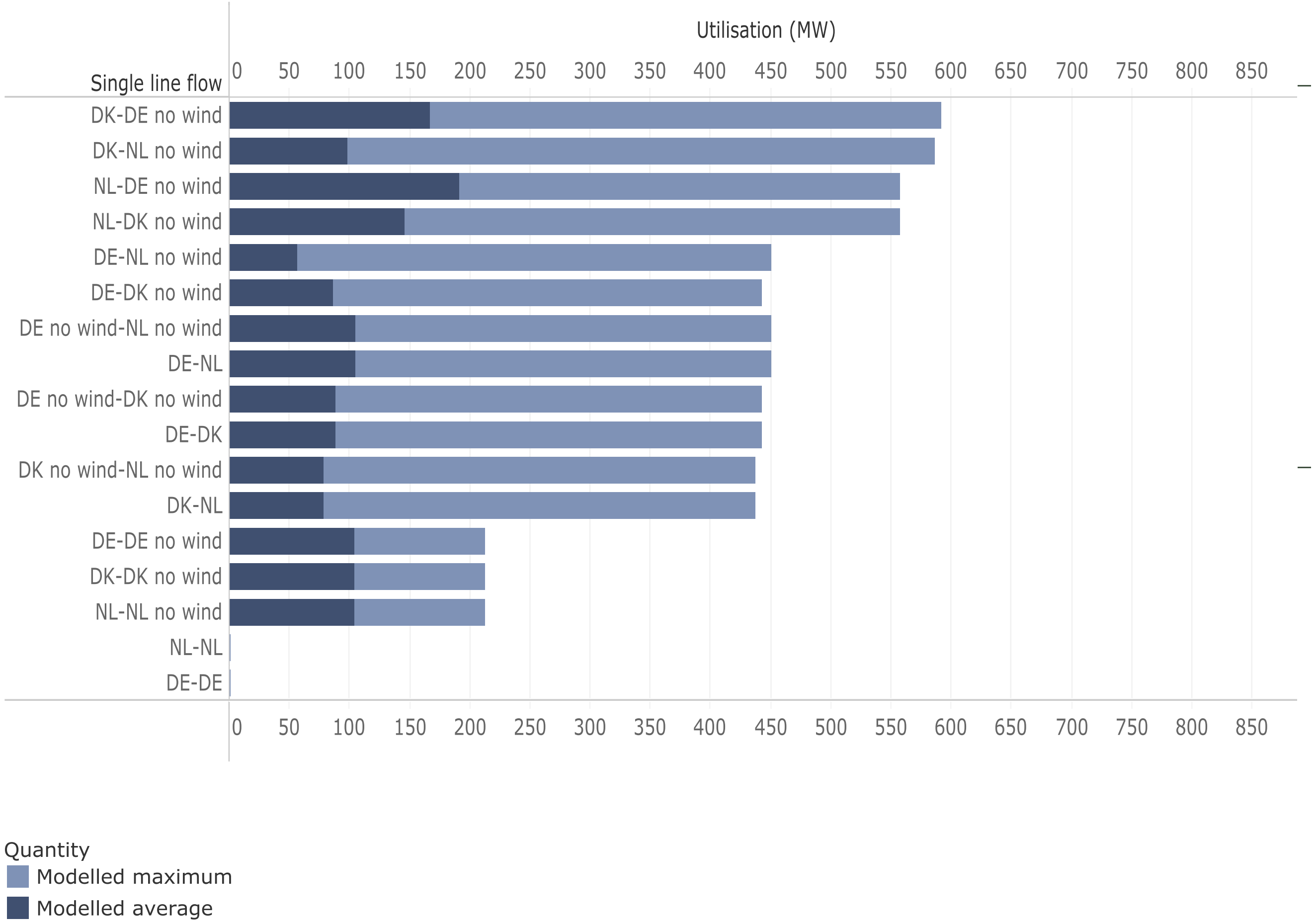
- The charts show:
  - On the LHS: The total flow for all lines between modules with and without OWFs associated to the same Core market (e.g. DK-DK line in this case (1)), for 2030 (dark blue) and 2040 (light blue); and the average flow over the two modelled years (black line); and
  - On the RHS: The OWF load factors.
- Flows on all lines between modules with and without wind farms associated to the same Core market are always equal and in proportion to the wind generation. Lines between two modules that accommodate an OWF and are associated to the same Core market have zero flows.
- Such flows occur due to the requirement that flow on all ICs between the hub and the same Core market are equal. This causes OWF generation at the hub to be redirected from the modules with associated OWFs to those without. For example if we assume that the flow on each DE IC is 1.75GW (towards the DE shore) and each OWF operates at maximum capacity – i.e. 2GW, then the balance on the 3 DE modules connected to an OWF is 0.25GW (towards the hub); while the balance on the single DE module without an OWF is 1.75GW (towards the DE shore). Some of the 3*0.25GW flow on the DE modules will eventually find its way toward the DE module exporting to the DE shore (in essence increasing the within-hub utilisation).

1. The flows shown are identical on all individual lines from modules with and without OWF associated to the same Core market; there are 3 such lines for DE, 2 for NL and 1 for DK

AFRY ÅF PÖYRY

MODELLED & THEORETICAL WITHIN HUB UTILISATION

Maximum observed utilisation on a single line is 592MW



COMMENTS

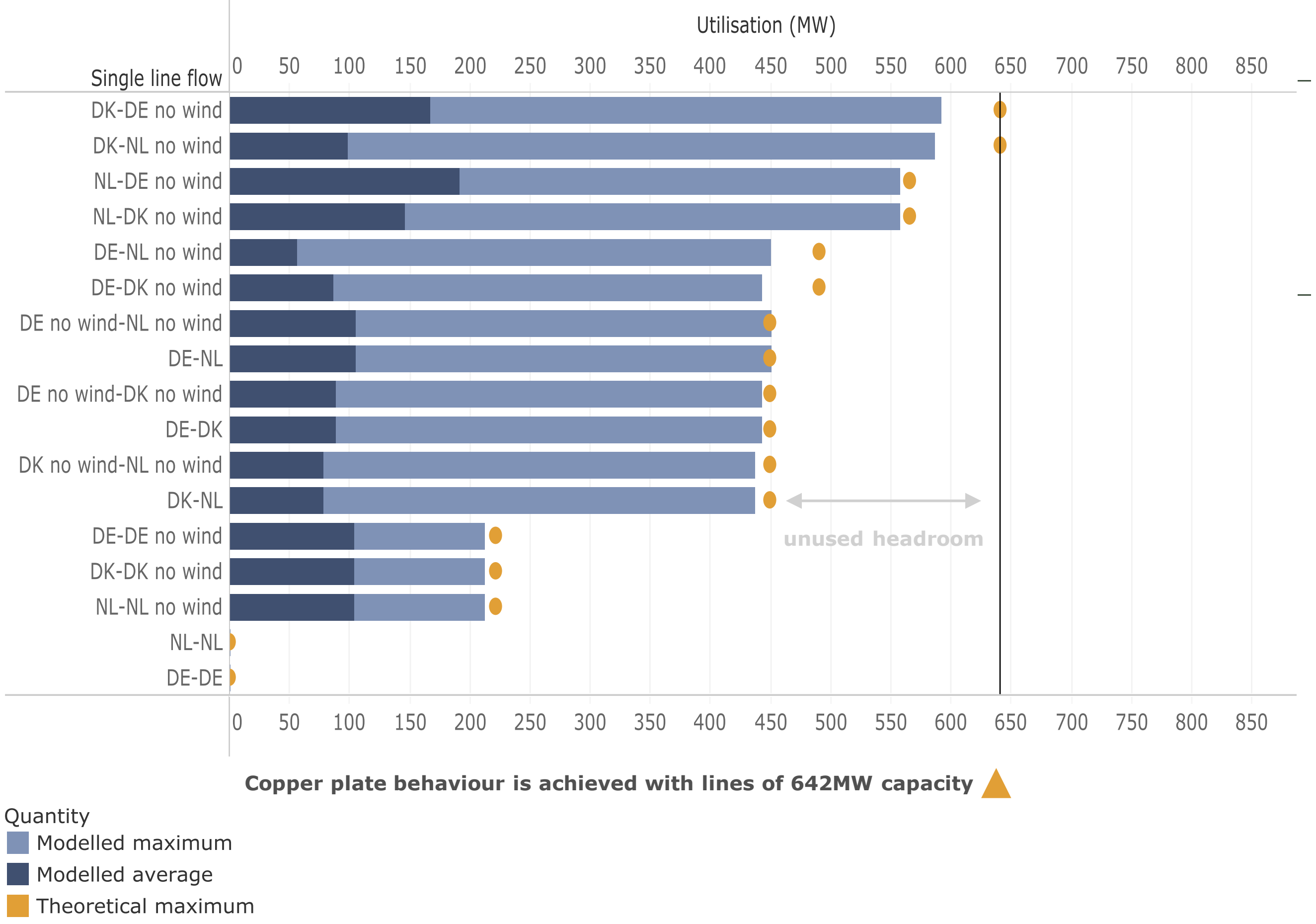
- The chart plots, for each hub-internal connector (or line) (1):
  - The outputs of the load flow modelling in terms of average hourly flow on each within-hub connector (dark blue) and the maximum hourly flow on each within-hub connector (light blue) – regardless of direction (i.e. the absolute value of flow) over the two modelled years 2030/40.
  - Lines are separated depending on the type of modules they serve to connect: those that have an OWF connected to them (in addition to the connection to the national shores) (e.g. DE); and those that only serve an IC from the hub to the national shores of the Core markets without accommodating any OWF (e.g. DE nowind).
- Summary of findings:
  - Maximum observed utilisation is 592MW on the single line between the DK module connected to an OWF and the DE module without OWF connection.
  - All lines are assumed to be of the same capacity. For example, if the capacity of one connector were to be scaled down or differ, then the modelled usage of the within-hub connectors would change.
  - Highest observed flows occur on lines connecting modules with OWFs to modules without OWFs connected to a different Core market.

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

AFRY ÅF PÖYRY

MODELLED & THEORETICAL WITHIN HUB UTILISATION

None of the lines actually reaches the 642MW theoretically calculated required capacity, with maximum flow on a single line remaining 50MW below this threshold



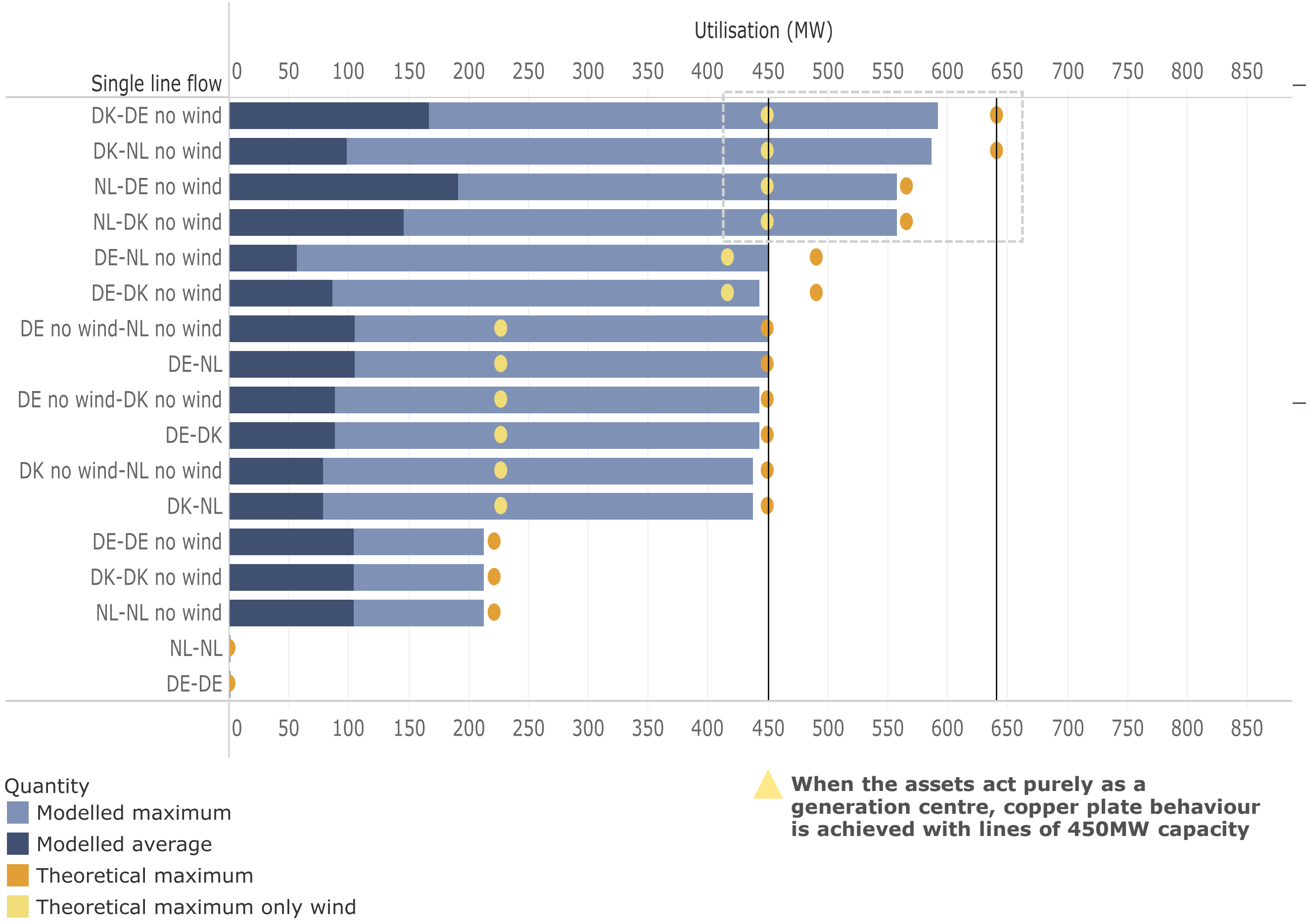
1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

COMMENTS

- Building on the analysis and the chart presented on the previous slide, this chart plots an additional set of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - With the orange marks, the calculated theoretical maximum flow on each hub-internal connector, as described in more detail in the 'Background to the load flow modelling & results' section in the Annex.
- Summary of findings:
  - Assumption that all lines are equal requires a capacity of 642MW per line (compared to 592MW maximum observed utilisation).
  - All lines are assumed to be of the same capacity. For example, if the capacity of one connector were to be scaled down or differ, then the usage of the within hub connectors would change impacting also on the modelled & theoretical maximum flow.
  - Equal capacity requirement leads to a high unused headroom on many lines. Doubling the number of power lines on certain paths (e.g. those between modules with an OWF and those without, which have the highest outturn flows) redirects flows onto these paths. This (i.e. increased number of lines, while maintaining equal capacities) may allow a reduction in the basic 642MW single line capacity (i.e. smaller required capacity) and lead to a smaller unused headroom.
  - Given that lines between modules of the same market have limited utilisation, it is worth exploring the impact of removing these lines. This would reduce total lines from 36 to 26. In this case, maximum theoretical flows of 784MW may occur (not shown in the chart).

MODELLED & THEORETICAL WITHIN HUB UTILISATION

When the hub acts purely as a generation centre (i.e. no flows from any of the national shores), the maximum flow is at 450MW



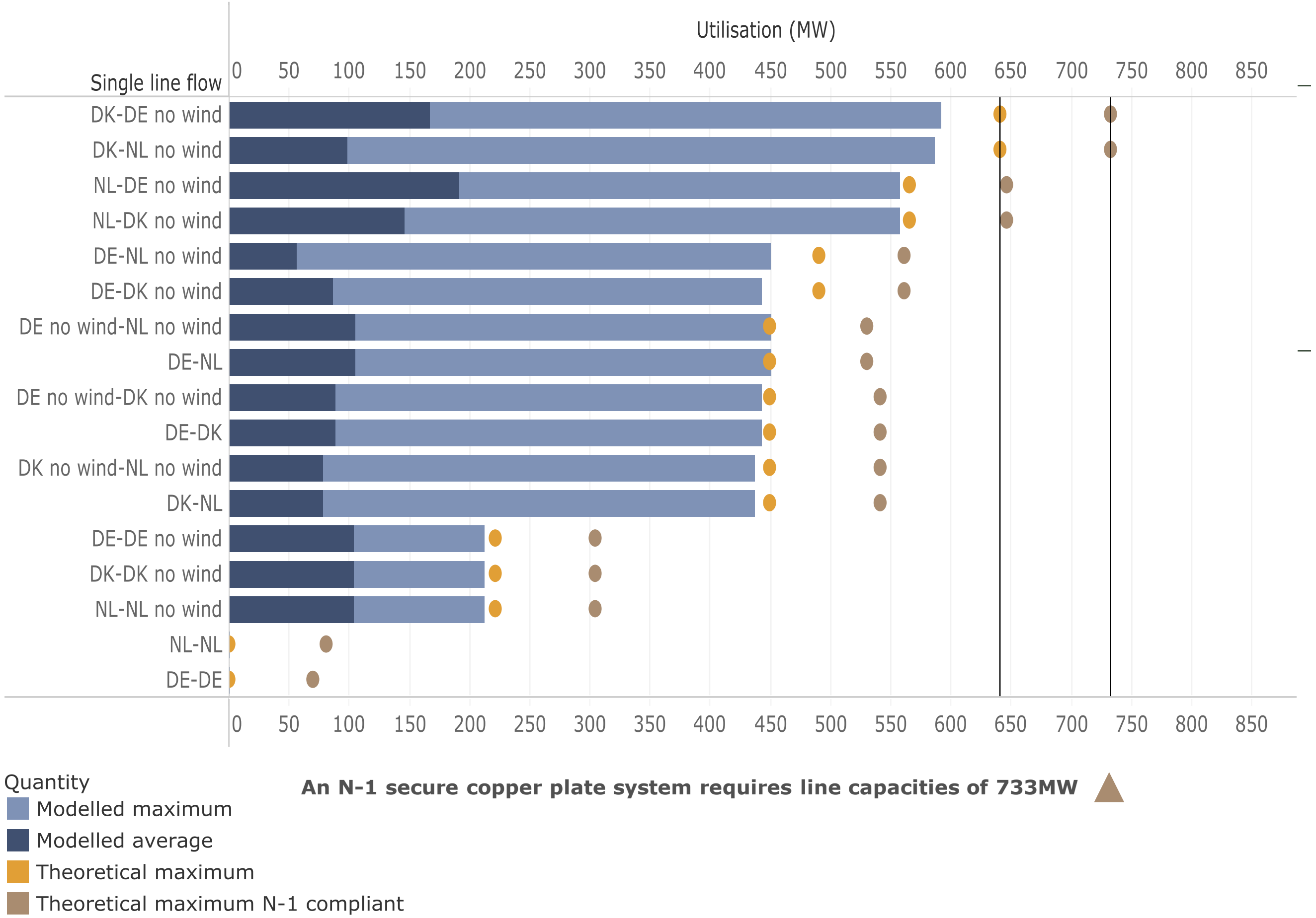
COMMENTS

- Building on the analysis and the chart presented on the previous slide, this chart plots an additional set of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - With the yellow marks, the calculated theoretical maximum flow on each hub-internal connector when the assets act purely as a generation centre (i.e. no flow originating from the onshore systems), as described in more detail in the 'Background to the load flow modelling & results' section in the Annex. The market modelling suggests that this operation happens for 92% of the time.
- Summary of findings:
  - When the asset acts purely as a generation centre, copper plate behaviour is achieved with lines of 450MW capacity.
  - Given that the hub acts for the majority of time purely as a generation centre (with flows from the national systems only appearing during a limited number of periods), it is worth exploring the impact of scaling-down the capacity of the hub-internal connectors to this theoretical threshold of 450MW capacity.
  - In fact, modelled flows surpassing the 450MW limit only occur on a minority of occasions and for specific, limited number of connectors (see indicated region on the chart). According to the market modelling a 450MW limit would be surpassed 124 times in 2030 and 175 times in 2040 (weather year average).

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

MODELLED & THEORETICAL WITHIN HUB UTILISATION & N-1 COMPLIANT

An N-1 secure copper plate system requires line capacities of 733MW



COMMENTS

- Building on the analysis and the chart presented on the previous slide, this chart plots an additional set of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - With the brown marks, the calculated theoretical maximum flow on each line when considering outages on any of the hub-internal connectors – under a "worst case scenario", i.e. resulting from the outage which has the greatest impact on the particular line.
- Summary of findings:
  - Considering outages on any of the hub-internal connectors increases the flow on the remaining lines as power would need to be redirected via the remaining operating lines.
  - An N-1 secure copper plate system requires line capacities of 733MW.

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

Agenda

1. Executive Summary
2. Wind Radial
3. Core
4. Core Increased IC
5. **Core Plus**
   - Load flow modelling results
6. Home Market sensitivity

SUPPORTING INFORMATION

Introduction to the Core Plus configuration results

I. Market-wide results

- This section focuses on a range of market indicators and provides comparisons of the Core Increased IC configuration against the Wind Radial. This background information supports and helps explain NSWPH specific operation patterns and outcomes.
- Summary of findings:
  - Baseload prices under the Core+ are relatively similar to the Wind Radial for most markets with an increase in prices for GB and Norway.
  - Limited spreads between the prices of the Core markets (and BE) which stay fairly correlated, with the addition of GB and NO creating a greater diversity in prices.

II. Hub-connected OWF operation

- This section provides an assessment of the generation and capture revenue of the hub-connected OWFs.
- Summary of findings:
  - The Core + configuration results in similar capture revenues overall for the OWF compared to the Wind Radial case with a capture price in the OBZ in-between the German and Dutch/Danish OWF capture prices (difference on the overall revenue is less than c.3%).
  - With the GB & NO prices decreasing in 2040, and thus affecting the price in the NSWPH, OWF revenues are negatively impacted in 2040.

III. IC operation

- This section provides an assessment of the operation of the NSWPH IC assets – with results presented for the total IC capacity between the hub and each of the Core markets.
- Summary of findings:
  - The Core markets and Belgium spokes are almost exclusively used to transport flows from the hub to their national systems.
  - With prices in GB and Norway being less correlated compared to the rest of the markets, the GB and NO spokes are used to transfer flows in both directions resulting in increased utilisation rates for these ICs.

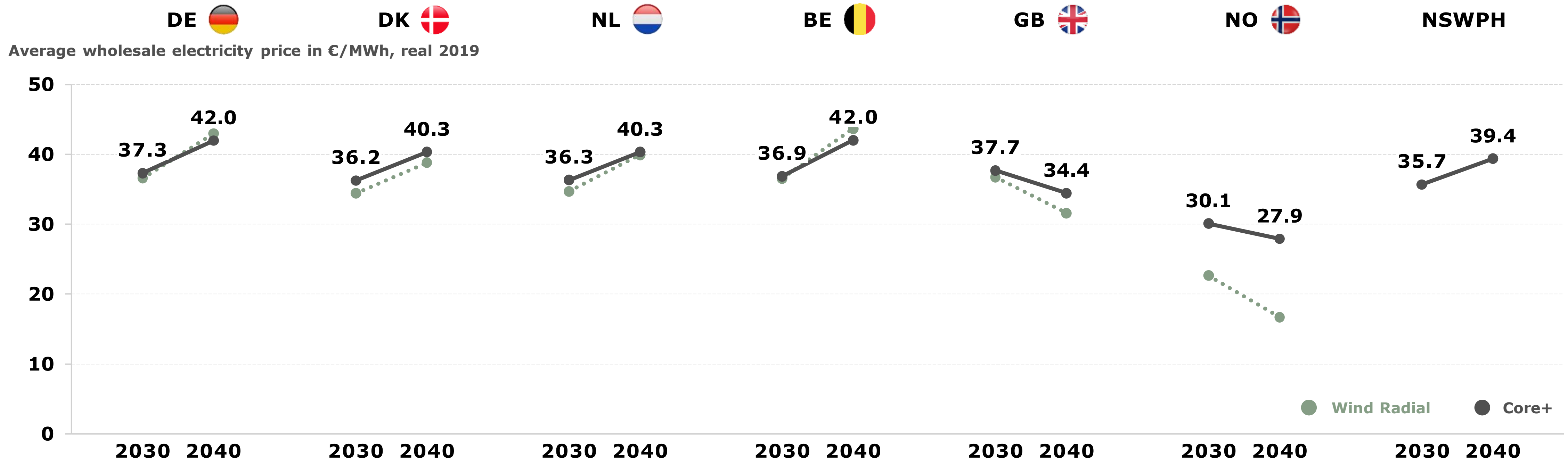
IV. Operation of within-hub connectors

- The section provides our assessment of the within-hub utilisation, presenting flow duration curves for all connectors and the required capacity of the internal lines to achieve copper plate operation. It also provides our analysis of the system stability to N-1 contingencies.
- Summary of findings:
  - Utilisation remains low across all connectors of the Core markets modules with higher utilisation when the connectors includes a Core+.
  - Required capacity on each line is 675MW, but the lines never reach this threshold. The system is stable to all internal transmission contingencies if line capacity is above 771MW.

AFRY ÅF PÖYRY

ANNUAL AVERAGE DAY-AHEAD WHOLESALE ELECTRICITY PRICES

Impact on electricity prices remains limited for the Core & BE markets, while prices in NO & GB increase driven by increased exports to the Core markets



COMMENTS

- The chart shows the average wholesale electricity price for the Core+ markets and the NSWPH for 2030 and 2040 – comparing them against the Wind Radial case.
- With increased cross-zonal capacity under the Core + configuration (compared to the Wind Radial), wholesale prices of the different markets are generally expected to converge with diverse impacts across the markets.
- Great Britain and Norway are the most impacted. These two markets are expected to be net exporters putting an upwards pressure on the their national electricity prices.
- NSWPH prices remain below the Core market prices, but higher than the Norway and GB prices.

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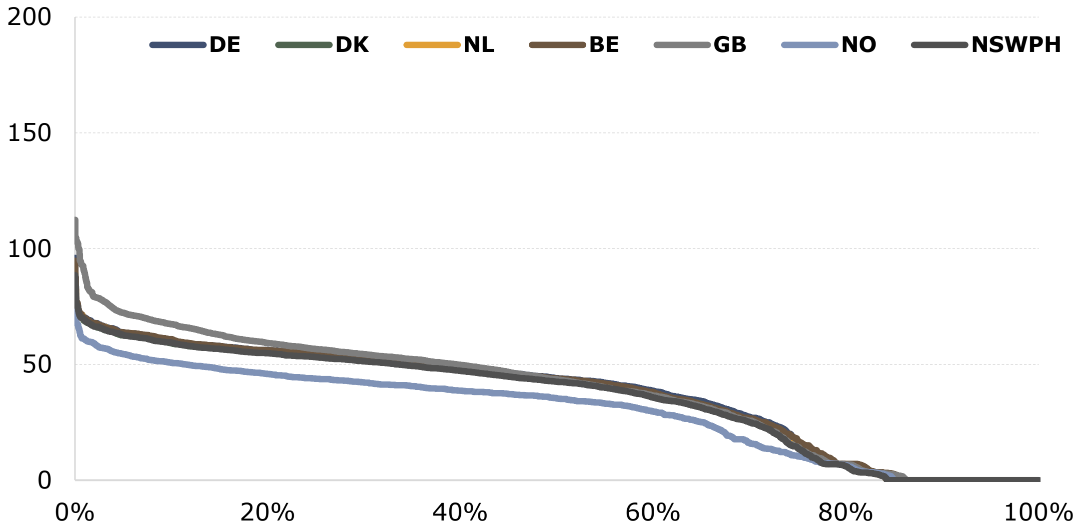
PRICE DURATION CURVE (PDC) OF DAY-AHEAD WHOLESALE ELECTRICITY PRICES

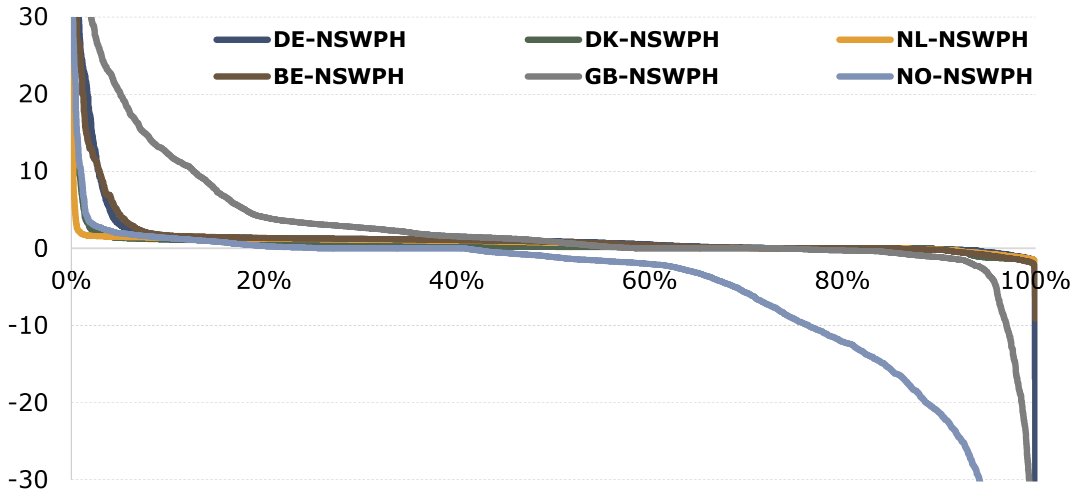
Hourly prices in 2030 are very similar between the three Core markets and Belgium, while Norway has generally lower prices and GB a greater spread

PRICE DURATION CURVES IN 2030

€/MWh, real 2019 – incl. all weather years (i.e. 26,280 hours)



DURATION CURVES OF PRICE SPREADS IN 2030



	DE	DK	NL	BE	GB	NO
% of low-priced periods (1)	16%	16%	16%	15%	15%	16%
% of high-priced periods (1)	0%	0%	0%	0%	0%	0%
% of time spreads lower than €2/MWh	97%	93%	99%	92%	58%	55%

COMMENTS

- Price shapes are very similar between the three Core markets and Belgium with very limited spreads between these markets.
- Norwegian prices are generally lower compared to the rest, while GB prices show a greater spread.
- Price spreads remain low between the NSWPH and the Core market and Belgium, while spreads between the hub and NO and GB are much higher (i.e. spreads are higher than €2/MWh for c. 40% of the time).

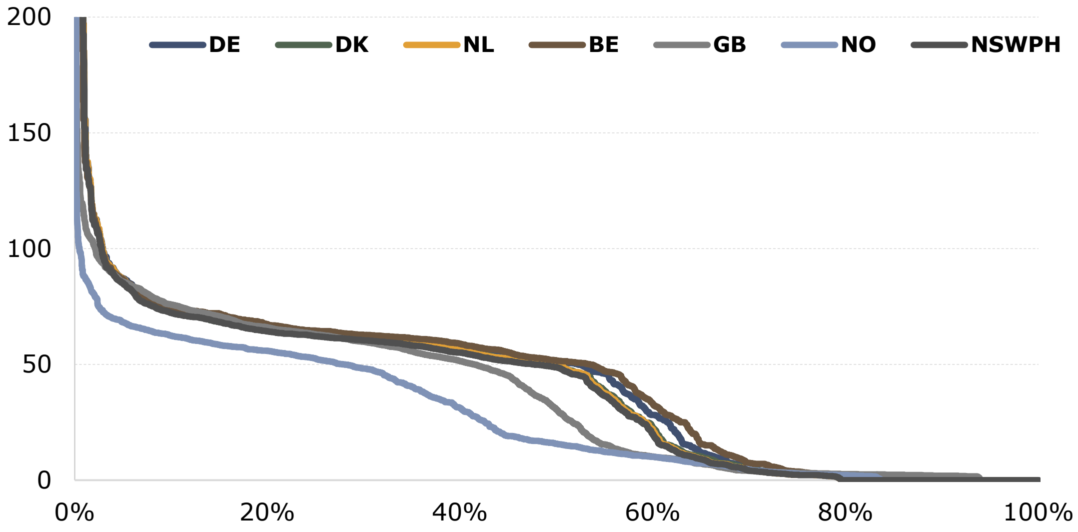
1. Here, prices below €2/MWh are considered as low-priced periods and prices over €100/MWh are considered as high-priced periods.

PRICE DURATION CURVE (PDC) OF DAY-AHEAD WHOLESALE ELECTRICITY PRICES

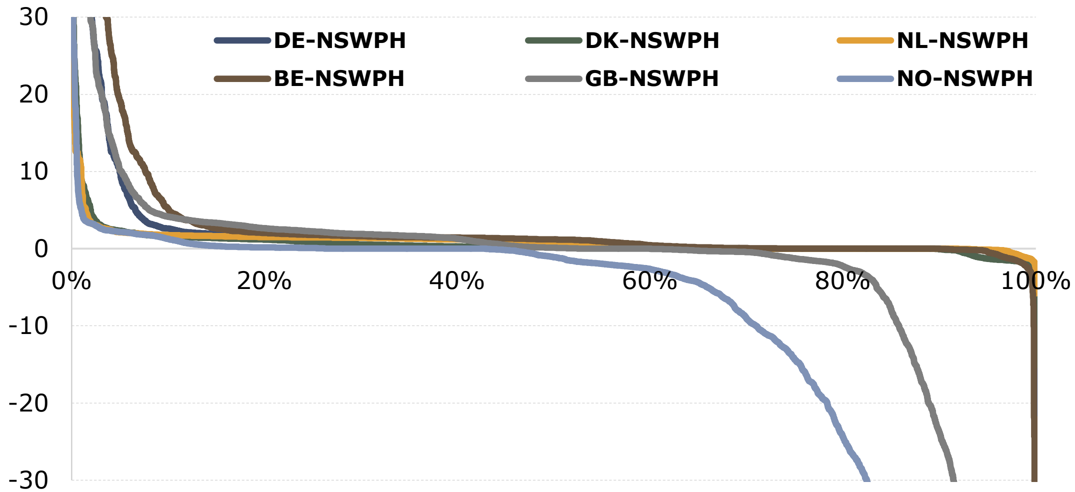
Hourly prices in 2040 are very similar between the three Core markets and Belgium; Norway & GB have generally lower prices across the year

PRICE DURATION CURVES IN 2040

€/MWh, real 2019 – incl. all weather years (i.e. 26,280 hours)



DURATION CURVES OF PRICE SPREADS IN 2040



	DE	DK	NL	BE	GB	NO
% of low-priced periods (1)	21%	22%	22%	18%	11%	19%
% of high-priced periods (1)	3%	3%	3%	3%	2%	0%
% of time spreads lower than €2/MWh	93%	86%	93%	78%	52%	49%

COMMENTS

- Price shapes are similar between the three Core markets and Belgium with very limited spreads between these markets.
- Norwegian and GB prices are generally lower compared to the rest across the whole period.
- Price spreads remain low between the NSWPH and the Core market and Belgium (i.e. 90% of the time these are lower than €2/MWh), while spreads between the hub and NO and GB are much higher (i.e. spreads are higher than €2/MWh for c. 50% of the time).

1. Here, prices below €2/MWh are considered as low-priced periods and prices over €100/MWh are considered as high-priced periods.

OPERATION OF HUB-CONNECTED OWF

OWF capture revenues are marginally higher under the Core+ configuration versus the Wind Radial operation in 2030 (by c. 2%)

		Core +	Wind Radial		
		NSWPH	DE	DK	NL
Volumes	**Available generation at the respective bidding zones** i.e. accounting for the losses on the transmission cables	**50.10 TWh**	24.47	8.16	16.31
			48.94 TWh		
	Generation post economic curtailment, at the respective bidding zones i.e. accounting for the volumes that need to be curtailed in each bidding zone	**48.90 TWh (46.52%)**	24.00	8.12	15.88
			47.99 TWh (45.65%)		
	Curtailment volume at the respective bidding zones i.e. resulting from rational economic dispatch of renewable generation, rather than driven by onshore transmission system issues and / or local constraints	**1.20 TWh**	0.47	0.04	0.43
			0.94 TWh		
Revenue	**Capture price in €/MWh, real 2019**	**€26.35/MWh**	€27.81/MWh	€24.16/MWh	€24.86/MWh
	Overall hub-connected OWF capture revenue in million Euros, real 2019	**€1,288m**	**€1,258m**		

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OPERATION OF HUB-CONNECTED OWF

OWF capture revenues are marginally lower under the Core+ configuration versus the Wind Radial operation in 2040 (by c. 3%)

		Core +	Wind Radial		
		NSWPH	DE	DK	NL
Volumes	**Available generation at the respective bidding zones** i.e. accounting for the losses on the transmission cables	**50.10 TWh**	24.47	8.16	16.31
			48.94 TWh		
	Generation post economic curtailment, at the respective bidding zones i.e. accounting for the volumes that need to be curtailed in each bidding zone	**49.92 TWh (47.49%)**	24.37	8.16	16.18
			48.71 TWh (46.33%)		
	Curtailment volume at the respective bidding zones i.e. resulting from rational economic dispatch of renewable generation, rather than driven by onshore transmission system issues and / or local constraints	**0.18 TWh**	0.10	0.00	0.13
			0.23 TWh		
Revenue	**Capture price in €/MWh, real 2019**	**€23.18/MWh**	€26.82/MWh	€21.91/MWh	€21.95/MWh
	Overall hub-connected OWF capture revenue in million Euros, real 2019	**€1,157m**	**€1,188m**		

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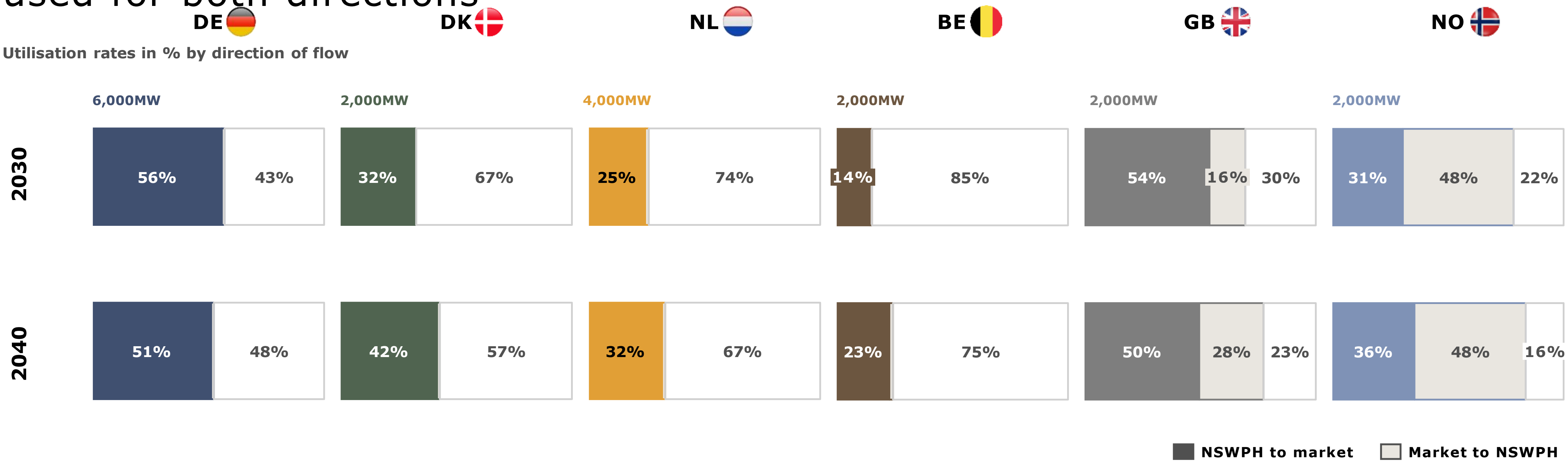
USAGE OF TRANSMISSION ASSETS

The Core market and BE spokes are mainly used to transport flows from the hub to their national systems, while the GB and NO spokes are more heavily used for both directions



COMMENTS

- The charts show the utilisation rates of the transmission assets by direction, defined as the physical flow accounting for losses divided by the capacity of each spoke.
- Utilisation varies for the different spokes connecting the onshore systems to the hub. The Core markets and Belgium spokes are almost exclusively used to transport flows from the hub to their national systems. The DE spoke is used significantly more compared to the other three, as the price signal is stronger in Germany.
- With prices in GB and Norway being less correlated compared to the rest of the markets, the GB and Norway spokes are used to transfer flows in both directions, with the Norway spoke used to transfer flow from the Norway national system to the hub for c. 50% of the time.
- More balanced utilisation across the spokes in 2040 (compared to 2030) – as prices (at least in the Core markets and Belgium) converge even further.

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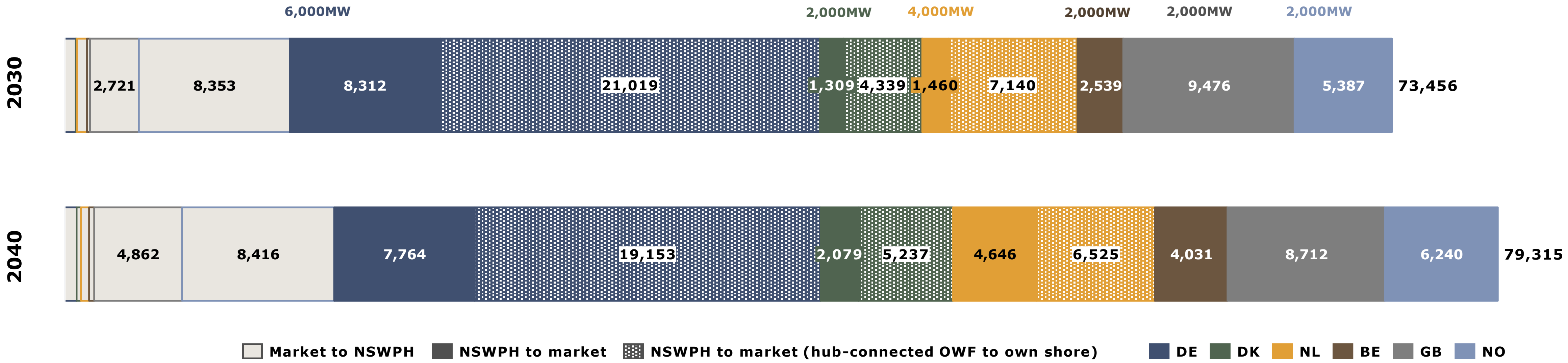
USAGE OF TRANSMISSION ASSETS

Transmission of hub-connected OWF to the onshore systems remains the main source of flow, with flows from the various onshore systems to the hub accounting for c. 20% of the total flow

Annual physical cross-zonal flows in GWh, incl. losses, by direction



COMMENTS

- The chart shows the physical flows accounting for losses on the transmission assets, as triggered by electricity price spreads, at the day-ahead stage.
- Please refer to section 'Utilisation of IC assets based on the market modelling' in the Annex for an explanation and an example of how to read this chart.
- For the Core markets, the majority of the flows (c. 70% of the flows linked to the Core markets) are related to the hub-connected OWF generation flowing to each respective onshore systems and mainly to Germany, i.e. without flowing via the hub-internal connectors (i.e. pattern-filled areas).
- The transmission assets connecting the hub to the GB and NO markets are used to transfer flows in both directions (i.e. from the hub to the onshore systems and vice versa). This is not the case for the transmission assets connecting the hub to Core markets and Belgium, where flows are mainly in the direction from the hub to the onshore systems. Overall, the flows originating from the national markets to the hub on the left part of the chart account for around 20% of the total flow.

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USAGE OF TRANSMISSION ASSETS

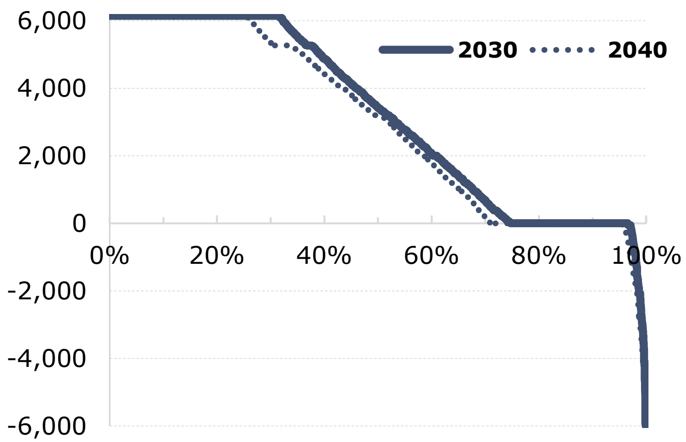
The DE spokes are used at their full capacity for c. 30% of the time, while the DK and NL spokes have a reduced use with the flow being zero for c. 50% of the time

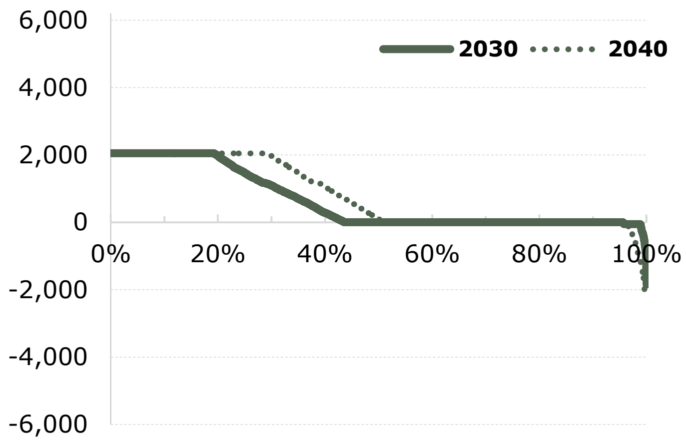
DE

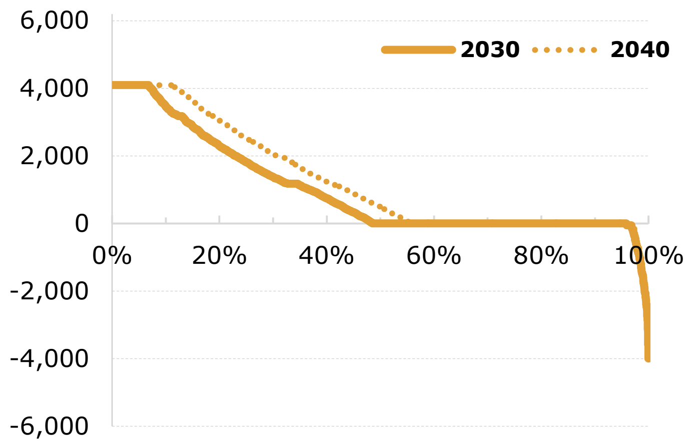
DK

NL

Flow duration curves for the ICs in MW – incl. all weather years (i.e. 26,280 hours). Positive values indicate flows from the hub to the onshore systems – negative values the opposite







COMMENTS

- The charts show the flow duration curve of the total interconnection between the hub and the Core markets in the direction from the hub to the national shores i.e. positive numbers represent flows going from the hub to the national systems and negative numbers represent flows going from the national systems to the hub.
- As seen previously, there are very limited flows in the direction from the national shores to the hub. The ICs are mainly used to transfer the hub-connected OWF to the national systems.
- The German spokes are used for around 30% at their full capacity. The Danish and Dutch spokes are used at full capacity for a more limited time. The Danish and Dutch spokes remain unutilised for a longer period of time – i.e. around 50% compared to 20% for the German spokes.
- As explained above, utilisation among the different spokes is somewhat more balanced in 2040 where we expect to see more use of the Danish and Dutch spokes.

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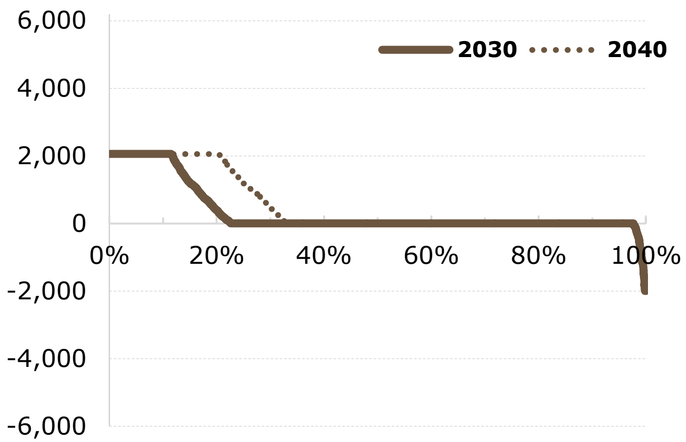
USAGE OF TRANSMISSION ASSETS

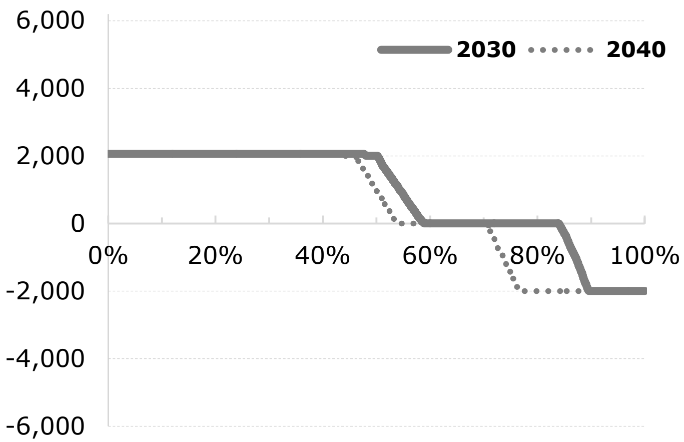
The flow on the BE spoke is limited and it remains unutilised for more than 70% of the time, whereas the GB and Norway spokes are used for more than 60% of the time at full capacity

Flow duration curves for the ICs in MW – incl. all weather years (i.e. 26,280 hours). Positive values indicate flows from the hub to the onshore systems – negative values the opposite

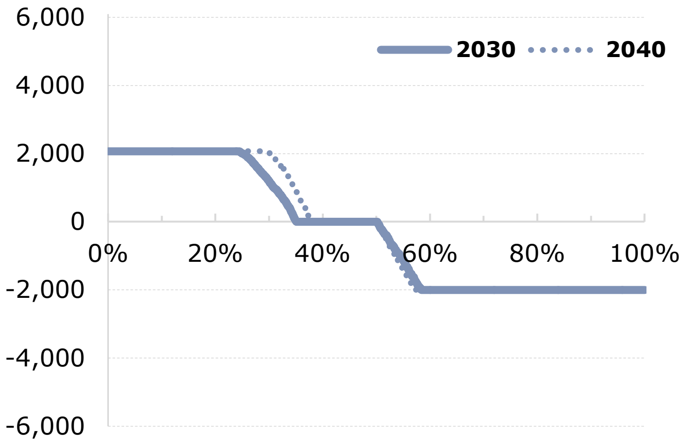
BE



GB



NO



COMMENTS

- The charts show the flow duration curve of the total interconnection between the hub and the Core markets in the direction from the hub to the national shores i.e. positive numbers represent flows going from the hub to the national systems and negative numbers represent flows going from the national systems to the hub.
- Limited flows on the Belgium spoke, remaining zero for c. 70-80% of the time.
- The GB and Norway spokes are used for more than 60% of the time at their full capacity (in either direction).
- When comparing 2030 and 2040 for the GB spoke, there is a shift from the right to the left, representing a greater number of periods in 2040 where GB is exporting from the shore to the hub driven by a higher renewable penetration and increased periods of low prices.

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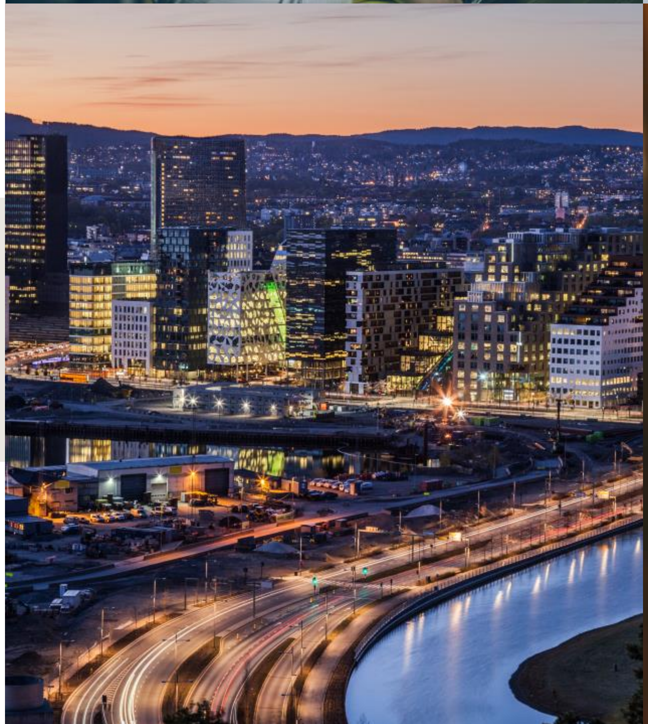
Agenda

1. Executive Summary
2. Wind Radial
3. Core
4. Core Increased IC
5. **Core Plus**
   - **Load flow modelling results**
6. Home Market sensitivity



SUPPORTING INFORMATION

Introduction to the load flow results of the Core+ configuration

SUMMARY

Focus

- To describe the expected pattern of flows within the hub and identify key drivers and trends in utilisation;
- To obtain an expectation for the required capacity of the internal connecting lines to achieve copper plate operation and to identify any internal connectors which may be removed; and
- To understand the stability of the system to N-1 contingencies.

Approach & Assumptions

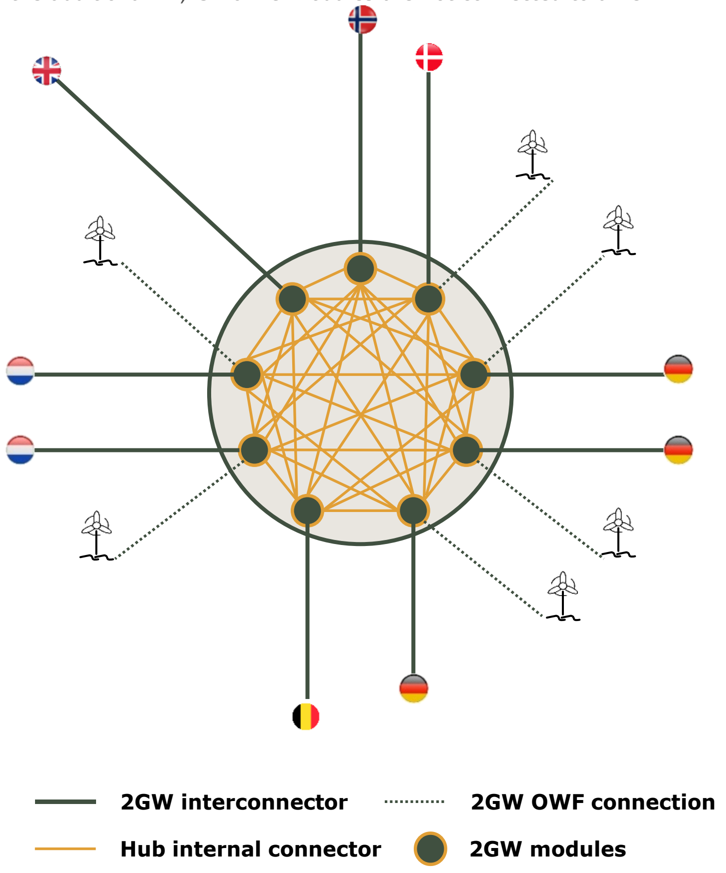
- Net position of the hourly flow at each 2GW module is based on the market modelling presented in the previous section.
- Hourly power flows within the hub have been determined using load flow modelling in BID3 via a calculated PTDF matrix.
- All hub-internal connectors are assumed to have identical physical characteristics.
- Losses on the (external) ICs vary for the Core+ markets. This impacts on the maximum power delivered to the respective modules.

Messages

- Utilisation remains low across all connectors of the Core markets modules with higher utilisation when the connectors includes a Core+ market.
- Required capacity on each line is 675MW, but the lines never reach this threshold (with maximum flow being 598MW). This required capacity is reduced to 453MW at times when the system acts purely as a generator.
- The system is stable to all internal transmission contingencies if line capacity is above 771MW.

SETUP USED FOR LOAD FLOW MODELLING

Note: the additional BE, GB & NO modules are not connected to an OWF



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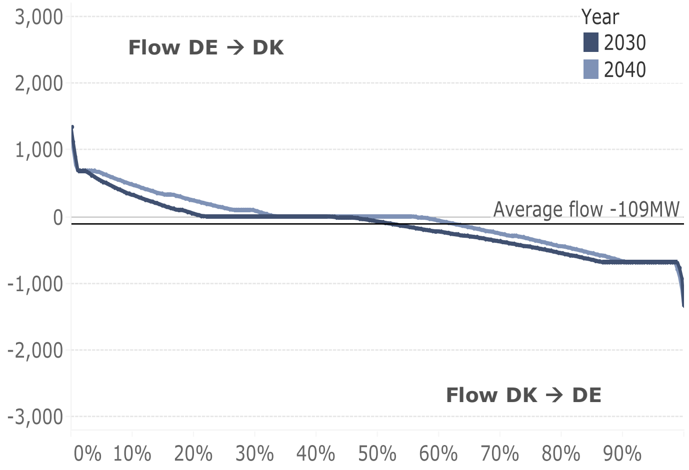
HUB INTERNAL FLOW DURATION CURVES (CORE MARKETS)

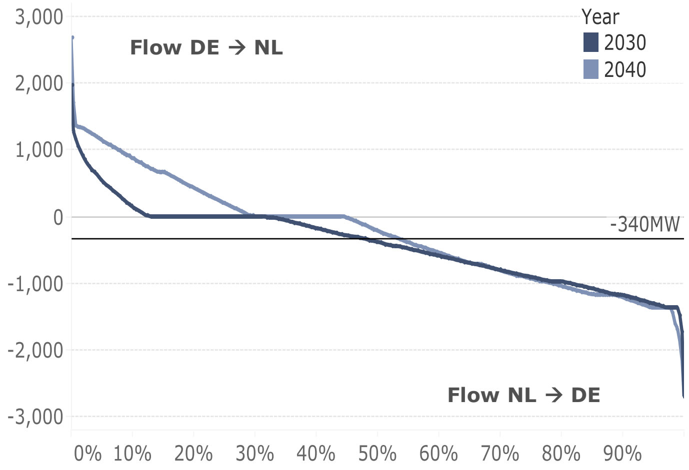
Low utilisation overall of the within-hub assets in line with the market modelling results

Flow duration curves for the hub-internal connectors in MW – incl. all weather years (i.e. 26,280 hours)

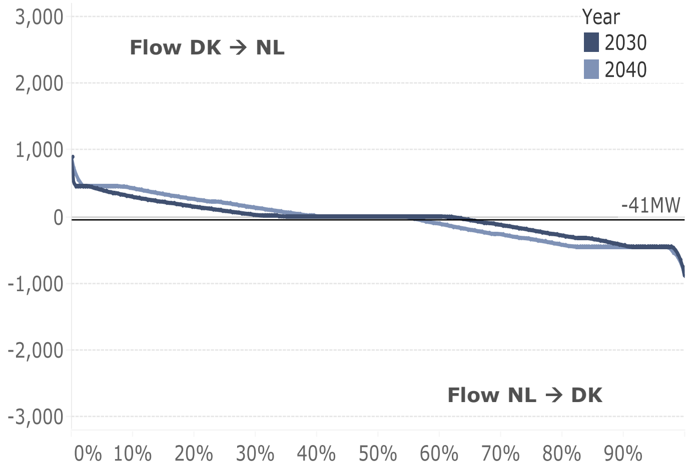
3 DE-DK CONNECTORS



6 DE-NL CONNECTORS



2 DK-NL CONNECTORS



COMMENTS

- The charts show:
  - The total flow for all hub-internal connectors (1) connecting any two modules of the different Core markets, for 2030 (dark blue) and 2040 (light blue); and
  - The average flow over the two modelled years (black line).
- Utilisation remains generally low across all connectors. For example, the total flow on the DE-DK connectors is close to zero for c.20% of the time in 2030&40. The same applies for the DE-NL connectors. This is in line with the market modelling results showing little use outside the transfer of wind to the connected markets on the Core market ICs.
- 2040 sees a transition to higher flows towards the NL modules (mainly from the DE modules). This is in line with the market modelling suggesting higher flows towards the NL shore (and lower flows towards the DE shore) in 2040 – driven by a more balanced IC use resulting from a stronger price convergence among the Core markets.

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-DK, they need to be divided by three.

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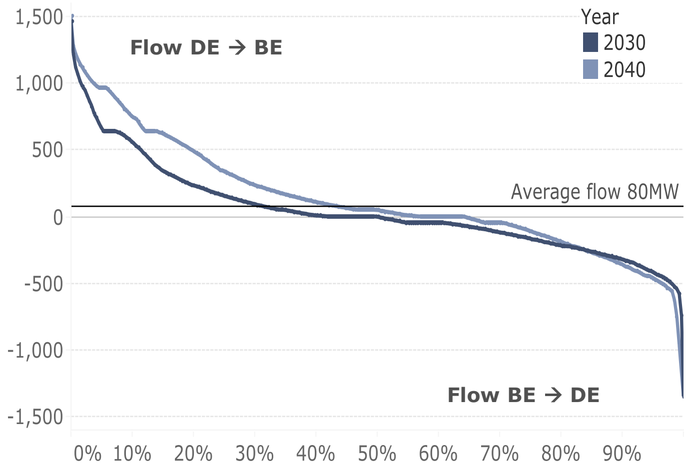
HUB INTERNAL FLOW DURATION CURVES (BELGIUM)

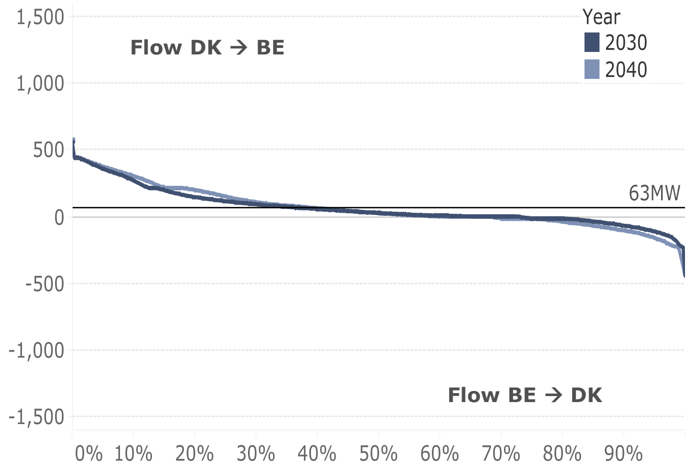
Flows on the lines connecting to the BE modules are limited and mainly associated with the transfer of OWF generation to the BE shore when the price signal is strong

Flow duration curves for the hub-internal connectors in MW – incl. all weather years (i.e. 26,280 hours)

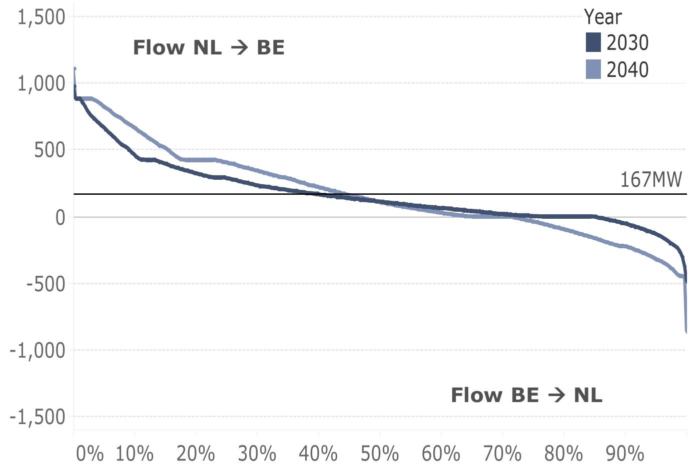
3 DE-BE CONNECTORS



1 DK-BE CONNECTOR



2 NL-BE CONNECTORS



COMMENTS

- The charts show:
  - The total flow for all hub-internal connectors (1) connecting any two modules of the different Core/ Core+ markets, for 2030 (dark blue) and 2040 (light blue); and
  - The average flow over the two modelled years (black line).
- Limited flows are associated with the Belgian market. The majority of the flow is linked to the transfer of the hub-connected OWF to the Belgian shore when the BE price signal is relatively strong.

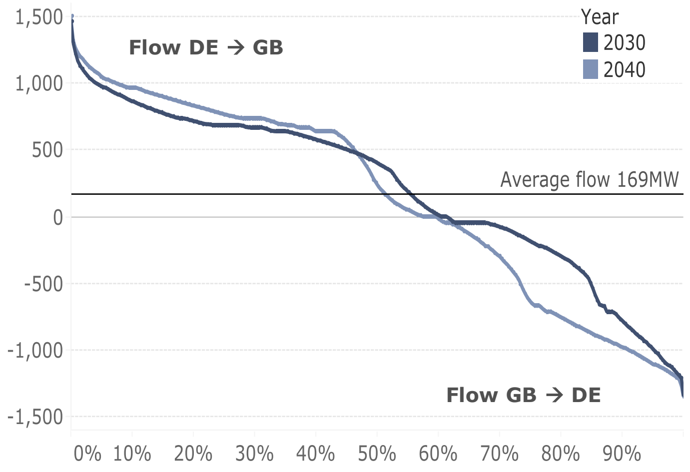
1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-BE, they need to be divided by three.

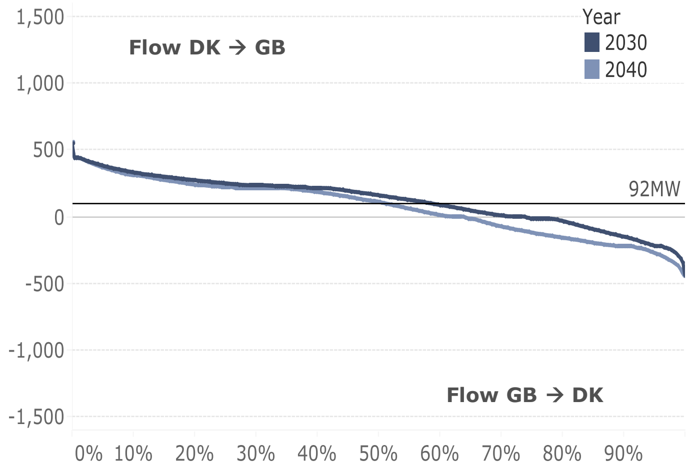
HUB INTERNAL FLOW DURATION CURVES (GB)

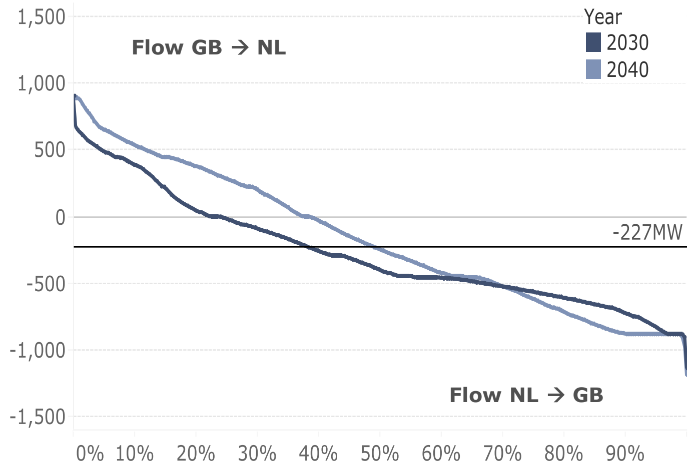
Utilisation for the lines connecting GB to the Core market modules is relatively high, with the NL-GB connector having the highest per line average flows in the Core+

3 DE-GB CONNECTORS | **1 DK-GB CONNECTOR** | **2 GB-NL CONNECTORS**

Flow duration curves for the hub-internal connectors in MW – incl. all weather years (i.e. 26,280 hours)







COMMENTS

- The charts show:
  - The total flow for all hub-internal connectors (1) connecting any two modules of the different Core / Core+ markets, for 2030 (dark blue) and 2040 (light blue); and
  - The average flow over the two modelled years (black line).
- Generally higher utilisation compared to the connectors among the Core markets – with a significantly smaller number of periods when flow is close to zero.
- While in 2030 most of the flows is towards the GB module, by 2040 there are increasing flows away from the GB module, as prices in GB fall.
- The NL-GB connector has the highest per line average flows in the Core+ configuration.

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-GB, they need to be divided by three.

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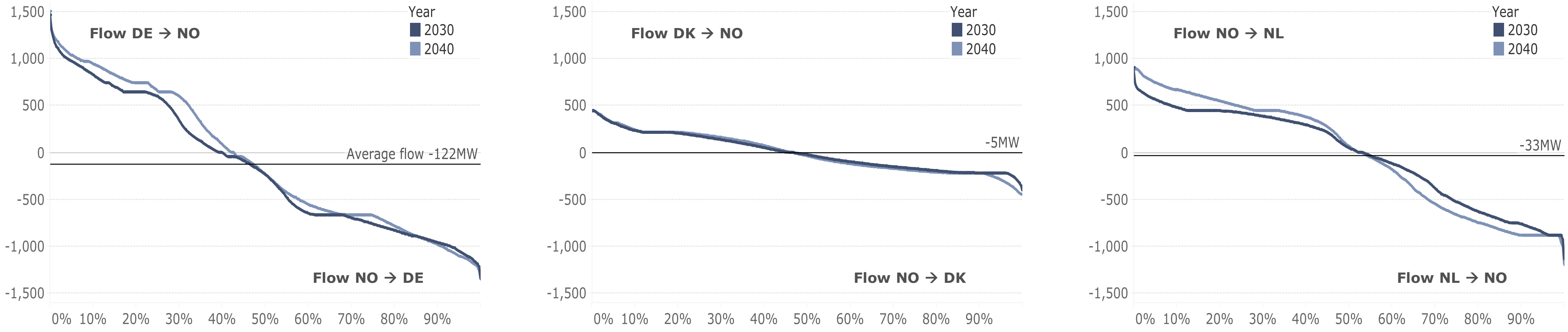
HUB INTERNAL FLOW DURATION CURVES (NORWAY)

Utilisation for the lines connecting NO to the Core market modules is relatively high

3 DE-NO CONNECTORS **1 DK-NO CONNECTOR** **2 NO-NL CONNECTORS**

Flow duration curves for the hub-internal connectors in MW – incl. all weather years (i.e. 26,280 hours)



COMMENTS

- The charts show:
  - The total flow for all hub-internal connectors (1) connecting any two modules of the different Core/ Core+ markets, for 2030 (dark blue) and 2040 (light blue); and
  - The average flow over the two modelled years (black line).
- Generally higher utilisation compared to the connectors among the Core markets – with a significantly smaller number of periods when flow is close to zero.
- Due to its lower prices and as seen previously, Norway tends to export to the hub. This leads to the average flow in most cases away from the NO module .

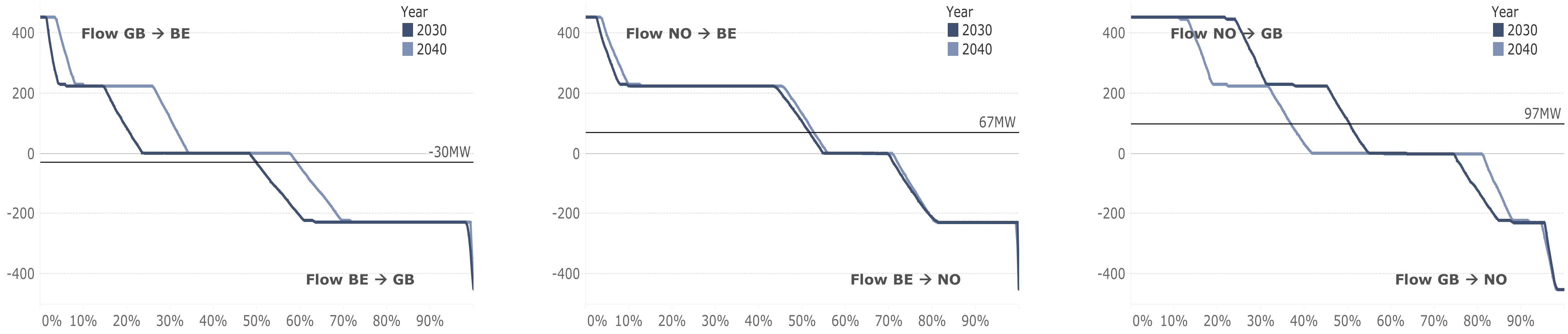
1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-NO, they need to be divided by three.

HUB INTERNAL FLOW DURATION CURVES (CORE+ MARKETS)

Highest flows occur towards GB, with the NO → GB flow occurring at maximum around 20% of the time

GB-BE CONNECTOR **NO-BE CONNECTOR** **NO-GB CONNECTOR**

Flow duration curves for the hub-internal connectors in MW – incl. all weather years (i.e. 26,280 hours)

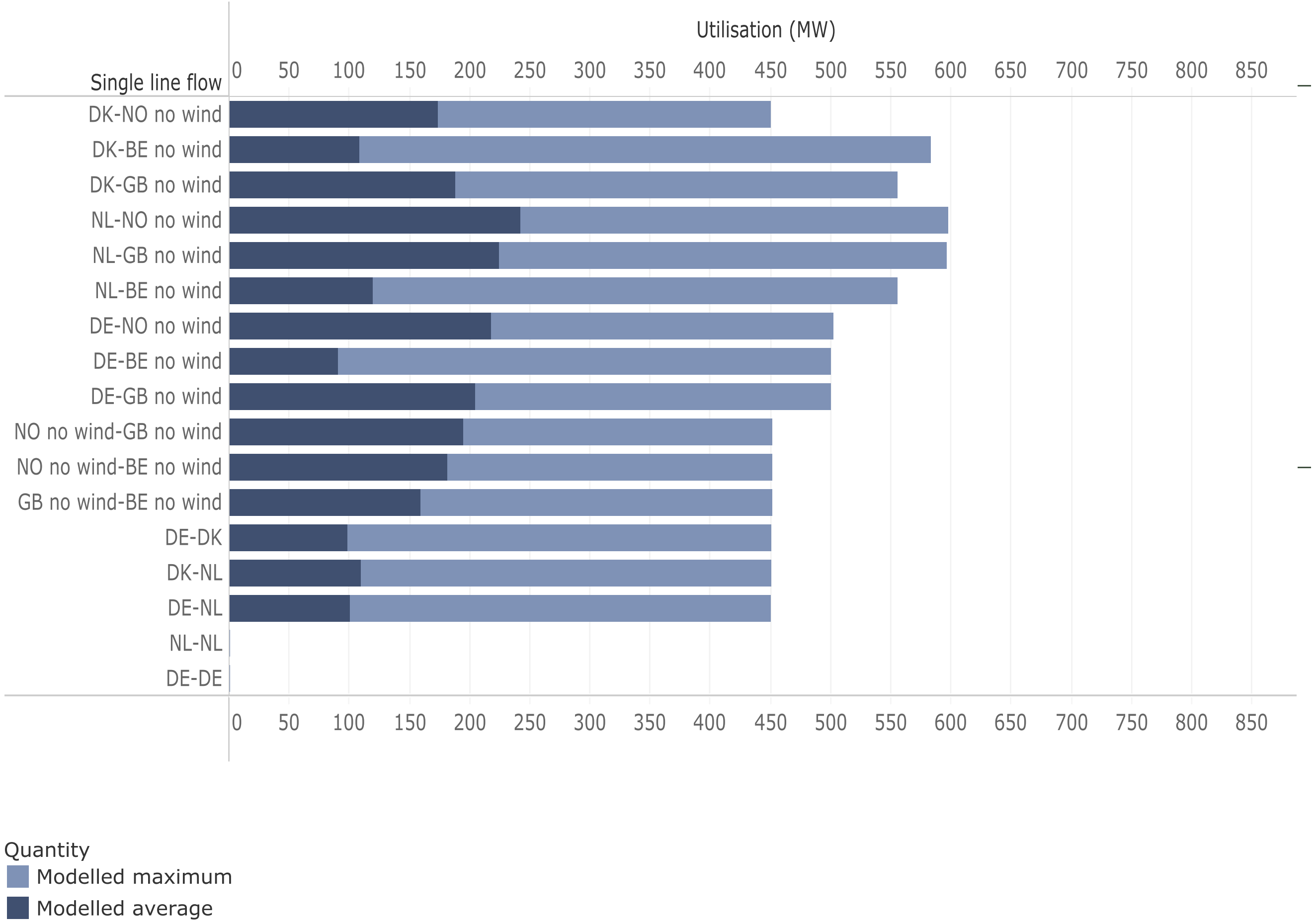


COMMENTS

- The charts show:
  - The total flow for all hub-internal connectors connecting any two modules of the different Core+ markets, for 2030 (dark blue) and 2040 (light blue); and
  - The average flow over the two modelled years (black line).
- Stepped structure of duration curve arises due to the fact these modules do not have associated wind farms – more specifically (taking the first chart as an example):
  - 225MW occurs when market 1 (e.g. BE) imports at full capacity from the hub and there are no flows to/from the module of market 2 (e.g. GB module) to the shore; and
  - 450MW occurs when market 1 (e.g. BE) imports at full capacity and market 2 (e.g. GB) simultaneously exports to the hub at full capacity.
- Highest flows occur towards GB, with the NO → GB flow occurring at maximum around 20% of the time.

MODELLED & THEORETICAL WITHIN HUB UTILISATION

Maximum observed utilisation on a single line is 598MW



COMMENTS

- The chart plots, for each hub-internal connector (or line) (1):
  - The outputs of the load flow modelling in terms of average hourly flow on each within-hub connector (dark blue) and the maximum hourly flow on each within-hub connector (light blue) – regardless of direction (i.e. the absolute value of flow) over the two modelled years 2030/40.
  - Separating the two types of modules: the modules that have an OWF connected to them (in addition to the connection to the national shores) (i.e. all Core markets in this configuration); and the modules that only serve an IC from the hub to the national shores of the Core markets without accommodating any OWF (i.e. all the Core+ markets in this configuration).
- Summary of findings:
  - Maximum observed utilisation is 598MW on each of the lines between the NL and NO modules.
  - Highest observed flows occur on lines connecting modules with OWFs to modules without OWFs.
  - We observe lower flows between geographically neighbouring markets, which have generally well-correlated prices; or can transfer power between them with lower associated losses than via hub flows.
  - All lines are assumed to be of the same capacity. If the capacity of one connector were to be scaled down the resulting flows would differ.

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

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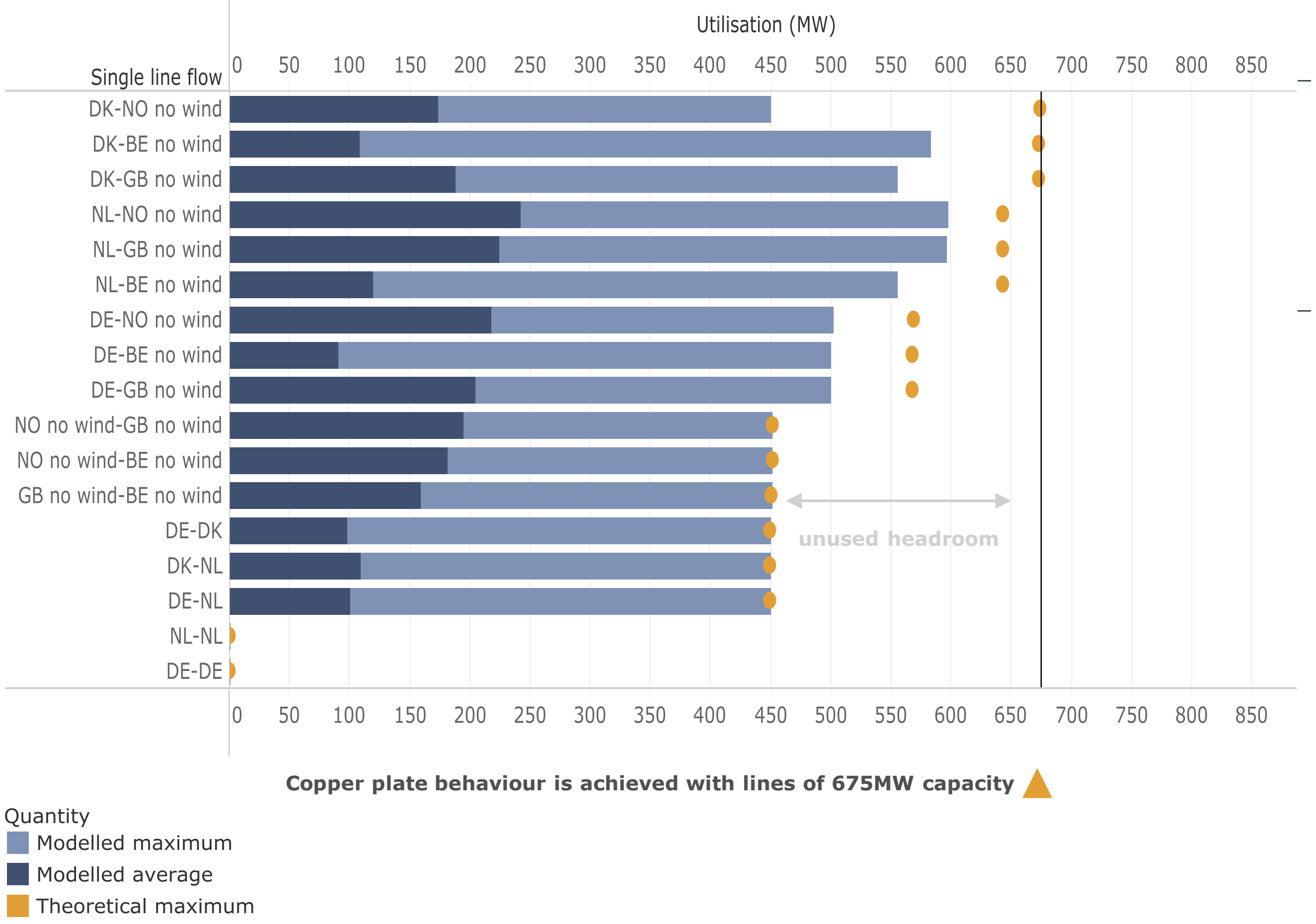
MODELLED & THEORETICAL WITHIN HUB UTILISATION

None of the lines actually reaches the 675MW theoretically calculated required capacity, with maximum flow on a single line remaining 77MW below this threshold



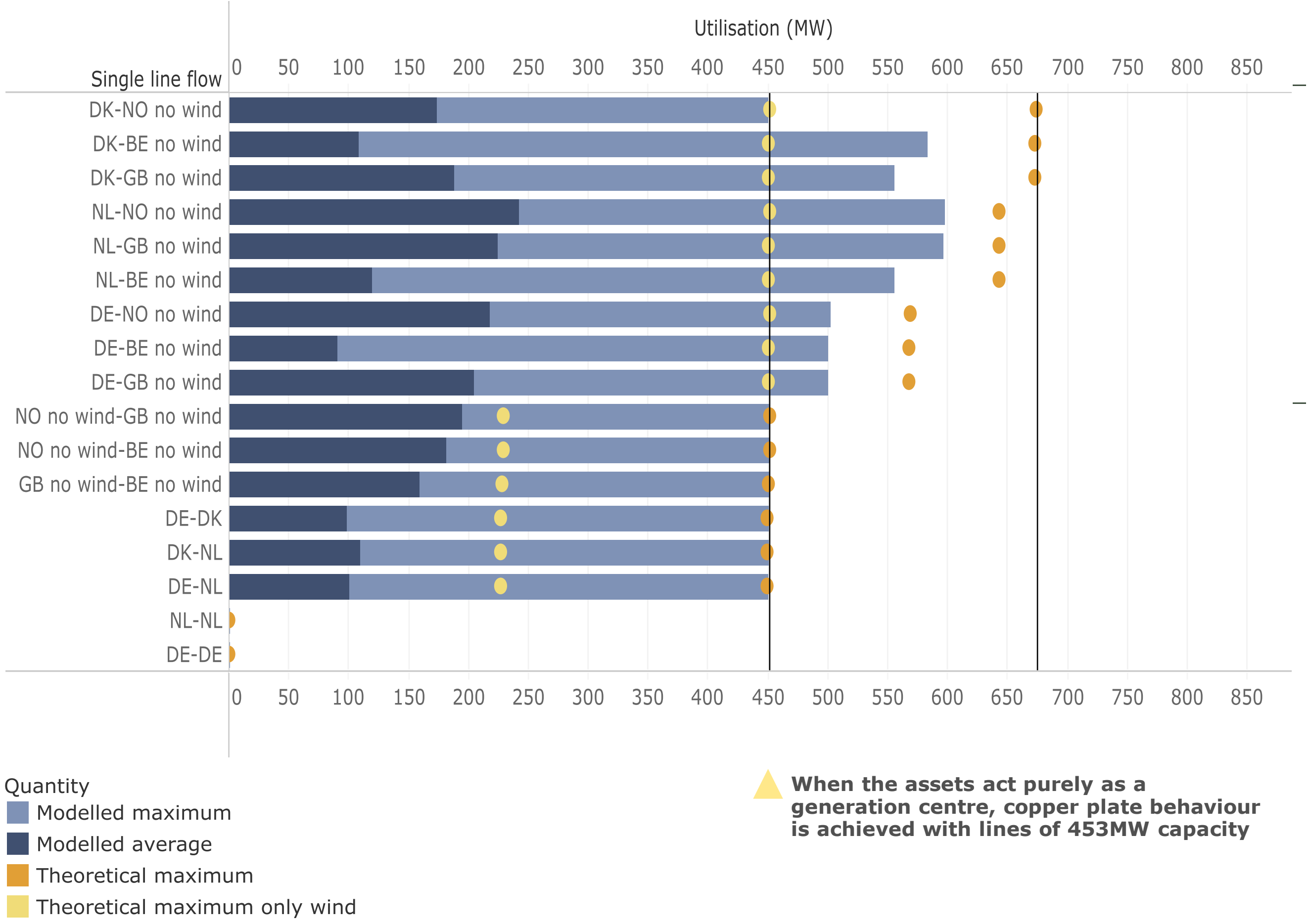
COMMENTS

- Building on the analysis and the chart presented on the previous slide, this chart plots an additional set of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - With the orange marks, the calculated theoretical maximum flow on each hub-internal connector, as described in more detail in the 'Background to the load flow modelling & results' section in the Annex.
- Summary of findings:
  - Assumption that all lines are equal requires a capacity of 675MW per line (compared to 598MW maximum observed utilisation).
  - All lines are assumed to be of the same capacity. For example, if the capacity of one connector were to be scaled down or differ, then the usage of the within-hub connectors would change impacting also on the modelled & theoretical maximum flow.
  - Equal capacity requirement leads to a high unused headroom on many lines.
  - Maximum theoretical capacity is not reached on all lines as these flows require very specific market conditions. e.g. maximum usage of the line between the DK and NO modules requires 100% OWF load factor as well as maximum flows from the DK shore to the hub and from the hub to NO the shore.

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

MODELLED & THEORETICAL WITHIN HUB UTILISATION

When the hub acts purely as a generation centre (i.e. no flows from any of the national shores), the maximum flow is at 453MW



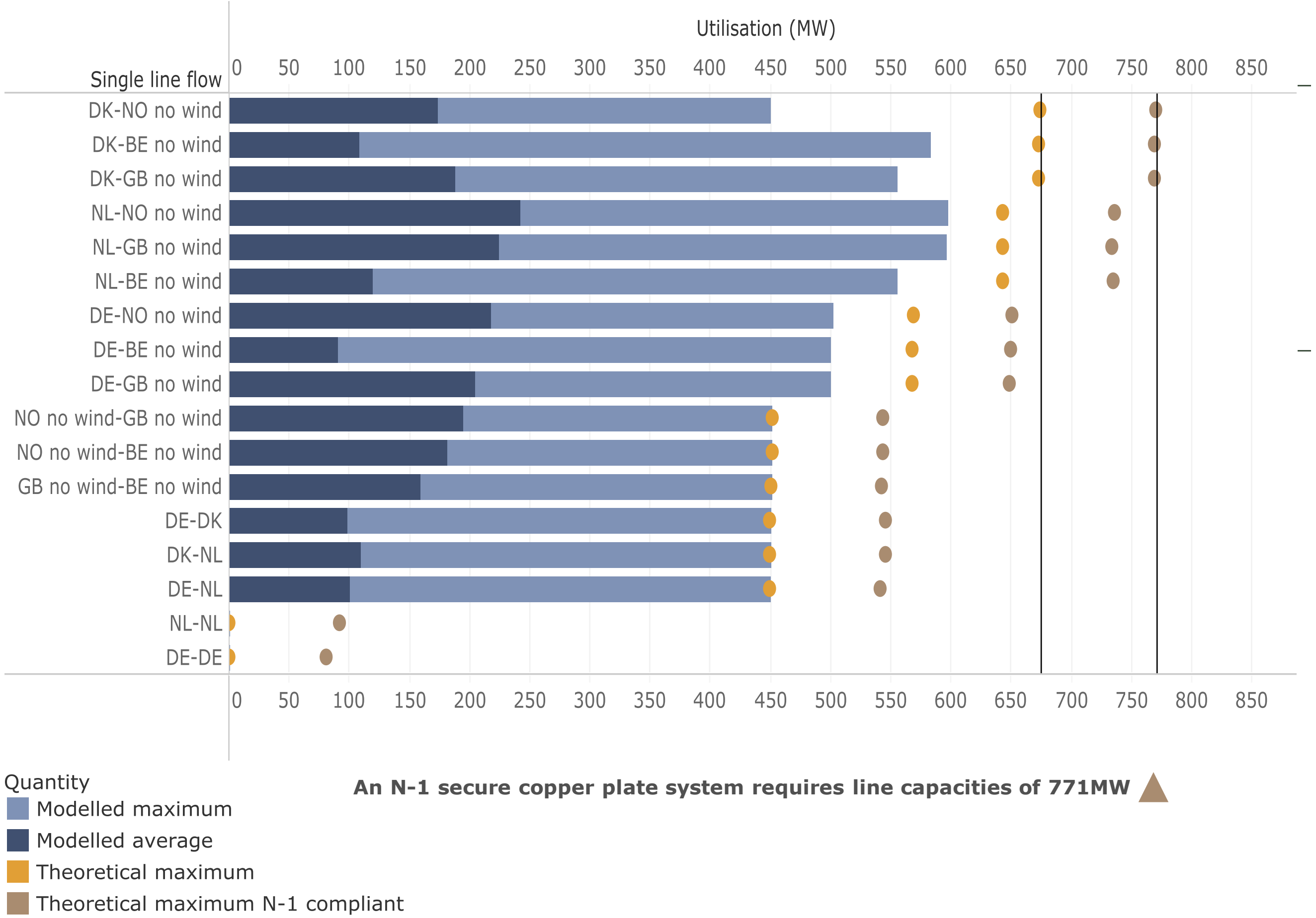
COMMENTS

- Building on the analysis and the chart presented on the previous slide, this chart plots an additional set of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - With the yellow marks, the calculated theoretical maximum flow on each hub-internal connector when the assets act purely as a generation centre (i.e. no flow originating from the onshore systems), as described in more detail in the 'Background to the load flow modelling & results' section in the Annex. The market modelling suggests that this operation happens 35% of the time (2).
- Summary of findings:
  - When the asset acts purely as a generation centre, copper plate behaviour is achieved with lines of 453MW capacity.
  - In practice the 453MW limit is only exceeded when any of the Core markets export power to the hub, which occurs on average only 11% of the time. It is therefore worth exploring the impact of scaling-down the capacity of the hub-internal connectors to this theoretical threshold of 453MW capacity.
  - In fact, despite increased usage as transmission, the 453MW limit would only be surpassed 54 times in 2030 and 136 times in 2040 (weather year average).

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.
2. Pure generation decreases from over 90% in the Core configuration mainly due to the addition of the Norway IC which frequently exports power via the hub.

MODELLED & THEORETICAL WITHIN HUB UTILISATION & N-1 COMPLIANT

An N-1 secure copper plate system requires line capacities of 771MW



COMMENTS

- Building on the analysis and the chart presented on the previous slide, this chart plots an additional set of data for each hub-internal connector (or line) that is part of the NSWPH (1):
  - With the brown marks, the calculated theoretical maximum flow on each line when considering outages on any of the hub-internal connectors – under a "worst case scenario", i.e. resulting from the outage which has the greatest impact on the particular line.
- Summary of findings:
  - Considering outages on any of the hub-internal connectors increases the flow on the remaining lines as power would need to be redirected via the remaining operating lines.
  - An N-1 secure copper plate system requires line capacities of 771MW.

1. Flows are for each line, e.g. 'DK-NL' is the flow on each of the two lines from the DK module to/from the two NL modules.

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Agenda

Lower within-hub utilisation under the HM setup for all connectors

SUMMARY

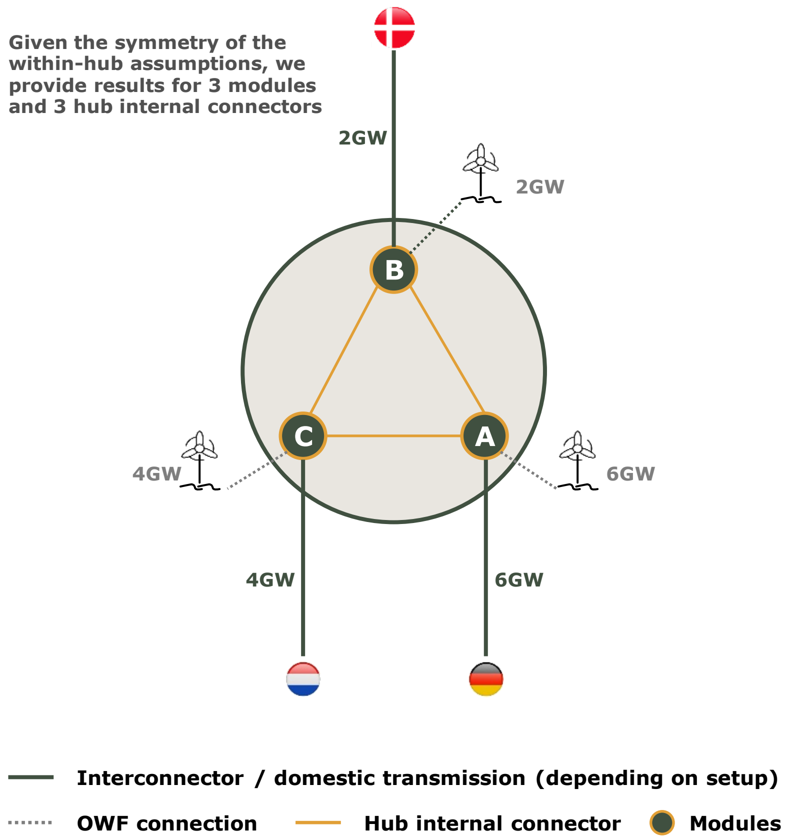
Focus	– Comparison of the hub-internal connectors' utilisation under the two market setups, Home Market and Offshore Bidding Zone, under the Core configuration. – Based on the results of the NSWPH study: NSWPH Study 'Market Setup Impact on Price Dynamics and Income Distribution' – Oct. 2020. – No load flow modelling was performed for this analysis. Therefore, the results of this section are not comparable with the previous sections.

Approach & Assumptions	– Based on post-processing (1) the hourly results of the market modelling, the within-hub flows are allocated among three hub-internal connectors, assuming:
	  – Under both setups, the hub-connected OWF generation, from a physical perspective, is first allocated to its respective national shore (respecting the price signals); and
	  – All flows from e.g. A to B are transferred via the single A-B connector (i.e. no flows are transferred via module C).
	– Given the symmetry of the modules, we assess three hub-internal connectors connecting the DE (A), DK (B), and NL (C) modules.

Messages	– Overall higher within hub utilisation under the OBZ setup compared to the HM setup; and – While the maximum flow for all connectors remains similar between the market setups, the overall utilisation of the cables is different under the market setups.

ILLUSTRATION OF CORE CONFIGURATION

Given the symmetry of the within-hub assumptions, we provide results for 3 modules and 3 hub internal connectors

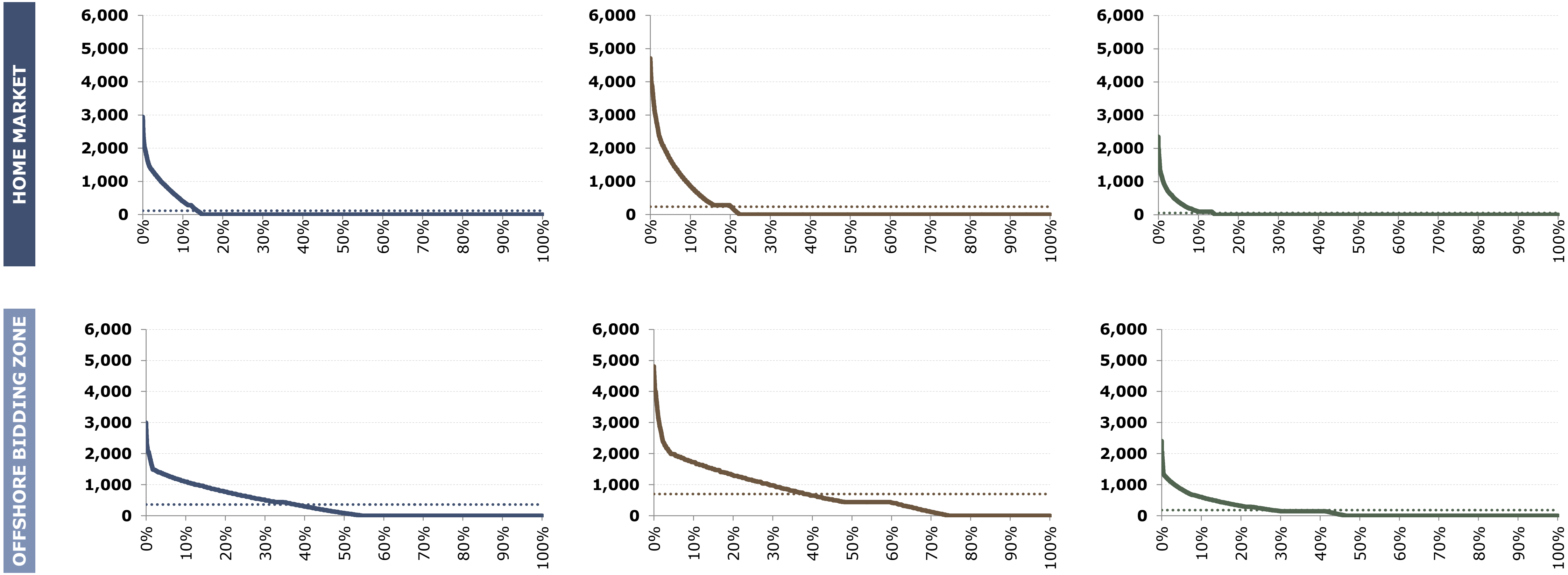


1. Please note that no load flow modelling was performed for this analysis; the results in this section should only be used for the comparison of the two market setups.

Higher overall within-hub utilisation under the OBZ setup, but both setups see a significant number of hours with very low use

DE-DK **DE-NL** **DK-NL**

Duration curves of overall utilisation of each hub internal connector in MW – incl. all weather years (i.e. 26,280 hours) and average hourly flow (dotted lines)



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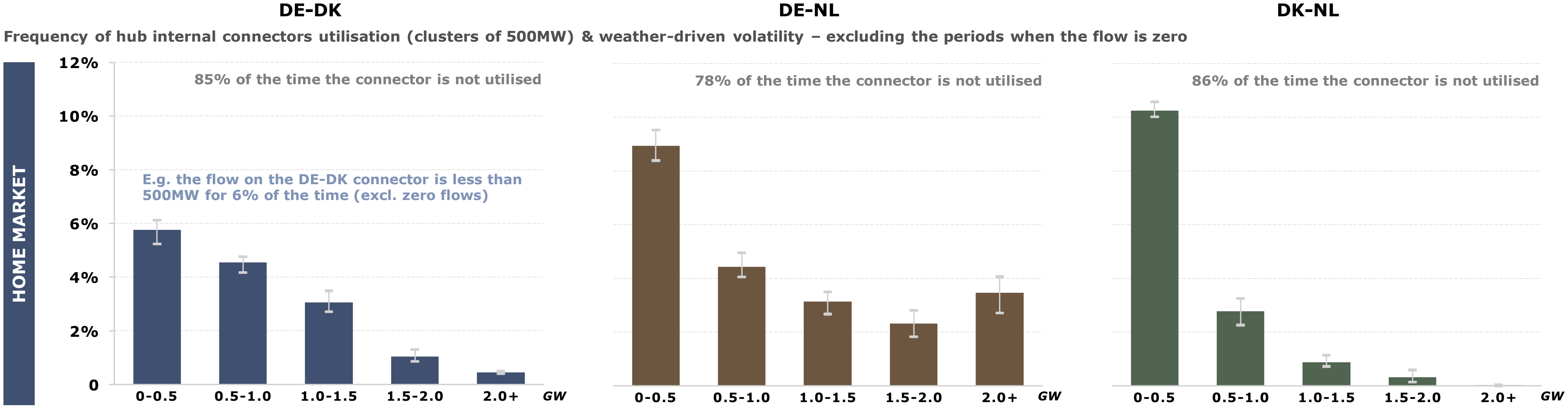
Limited within-hub flows under the HM setup, with maximum hourly flow largely below 1,000MW (DE-DK & DE-NL) or 500MW (DK-NL)



COMMENTS

- The charts show how often the within-hub flow is between 0-500MW, 500-1,000MW, etc. The charts do not include the periods when the flow is equal to zero.
- As discussed in the previous study, the NSWPH assets are mainly utilised to transfer the hub-connected OWF generation to the respective home markets. This means that limited flows are been transferred via the hub to the opposite markets (i.e. cross-zonal flows are limited). For all three connectors, around 80-85% of the time the connectors remain unutilised.
- The maximum hourly flow remains mostly below 1,000MW (for DE-DK & DE-NL) or even below 500MW (for DK-NL).
- There is little variability driven by weather patterns on the overall figures. Results vary by no more than ±1% (in absolute terms) when assessing the weather years individually (i.e. looking at the maximum and minimum figures from the three weather years modelled).

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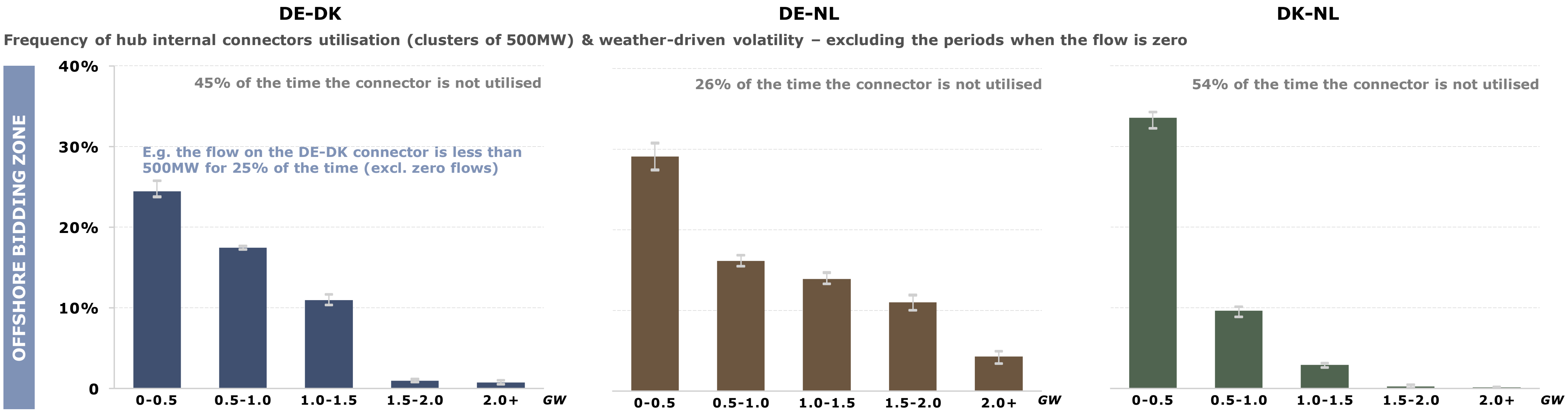
Increased within-hub flows under the OBZ setup, with maximum hourly flow below 1,500MW (DE-DK), 2,000MW (DE-NL), or 1,000MW (DK-NL)

Frequency of hub internal connectors utilisation (clusters of 500MW) & weather-driven volatility – excluding the periods when the flow is zero



COMMENTS

- The charts show how often the within-hub flow is between 0-500MW, 500-1,000MW, etc. The charts do not include the periods when the flow is equal to zero.
- As discussed in the previous study, this setup allows for increased cross-zonal flows (compared to the HM setup). This essentially means that more flows will be transferred via the hub. A big part of this flow is from the hub-connected OWF generation going to an 'opposite market' triggered by a price signal.
- The maximum hourly flow remains mostly below 1,500-2,000MW (for DE-DK & DE-NL); or even below 500MW (for DK-NL).
- There is little variability driven by weather patterns on the overall figures. Results vary by no more than ±1% (in absolute terms) when assessing the weather years individually (i.e. looking at the maximum and minimum figures from the three weather years modelled).

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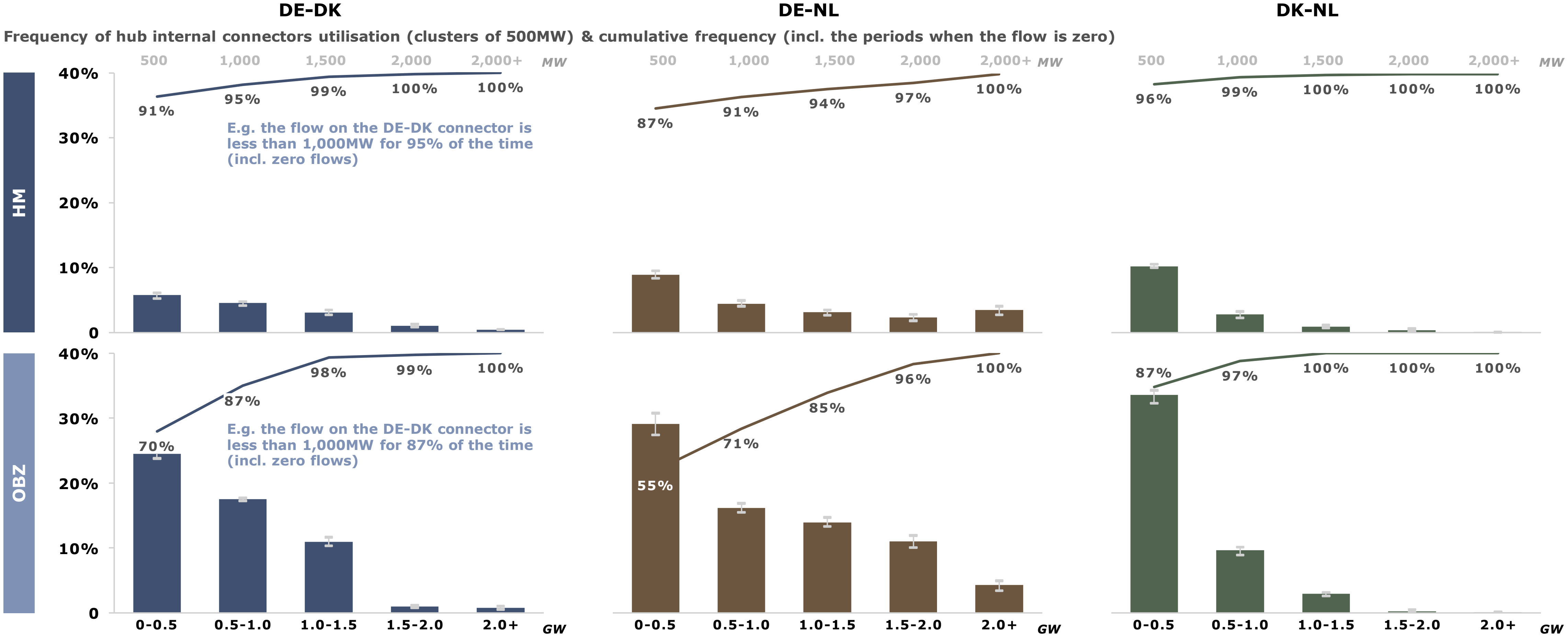
Increased periods of flow ranging between 500-1,500MW under the OBZ setup



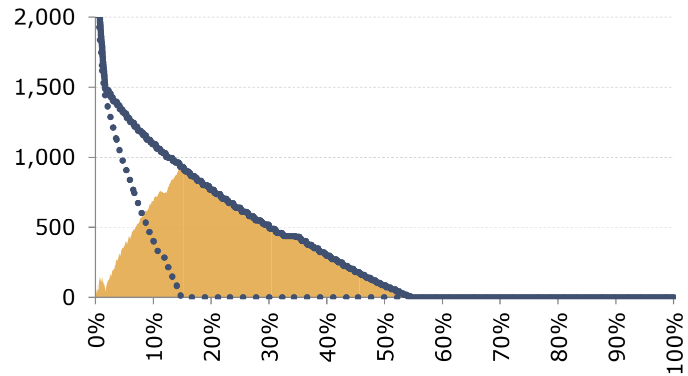
Both setups accommodate similar maximum flows, however, the utilisation of the cables can change considerably for the remaining hours

OBZ ······ HM OBZ – HM difference

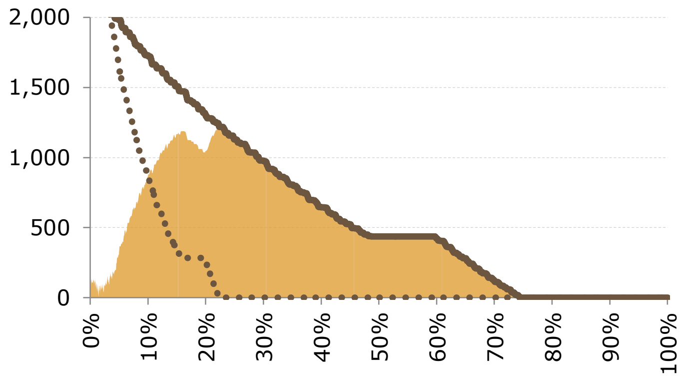
SETUP COMPARISON

Duration curves of overall utilisation of each hub internal connector in MW – incl. all weather years (i.e. 26,280 hours) and spread between the market setups

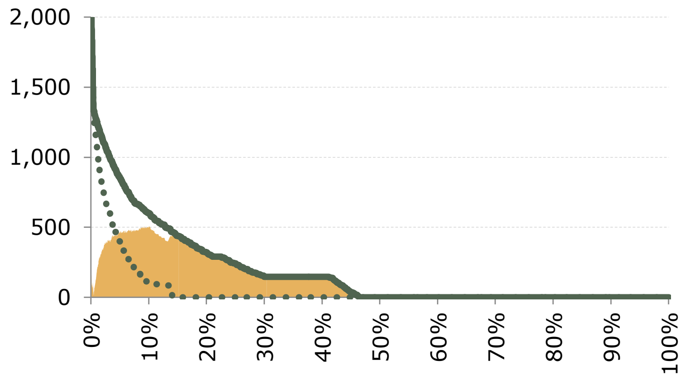
DE-DK



DE-NL



DK-NL



	DE-DK HM	DE-DK OBZ	DE-NL HM	DE-NL OBZ	DK-NL HM	DK-NL OBZ
% of time flow more than 1,500MW	1%	2%	6%	15%	c. 0%	c. 0%
% of time flow more than 1,000MW	5%	13%	9%	29%	1%	3%
% of time flow more than 500MW	9%	30%	13%	45%	4%	13%

COMMENTS

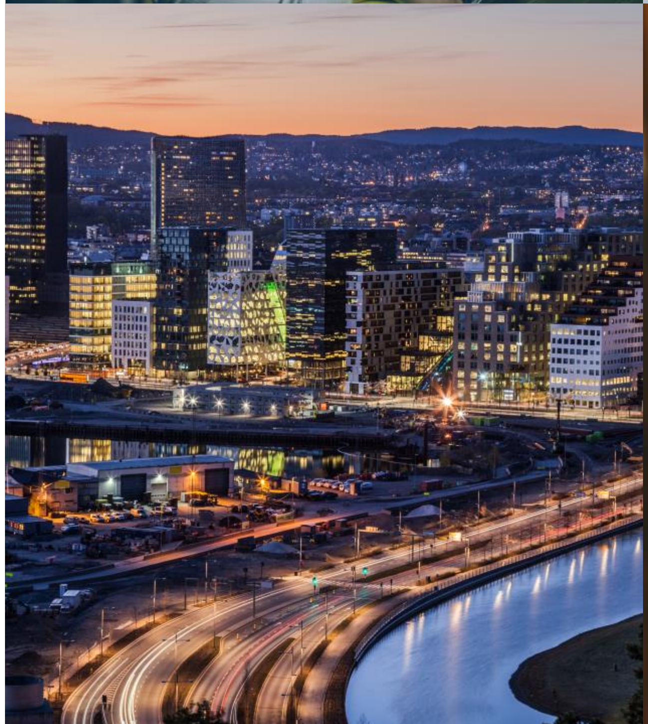
- The charts show the flow duration curves for each connector under both setups. The orange shaded area shows the difference between the flow under the OBZ and the HM setup.
- While the maximum flow for each connector tends to be very similar between the market setups, the utilisation of the cables can change considerably for the remaining hours. For example, the flow on the DE-DK connector is more than 1,000MW for 5% of the time under the HM setup, but it is more than 1,000MW for 13% of the time under the OBZ setup. In practice, this means that if the capacity of the cable was scaled down at 1,000MW, there would be an increasing number of hours when there would be a curtailment issue under the OBZ setup.

AFRY ÅF PÖYRY

Annex – Supporting Information

Annex Agenda

- **Summary of copper plate capacity requirement per configuration**
- Additional flow duration curves (Core & Core+)
- High level comparisons of the configurations
- Utilisation of IC assets based on the market modelling
- Background to the load flow modelling & results
- TYNDP 2020 National Trends assumptions



COPPER PLATE REQUIREMENTS IN MW

Core

Please see slides 38-40 for additional information

Values presented in this table are in MW	Copper plate requirement per line	DE-DK	DE-NL	DK-NL	Lines between modules of same markets	Total copper plate capacity requirement for the hub
# of lines		**3**	**6**	**2**	**4**	
All hub-internal connectors are commissioned	**675**	**2,025**	**4,050**	**1,350**	**2,700**	**10,125**
Removal of lines between modules of the same market (1)	675	2,025	4,050	1,350	0	7,425
Assets act purely as a generation centre and all hub-internal connectors are commissioned	**342**	**1,026**	**2,052**	**684**	**1,368**	**5,130**
Removal of lines between modules of the same market (1)	342	1,026	2,052	684	0	3,762
N-1 compliant with all hub-internal connectors available	**844**	**2,532**	**5,064**	**1,688**	**3,376**	**12,660**
Removal of lines between modules of the same market (2)	1,040	3,120	6,240	2,080	0	11,440

1. Lines between modules of the same market (e.g. DE-DE) have zero flows, and thus removing them does not change the utilisation of the other lines. │ 2. Removing lines between modules of the same market increases the required line capacity for N-1 security (to 1,040MW per remaining line) as the possibility for redirecting flows is further reduced.

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Core Increased IC

Please see slides 55-58 for additional information

Values presented in this table are in MW	**Copper plate requirement per line**	**DE-DK**	**DE-NL**	**DK-NL**	**Lines between modules of same markets**	**Total copper plate capacity requirement for the hub**
# of lines		**8**	**12**	**6**	**10**	
All hub-internal connectors are commissioned	**642**	**5,136**	**7,704**	**3,852**	**6,420**	**23,112**
Removal of lines between modules of the same market (1)	784	6,272	9,408	4,704	0	20,384
Assets act purely as a generation centre and all hub-internal connectors are commissioned	**450**	**3,600**	**5,400**	**2,700**	**4,500**	**16,200**
Removal of lines between modules of the same market (2)	450	**3,600**	**5,400**	**2,700**	2,700 [i.e. 6*450]	14,400
N-1 compliant with all hub-internal connectors available	**733**	**5,864**	**8,796**	**4,398**	**7,330**	**26,388**

1. Lines between modules of the same market have limited utilisation (see slide 52/53), and thus removing them increases the maximum theoretical flows to 784MW. | 2. In this case, we calculate the copper plate capacity when removing only the four lines between the modules of the same markets that accommodate an OWF.

COPPER PLATE REQUIREMENTS IN MW

Core+

Please see slides 77-80 for additional information

Values presented in this table are in MW	**Copper plate requirement per line**	**DE-DK**	**DE-NL**	**DK-NL**	**Lines between a Core market module & a Core+ market module**	**Lines between Core+ market modules**	**Lines between modules of same (Core) markets**	**Total copper plate capacity requirement for the hub**
# of lines		**3**	**6**	**2**	**18**	**3**	**4**	
All hub-internal connectors are commissioned	**675**	**2,025**	**4,050**	**1,350**	**12,150**	**2,025**	**2,700**	**24,300**
Removal of lines between modules of the same market (1)	675	2,025	4,050	1,350	12,150	2,025	0	21,600
Assets act purely as a generation centre and all hub-internal connectors are commissioned	**453**	**1,359**	**2,718**	**906**	**8,154**	**1,359**	**1,812**	**16,308**
Removal of lines between modules of the same market (1)	453	1,359	2,718	906	8,154	1,359	0	14,496
N-1 compliant with all hub-internal connectors available	**771**	**2,313**	**4,626**	**1,542**	**13,878**	**2,313**	**3,084**	**27,756**

1. Lines between modules of the same market (e.g. DE-DE) have zero flows, and thus removing them does not change the utilisation of the other lines.

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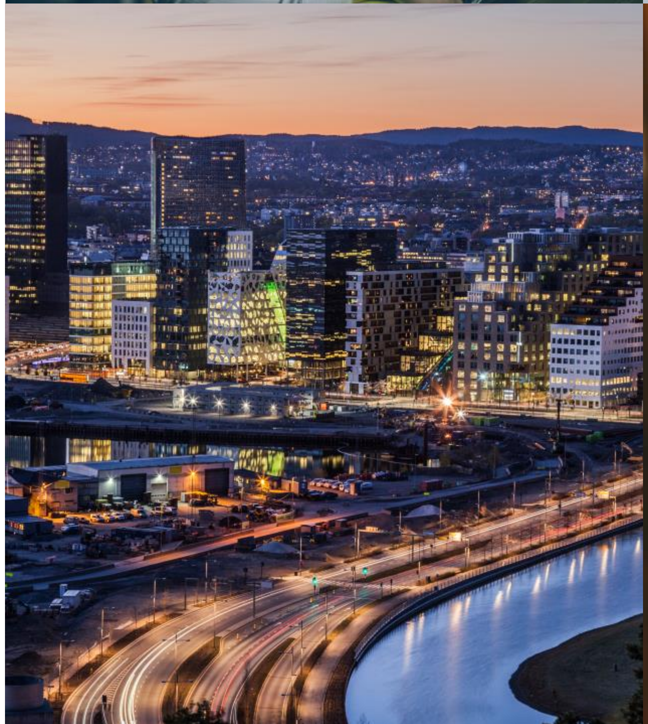
Annex Agenda

- Summary of copper plate capacity requirement per configuration
- **Additional flow duration curves (Core & Core+)**
- High level comparisons of the configurations
- Utilisation of IC assets based on the market modelling
- Background to the load flow modelling & results
- TYNDP 2020 National Trends assumptions





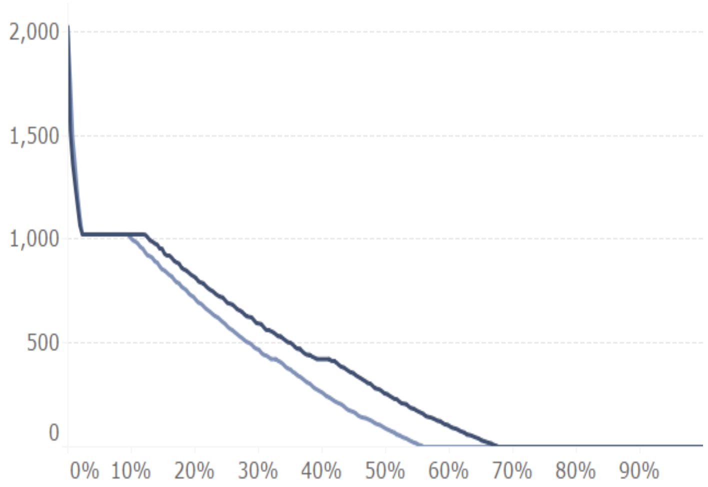

HUB INTERNAL FLOW DURATION CURVES

Low utilisation overall of the within-hub assets in line with the market modelling results

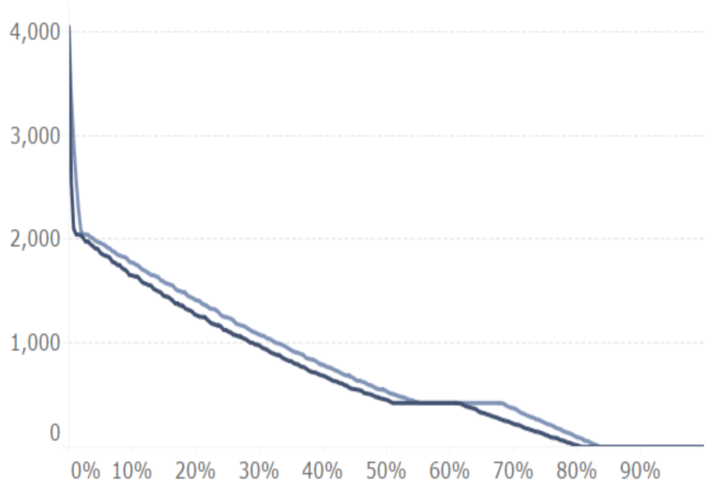
Flow duration curves for the hub-internal connectors in MW irrespective of direction – incl. all weather years (i.e. 3*8,760 = 26,280 hours)

Note: the different scale on the y-axis , which is determined by the maximum value on each connector

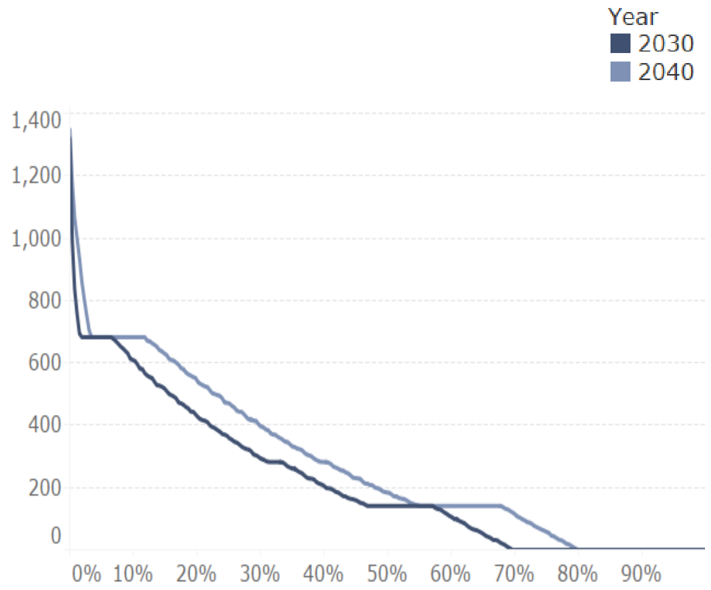
3 DE-DK CONNECTORS



6 DE-NL CONNECTORS



2 DK-NL CONNECTORS



The charts show the total flow (irrespective of direction) for each hub-internal connector (1) connecting any two modules of the different markets, for 2030 (dark blue) and 2040 (light blue).

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-DK, they need to be divided by three.

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HUB INTERNAL FLOW DURATION CURVES (CORE MARKETS)

Low utilisation overall of the within-hub assets in line with the market modelling results

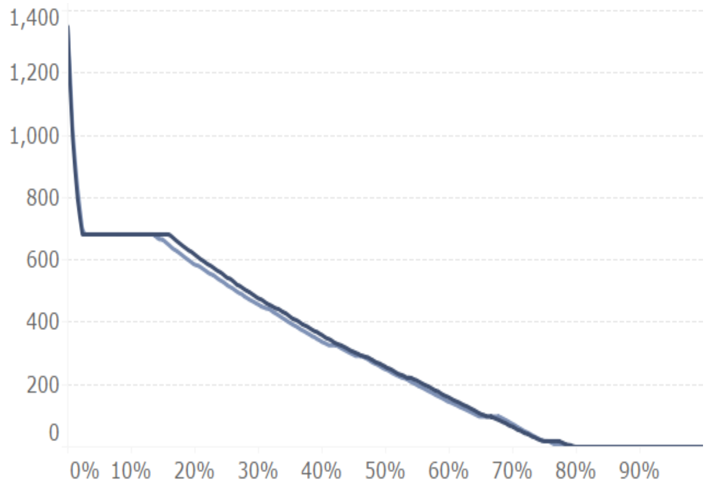
3 DE-DK CONNECTORS

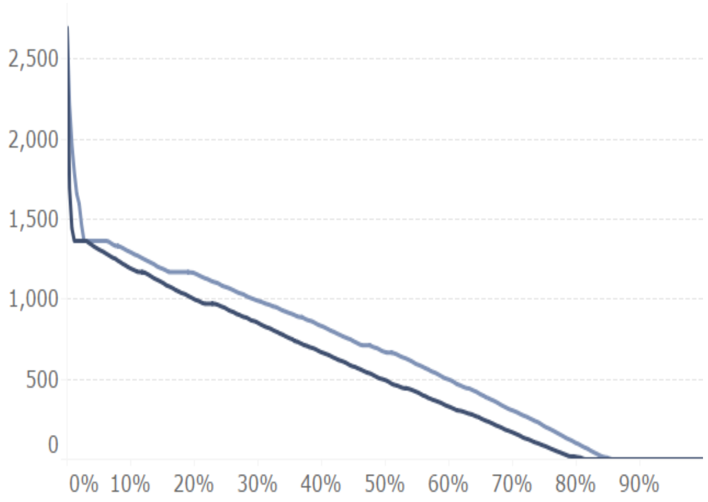
6 DE-NL CONNECTORS

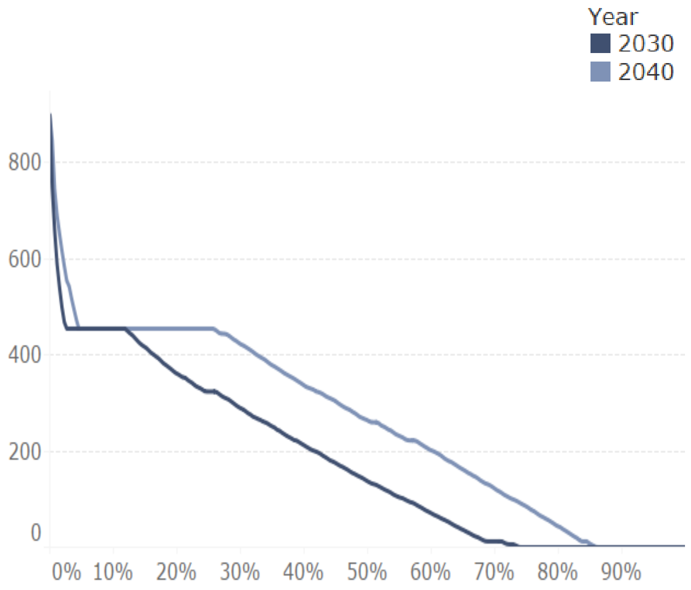
2 DK-NL CONNECTORS

Flow duration curves for the hub-internal connectors in MW irrespective of direction – incl. all weather years (i.e. 3*8,760 = 26,280 hours)

Note: the different scale on the y-axis , which is determined by the maximum value on each connector







The charts show the total flow (irrespective of direction) for each hub-internal connector (1) connecting any two modules of the different markets, for 2030 (dark blue) and 2040 (light blue).

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-DK, they need to be divided by three.

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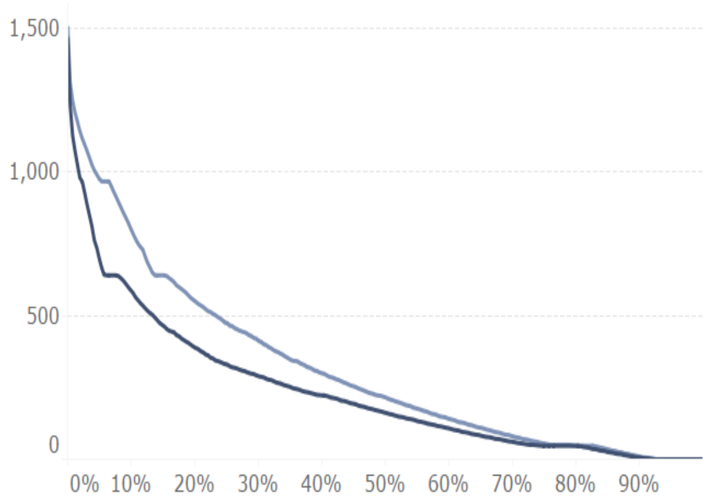
HUB INTERNAL FLOW DURATION CURVES (BELGIUM)

Flows on the lines connecting to the BE modules are limited and mainly associated with the transfer of OWF generation to the BE shore when the price signal is strong

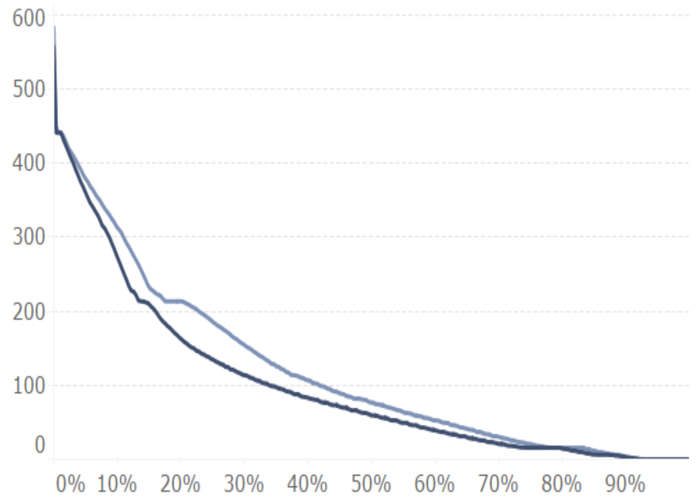
Flow duration curves for the hub-internal connectors in MW irrespective of direction – incl. all weather years (i.e. 3*8,760 = 26,280 hours)

Note: the different scale on the y-axis , which is determined by the maximum value on each connector

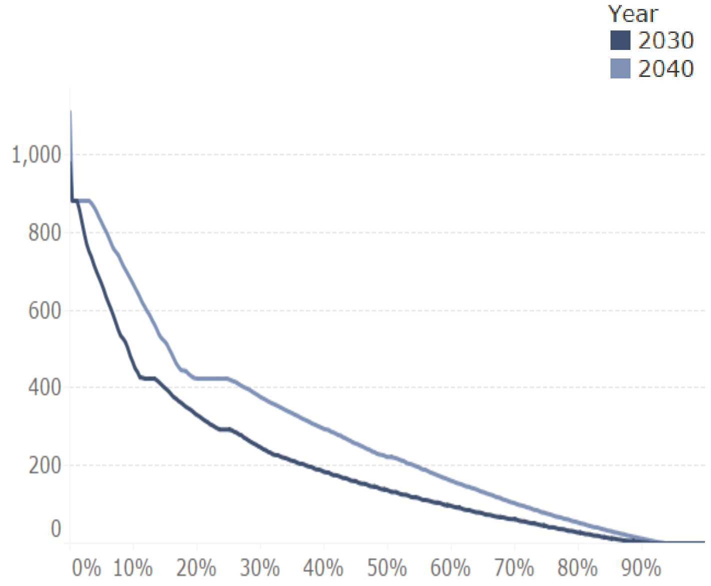
3 DE-BE CONNECTORS



1 DK-BE CONNECTOR



2 NL-BE CONNECTORS



The charts show the total flow (irrespective of direction) for each hub-internal connector (1) connecting any two modules of the different markets, for 2030 (dark blue) and 2040 (light blue).

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-BE, they need to be divided by three.

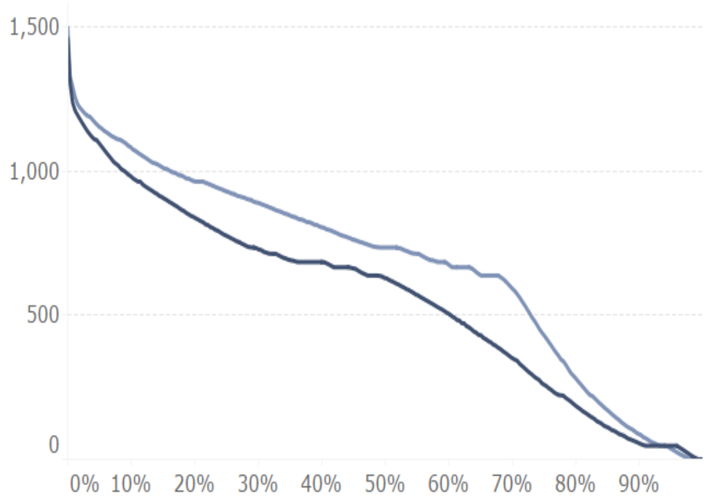
HUB INTERNAL FLOW DURATION CURVES (GB)

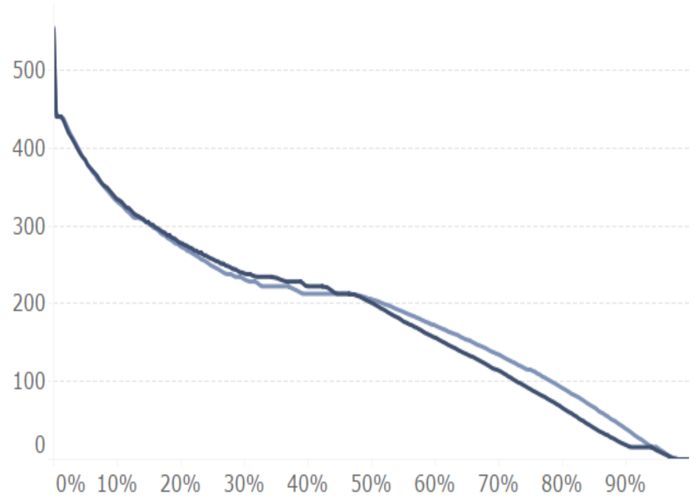
Increased utilisation for the lines connecting GB to the Core market modules, with the NL-GB connector having the highest per line average flows in the Core+

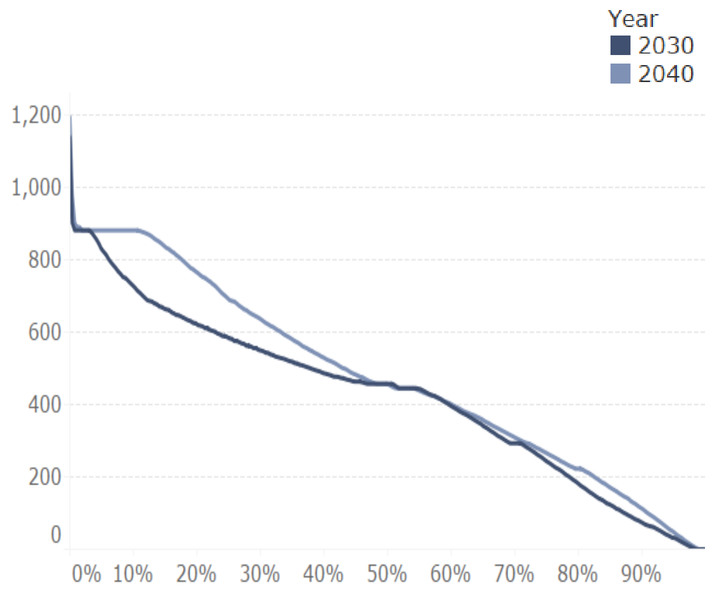
3 DE-GB CONNECTORS | **1 DK-GB CONNECTOR** | **2 GB-NL CONNECTORS**

Flow duration curves for the hub-internal connectors in MW irrespective of direction – incl. all weather years (i.e. 3*8,760 = 26,280 hours)

Note: the different scale on the y-axis , which is determined by the maximum value on each connector







The charts show the total flow (irrespective of direction) for each hub-internal connector (1) connecting any two modules of the different markets, for 2030 (dark blue) and 2040 (light blue).

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-GB, they need to be divided by three.

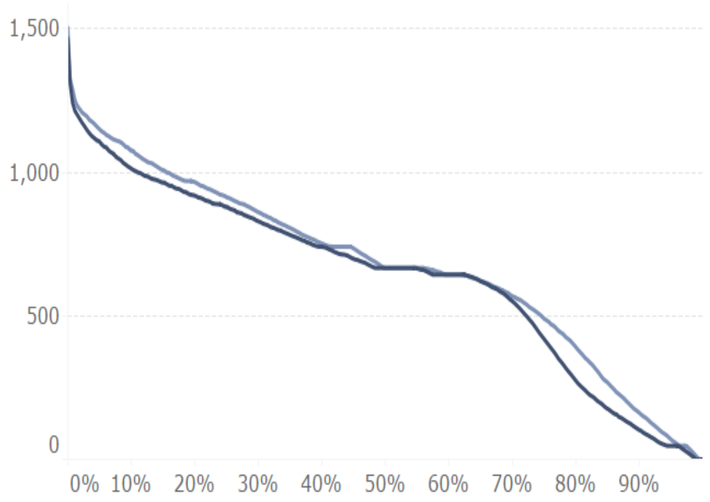
HUB INTERNAL FLOW DURATION CURVES (NORWAY)

Increased utilisation for the lines connecting NO to the Core market modules

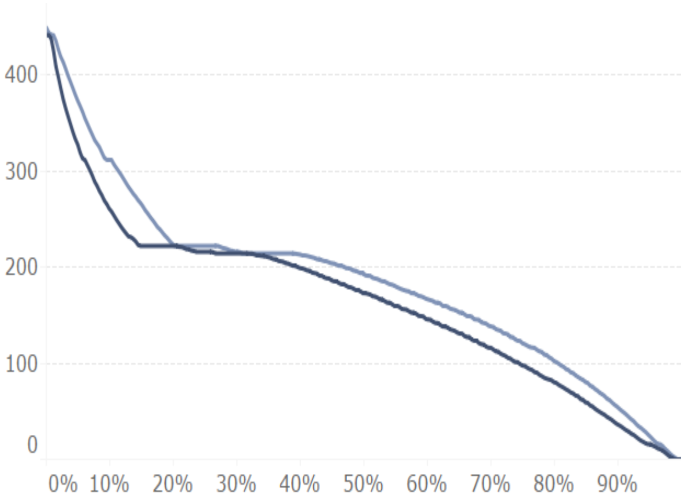
Flow duration curves for the hub-internal connectors in MW irrespective of direction – incl. all weather years (i.e. 3*8,760 = 26,280 hours)

Note: the different scale on the y-axis , which is determined by the maximum value on each connector

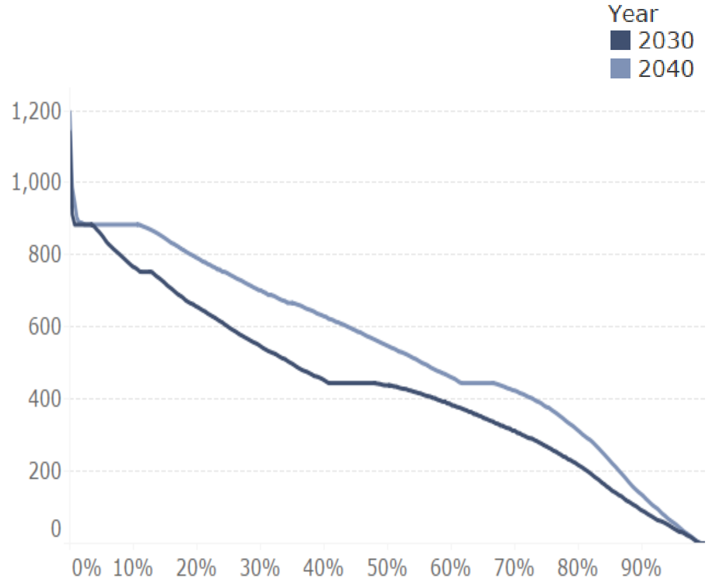
3 DE-NO CONNECTORS



1 DK-NO CONNECTOR



2 NO-NL CONNECTORS



The charts show the total flow (irrespective of direction) for each hub-internal connector (1) connecting any two modules of the different markets, for 2030 (dark blue) and 2040 (light blue).

1. To estimate the flow for one individual connector, the values above would need to be divided by the right figure – e.g. for the DE-NO, they need to be divided by three.

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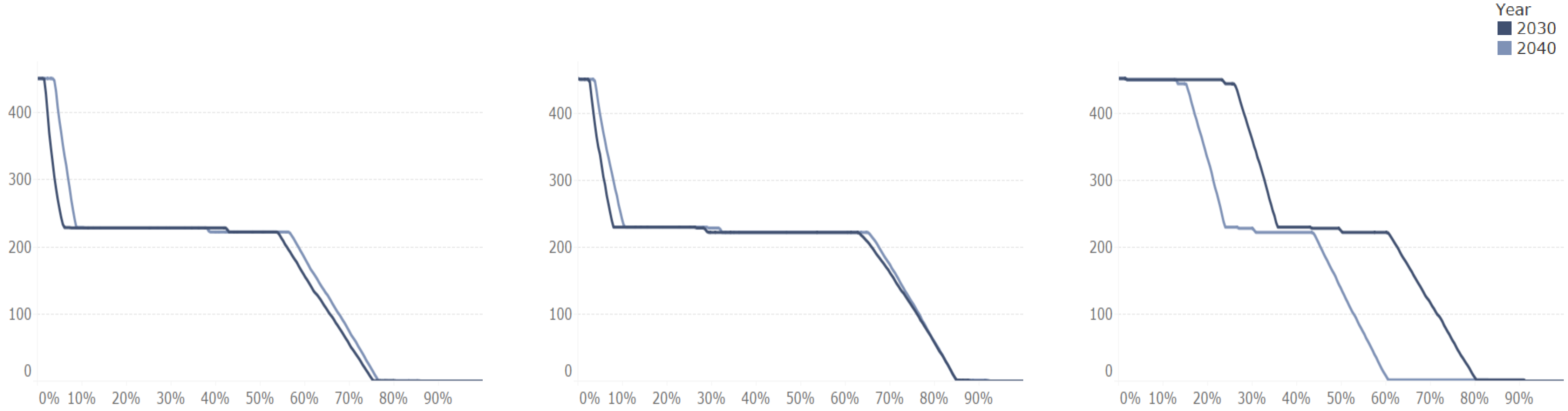
HUB INTERNAL FLOW DURATION CURVES (CORE+ MARKETS)

Highest flows occur towards GB, with the NO → GB flow occurring at maximum around 20% of the time

GB-BE CONNECTOR | **NO-BE CONNECTOR** | **NO-GB CONNECTOR**

Flow duration curves for the hub-internal connectors in MW irrespective of direction – incl. all weather years (i.e. 3*8,760 = 26,280 hours)



The charts show the total flow (irrespective of direction) for each hub-internal connector (1) connecting any two modules of the different markets, for 2030 (dark blue) and 2040 (light blue).

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Annex Agenda

- Summary of copper plate capacity requirement per configuration
- Additional flow duration curves (Core & Core+)
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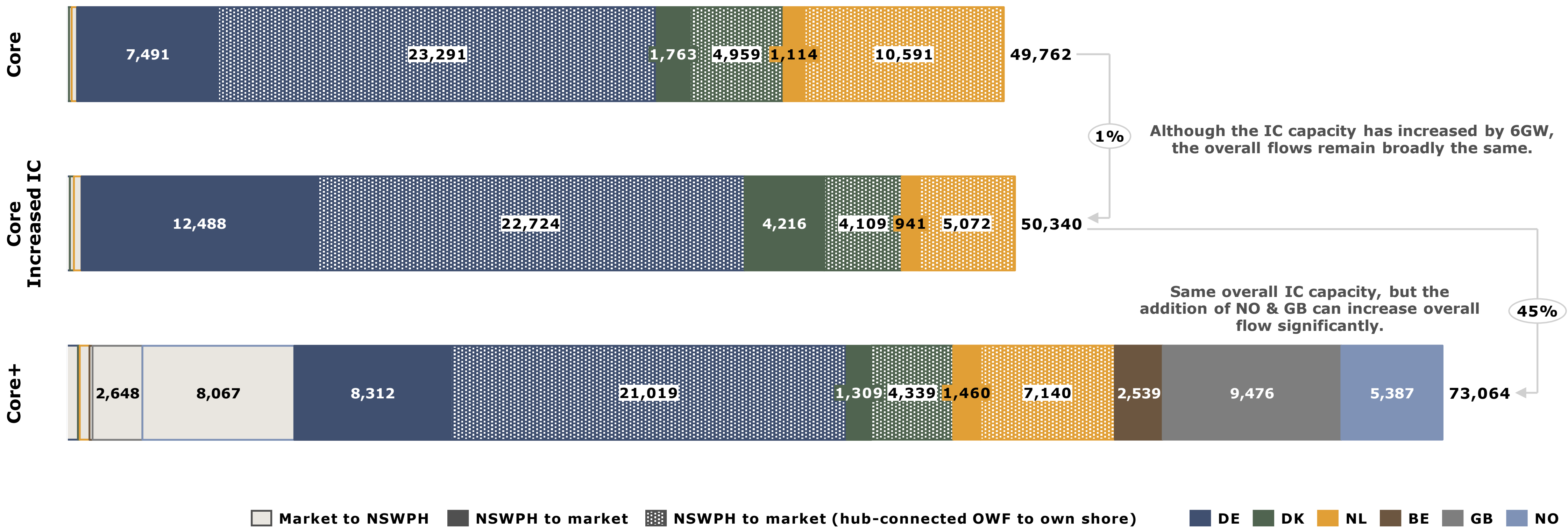
USAGE OF TRANSMISSION ASSETS

Increasing the IC capacity with the Core markets has little effect on the overall flow, however, the addition of GB and Norway spokes increases flows by as much as 45% in 2030

Annual physical cross-zonal flows in GWh, incl. losses, by direction



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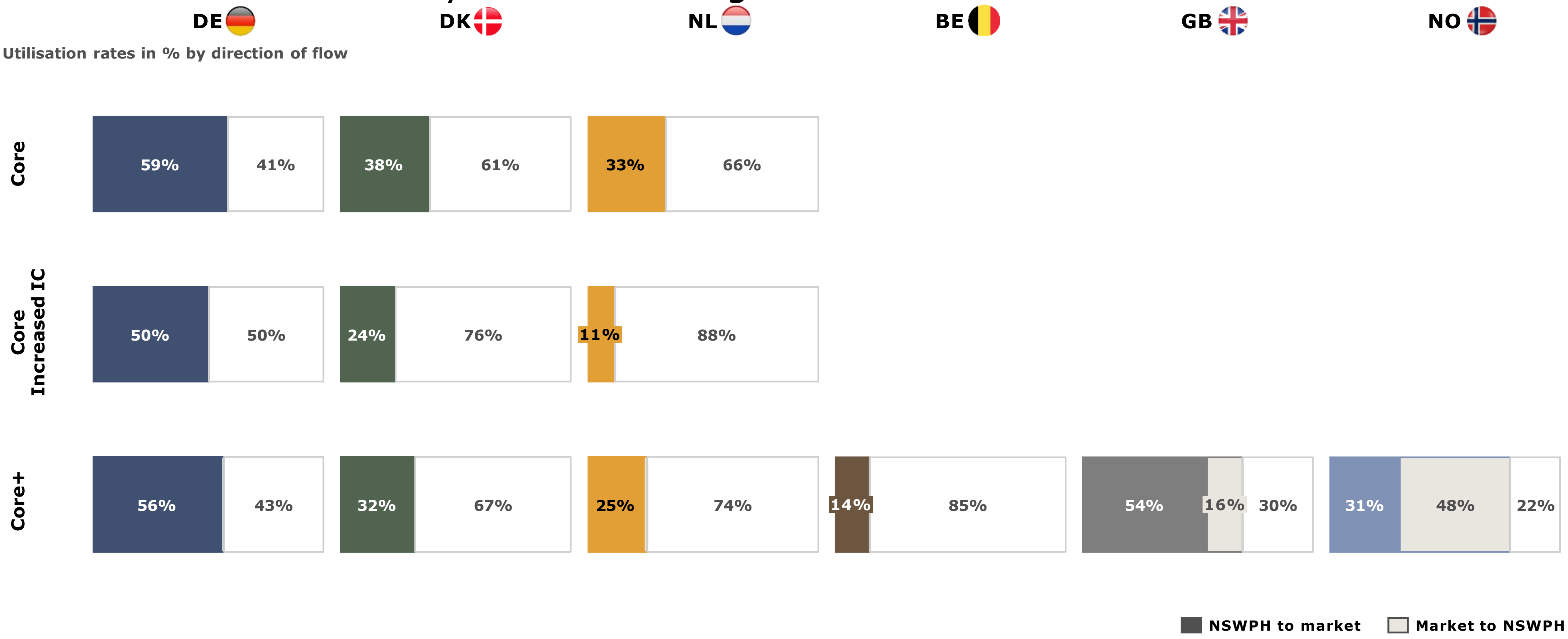
USAGE OF TRANSMISSION ASSETS

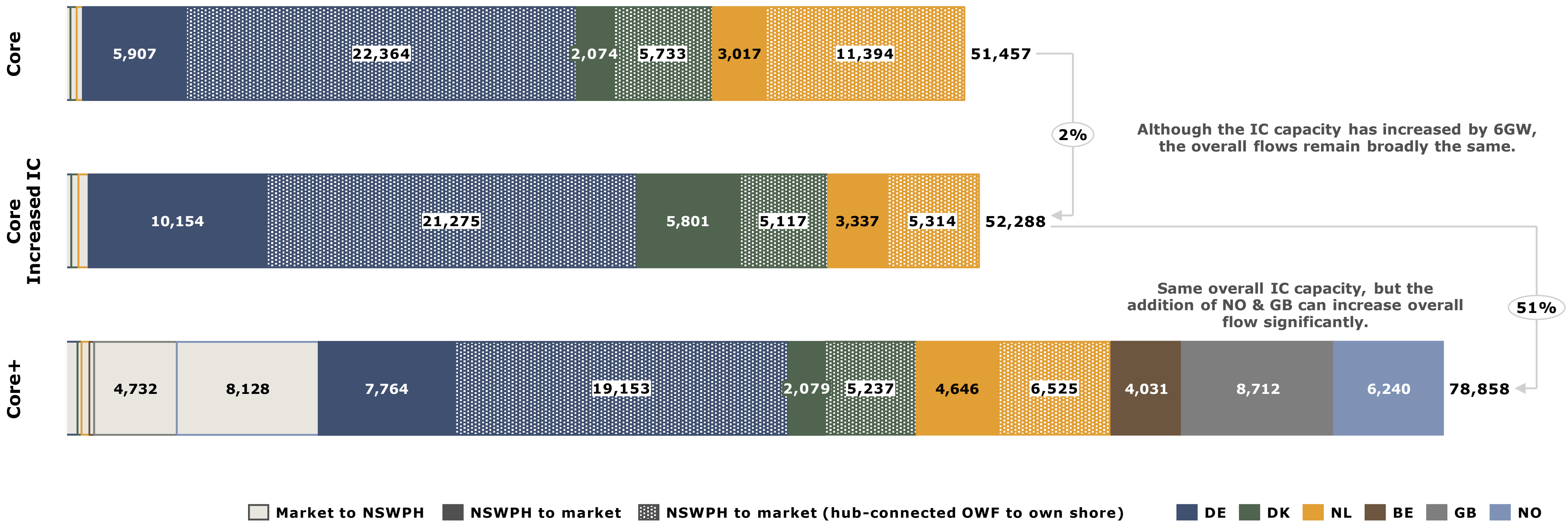
Total utilisation drops in the Core Increased IC case, as the IC capacity increases but price spreads remain limited, while total utilisation increases in the Core+ with Norway and GB being connected to the hub



USAGE OF TRANSMISSION ASSETS

Increasing the IC capacity with the Core markets has little effect on the overall flow, however, the addition of GB and Norway spokes increases flows by as much as 51% in 2040

Annual physical cross-zonal flows in GWh, incl. losses, by direction



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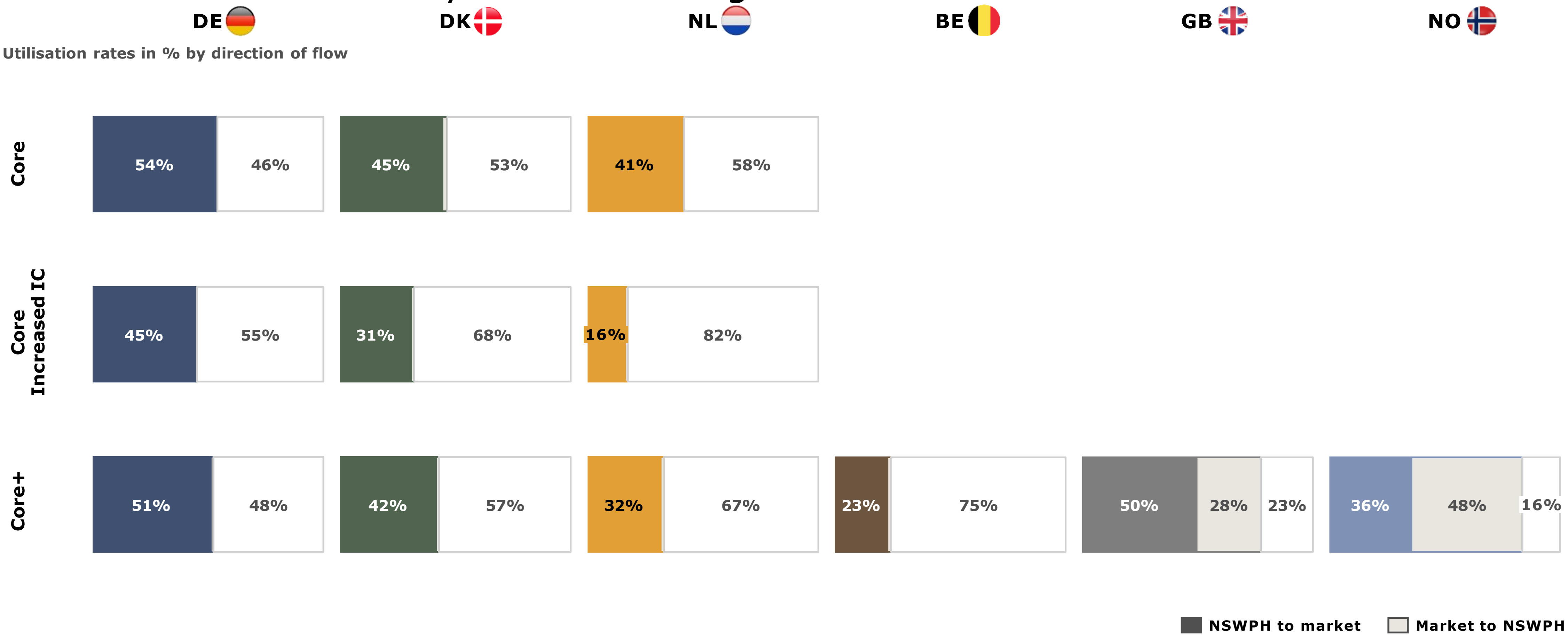
USAGE OF TRANSMISSION ASSETS

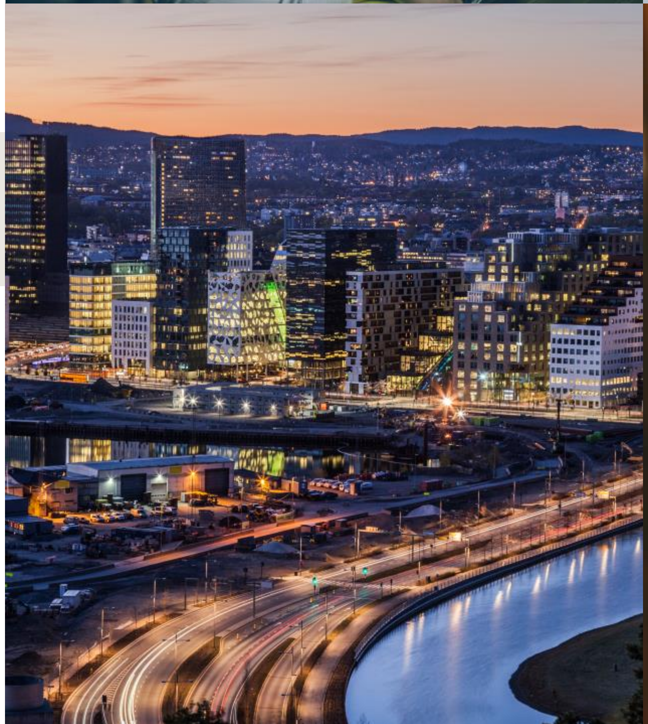
Total utilisation drops in the Core Increased IC case, as the IC capacity increases but price spreads remain limited, while total utilisation increases in the Core+ with Norway and GB being connected to the hub



Annex Agenda

- Summary of copper plate capacity requirement per configuration
- Additional flow duration curves (Core & Core+)
- High level comparisons of the configurations
- **Utilisation of IC assets based on the market modelling**
- Background to the load flow modelling & results
- TYNDP 2020 National Trends assumptions






How to read the chart [1/2]

Annual physical cross-zonal flows in GWh, incl. losses, by direction

The light grey-coloured areas represent the flows linked to exports from the national onshore systems towards the hub.

These flows feed into the nodal modelling.

See example I on next slide.

The non-shaded coloured areas represent the overall flows that are transferred to the national onshore systems from the hub, via the internal connectors. These include: i) flows from the hub originating from the national systems; and ii) the hub-connected OWF generation that is directed towards an 'opposite' market –i.e. not the market connected to the OWF-specific module.

These flows feed into the nodal modelling.

See example II on next slide.

The shaded coloured areas represent the flows that go directly from the hub-connected OWF to the onshore system – i.e. without flowing into the hub. In most cases, they represent the majority of the flows.

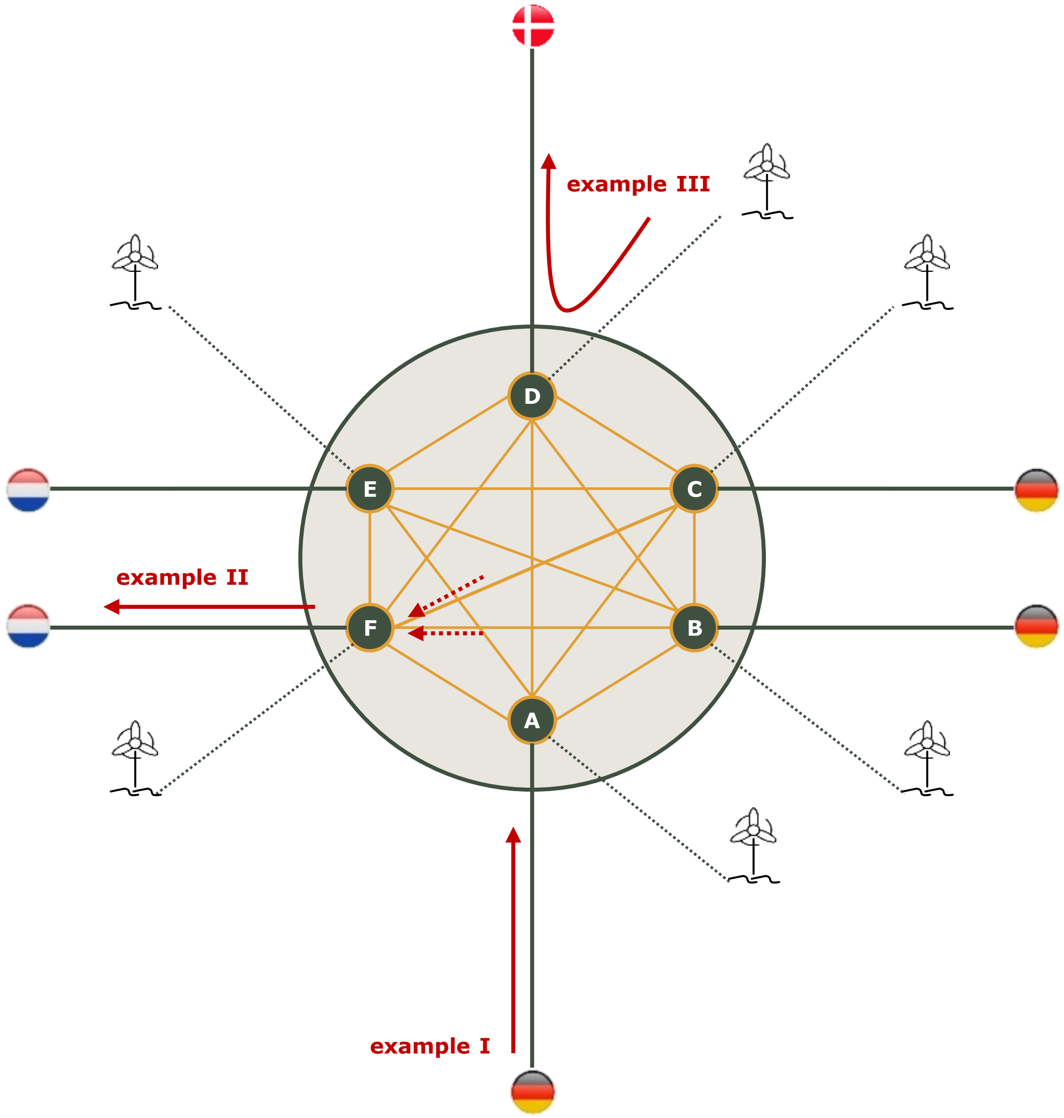
These flows do not feed into the nodal modelling.

See example III on next slide.

How to read the chart [2/2]

Illustrative examples of flows (1)

Example I	**These flows feed into the nodal modelling.**
Example II	
Example III	**These flows do not feed into the nodal modelling.**

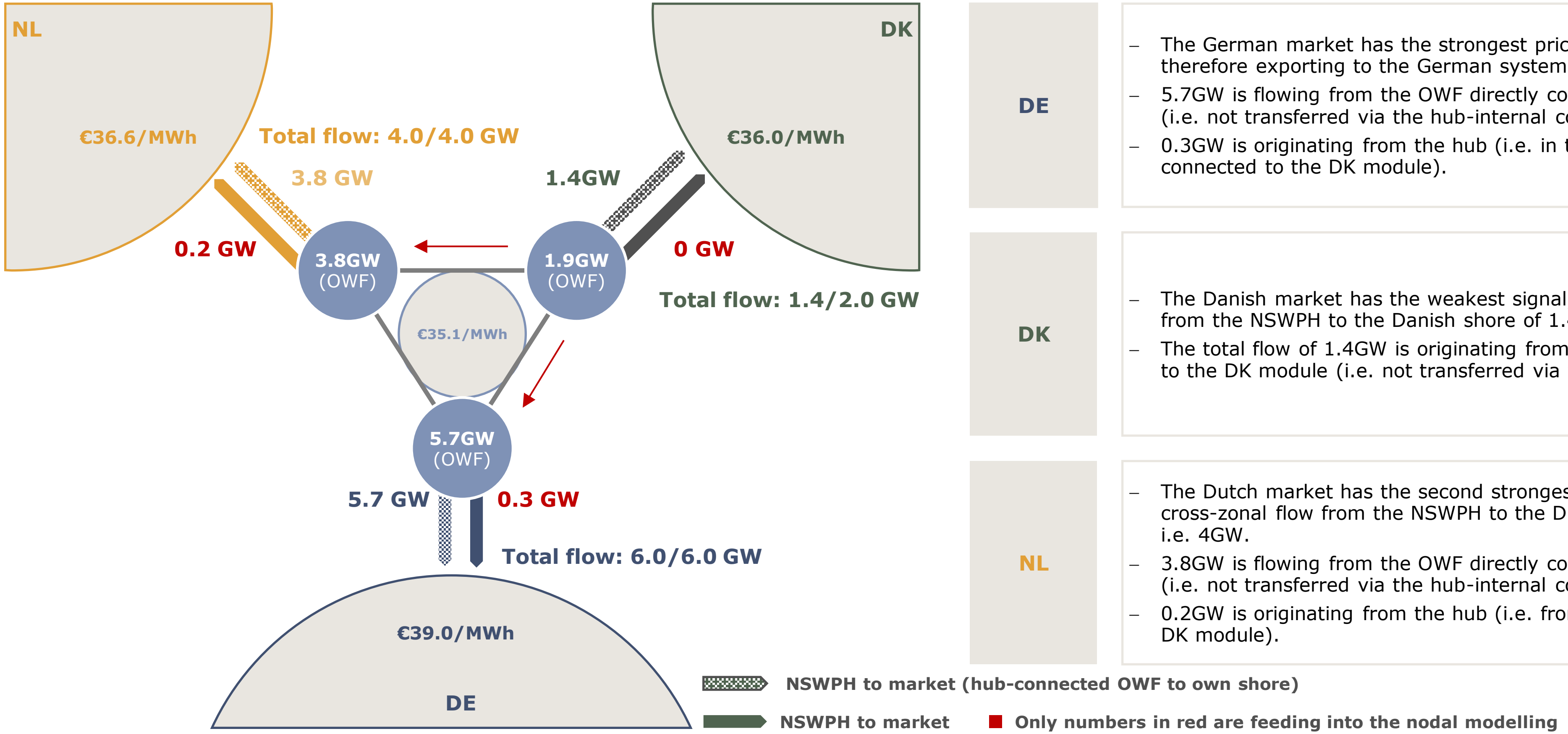


1. Examples do not necessarily reflect the same hour.

WHY IS THE UTILISATION OF THE HUB-INTERNAL CONNECTORS EXPECTED TO BE LOWER COMPARED TO THE OVERALL UTILISATION OF THE ICS?

Example 1: NSWPH exporting to DE & NL at full IC capacity

Flows shown here do not account for losses on this illustrative chart based on actual modelled results. The NSWPH price accounts for losses.
The red arrows are illustrative; the actual path that the within-hub flow will follow is assessed under the load flow modelling .



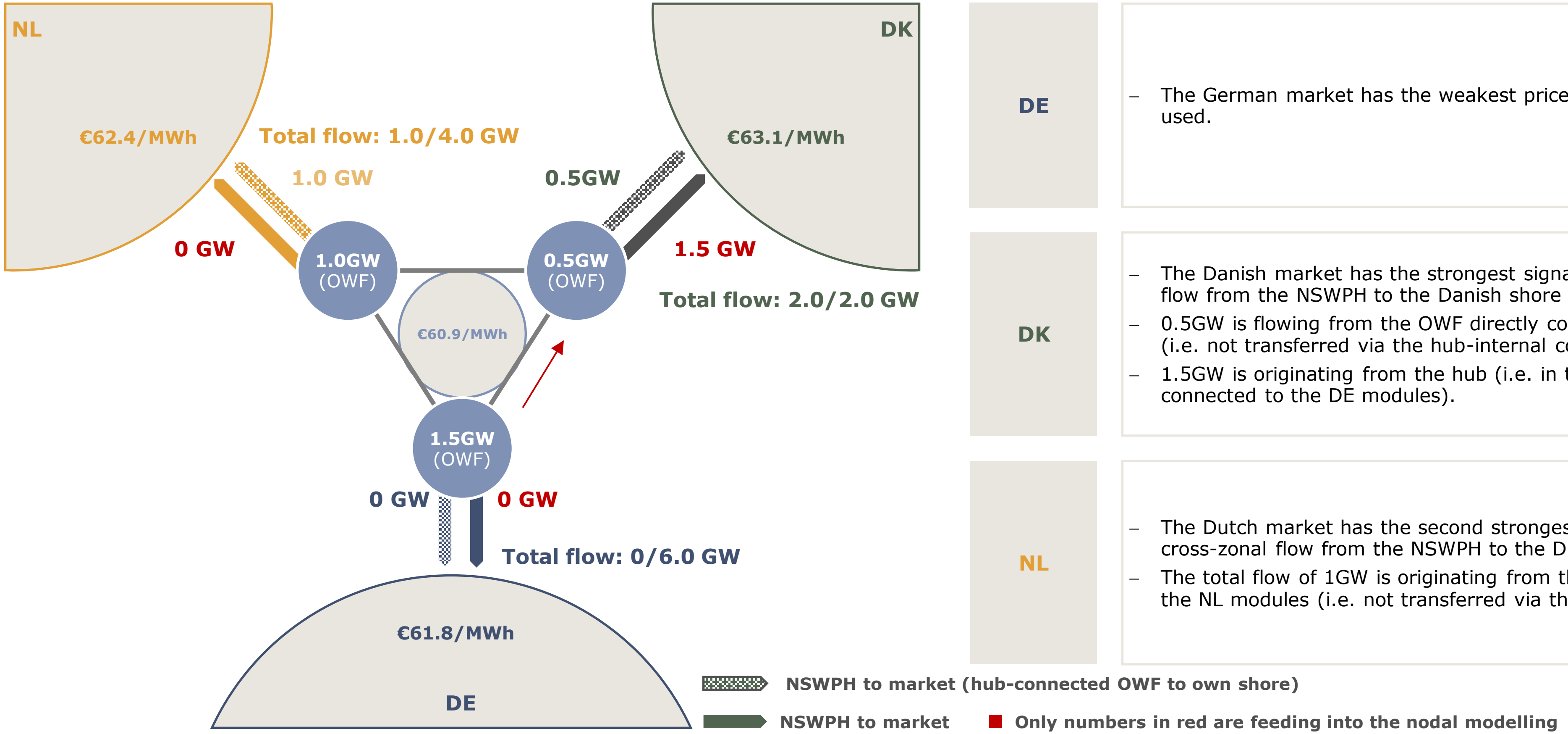
DE	– The German market has the strongest price signal, the NSWPH is therefore exporting to the German system at full capacity – i.e. 6GW. – 5.7GW is flowing from the OWF directly connected to the DE modules (i.e. not transferred via the hub-internal connectors). – 0.3GW is originating from the hub (i.e. in this case, from the OWF connected to the DK module).
DK	– The Danish market has the weakest signal, triggering a cross-zonal flow from the NSWPH to the Danish shore of 1.4GW. – The total flow of 1.4GW is originating from the OWF directly connected to the DK module (i.e. not transferred via the hub-internal connectors).
NL	– The Dutch market has the second strongest signal, thus triggering a cross-zonal flow from the NSWPH to the Dutch shore at full capacity – i.e. 4GW. – 3.8GW is flowing from the OWF directly connected to the NL modules (i.e. not transferred via the hub-internal connectors). – 0.2GW is originating from the hub (i.e. from the OWF connected to the DK module).

Year 2030 // Hour 240 // Weather year 2012

WHY IS THE UTILISATION OF THE HUB-INTERNAL CONNECTORS EXPECTED TO BE LOWER COMPARED TO THE OVERALL UTILISATION OF THE ICS?

Example 2: NSWPH exporting to DK at full IC capacity

Flows shown here do not account for losses on this illustrative chart based on actual modelled results. The NSWPH price accounts for losses.
The red arrows are illustrative; the actual path that the within-hub flow will follow is assessed under the load flow modelling .



DE	– The German market has the weakest price signal, the DE ICs are not used.
DK	– The Danish market has the strongest signal, triggering a cross-zonal flow from the NSWPH to the Danish shore at full capacity – i.e. 2GW. – 0.5GW is flowing from the OWF directly connected to the DK modules (i.e. not transferred via the hub-internal connectors). – 1.5GW is originating from the hub (i.e. in this case, from the OWF connected to the DE modules).
NL	– The Dutch market has the second strongest signal, thus triggering a cross-zonal flow from the NSWPH to the Dutch shore of 1GW. – The total flow of 1GW is originating from the OWF directly connected to the NL modules (i.e. not transferred via the hub-internal connectors).

Year 2040 // Hour 892 // Weather year 2012

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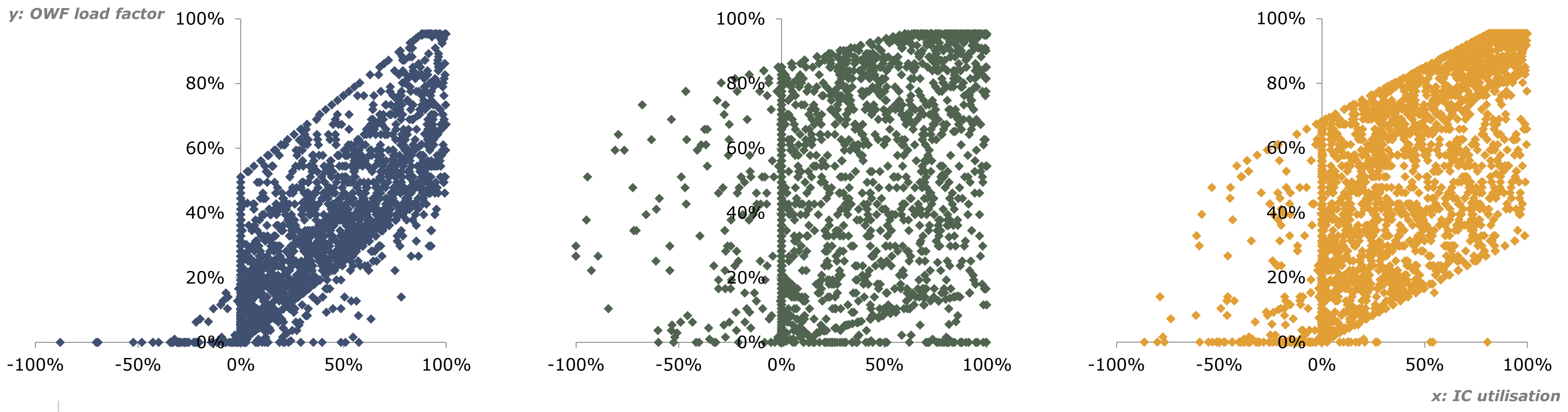
CORRELATION OF HUB-CONNECTED OWF GENERATION AND IC FLOWS

Transmission assets are primarily used to transfer hub-connected OWF generation to the various shores

DE | **DK** | **NL**

Correlation between OWF generation and flows (2030, 2012 weather year)



COMMENTS

- The charts show the correlation between the hub-connected OWF load factors (y axis) and the utilisation of the various ICs (x axis) at an hourly level for 2030. Positive numbers on the x axis indicate a flow from the hub to the national systems; negative numbers on the axis indicate a flow from the national systems to the hub.
- The utilisation rates of the various ICs are highly correlated to the output of the hub-connected OWFs.

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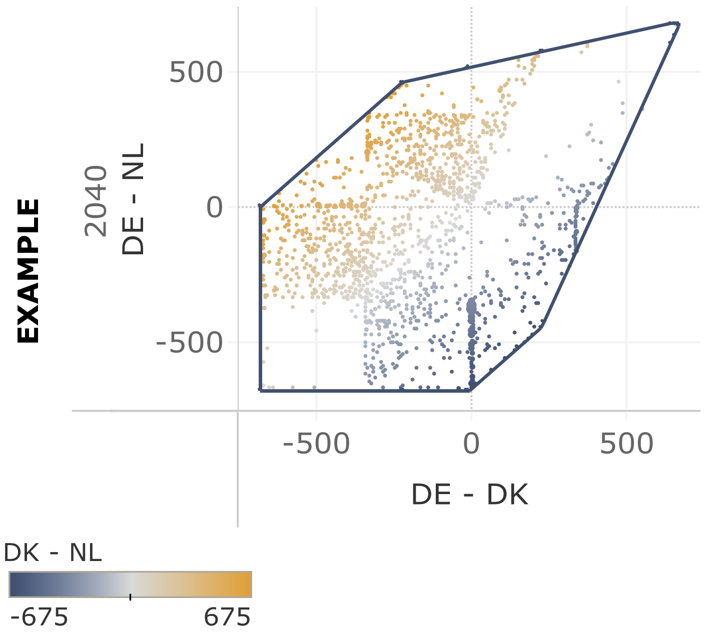
LOAD FLOW MODELLING

Calculation of maximum theoretical volume on the lines

Hourly flow on each of the DE-NL, DE-DK & DK-NL hub-internal connector by direction; and maximum theoretical volume in MW



Blue values: from DK to NL // Orange values: from NL to DK

x axis: negative values from DK to DE // positive values from DE to DK

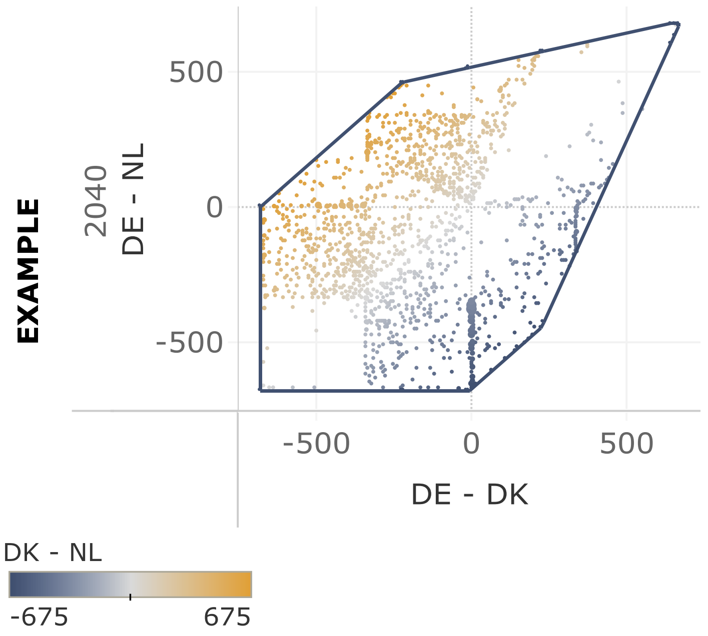
y axis: negative values from NL to DE // positive values from DE to NL

- **The chart shows:**
  - **Flows in each hour, represented by a point;**
  - **The axes indicate hourly flow along each hub-internal connector for DE-NL (y axis) and DE-DK (x axis) (directional);**
  - **The colour 'axis' indicates flow along the DK-NL hub-internal connector (directional); and**
  - **We expect flows to be inside the blue polygon, which represents the maximum possible theoretical flows (see next slide for more information).**
- **In the Core configuration, symmetry of the modules (i.e. capacity, distance from each other, etc.) means the flows on lines between the same pairs of markets are identical (e.g. flows on all six lines that connect a DE with a NL module are the same for any given hour); and flows on lines between the modules of the same market are zero (e.g. flows on all three lines that connect the DE modules to each other). This means that it is sufficient to present results for three hub-internal connector cases, i.e. DE-NL, DE-DK & DK-NL.**

LOAD FLOW MODELLING

Calculation of maximum theoretical volume on the lines

Hourly flow on each of the DE-NL, DE-DK & DK-NL hub-internal connector by direction; and maximum theoretical volume in MW [based on Core configuration]



Blue values: from DK to NL // **Orange values: from NL to DK**

x axis: negative values from DK to DE // positive values from DE to DK

y axis: negative values from NL to DE // positive values from DE to NL

- **DC load flow relates module imports and exports to flows on the hub-internal connectors via a Power Transfer Distribution Function (PTDF) matrix.**
- **For example, in the highly symmetric Core configuration the PTDF matrix is:**

$$\begin{pmatrix} \textit{flow on any of the lines from DK to DE} \\ \textit{flow on any of the lines from DE to NL} \\ \textit{flow on any of the lines from NL to DK} \end{pmatrix} = \frac{1}{36} \cdot \begin{pmatrix} 0 & 8 & 2 \\ 0 & -2 & -5 \\ 0 & -6 & 3 \end{pmatrix} \cdot \begin{pmatrix} \textit{wind generation at DE modules} + \textit{net import from DE shore} \\ \textit{wind generation at DK modules} + \textit{net import from DK shore} \\ \textit{wind generation at NL modules} + \textit{net import from NL shore} \end{pmatrix}$$

- **e.g. maximum flow from DK to DE is obtained when imports from DK and NL are maximised, subject to the export capacity limit from DE. As the wind generation is simultaneous across modules the flow maximises to 667MW (675MW when losses are considered).**
- **Taking the PTDF in conjunction with the additional constraints on the system allows a feasible region to be plotted within which flows can occur (i.e. blue polygon).**

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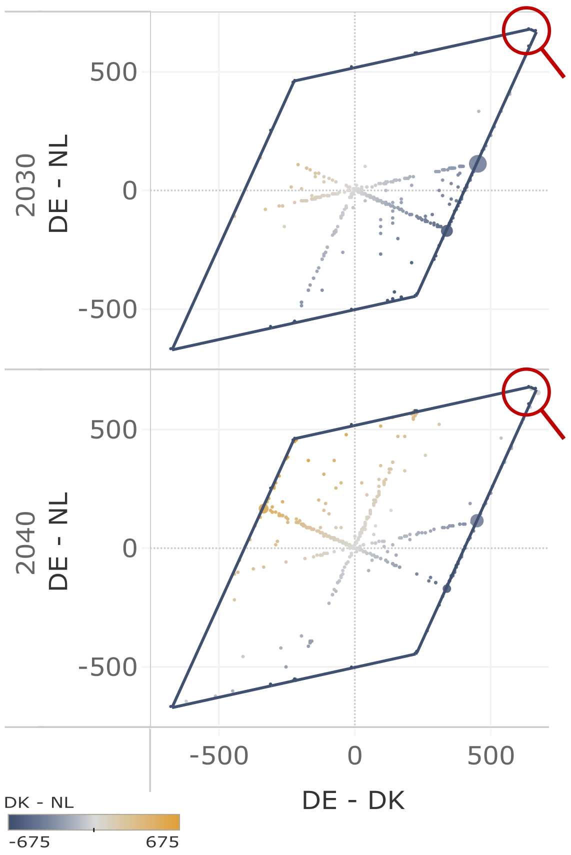
MAXIMUM THEORETICAL VOLUME

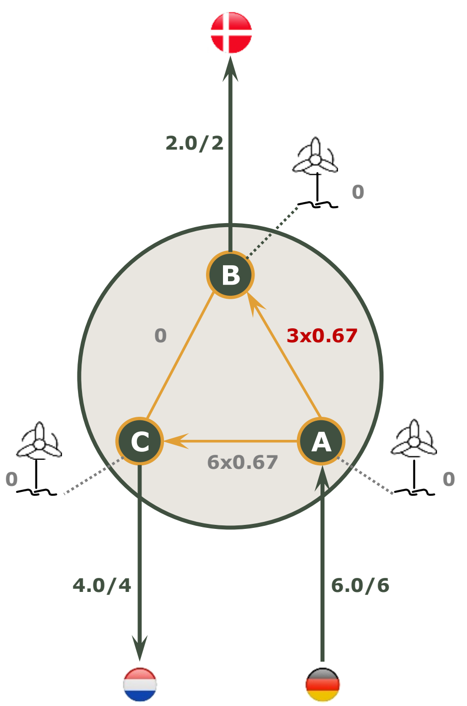
Example 1 of max theoretical volume

Transmission only (i.e. OWF generation is zero, only flows originating from the national systems)

FLOWS ON EACH LINE



EXAMPLE FLOWS



COMMENTS

- Under this 'regime', the maximum theoretical flow on e.g. each DE-DK connector is 667MW (or 675MW once export losses are considered), as indicated by the chart and displayed on the illustrative example (1).
- In other words, the 667MW flow on each DE-DK line (i.e. A → B) cannot be exceeded. This is because:
  - All ICs are constrained – i.e. operating at maximum flow; and
  - Any additional wind generation therefore cannot be accommodated and lead to higher within-hub flows as this extra generation can not be exported to any market.
- In summary, IC limits to / from the national shores constrain maximum within-hub flows on each line.
- Same calculations and values apply to the remaining two connectors: i.e. DE-NL & DK-NL.

NOTES

- Use of the assets as a pure transmission asset occurs 1.4% of the time (years with more wind) and 2.7% of the time (years with less wind).
- Internal connectors have been simplified as lines between any pairs of countries are identical and thus carry the same flows. These are represented as "n x f", where n is the number of relevant lines and f is the flow for the example hour in GW.
- Losses have been ignored for purposes of illustration.

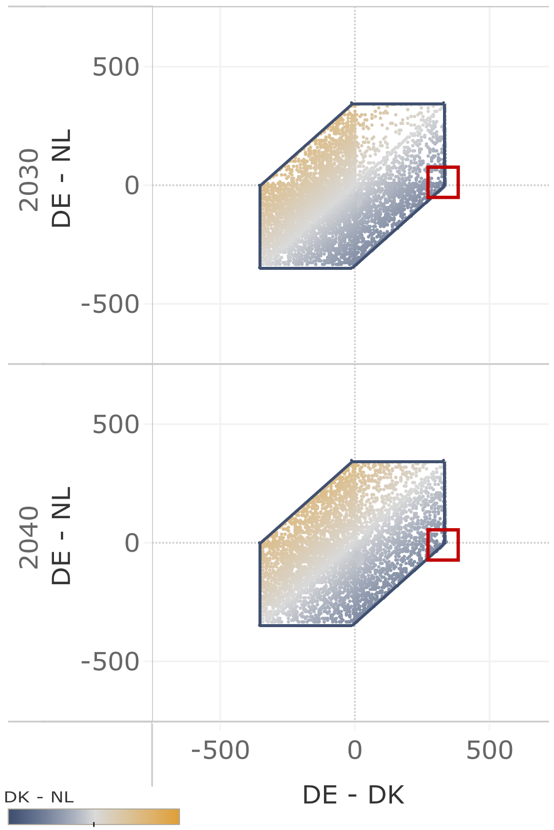
1. Multiplying the PTDF matrix by the balance of each country (in this example, net import at each of A, B, C) of $(6,-2,-4)^T$ gives the flow $(-0.67,0.67,0)^T$ on each line.

MAXIMUM THEORETICAL VOLUME

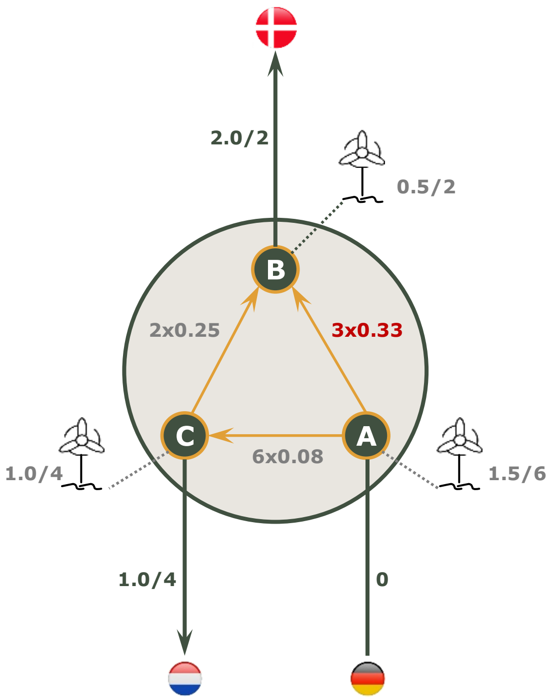
Example 2 of max theoretical volume

Generation assets (i.e. OWF generation only, no flows from the national systems)

FLOWS ON EACH LINE



EXAMPLE FLOWS



COMMENTS

- Under this ‘regime’, the maximum theoretical flow on e.g. each DE-DK connector is 333MW (or 342MW once export losses are considered), as indicated by the chart and displayed on the illustrative example (1).
- In other words, the 333MW flow on each DE-DK line (i.e. A → B) cannot be exceeded. This is because:
  - Consider increasing OWF generation by 0.6GW overall (i.e. 0.1MW per module: 0.3MW at A, 0.1MW at B, and 0.2MW at C) – exporting this increased hub generation to the NL shore (as the IC is not constrained).
  - The PTDF matrix tells us that an injection of 0.3MW at DE with extraction at NL leads to an increase in flow of 0.05MW on A → B.
  - Similarly, an injection of 0.1MW at DK increases flow B → A by 0.05MW.
  - The additional flow cancels and the net effect is that the flow on A → B reaches a maximum 333MW.
- In summary, IC export limits to the national shores and correlation of OWF generation constrain maximum flows.
- Same calculations and values apply to the remaining two connectors: i.e. DE-NL & DK-NL.

NOTES

- Use of the assets as a pure generation occurs 93% of the time (with a weather variability of ±3%).
- Internal connectors have been simplified as lines between any pairs of countries are identical and thus carry the same flows. These are represented as “n x f”, where n is the number of relevant lines and f is the flow for the example hour in GW.
- Losses have been ignored for purposes of illustration.

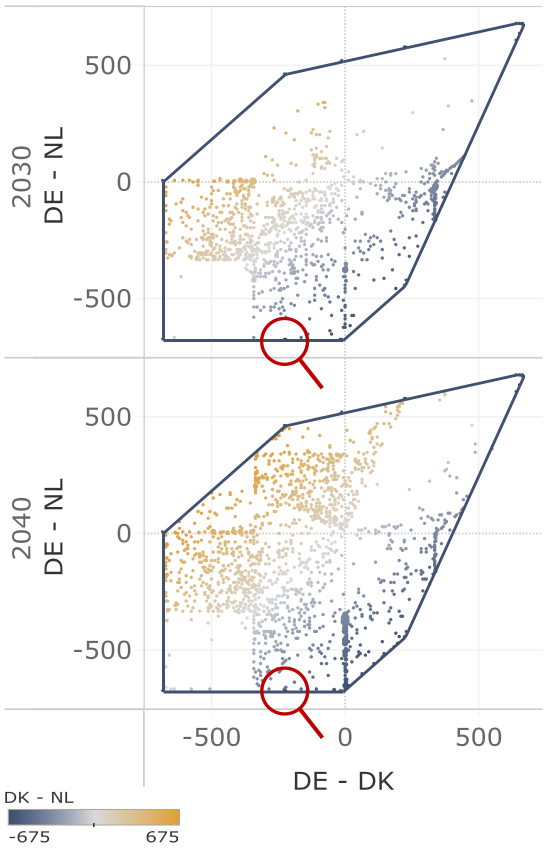
1. Multiplying the PTDF matrix by the balance of each country (in this example, net import at each of A, B, C) of $(1.5,-1.5,0)^T$ gives the flow $(-0.33,0.08,0.25)^T$ on each line.

MAXIMUM THEORETICAL VOLUME

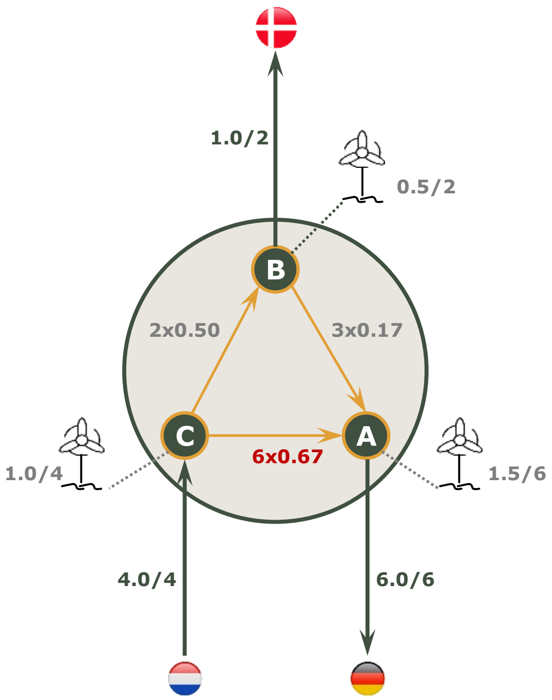
Example 3 of max theoretical volume

Transmission & generation (i.e. OWF generation & flows from the national systems)

FLOWS ON EACH LINE



EXAMPLE FLOWS



COMMENTS

- Under this 'regime', the maximum theoretical flow on each e.g. DE-NL connector is 667MW (or 675MW once export losses are considered), as indicated by the chart and displayed on the illustrative example (1).
- In other words, the 667MW flow on each DE-NL line (i.e. C → A) cannot be exceeded. This is because:
  - Similar to example 2, consider increasing OWF generation – thus exporting this increased hub generation to the DK shore (i.e. the only IC that is not constrained).
  - The increase in flow on C → A is counteracted by the flow resulting from increased generation at A (i.e. flow from A →C).
  - Increased generation at C has balance $(0,-x,x)^T$, with flow x/12 on C → A; increased generation at A has balance $(y,-y,0)^T$ with flow y/18 on A → C
  - Coincidence of wind generation implies 3x=2y (i.e. proportional to capacities), so the additional flow cancels and the net effect is that the flow on C → A reaches a maximum 667MW.
- In summary, IC export limits to the national shores and correlation of OWF generation constrain maximum flows.
- Same calculations and values apply to the remaining two connectors: i.e. DE-DK & DK-NL.

NOTES

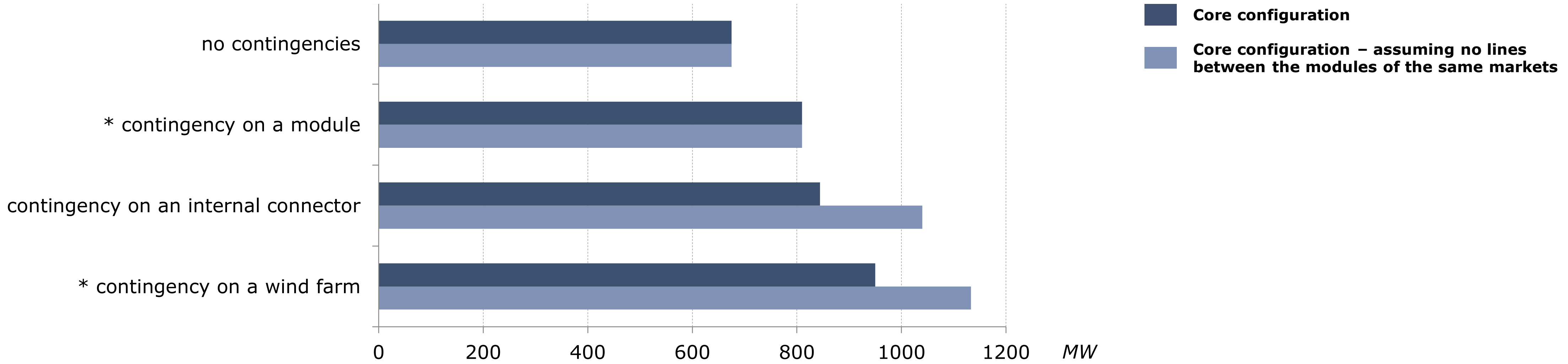
- Joint utilisation as generation and transmission increases from an average 4.3% of hours in 2030 to 6.4% in 2040.
- Internal connectors have been simplified as lines between any pairs of countries are identical and thus carry the same flows. These are represented as "n x f", where n is the number of relevant lines and f is the flow for the example hour in GW.
- Losses have been ignored for purposes of illustration.

1. Multiplying the PTDF matrix by the balance of each country (in this example, net import at each of A, B, C) of $(-4.5,-0.5,5.0)^T$ gives the flow $(0.17,-0.67,0.50)^T$ on each line.

N-1 CONTINGENCIES ANALYSIS

The core setup is stable to N-1 contingencies

INTERNAL CONNECTOR CAPACITIES REQUIRED IN ORDER TO MAINTAIN COPPER PLATE BEHAVIOUR WITHIN THE HUB



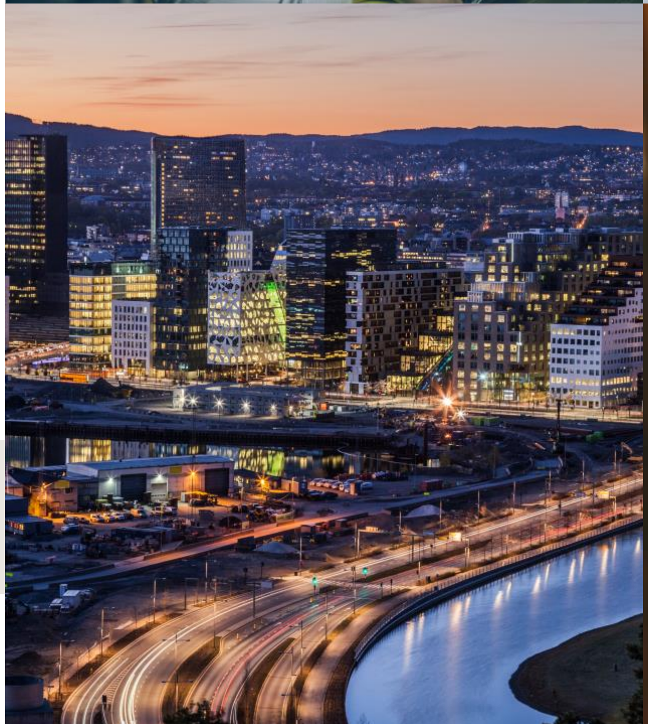
COMMENTS

- The chart shows the results of a simple contingency analysis that was performed to evaluate the stability of the hub to removal of any one of its components. It plots the resulting maximum line requirements in order to balance any excess flows and maintain copper plate behaviour– for the Core configuration in dark blue; and for the Core configuration assuming no lines between the modules of the same markets in light blue.
- Summary of findings:
  - Removal of any component increases flows on internal lines as power would need to be redirected via the operating lines.
  - A setup excluding connectors between the same markets has equal base flows but leads to more serious contingencies.
  - Contingencies on an internal connector lead to flows surpassing 1000MW on average 0 times in 2030 and 5 times in 2040.
- Contingencies marked with a star (*) have not been assessed for consistency with the range of modelled flows, as these setups change the market operation.
- Additional corrective actions (e.g. curtailing wind farms) have not been considered.

Annex Agenda

- Summary of copper plate capacity requirement per configuration
- Additional flow duration curves (Core & Core+)
- High level comparisons of the configurations
- Utilisation of IC assets based on the market modelling
- Background to the load flow modelling & results
- **TYNDP 2020 National Trends assumptions**






The 'National Trends' TYNDP 2020 scenario forms the basis of the market scenario for the assessment

Scenario	**National Trends (NT)**	**Global Ambition (GA)**	**Distributed Energy (DE)**
Climate target	**Based on National Energy and Climate Plans (NECPs)**	**Compliant with the 1.5°C target of the Paris Agreement**	**Compliant with the 1.5°C target of the Paris Agreement**
Description	Central bottom-up scenario. In accordance with the governance of the energy union and climate action rules, as well as on further national policies and climate targets already stated by the EU member states. Compliant with the EU's 2030 Climate and Energy Framework (32 % renewables, 32.5 % energy efficiency) and EC 2050 Long-Term Strategy with an agreed climate target of 80–95 % CO_2 reduction compared to 1990 levels**.**	Looks at a future that is led by economic development in **centralised generation.** Economies of scale lead to significant cost reductions in emerging technologies such as offshore wind, but also imports of energy from cheaper sources are considered as a viable option.	Embraces a **de-centralised approach to the energy transition.** A key feature of the scenario is the role of the energy consumer, who actively participates in the energy market and helps to drive the system's decarbonisation by investing in small-scale solutions and circular approaches.

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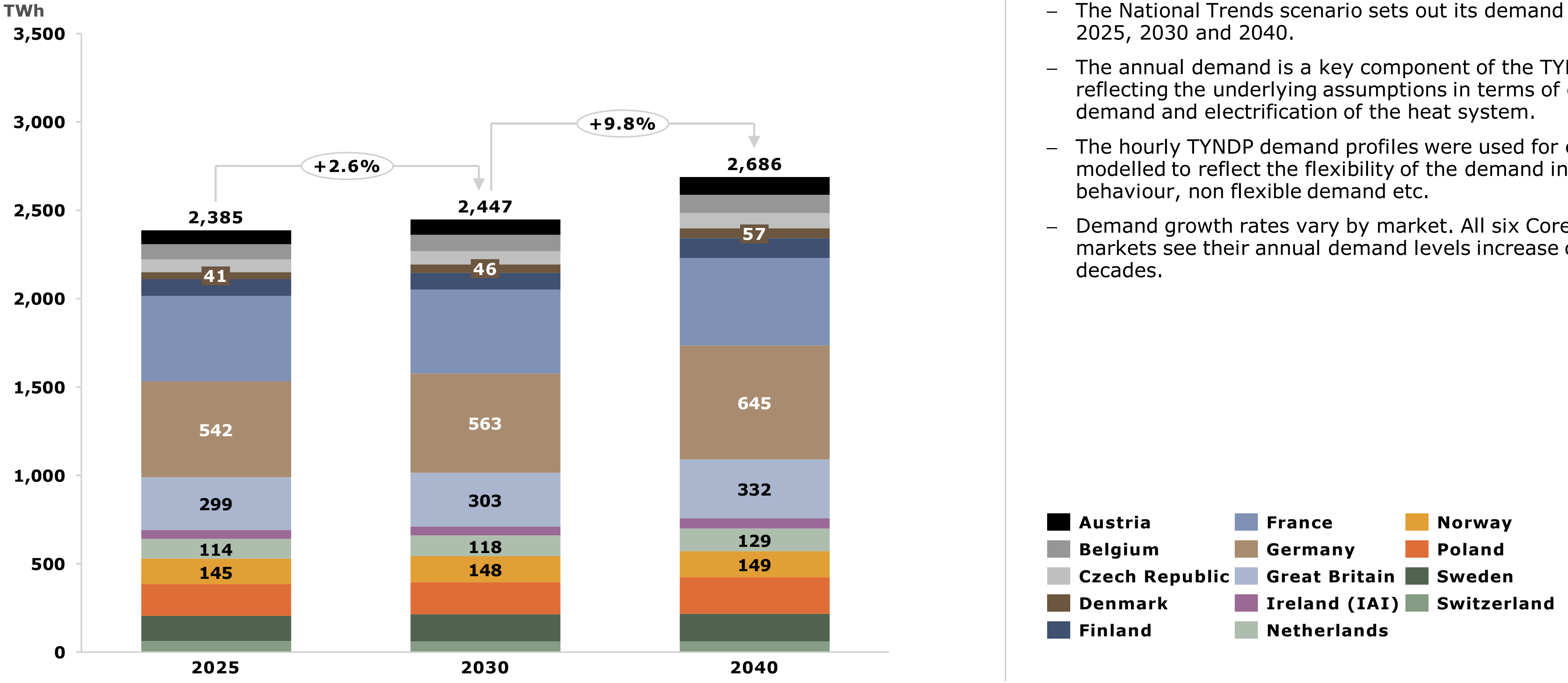
National Trends includes growing demand in most of the markets reflecting assumptions of a strong uptake in electric vehicles and heat pumps

ANNUAL DEMAND IN THE NW EUROPEAN MARKETS – NATIONAL TRENDS

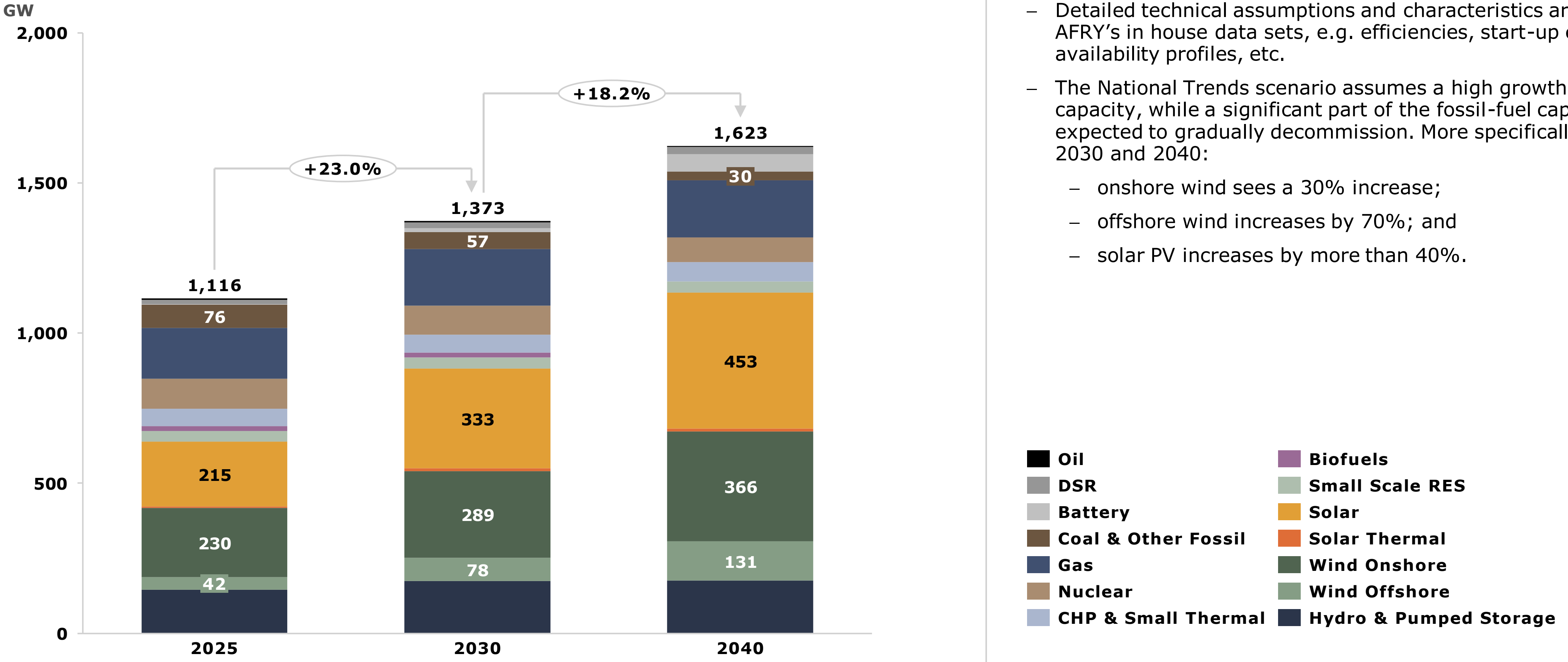


COMMENTS

- The National Trends scenario sets out its demand forecast for 2025, 2030 and 2040.
- The annual demand is a key component of the TYNDP scenario reflecting the underlying assumptions in terms of growing EV demand and electrification of the heat system.
- The hourly TYNDP demand profiles were used for each country modelled to reflect the flexibility of the demand in terms of EV behaviour, non flexible demand etc.
- Demand growth rates vary by market. All six Core / Core+ markets see their annual demand levels increase over the next decades.

National Trends includes significant additional capacities across all markets to support growing demand, coal decommissioning and RES targets

EU-28 CAPACITY MIX – NATIONAL TRENDS

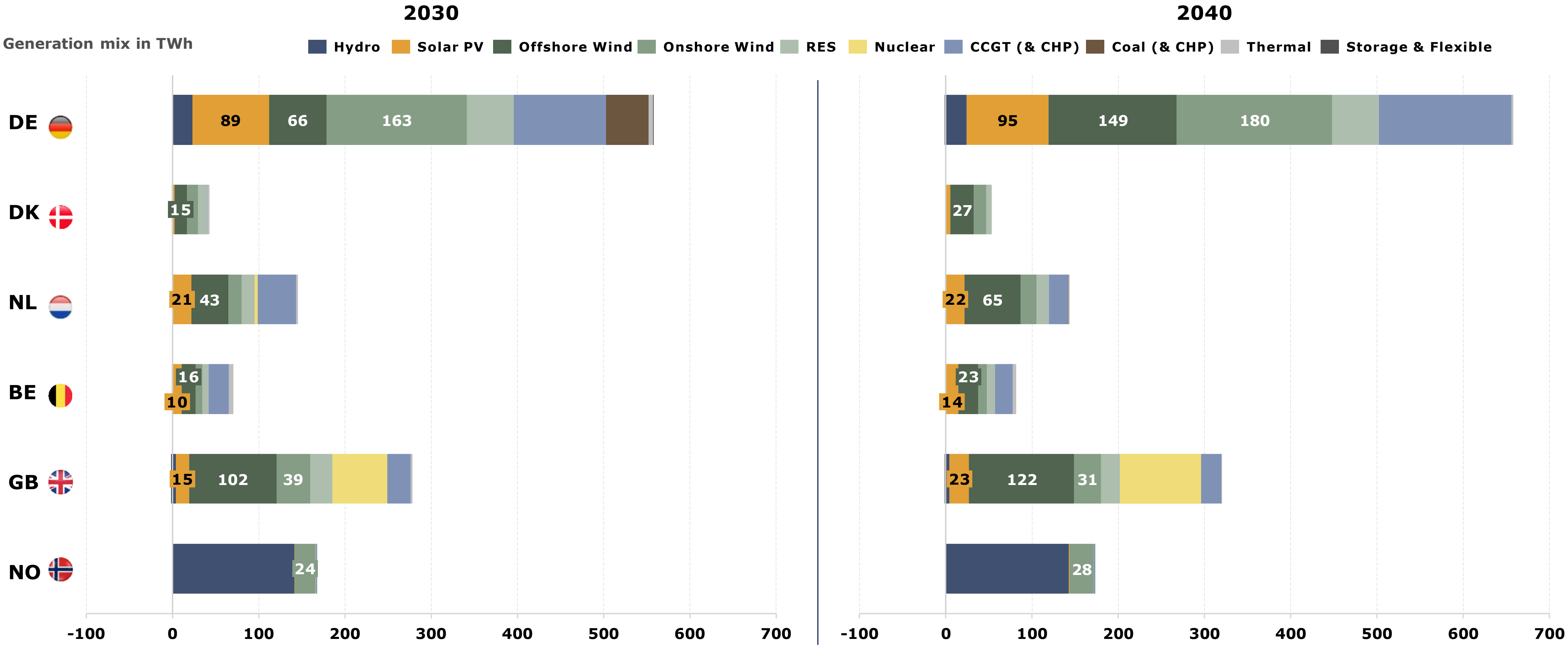


COMMENTS

- Detailed technical assumptions and characteristics are based on AFRY's in house data sets, e.g. efficiencies, start-up costs, plant availability profiles, etc.
- The National Trends scenario assumes a high growth of RES capacity, while a significant part of the fossil-fuel capacity is expected to gradually decommission. More specifically between 2030 and 2040:
  - onshore wind sees a 30% increase;
  - offshore wind increases by 70%; and
  - solar PV increases by more than 40%.

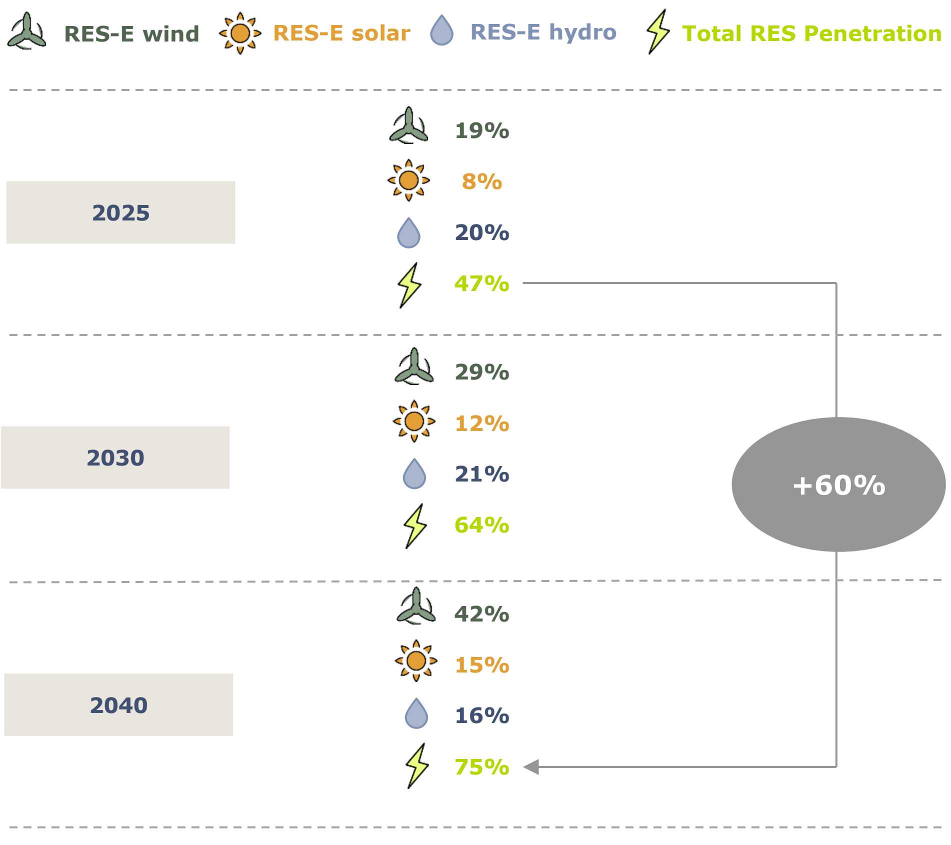
ANNUAL GENERATION MIX

Based on National Trends inputs, the modelled generation mix has a high level of RES generation, with gas-fired generation still evident in Germany

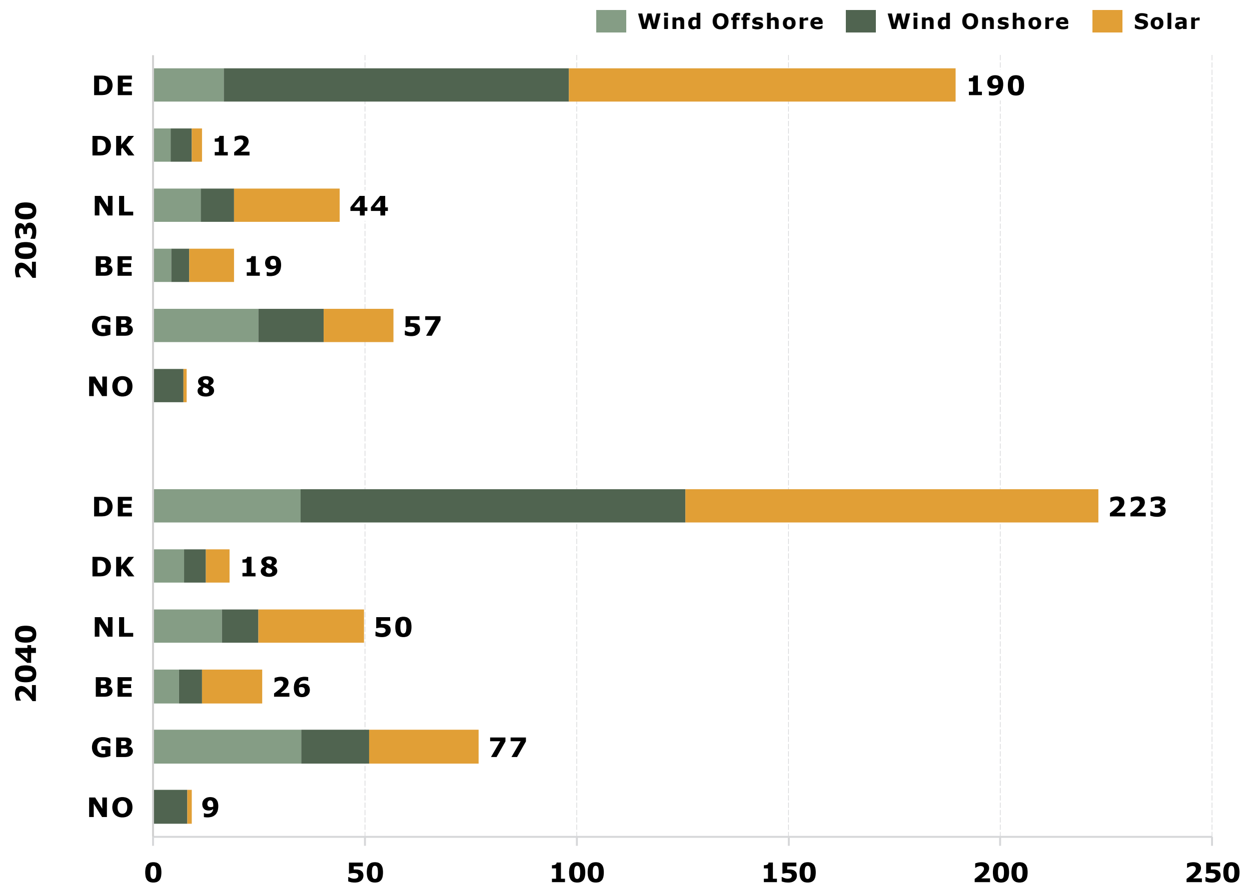


RES penetration reaches 75% by 2040 in National Trends, with significant capacity in the study markets

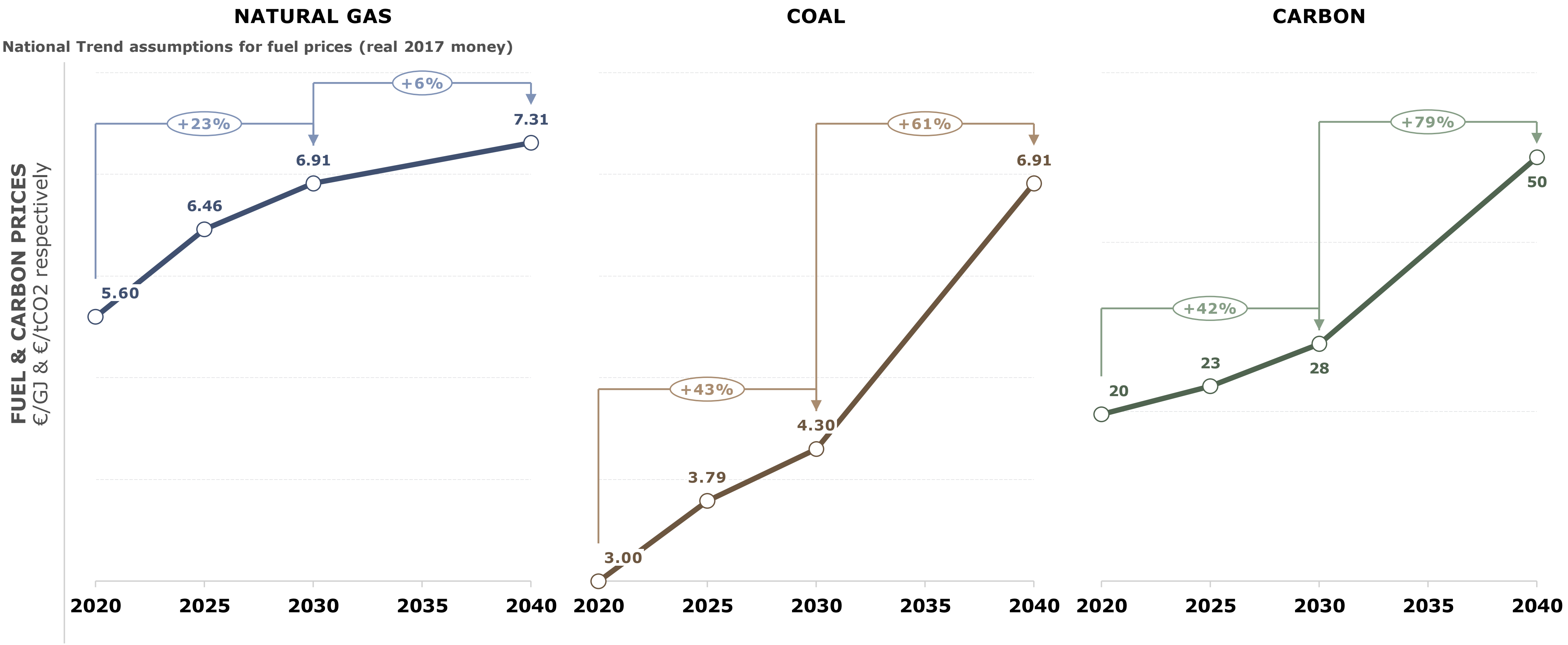
LOW CARBON PENETRATION TARGETS EU-28



RES CAPACITY IN THE STUDY MARKETS (GW)



National Trends assumes increasing fuel and carbon prices



Underlying profiles (e.g. monthly , seasonal, etc.) are based on AFRY's assumptions

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