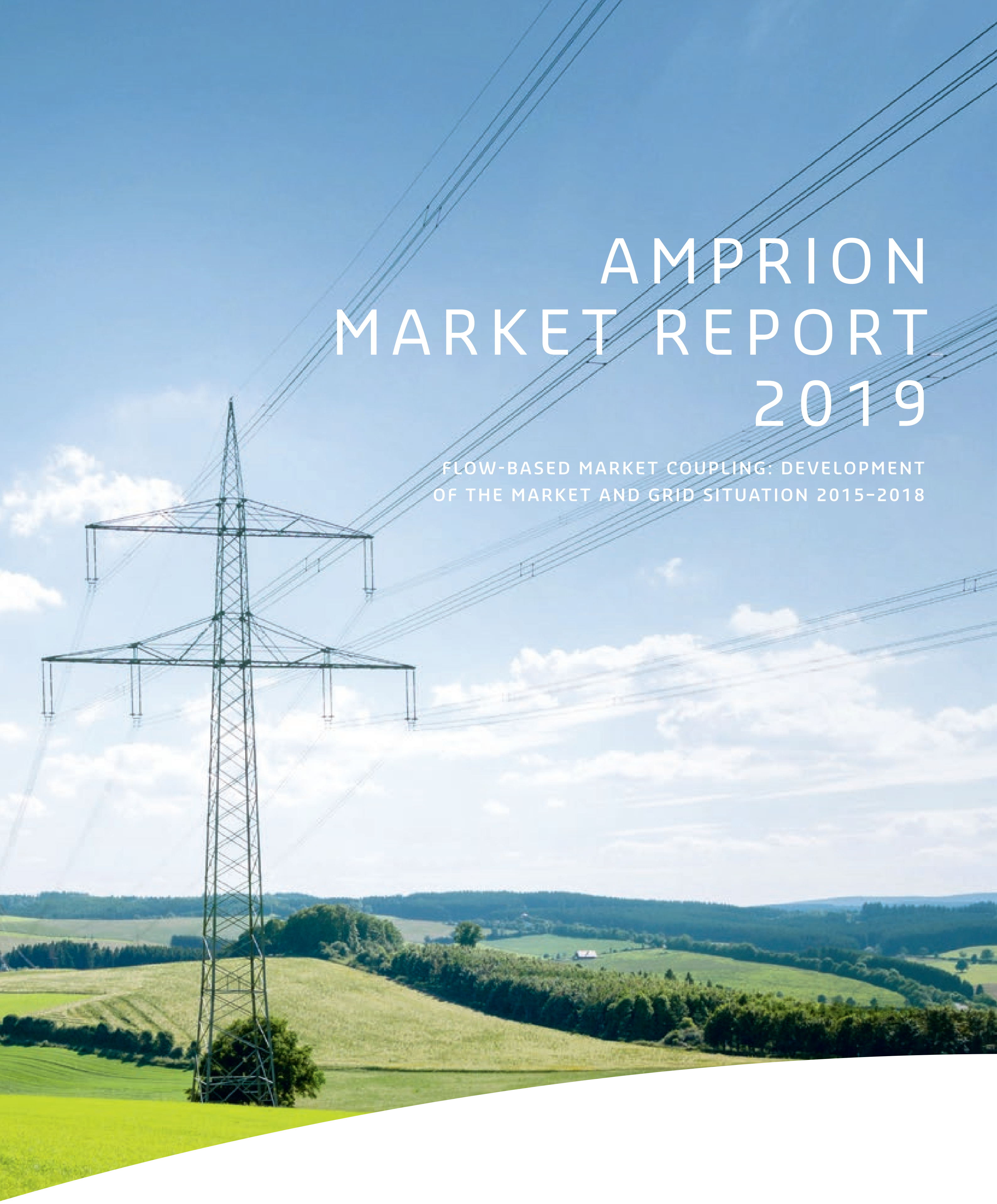


AMPRION MARKET REPORT 2019

FLOW-BASED MARKET COUPLING: DEVELOPMENT OF THE MARKET AND GRID SITUATION 2015–2018

amprion

CONTENTS


Amprion

Management Summary

As the backbone of the electricity system, transmission system operators (TSOs) play an important role in the success of the European energy transition, as well as in the implementation of a functioning internal energy market. Efficient cooperation is the key to achieving the EU energy policy goals, which is why TSOs work around the clock to ensure a secure network and promote security of the European electricity system and cross-border trade. Examples of this are the numerous market coupling projects, one of which is flow-based market coupling (FB MC). FB MC accommodates a more detailed consideration of the technical limits of the electrical transmission networks, leading to an optimal use of the available transmission capacity for cross-border trade, without jeopardising grid security.

In the current debate on the further development of the FB MC, the most prominent criticism is the alleged limitation of cross-zonal exchanges by TSOs. This is said to be due to insufficient coordination amongst TSOs and, more importantly, the discrimination of cross-zonal exchanges in favour of internal exchanges. Regrettably, the significant progress of market integration over the last years as well as the strong mutual support between TSOs during critical electricity grid and supply situations are rarely mentioned in this context. Right from the very beginning of market integration, Amprion has been actively participating together with its neighbouring TSOs in a large number of regional and European initiatives [1]. Furthermore, Amprion's grid is interconnected with other transmission grids within Germany and also with the Netherlands, Luxembourg, France, Switzerland and Austria. Furthermore, an interconnection to Belgium is currently under construction. In a sense, then, mutual cooperation in the European electricity system is in our DNA.

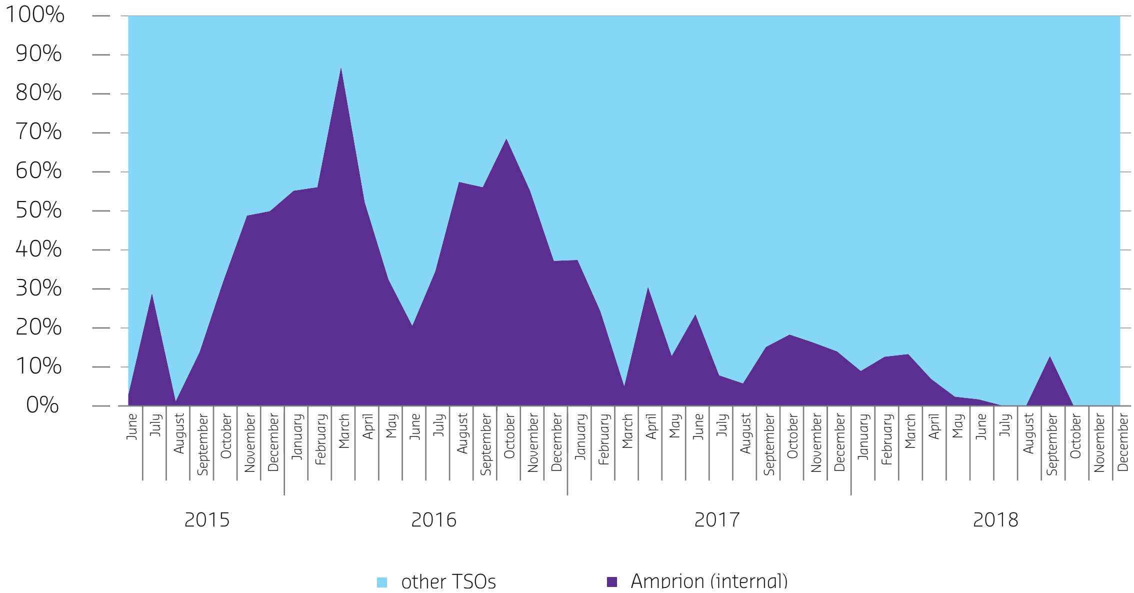
This report provides evidence for the significant benefits resulting from Amprion's strong and steadily enhanced cooperation within the Central Western Europe (CWE) region and beyond.

In more concrete terms:

- Due to its central location in Europe, Amprion serves as an important electricity transit zone. German exports towards its neighbours reach absolute levels of up to 15 GW, ensuring security of supply in those regions, in particular during electricity shortage situations. Amprion provides the transmission capacity for a significant contribution of up to 8 GW to this overall German export.
- In recent years, price convergence within the CWE region occurred in 30% of all hours, or in other words: almost every third hour day-ahead prices in CWE countries have been equal. This provides evidence for a vastly integrated CWE market which is continuously increasing.
- Capacities provided to the CWE market remain constantly high, supporting a higher market liquidity. Amprion supports this trading by applying the lowest reliability margin on its network elements for the flow-based capacity calculation in CWE: while the average reliability margin for CWE is 13%, Amprion applies only 9% on average.
- While an integrated European market and a strong interconnection with neighbouring countries is important to ensure a secure grid operation, this support comes at costs. Increasing RES infeeds and partly high import requirements from neigbours lead to a high utilization of the Amprion network and make the application of costly remedial actions necessary.
- The publication of critical network elements provides an indication of major bottlenecks in the CWE region, which have been effectively resolved by Amprion. As shown in the following figure, the frequency of Amprion's internal network elements constraining the market has reduced substantially over the past few years:

[1] Including market coupling projects: Central Western Europe (CWE), CORE and Cross-Border Intraday (XBID). Security cooperations: Transmission System Operator Security Cooperation (TSC), Security Service Centre (SSC). Balancing projects: International Grid Control Cooperation (IGCC).

Decreasing share of Amprion's market-constraining internal network elements



Relative frequency of top 10 active CBs per hour of the day from 06.2015 – 12.2018
Please note that only internal network elements are shown for Amprion

Energy Transition Confronts Electricity Systems with Challenges

An aspect which is often missed in the ongoing discussions is that the market is not exclusively driven by the grid and the related transaction constraints. Other fundamental factors significantly impact the market as well. Considerable changes in the generation mix, i. e. decommissioning and unavailability of conventional generation units, have led to a shift of generation centres in CWE countries. Furthermore, import needs are strongly driven by the infeed from variable RES and the electricity demand, which in turn are heavily impacted by the natural variability of climate and weather conditions.

Amprion as centrally located TSOs supports the integration of the European energy market

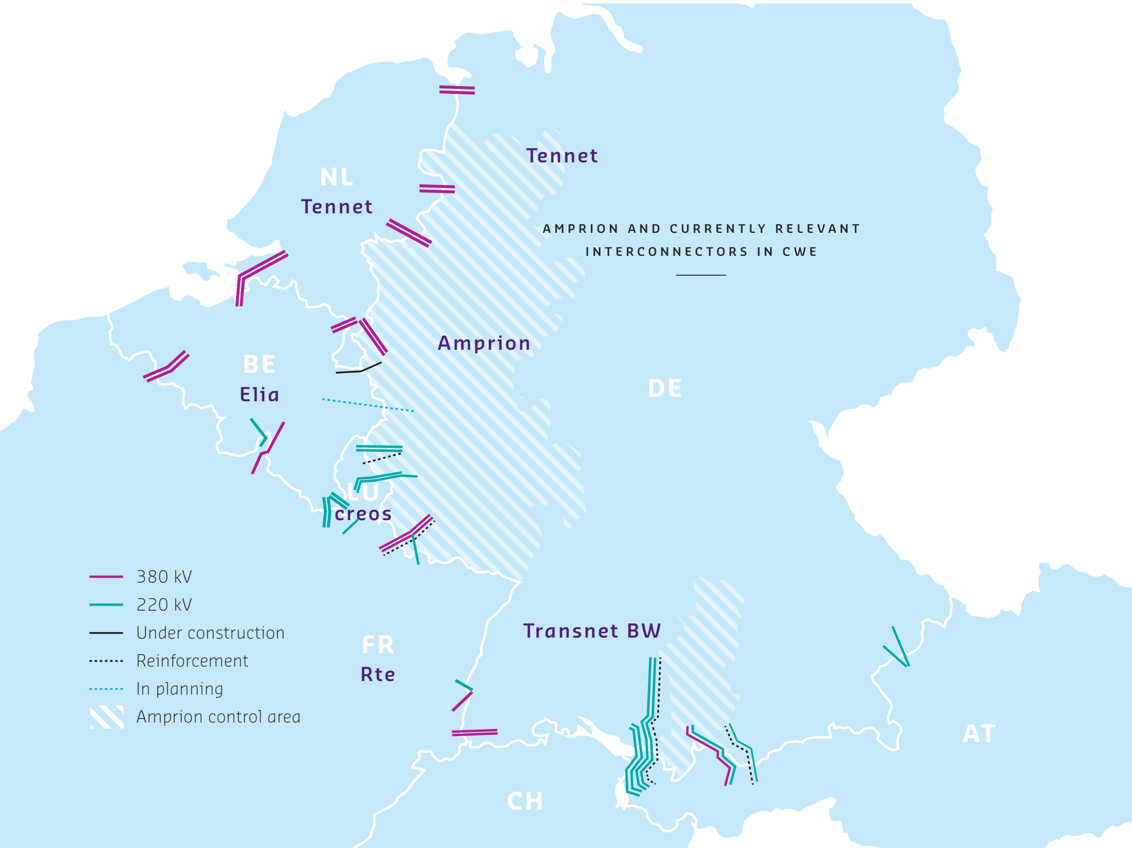
In particular during winter periods, a considerable flow from northern CWE borders to southern borders can be observed. This higher demand for imports in the south of CWE is mainly caused by generation scarcities in some countries. Exports from Germany and in particular the Amprion control zone into the CWE region remain constantly at high levels. Despite Amprion's central location, the number of hours in which network elements within the Amprion control zone limited the European trading decreased significantly in the last two years. To ensure a secure grid operation while supporting European market integration, costly remedial actions are essential. Amprion's increasing redispatch volumes over the last two years show the strong commitment to the integration of the European energy market.

In summary, the overall measures taken by TSOs over the past years have provided very effective support for cross-border trading and security of supply in neighbouring European countries.

Introduction

Today, Amprion's grid is interconnected with other transmission grids within Germany and also with the Netherlands, Luxembourg, France, Switzerland and Austria. Furthermore, an interconnection to Belgium is currently under construction. In a sense, then, mutual cooperation in the European electricity system is in our DNA.

This report provides evidence for the significant mutual benefits resulting from Amprion's strong and steadily enhanced cooperation with TSOs, Power Exchanges and Market Parties of the CWE region and beyond.



Amprion's control zone and relevant interconnectors in CWE

This study provides evidence for the effective support by first giving a general overview of the current situation in CWE in section 1. Section 2 provides an explanation of the general flow-based concept. After an overview of the recent developments in the FB MC and the respective improvements in section 3, the inputs to the capacity calculation are analyzed in section 4 while its outputs (i.e. the market coupling and the capacity allocation) are discussed in section 5. Section 6 complements the report by focusing on system operation and in particular redispatch activities taken by Amprion to accommodate significant cross-border exchanges, in particular during the winter period 2016/17. To complement this, section 7 highlights the recent grid developments. Furthermore, an analysis of the impact of fundamental factors to the CWE FB MC is performed in section 8. Section 9 concludes the report and provides an overview of the measures and projects planned by Amprion for the next years.

1. Current Trend in Electricity Production: Decreasing Levels of Conventional Generation and Increasing Shares of Renewable Generation

While electricity demand has been staying relatively stable, conventional generation capacities have been decreasing in all CWE countries in recent years. In combination with a historically high unavailability of generation facilities, high national and local supply scarcities are becoming more likely, increasing the price level on the electricity markets and leading to steadily increasing requests for cross-zonal capacity. A continuation of this trend is expected over the next years.

In **Germany**, the nuclear phase-out has already led to a shutdown of about 2.5 GW of generation capacity since 2015. By 2022, all remaining nuclear plants (9.5 GW in 2018) will be shut down successively. Moreover, old coal units and unprofitable gas plants have been decommissioned in recent years, leading to an overall reduction of conventional generation capacity by 4.6 GW so far.[2] Currently, the installed firm capacity remains at about 116 GW, which is sufficient to cover the national peak load of 87.9 GW (with high probability).[3]

Beyond that, Germany is currently planning to entirely shut down and phase out the remaining coal-fired plants on its territory by 2038. In the context of the nuclear phase-out, the installed nuclear and fossil generation capacities will be reduced by 22.1 GW by 2022 and by an additional 13 GW by 2030[4].

[2] See national adequacy report: https://www.netztransparenz.de/portals/1/Content/Ver%C3%B6ffentlichungen/Bericht_zur_Leistungsbilanz_2018.pdf

[3] See Abschlussbericht Systemanalysen 2018: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Versorgungssicherheit/Berichte_Fallanalysen/Systemanalyse_UeNB_2018.pdf?__blob=publicationFile&v=2

[4] See recommendations of Kohlekommission and Fraunhofer ISE: Kommission „Wachstum, Strukturwandel und Beschäftigung“ Abschlussbericht, https://www.kommission-wsb.de/WSB/Redaktion/DE/Downloads/abschlussbericht-kommission-wachstum-strukturwandel-und-beschaeftigung-2019.pdf?__blob=publicationFile&v=5

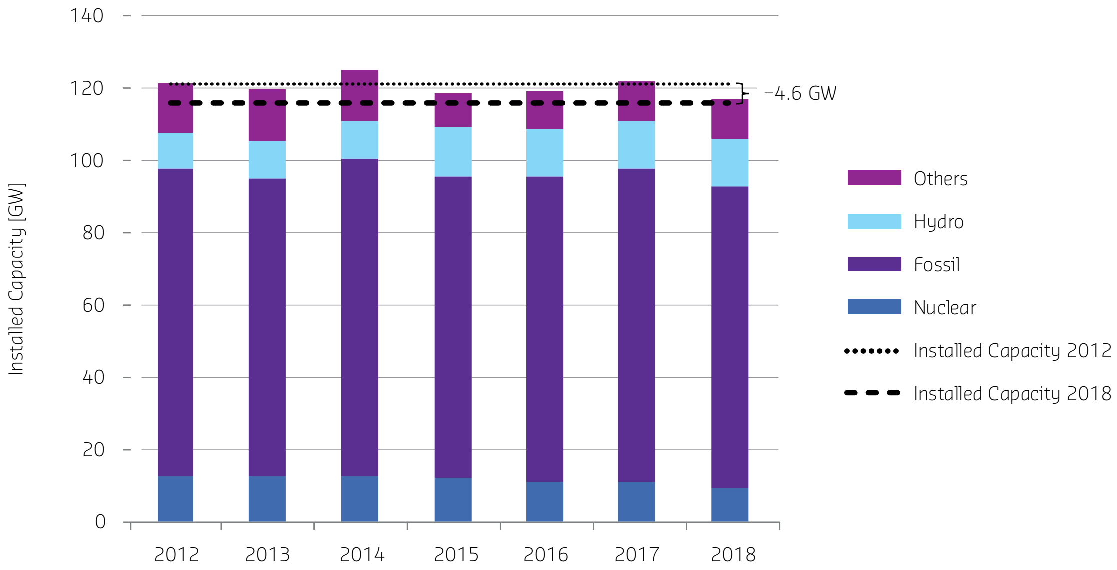


Figure 1: Development of installed generation capacity in Germany (without wind & solar), source: BMWi (Energiedaten), Entso-E transparency platform

Besides conventional generation, the CWE region is affected by the infeed of variable renewable energy sources. As well as the local scarcity of conventional generation in CWE countries, wind generation in Germany in particular is considered a main driver of transmission capacities and cross-border exchanges.

Between 2014 and 2018, wind capacities increased from 38 GW to more than 59 GW (+55 %) in Germany. Wind generation reached more than 111 TWh in 2018. The variability of the wind infeed increased significantly (e. g. more than 25 % between 2015 and 2017), leading to higher uncertainty in the capacity calculation process.

In their flow-based capacity calculation methodology, CWE TSOs consider the best forecasts with regard to generation and load patterns. In addition to best estimates of exchange programs, outages of transmission lines, production and unavailabilities of generation facilities and load patterns, TSOs consider forecasts of the infeed from wind and solar power for the congestion forecasts (D2CF and DACF)[5] as input for the capacity calculation process. The increasing share of these variable renewable energy sources adds uncertainty to this capacity calculation process.

Besides impacts on the available capacities, the high concentration of wind generation in Northern Germany leads to increasing volatility of the overall German wind infeed and to considerable increases in the utilisation of the existing transmission infrastructure, with obvious consequences and increased uncertainty for power system operation.

[5] Day-Ahead Congestion Forecast (DACF), Two-Days-Ahead Congestion Forecast (D2CF)

It is worthwhile emphasising that these external fundamental factors like variable renewables infeed and available conventional generation units impact capacity calculation and market coupling without TSOs being able to influence them.

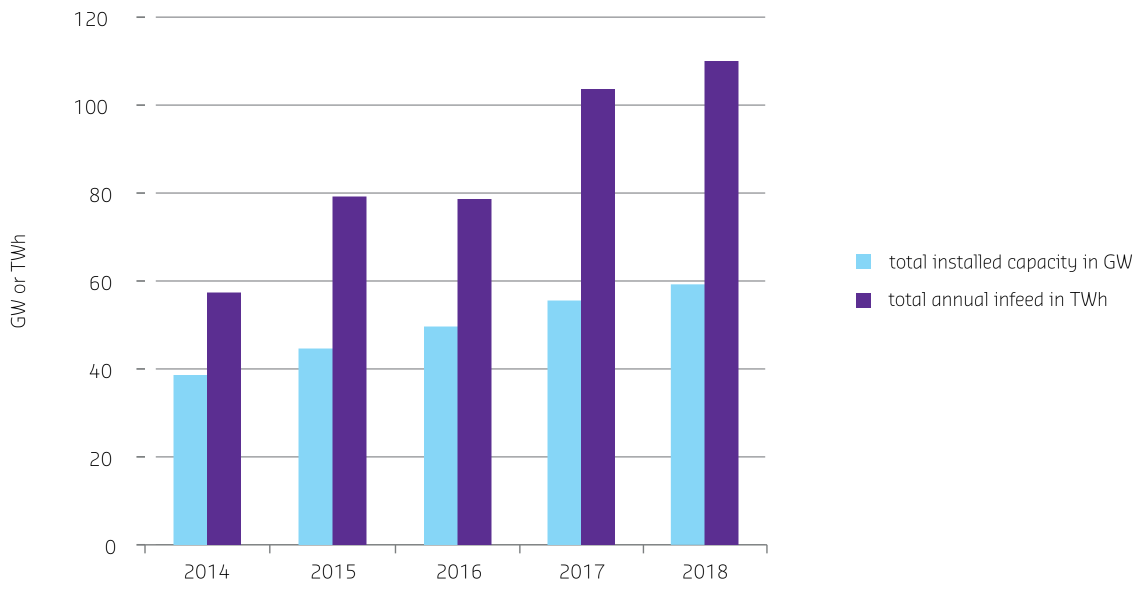


Figure 2: Installed wind capacity and wind generation in Germany, source: Fraunhofer ISE energy charts

As Figure 2 reveals, installed wind capacities in Germany increased from 39 GW to more than 59 GW (+55%) between 2014 and 2018. Wind generation reached more than 111 TWh in 2018.

When analysing exchange capacities, market coupling results and the grid situation, such considerable changes in the system conditions have to be considered. Such a detailed analysis of fundamental impact factors like wind infeed and the generation and load situation of neighbouring countries is provided in section 8.

For the near future, the decrease in conventional generation capacities is expected to continue in all CWE countries, further increasing the likelihood of local scarcities and changing capacity calculation inputs.[6]

[6] See Second Report on Generation Adequacy Assessment within PLEF Region: https://www.amprion.net/Dokumente/Dialog/Downloads/Studien/PLEF/2018-01-31-2nd-PLEF-GAA-report.pdf

In **France**, the electricity demand is supplied to a large extent by nuclear generation units. While the installed generation capacity of nuclear has remained constant, a considerable amount of fossil units (coal and gas) have been shut down over the past years, making France increasingly dependent on imports from neighbouring countries. In January 2019, the French government published a new law[7] that requires a shut-down of 3 GW coal plants before 2022 and of a significant amount of nuclear power plants (2025-2030: 4-6 nuclear units, 2030-2035: 14 nuclear units), while an increase of only 3.5 GW of offshore capacity is planned.

In **Belgium**, the amount of installed conventional generation capacities has not changed considerably. Installed firm capacity remains at about 15 GW which is, however, insufficient for a self-sustainable electricity supply. Under consideration of (planned and unplanned) unavailabilities of generation units, the national peak demand of up to 14.5 GW (2010) is likely to exceed the available generation capacity, making Belgium reliant on imports during periods of high electricity demand. In winter 2019-2020 the peak demand is expected to reach up to 14.7 GW.[8]

In the **Netherlands**, installed capacities – mainly of hard coal – have been decreasing in recent years, with a shutdown of about 3 GW from 2015 to 2018. Installed firm capacity remains at about 25 GW, while the national peak load is about 18.4 GW[9].

[7] See Programmation Pluriannuelle de L'Énergie

[8] See national adequacy report: http://www.elia.be/~/media/files/Elia/Products-and-services/Strategic-Reserve/2018/20181128_Adequacy-study.pdf

[9] See national adequacy report: https://www.tennet.eu/fileadmin/user_upload/Company/Publications/Technical_Publications/Dutch/Rapport_Monitoring_Leveringszekerheid_2018.pdf

2. Overview of the Flow-Based Concept in CWE

In order to achieve the target model of a single European market, power markets have been gradually integrated and coupled at a regional level as from 2006 with the first market coupling of the Belgian, Dutch and French day-ahead markets. The last major step towards the target model was the introduction of Flow-Based Market Coupling (FB MC) in Central Western Europe (CWE) back in 2015. Currently, TSOs are already working on the introduction of FB MC in the Capacity Calculation Region (CCR) Core, which considers Eastern Europe in addition to Central and Western Europe. TSOs of the Core CCR shall implement CORE FB MC no later than 1 December 2020, as stipulated in the ACER CORE CCM decision (Art. 28)[10].

Generally in a zonal electricity market, the determination of the available capacity between bidding zones requires a translation of physical transmission constraints into commercial transaction constraints (see step 'Capacity Calculation' in Figure 3). These simplified commercial transaction constraints are then considered in the market clearing algorithm determining market prices and cross-border exchanges between participating bidding zones (cf. step 'Market Coupling' in Figure 3). Congestions occurring after the Market Coupling require redispatching measures, which are coordinated by affected TSOs during real-time grid operation (cf. step 'Grid Operation' in Figure 3).

The following figure gives an overview of relevant inputs and outputs of the flow-based capacity calculation and allocation as well as grid operation.

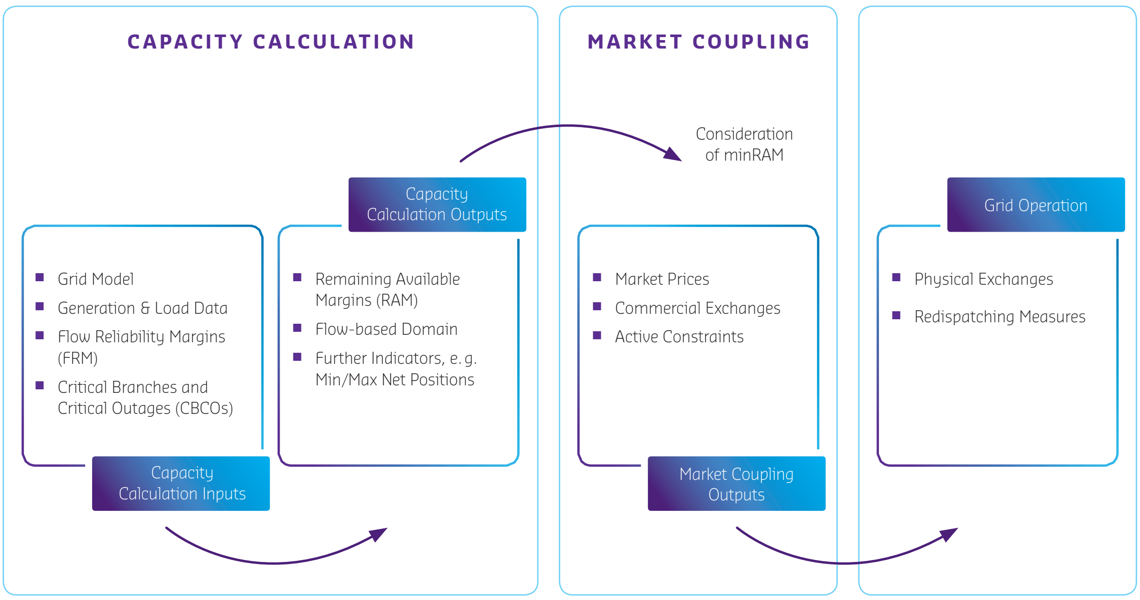


Figure 3: Overview of flow-based capacity calculation and market coupling

[10] See ACER Decision 02-2019 on the Core CCR TSOs' proposals for the regional design of the day-ahead and intraday common capacity calculation methodologies

Main Feature of Flow-Based Market Coupling: Direct Consideration of Physical Transmission Constraints in the Market

The main enhancement of the FB MC compared to the NTC[11]-based market coupling is the (direct) consideration of physical transmission constraints in the market clearing algorithm. Accordingly, all critical network elements relevant for cross-border exchanges are taken into account in the market clearing, bringing commercial transactions closer to the physical reality.

The impact of commercial transactions (i.e. change of net positions) on flows through critical network elements is determined by so-called zonal Power Transfer Distribution Factors (PTDFs). In CWE, the only network elements that are considered to be cross-border relevant are those that show a minimum zonal PTDF of 5% (while Amprion applies 8% for identifying its CBCOs). Or in other words, only network elements that fulfil the cross-border relevance criterion of 5% minPTDF are considered a potential constraint in the Market Coupling algorithm (as so-called CBCOs).

The flows through critical network elements (i.e. CBCOs) are limited by the Remaining Available Margin (RAM), which is derived from technical parameters and the system state within the flow-based capacity calculation process.

Both parameters define the flow-based domain representing all feasible combinations of commercial exchanges between participating bidding zones. Hence, in contrast to the NTC-based approach, commercial exchanges between two bidding zones are dependent on feasible commercial exchanges between other bidding zones.

Due to the better representation of the physical characteristics of the transmission grid, i.e. conservative determination of the flow-based parameters is possible. This leads in most cases to a larger flow-based domain and higher welfare gains than under the NTC-based approach.

Since 26th April 2018, a mandatory minimum trading capability of 20% on all critical network elements in CWE has been applied (so-called minRAM), but this is neglecting grid security.[12]

The Appropriate Determination of Input Parameters is Crucial

To calculate flow-based capacities, TSOs have to prepare several inputs used in the capacity calculation process. Fundamentally, TSOs consider best estimates of the state of the CWE electric system containing forecasts with regard to grid topology, generation and load. In particular, generation and load assumptions can considerably impact the system state and therefore determine the active constraints and corresponding exchange capabilities. The impacts of these fundamental factors are analysed in more detail in section 8.

Moreover, TSOs have to determine parameters for the relevant critical network elements, i.e. maximum current on a critical network element (Imax) and Flow Reliability Margins (FRM). In order to map changes in net positions to the generating units in a bidding zone, Generation Shift Keys (GSK) are defined. To ensure secure power system operation, TSOs take into account remedial actions during capacity calculation, e.g. change of the tap position of a phase shifter transformer or other topological measures.[13]

The main changes and developments in CWE in 2018 are highlighted in section 3. Then, an overview of the recent developments, focusing on particular quantitative indicators, is provided, describing the development of the Flow-Based Capacity Calculation (cf. section 4), the Market Coupling (cf. section 5) and Grid Operation (cf. section 6).

[11] Net Transfer Capacity (NTC)

[12] Via an artificial increase of the flow-based domain

[13] For further details, see "Documentation of the CWE FB MC solution" available at http://www.jao.eu

3. Main Flow-Based Market Coupling Developments in CWE in 2018

In 2018, several fundamental changes were made to the FB MC design in CWE. In 04/2018, a minimum Remaining Availability Margin to commercial exchange capabilities (so called minRAM) of 20% was introduced for all CWE borders. In 10/2018, the largest bidding zone of CWE was split by introducing the Austrian-German bidding zone border. This was accompanied by the removal of external constraints (including external constraints for the former D-LUX-AT bidding zone) to further enhance cross-border trading opportunities. In 2018, Amprion supported cross-border trading by taking several additional measures that are explained below.

INTRODUCTION OF MINIMUM MARGINS (MINRAM) TO COMMERCIAL EXCHANGE CAPABILITIES (04/2018)

Since 26th April 2018, CWE TSOs are exposed to regulatory requirements of offering more capacities to the day-ahead market by increasing the flow-based domain artificially. This mechanism is called minRAM.

CWE TSOs have to guarantee that at least 20% of the thermal capacity of each CBCO considered in the flow-based approach can be used for commercial exchanges. This 20% threshold shall be made available whatever the baseloading of the CBCOs is. This mandatory minRAM mechanism ignores the physics of the transmission grid and limits one of the most crucial advantages of the flow-based approach, which is to better align market and physics.

INTRODUCTION OF THE AUSTRIAN-GERMAN BIDDING ZONE BORDER (10/2018)

On 1st October 2018, the CWE flow-based capacity calculation and allocation with the addition of a new hub – the fifth one – went successfully live. This was without any delays. Newly developed market processes and IT have proven to be robust, scalable and future-proof. This will become increasingly important in view of the increased amount of hubs in the capacity calculation region Core, which will count 12 hubs.

Market parties, NRAs and stakeholders have been well prepared for this major step via three Market Fora with intensive exchange. SPAIC analyses enabled market parties to anticipate the impact on market outcomes.

The introduction of Financial Transmission Rights (FTRs) as long-term hedging products guarantees fair competition for long-term capacity at the border between DE-LUX and AT. In the day-ahead timeframe, the fair flow-based-mechanism has been introduced to optimise welfare. It partly allocates this welfare towards neighbouring countries, leading to (higher) price-spreads between DE-LUX and AT. These price spreads reached an average level of 7.30 €/MWh for the first three operational months (winter season), close to the SPAIC results provided by TSOs.

REMOVAL OF EXTERNAL CONSTRAINTS TO FACILITATE CROSS-BORDER TRADING (10/2018)

Until the end of September 2018, the net position of the German bidding zone was limited by an external constraint in the FB MC algorithm. By introducing the Austrian-German bidding zone border, this external constraint has been removed. CBCOs are now the main input to define the flow-based domain. This measure has increased trading possibilities, providing clear evidence for Amprion's support for the European integrated market.

FURTHER MEASURES TAKEN BY AMPRION IN 2018

New Interconnector between Amprion and the Netherlands
In 2018, a new double-circuit 380 kV line, the interconnector from Wesel to Doetinchem, between Germany and the Netherlands was commissioned by Amprion together with the Dutch TSO TenneT. The commissioning of this new extra-high voltage line increases the cross-border transmission capacity between Germany and the Netherlands and at the same time homogenises the electricity flow pattern on all existing lines. New interconnectors contribute significantly to a European integrated market and at the same time increase system reliability.

Ongoing Improvement of the Dynamic Line Rating
Amprion has taken the next step in the application of dynamic line rating in the capacity calculation. Within this second step, Amprion has progressed from the four line rating temperature categories towards the Cigre Curve[14]. Furthermore, temperature forecasts from 14 weather stations are now used and linked to the lines nearby.

Impact of the Introduced Measures
The described developments in 2018 (as already shown in 2017) significantly reduced the share of constraints in the Amprion grid that are limiting the market. The measures taken by Amprion in the last two years can therefore be considered highly beneficial for the CWE market coupling.

It is Amprion's persistent aim to maintain a high level of cross-border exchange capacities, while guaranteeing system security at all times. On top of Amprion's efforts to improve market coupling in recent years, further improvements are expected in the near future.

[14] The Cigre Curve is based on the thermal balance between the heat gained and lost in the conductor due to the load and environmental conditions. Variables that are considered are the ambient temperature, solar radiation, wind speed, wind direction and the current of the conductor.

4. Flow-Based Capacity Calculation

The main feature of the FB MC is a better consideration of transmission constraints in the market. Therefore, the determination of the available capacities between bidding zones requires a translation of physical transmission constraints into (simplified) commercial transaction constraints.

In the following, the development of crucial flow-based capacity parameters are highlighted by focusing on allowable power flows and considered flow reliability margins in CWE.

HIGHER MAXIMUM ALLOWABLE POWER FLOWS

The capacities given to the market are – amongst other parameters – determined by the maximum allowable power flow on a critical network element (Fmax) as an input parameter for the flow-based capacity calculation process.

In order to support cross-border trade and as part of continuous improvements of the FB MC, CWE TSOs introduced seasonal Fmax values. Moreover, some TSOs (like Amprion) implemented dynamic line rating leading to higher capacities, in particular during cold periods with a higher electricity demand. Accordingly, import and export capabilities have been increased during the winter period in particular, with a higher electricity demand and a corresponding higher socio-economic value.

The maximum allowable power flow on a critical network element (Fmax) is derived from the maximum current on a critical network element (Imax). Imax is the physical (thermal) limit of the critical network element, which depends on the weather conditions and is usually fixed at least per season. Further to the physical limits of the network element itself, other relevant limitations need to be acknowledged. Such limitations include, in particular, maximum allowable voltage inductions into parallel infrastructure, e. g. gas pipelines that must not exceed certain threshold values. Otherwise, safe and secure operation of the infrastructure ensuring human safety in particular is no longer guaranteed.

After go-live of the FB MC in 2015, CWE TSOs have focused on developing a regional process to coordinate remedial actions, in particular for the coordination of phase shifting transformers and topological measures. Consequently, in order to maintain secure grid operation, TSOs considered seasonal Fmax values only on selected critical network elements during the winter period 2015/16, i. e. transmission line Siersdorf-Maasbracht.

After implementation of the process for coordinated remedial actions and the subsequent elimination of Final Adjustment Values (FAV)[15] on critical network elements, Amprion introduced seasonal Fmax values on further lines for the winter period 2016/17. In 2017 and 2018, CWE TSOs continued the development. Amprion, for example, introduced a dynamic line rating approach on its transmission lines, allowing adaptive Fmax values as a function of weather conditions, i. e. temperature. Through the aforementioned measures, thermal limits can be increased by more than 20 %, in particular during cold weather conditions usually associated with a high electricity demand.

[15] FAV can be used by TSOs to reduce or increase remaining available margin (RAM) on a critical network element for very specific reasons, i. e. system security reasons.

LOW FLOW RELIABILITY MARGINS SUPPORT HIGHER CAPACITIES

In order to cope with uncertainty, i. e. deviations from forecasts, between the points in time of the capacity calculation and real-time operation, TSOs apply reliability margins for the critical network elements under consideration. The so-called Flow Reliability Margin (FRM) is deducted from the corresponding Fmax value and accordingly reduces the remaining available margin considered in the capacity calculation process. FRM values observed for CWE are in the range between 5 and 20 % of the respective Fmax value.

The lowest FRM values can be observed for Amprion with only 8.8 % on average, which in turn leads to comparatively higher capacities made available to the market.

Considering FRM values on all active critical network elements in CWE, the decrease in the remaining available margin (RAM) due to uncertainty for 2015-2018 ranges from 40 to 357 MW (177 MW or 13 % of Fmax on average) in the CWE region.

Right from the beginning of the FB MC in 2015, Amprion applied FRM values much lower than the average of CWE. As shown in Figure 4, FRM values on active critical network elements of Amprion amount to only 155 MW or 8.8 % of Fmax on average. Accordingly, the restriction of cross-border trade due to uncertainty is rather limited for critical network elements of Amprion for which FRM values range from 82 to 256 MW.

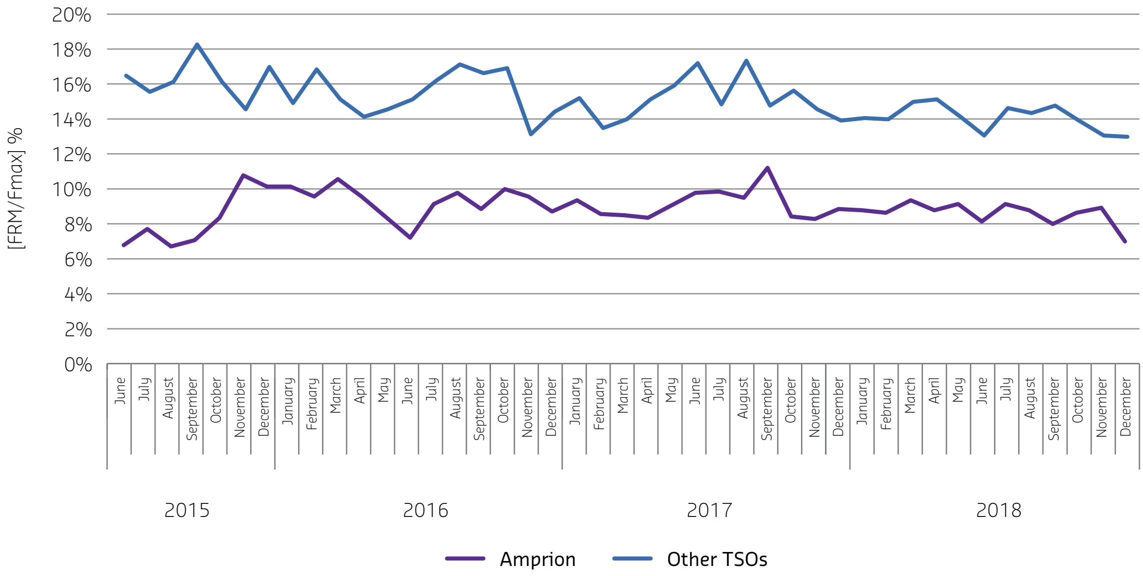


Figure 4: Monthly average FRM values of active constraints in CWE

According to a recalculation of FRM values in the course of a study performed by CWE TSOs in 2016, uncertainty and corresponding FRM values increased after the go-live of the CWE FB MC. However, in order to not limit cross-border trade, CWE TSOs decided not to increase FRM values, meaning that TSOs take the risk.

5. Market Coupling and Capacity Allocation

The outputs of the flow-based capacity calculation process are submitted to the market operators by TSOs. Subsequently, the market coupling algorithm determines optimal market prices and net positions (importing or exporting), taking into account the flow-based constraints.

Transmission capacity between bidding zones is allocated in an implicit way and (bilateral) cross-border exchanges can be derived from the market results, i.e. net positions.

One of the main targets of market coupling is the reduction of market price differences in the market coupling region. In the event of sufficient cross-border transmission capacities, electricity generation and demand can be regionally balanced, leading to welfare gains.

In this section, the development of the market situation in CWE is analysed by focusing on bilateral exchanges, net positions, market prices and active constraints.

CONSTANTLY HIGH GERMAN EXPORT CAPABILITIES IN CWE

The following section focuses on the CWE region and the maximum import and export capability of CWE bidding zones.

Technically, maximum and minimum net positions for CWE – showing the export and import capabilities of a bidding zone – are extracted from the vertices of the final flow-based domain given to the market coupling[16].

For CWE, Germany's export capabilities remain constantly on a high level (average of 5,447 MW). While the export capabilities of France are also high (average of 5,797 MW), those of the Netherlands and Belgium are significantly lower (average of 3,505 MW and 2,539 MW respectively). In contrast, the import capabilities of the Netherlands and Belgium reveal constantly high (average 4,135 MW respectively 4,183 MW).

Through the introduction of the new DE-LUX/AT bidding zone border and the linked removal of the external constraint on German borders, Germany's export capabilities have been increased to more than 17,000 MW in Q4/2018.

Disclaimer:

Please note that the following figures show net import and net export positions up to the end of 2018, meaning they also consider the introduction of the DE-LUX/AT border (01.10.2018). However, its introduction changed the number of borders considered and therefore the base for comparison significantly. Because of this, the last three months of 2018 are shown in the graphs, but are not considered in the following analysis.

[16] As the maximum and minimum net positions depend on the net positions of the other hubs they are not simultaneously feasible.

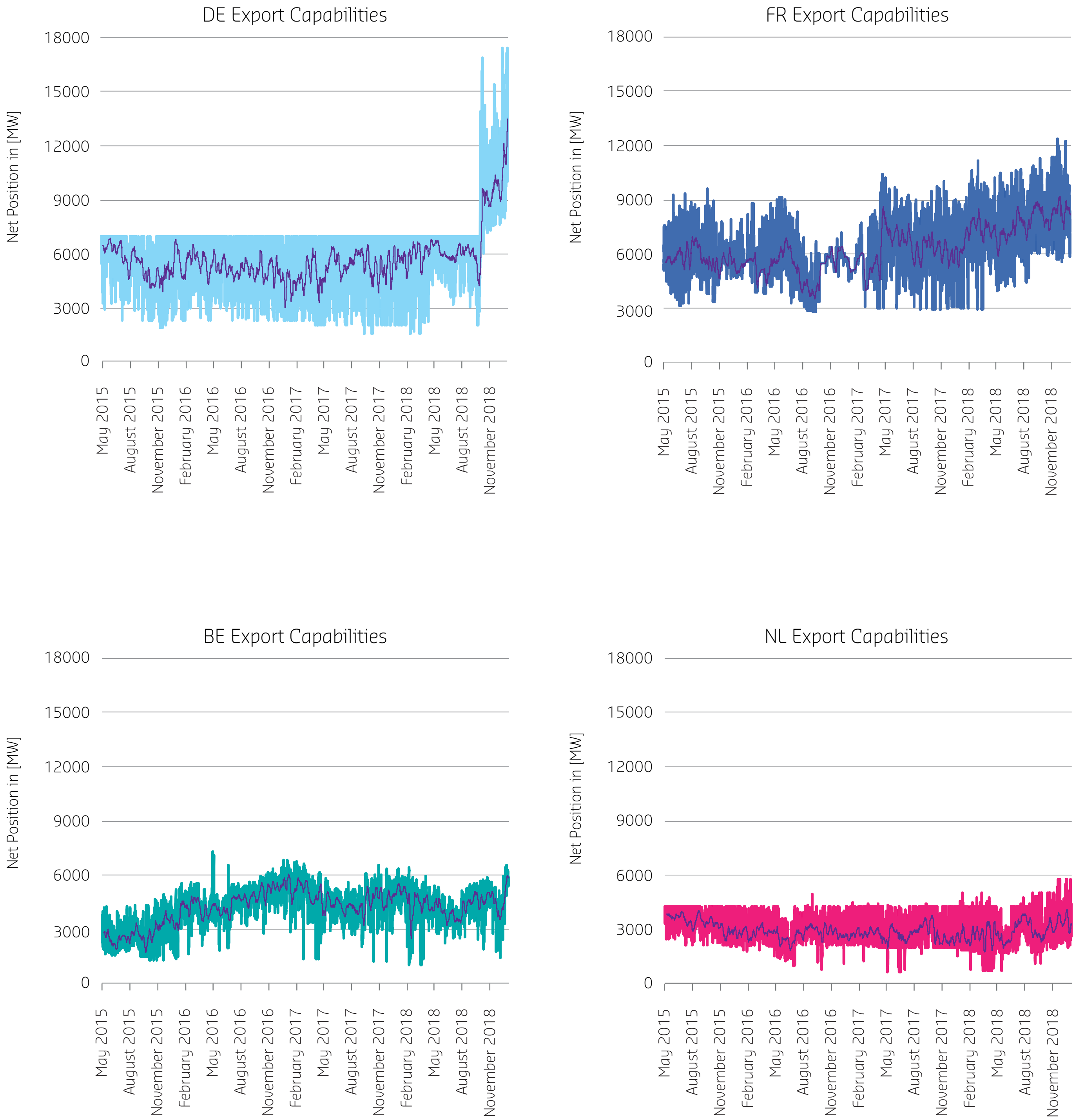


Figure 5: Comparison of export capabilities for Germany, France, Belgium and the Netherlands in CWE, (purple line: moving weekly average), source: NRA Reports

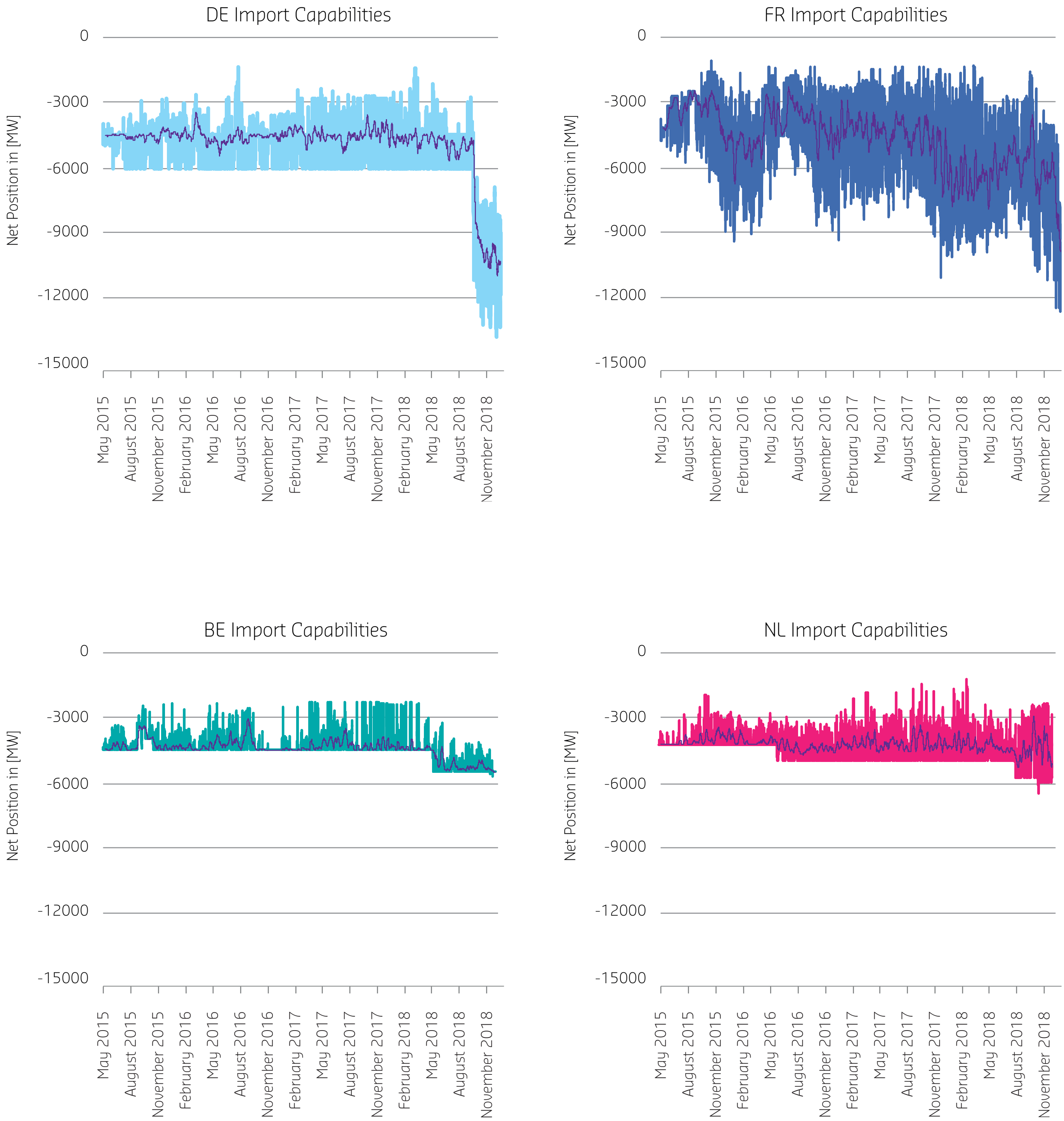


Figure 6: Comparison of import capabilities for Germany, France, Belgium and the Netherlands in CWE, (purple line: moving weekly average), source: NRA Reports

Germany's export capabilities remain at a constantly high level. The spikes in the last three months can be explained by the introduction of the German-Austrian bidding zone border, which changed the number of CWE borders. A comparison of the time span before and after the split, in particular with regard to import and export capabilities, would therefore not be appropriate.

For **Belgium**, the import capabilities remain at a constant high level while the export capabilities are significantly lower than the ones of Germany and France. In particular during the winter 2016/2017, import capabilities remained stable at a level of –4.5 GW.

The import and export capabilities of **the Netherlands** remain at a constant level.

For **France**, the development of the import capabilities is quite volatile. In particular during the winter period, minimum import capabilities exceeded –10 GW.

Since the end of April 2018, a mandatory minimum trading capability of 20% (i.e. minRAM) on all critical network elements in CWE has to be applied, irrespective of grid security concerns[17]. The impact of this mandatory application of the minRAM becomes particularly visible in the significantly increased export capabilities of Germany and France from May 2018, while the import capability of Belgium simultaneously increased.

BILATERAL DAY-AHEAD EXCHANGES IN CWE

While the previous figures have shown the theoretically possible exports and imports of a CWE bidding zone, the following graphs show the bilateral day-ahead exchanges resulting from day-ahead market coupling. Such day-ahead exchanges can also be described as commercial exchanges (in contrast to physical flows that are shown in section 6).

In line with the development of the day-ahead import and export capabilities shown previously, bilateral day-ahead exchanges from Germany to the CWE region remain at a high level.

Continuously high flows from northern CWE borders to southern borders can be observed. In particular during winter periods, imports to France from Germany and Belgium increase, mainly caused by a more scarce generation situation in France.

[17] The application of the minRAM can only be denied by the concerned TSO in exceptional cases.

Apart from seasonal patterns, the level of day-ahead exchanges from Germany to the CWE region (i.e. DE to FR and NL) reveals no structural decrease (see Figure 7). In contrast, an increase of exports to NL and FR can be observed with the introduction of the German-Austrian bidding zone border in October 2018.

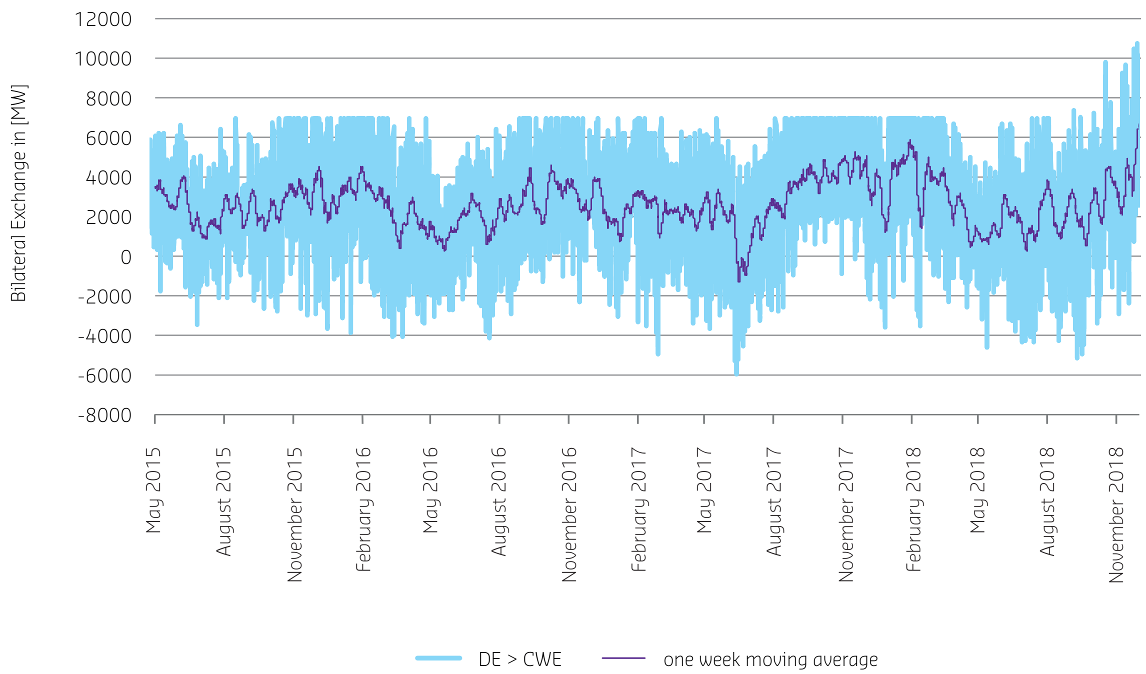


Figure 7: Day-ahead exchange from Germany to CWE region (i.e. DE to FR and NL), (purple line: moving weekly average).
Please note that the exchange to Austria is not considered for the last three months of 2018.

Figure 8 shows the considerable North-South-flows in CWE (without AT)[18] over the past few years. In particular during the winter periods, higher exchanges in CWE from North to South can be observed.

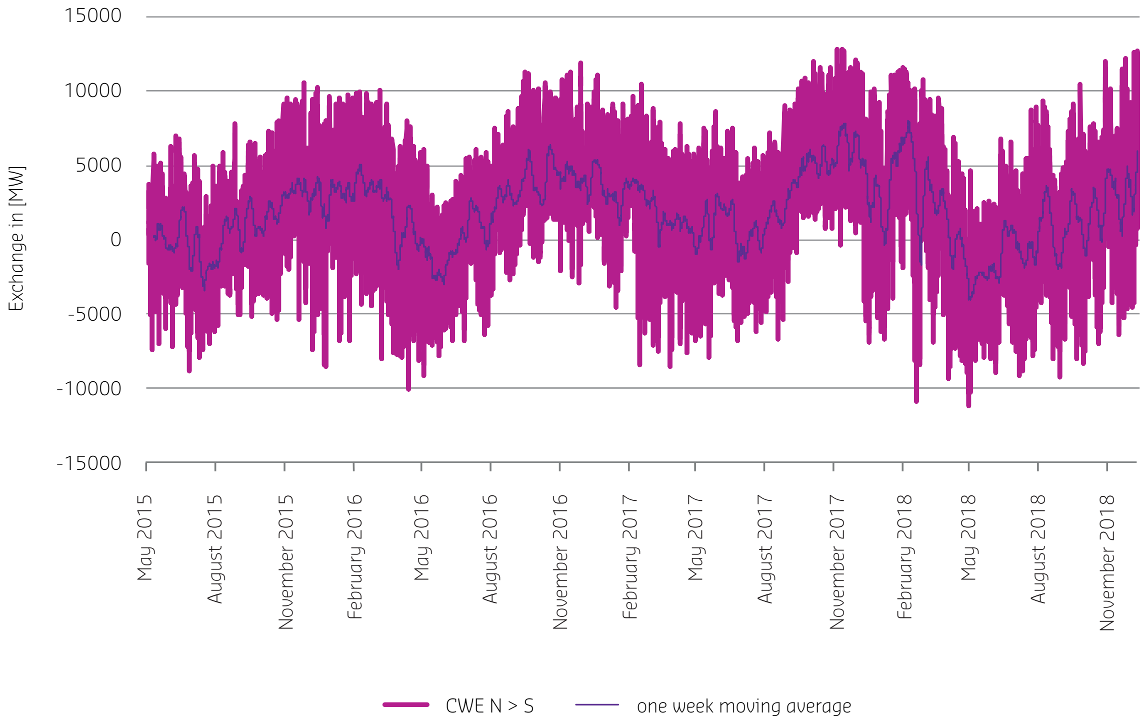


Figure 8: Day-ahead exchanges from CWE North to South (without AT),
(purple line: moving weekly average).
Please note that the exchange to Austria is not considered.

[18] Sum of exchanges: DE to NL + NL to BE + BE to FR + DE to FR

As shown in the following figures, in particular during the winter periods, the French exports to Belgium are low, even turning into a flow from Belgium to France at times. Over long periods, France imports from Germany with peaks found during the winter periods.

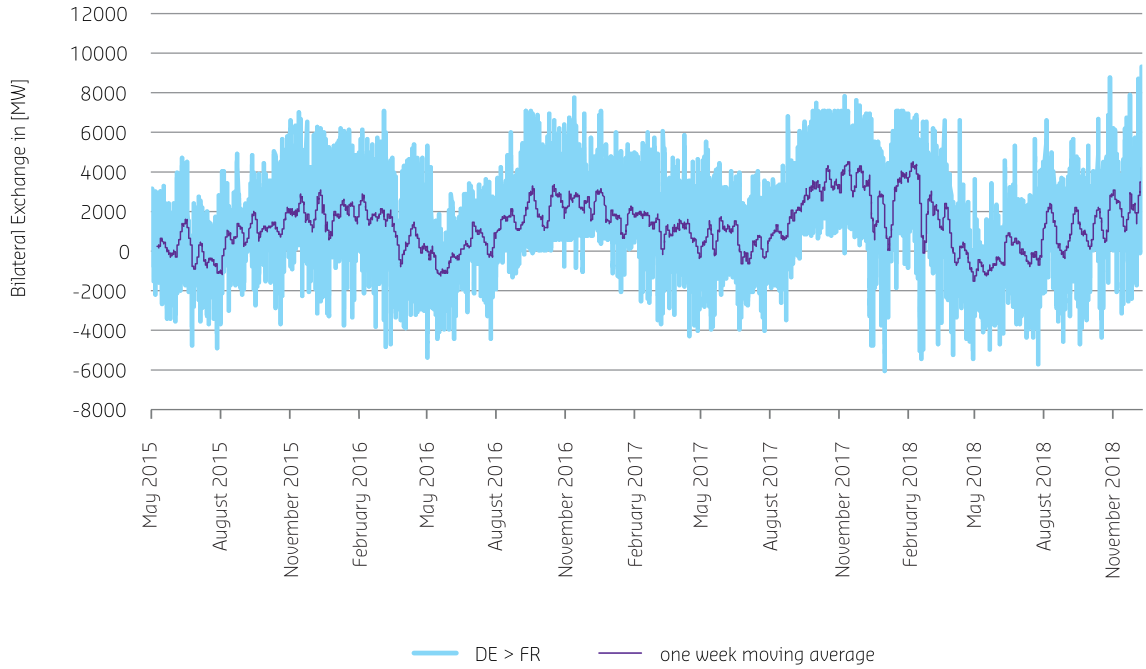


Figure 9: Day-ahead exchange from Germany to France, (purple line: moving weekly average)

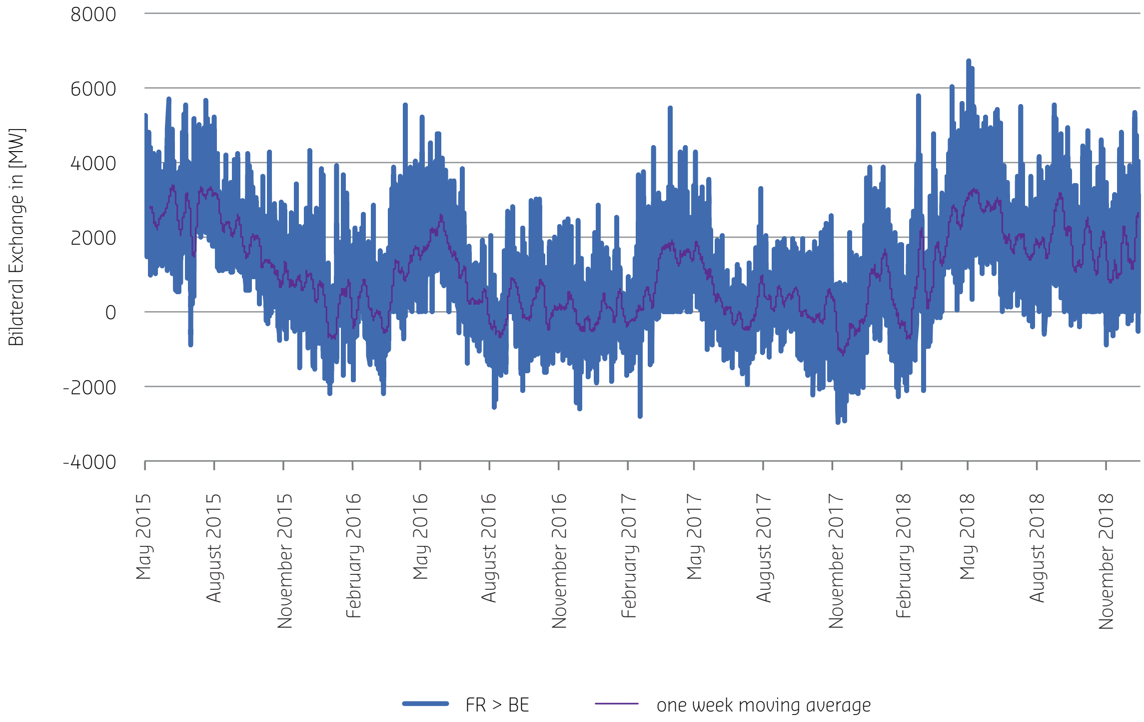


Figure 10: Day-ahead exchange from France to Belgium, (purple line: moving weekly average)

EXCURSUS: INCREASING GERMAN DAY-AHEAD NET POSITIONS

In order to provide a full picture regarding the import and export situation of the CWE bidding zones, the following figures consider all bidding zone borders (not only CWE).

In general, the net position of a bidding zone shows the total day-ahead imports and exports at all bidding zone borders. Therefore, a positive net position indicates a net exporting bidding zone while a negative net position shows a net importing bidding zone.

While for Germany the day-ahead net positions remain at a high level, the net positions of the Netherlands and Belgium have also been stable over the last few years.

For France, lower net positions are observed, mainly caused by lower available generation capacity in France. For Germany, in particular during Q4/2017 and Q1/2018, exports exceeded historical levels.

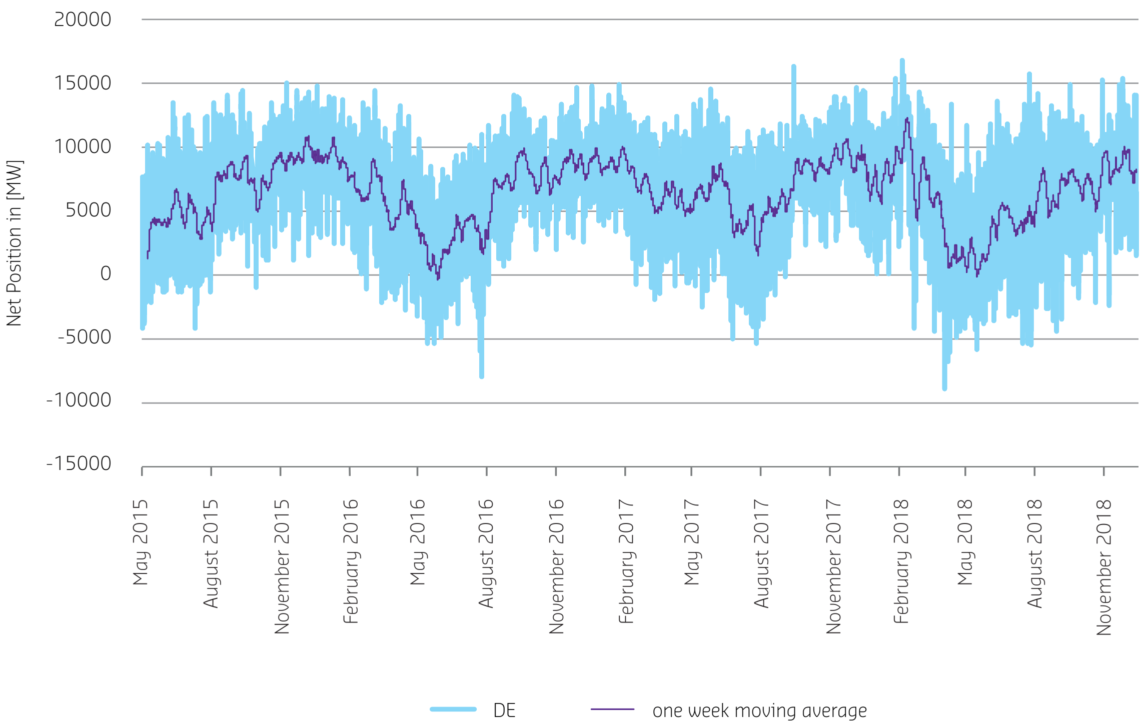


Figure 11: Net positions for Germany (considering all German borders, not just CWE borders), (purple line: moving weekly average)

As shown in Figure 12, net positions for Germany and France reveal significantly higher levels over the years while Belgium and the Netherlands are mainly net importers.

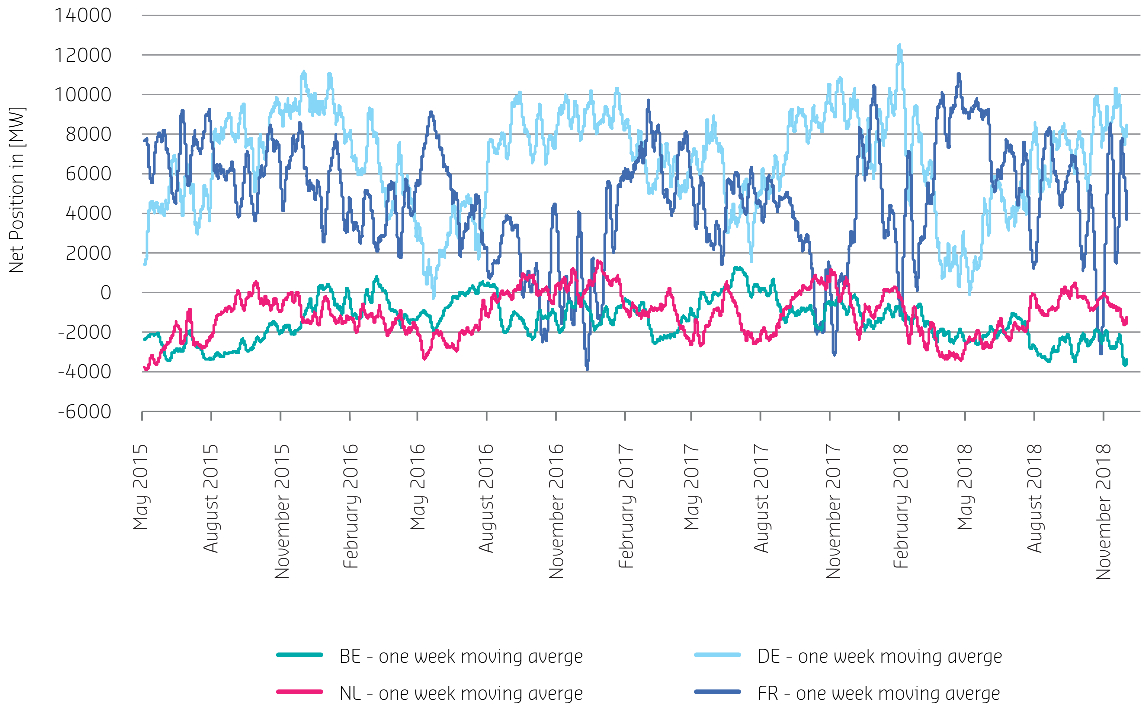


Figure 12: Comparison of net positions for Belgium, Netherlands, France and Germany (considering all borders, not just CWE borders)

Net positions for **Germany** reveal a slightly increasing trend of exports. In particular, during Q4/2017 and Q1/2018, exports exceed historical levels, also as a result of measures introduced by Amprion and other CWE TSOs (i. e. winter values).

For **Belgium**, a slightly decreasing level of net positions is observed. Belgium remains a net importing country (see Figure 12).

For **the Netherlands**, an increasing trend of net positions is found. However, the Netherlands remains a net importer in many hours.

For **France**, an overall decreasing level of net positions is observed. While France was mainly exporting until Q2/2016, increased imports led to considerably lower net positions afterwards (see Figure 12).

INCREASING TREND OF PRICE CONVERGENCE IN CWE

The reduction of price differences within a region is one of the main targets of market coupling. Sufficient cross-zonal transmission capacities are a crucial prerequisite for achieving price convergence (i.e. price differences equal zero).

However, other fundamental factors significantly impact the market as well. On the one hand, considerable changes in the generation mix, i.e. decommissioning and unavailability of conventional generation units, have led to a shift of generation centres in CWE countries. On the other hand, import needs are strongly driven by the infeed from variable renewable energy sources and the electrical demand, which in turn are heavily impacted by the natural variability of climate and weather conditions.

Although CWE countries face an increasingly stressed supply situation, a steady increase of hours with full price convergence is observed. This provides evidence for the significant contribution of CWE TSOs to a cost-efficient balancing of supply and demand across the CWE region.

In the case of sufficient cross-border exchange capacities, no price differences between CWE bidding zones occur. If commercial exchanges are limited by active transmission constraints, prices between CWE countries diverge. Accordingly, price convergence is an indicator for the level of market integration in the CWE region.

Figure 13 and Figure 14 show that the level of market integration increased over the past years.

In 2018, the commissioning of the new Niederrhein/Doetinchem interconnector between Germany (Amprion) and the Netherlands positively impacted the price convergence (due to the additional exchange possibility). In contrast, the introduction of the DE-LUX/AT bidding zone border had a decreasing impact on the overall price convergence in CWE for the three last months of 2018. However, the overall impact of the introduction of the DE-LUX/AT bidding zone border on the price convergence in CWE is not straightforward. While the new bidding zone border facilitates competition between all CWE bidding zones for cross-border relevant transmission capacities located within Germany, it also limits de facto the exchanges between Germany and Austria.

In total, an overall increasing trend for price convergence in CWE is observed (cf. Figure 13).

However, Figure 13 shows that price convergence is also driven by seasonal impacts. In particular during winter periods, price convergence in CWE decreased regularly over the past years. Besides the infeed of renewables, the availability of base load power plants (in particular nuclear plants) and load peaks also impact the prices in CWE. The lower level of price convergence during the winter periods 2016/17 and 2017/18 is moreover driven by the stressed supply situation in the CWE countries.

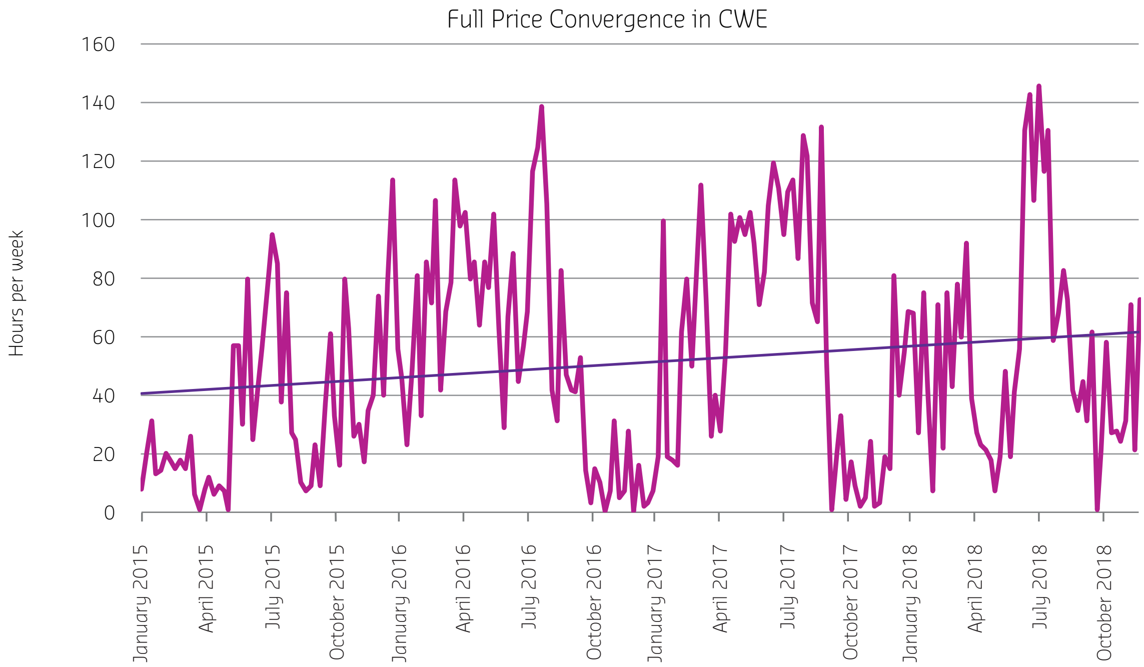


Figure 13: Hours per week with full price convergence in CWE
(price spreads between CWE bidding zones equals 0), source: ENTSO-E transparency platform

Figure 14 shows the price convergence per bidding zone border, which also considers the newly introduced DE-LUX/AT border. Compared to the previous winter periods, in 2018 a higher price convergence can be observed.

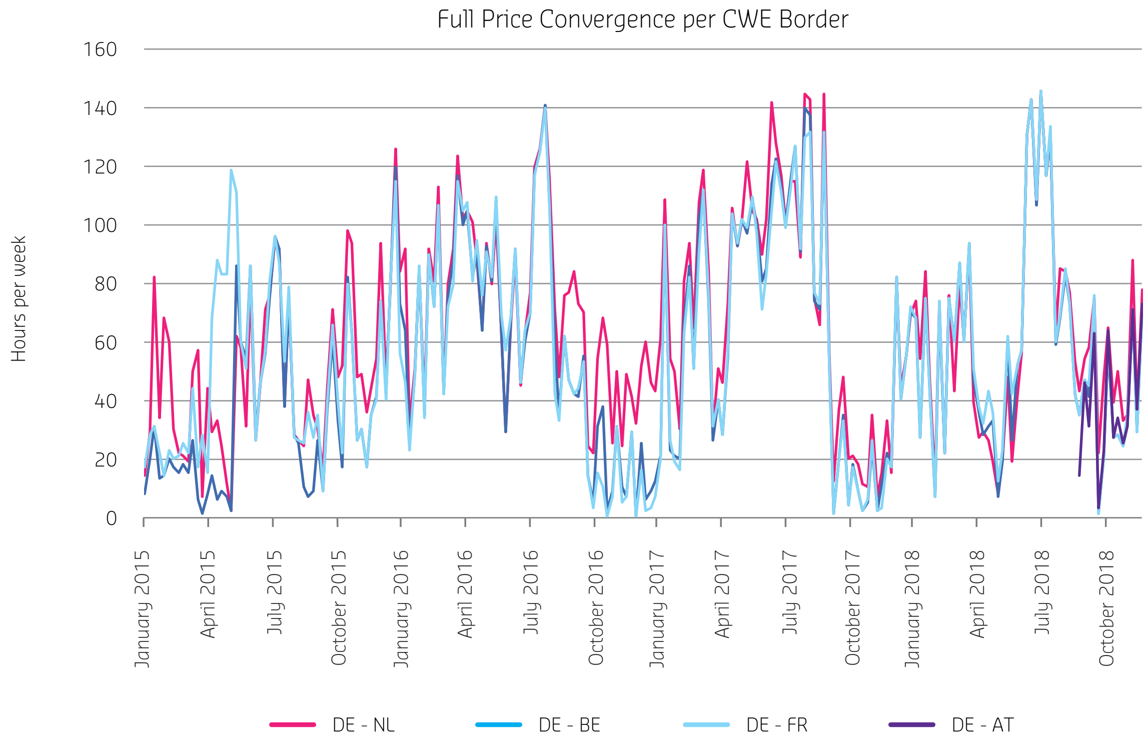


Figure 14: Hours per week with price convergence per CWE border
(price spread between respective bidding zones equals 0), source: ENTSO-E transparency platform

Although the variance of the hourly day-ahead prices is quite high, the table below aims to give a first impression on the absolute price levels in CWE. However, prices follow seasonal patterns and might vary widely over the year. It should also be noted that the average price shown for the new bidding zone AT is based on prices for three months only, which may not represent a consistent pattern.

Table 1: Day-ahead average price levels in CWE (in €/MWh), source: ENTSO-E transparency platform

€/MWH	2015	2016	2017	2018	UNTIL 09/2018	FROM 10/2018
DE-LUX/AT	31.82	28.99	34.19	–	41.73	–
DE-LUX	–	–	–	–	–	52.59
AT	–	–	–	–	–	59.92
NL	40.06	32.24	39.31	52.53	–	–
BE	44.72	36.58	44.58	55.27	–	–
FR	38.45	36.70	44.97	50.20	–	–

FREQUENCY OF ACTIVE CONSTRAINTS IN CWE

As described in section 2, critical network elements (so-called CBCOs) are necessary input parameters of the flow-based capacity calculation. However, depending on the likely market direction, only some of these CBCOs will act as limiting elements in the flow-based domain and therefore limit the exchanges in the CWE region. Such limiting elements are called active (in the sense of limiting) constraints.

> The frequency of active constraints is subject to seasonal effects and driven by generation and load patterns in CWE countries. Improvements like the introduction of winter values and dynamic line rating on Amprion CBs have reduced the frequency of Amprion's active CBCOs significantly over the last two years, further enhancing market integration in CWE.

The development of active Critical Branches (CBs) is subject to dynamic changes (see Figure 15). While active cross-zonal elements are shown in Figure 15 as cross-hatched areas, internal active constraints of BE (Elia), NL (TTN) and DE (Amp) are shown as green, red and light blue areas.

While in the beginning of CWE FB Market Coupling, mainly cross-zonal CBs limited cross-zonal trades (see cross-hatched areas), from November 2015 on internal CBs also actively limited cross-zonal exchanges. Limiting cross-zonal elements were mainly located at the German-Dutch and Dutch-Belgian borders. The main active internal elements were located close to the German-Dutch border in the Amprion control zone (see light blue area).

In particular during the winter periods with high North-South flows, internal elements become relevant, whereby the introduction of winter values on Amprion CBs in November 2016 led to a considerable reduction in the frequency of the active constraints. For the last two years, a shift to internal elements in the Netherlands and Belgium could also be monitored (see red and green areas). Moreover, since 2017, cross-zonal elements at the German-Dutch border have been limiting more often (see crosshatched areas).

Over the last two years, Amprion could significantly reduce the frequency of internal active CBs (see light blue area) and therefore significantly contribute to the market integration progress in CWE.

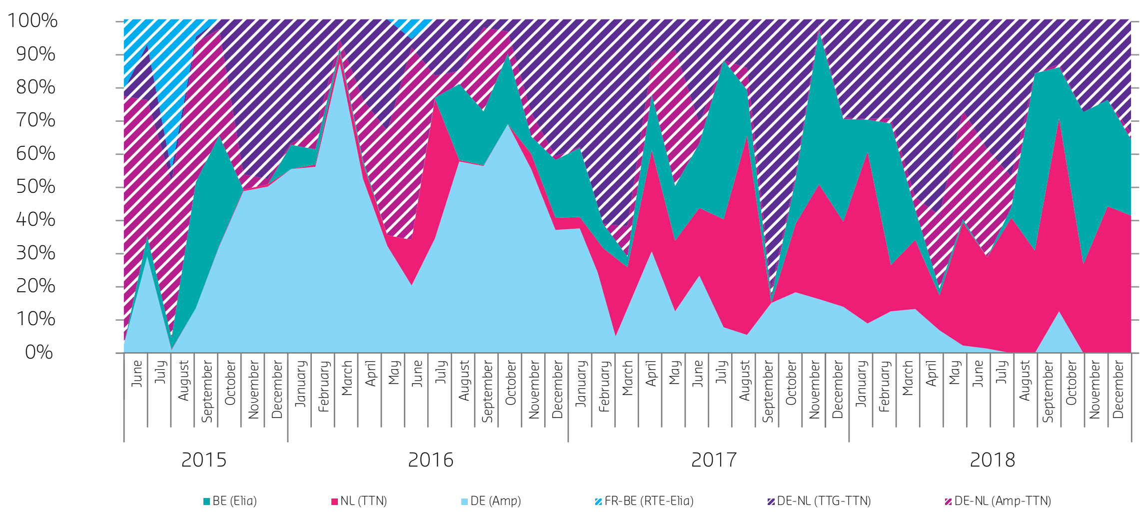


Figure 15: Relative frequency of top 10 active CBs (crosshatched areas = cross-zonal elements)

6. Grid Operation

The market coupling results are submitted to the TSOs and subsequently translate into physical flows during real-time grid operation on the basis of schedules nominated by market participants. In order to avoid overloading of grid elements, TSOs apply remedial actions, i.e. redispatching measures, in order to maintain a secure grid operation.

This section focuses on the grid situation by analysing physical exchanges between CWE countries and redispatch volumes of German TSOs.

PHYSICAL EXCHANGES IN CWE

The physical exchanges from Germany to CWE remain at a high level, as do the commercial exchanges. In 2018, the trend of high transits from North to South can also be observed.

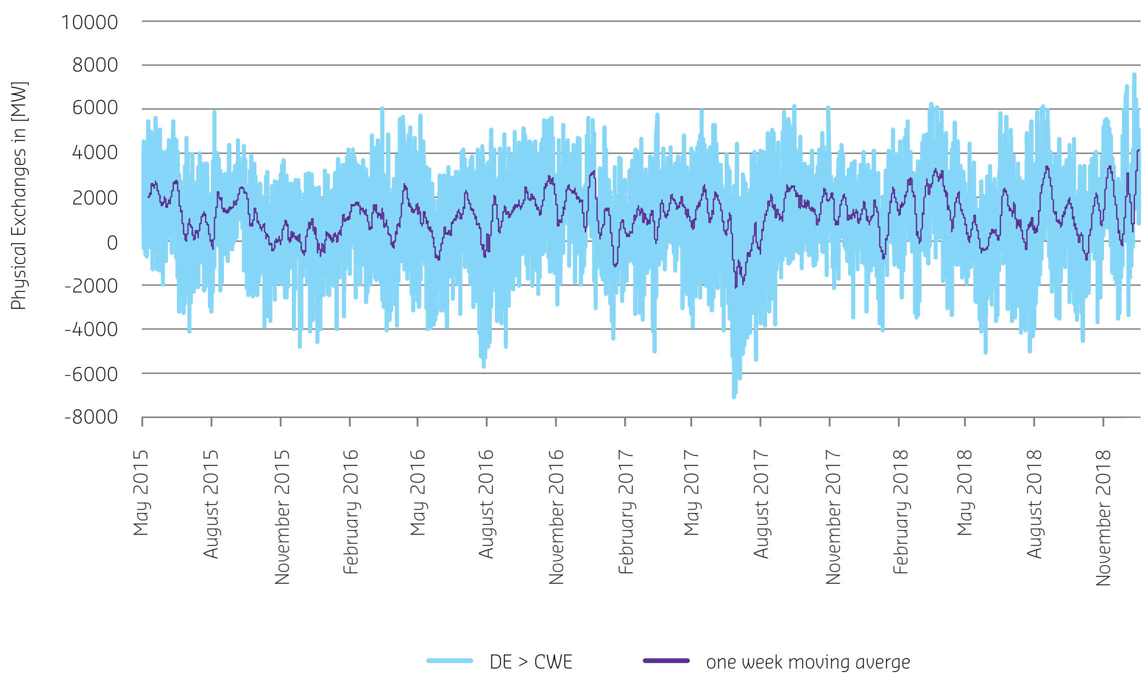


Figure 16: Physical exchange from Germany to CWE (without AT), (purple line: moving weekly average).

Please note that the exchange to Austria is not considered.

Like the commercial exchanges, the physical exchanges from Germany to CWE also remain at a high level (cf. Figure 16). High export flows from Germany are to a large extent caused by thermal generation and corresponding physical exports from the Amprion control zone. During the winter period 2016/17, net exports of Amprion exceeded 12 GW representing nearly 70% of the maximum vertical load of the Amprion control zone. At the same time, imports of southern control zones reached 15 GW.

Figure 17: Physical exchanges from CWE (without AT) North to South[19], (purple line: moving weekly average).
Please note that the exchange between Germany and Austria is not considered.

REDISPATCH VOLUMES IN GERMANY

> The increase in North-South transits in the CWE region led to considerably higher redispatch volumes, in particular during the winter period 2016/17. Amprion's increasing redispatch volumes over the last two years demonstrate its strong commitment to European market integration and the support provided to Amprion's neighbours.

[19] Sum of exchanges: DE to NL + NL to BE + BE to FR + DE to FR

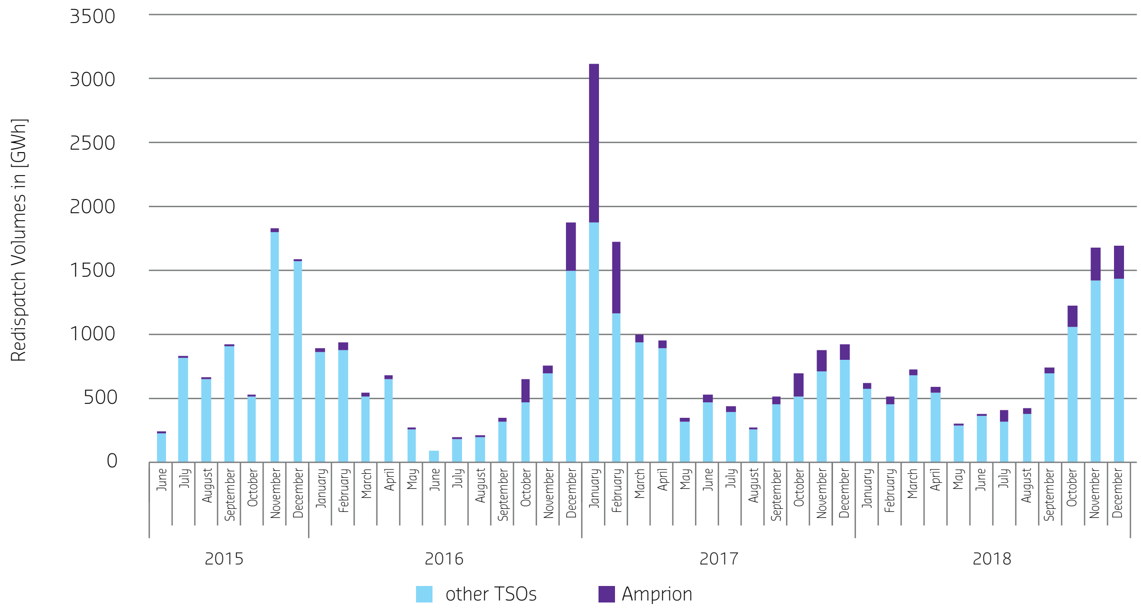


Figure 18: Total monthly redispatch volumes for Germany, source: www.netztransparenz.de

As emphasised in Figure 18, all German TSOs face higher redispatch needs during winter periods when the North-South transit occurs.[20]

The main drivers of the German redispatch are wind infeed (in particular for TenneT DE and 50Hertz) and the load and supply situation in southern CWE countries (in particular for Amprion) due to the corresponding import flows. A more detailed analysis of the drivers can be found in section 8.

The number of redispatch measures per day indicates the occurrence of critical grid situations, where TSOs had to intervene in real-time operation. The average number of redispatch measures per day in Germany for 2018 was 15. The maximum in 2018 was 76 redispatch measures per day. Over the past few years, redispatch measures became the rule rather than the exception and reached a historic maximum with 96 redispatch measures per day in winter 2016/2017.

[20] During the winter period 2016/2017, German TSOs faced a historical situation with considerable redispatch needs in combination with low availability of generation capacities and low redispatch potential. There had never been such a critical situation before, with up to 92 redispatch measures per day.

7. Grid Development and Enhancement

FURTHER DEVELOPMENT OF THE DYNAMIC LINE RATING

In 2018, Amprion launched the first step of the dynamic line rating concept (out of four) to increase the capacity of overhead lines depending on the current weather conditions. In addition to the 14 weather stations already installed in substations, 28 additional measuring stations have been installed along the most heavily loaded circuits at meteorologically exposed masts.

For the short-term increase of the transmission grid capacity, Amprion launched the first step of the dynamic line rating concept in 2018, considering the weather-dependent adaptation of transmission line capacities. In order to determine the capacity of selected lines based (among other factors) on the ambient temperature, 14 weather stations have been installed. Under appropriate weather conditions, the capacities can therefore be increased by up to 37% and thus allow a sustainable reduction of redispatch measures.

In order to enlarge the capacity-increasing and therefore redispatch-reducing impact of the weather-dependent operation of overhead lines, the next phase of the dynamic line rating concept has already been initiated. For this purpose, in 2018, Amprion installed 28 additional weather stations located along the most heavily loaded circuits at meteorologically exposed locations (i.e. pylons and substations).

When introducing the dynamic line rating concept, priority has been given to those internal circuits that appeared as critical branches in the CWE flow-based market coupling.

Thus, Amprion significantly contributes to the integration of the entire European electricity market.

NEW INTERCONNECTOR BETWEEN GERMANY AND THE NETHERLANDS

The interconnector from Wesel in Germany to Doetinchem in the Netherlands was commissioned by Amprion in 2018 together with the Dutch TSO TenneT. The commissioning of this new extra-high voltage line increases the cross-border transport capacity between Germany and the Netherlands and at the same time homogenises the flow of electricity on all existing lines. New interconnectors contribute significantly towards a European integrated market and at the same time increase system reliability.

For the realisation of the new German-Dutch interconnector, Amprion has set up a roughly 30-kilometre-long 380 kV line on the German side of the substation Niederrhein near Wesel. It runs in two route sections from Wesel to Wittenhorst and from there to the transfer point on the German-Dutch border near Isselburg. The first circuit was put into operation in August 2018. In September 2018, commissioning of the second circuit followed. The interconnector is also known as Project No. 13 of the German Energy Line Expansion Action (Energieleitungsausbaugesetz).

In addition, Amprion further develops the pylon designs. For the first time, newly developed solid panel pylons have been built in the interconnector project Niederrhein – Doetinchem. The first pylons have been constructed on the approximately seven-kilometre section between Millingen and the Federal border with the Netherlands, which went into operation in autumn 2018. They are used to test public acceptance and to gain technical experience.

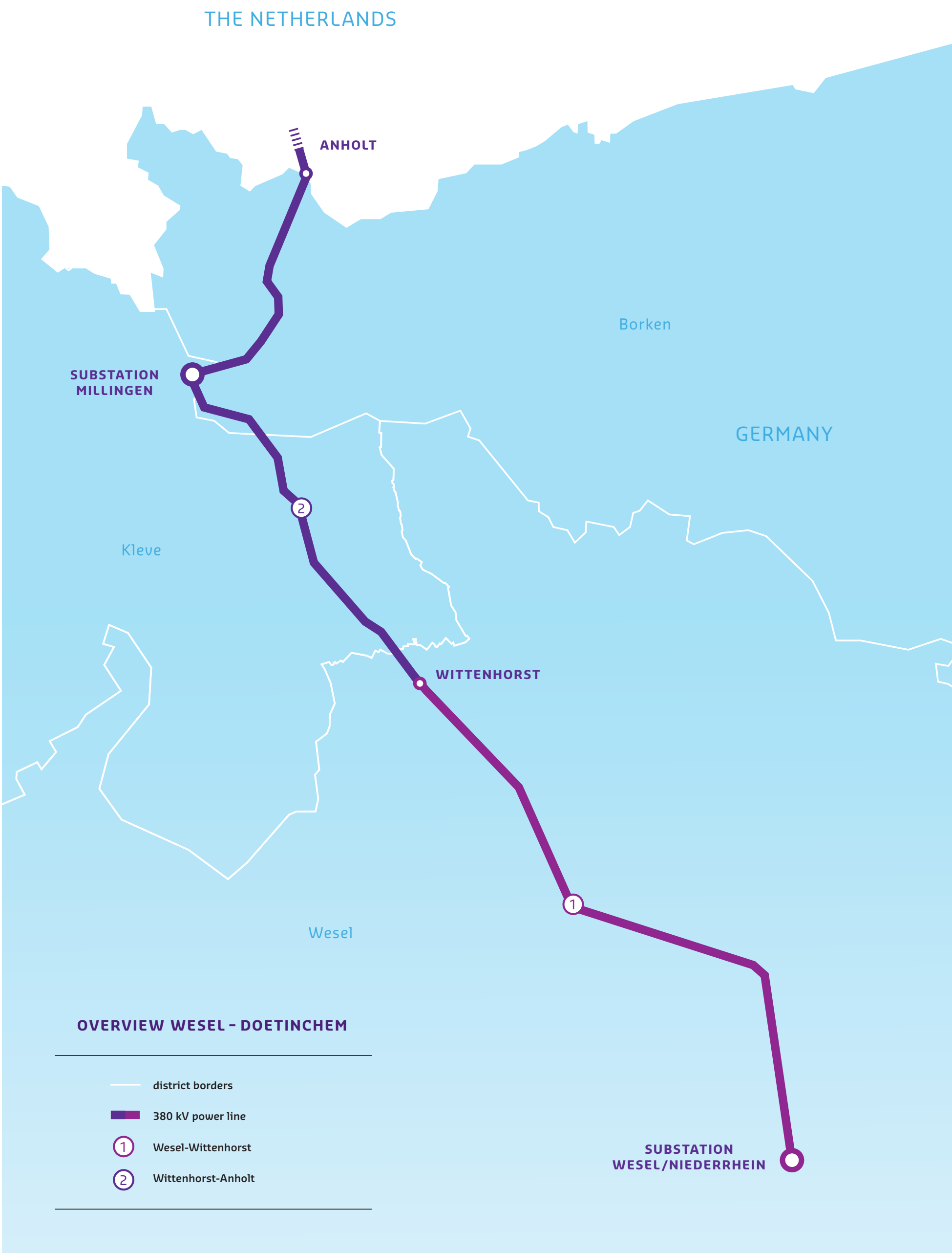


Figure 19: Overview of new interconnector between Germany and the Netherlands (Wesel/Doetinchem)

8. Impact of Fundamental Factors on CWE Flow-Based Market Coupling

Based on historical data, a statistical analysis is performed in order to assess the interdependencies between fundamental factors (i. e. wind infeed, conventional generation and electricity demand) and outcomes of the capacity calculation and allocation process (i. e. flow-based capacity calculation parameters and commercial exchanges). The analysis of the fundamental drivers will become increasingly important with the tense security of supply situation that is expected in future.

As market integration progresses, market results become increasingly dependent on particular generation and load situations in the countries concerned. So far, wind power generation has been identified as one main driver of commercial exchange capabilities and cross-border power flows (cf. e. g. Bucksteeg et al. (2015)[21] and Zugno et al. (2013)[22]). The increasing level of wind infeed with very low marginal costs in Germany has led to considerable price differences between bidding zones and corresponding export flows in recent years. In line with this development and due to physically limited cross-zonal exchange capabilities, there is an increasing frequency of low or negative market prices in Germany.

However, there is also an increasing frequency of (extremely) high market prices in the CWE region that cannot solely be attributed to excess supply due to wind infeed in Germany. There is reason to believe that decreasing levels of conventional generation as observed in France and Belgium in recent years could provide an explanation for these high prices and corresponding cross-border exchanges. The analysis of the impact of such drivers will become increasingly important with the expected coal and nuclear phase-outs in CWE countries.

Against this background, a statistical model framework is applied in order to study the relationships between generation and load patterns and commercial exchange capacities and market outcomes in CWE.

The data used for the statistical analysis is taken from publicly available data sources[23] considering May 2015 to May 2018.

The procedure implemented can be divided into three major steps: (I.) Definition of dependent and explanatory variables, (II.) Principal Component Analysis and (III.) Local polynomial regression. The mathematical analysis and all relevant formulae can be found in the appendix. A more detailed and comprehensive description of the analysis is available in Bucksteeg (2019)[24].

[21] M. Bucksteeg, K. Trepper and C. Weber (2015): Impacts of renewables generation and demand patterns on net transfer capacity: implications for effectiveness of market splitting in Germany, in IET Generation, Transmission & Distribution, 9 (12), pp. 1510-1518

[22] M. Zugno, P. Pinson and H. Madsen (2013): Impact of Wind Power Generation on European Cross-Border Power Flows, in IEEE Transactions on Power Systems, 28 (4), pp. 3566-357

[23] Sources: ENTSO-E Transparency platform, CWE utility tool, https://open-power-system-data.org/

[24] M. Bucksteeg (2019): Impact of Generation and Load Patterns on the Central Western European Flow Based Market Coupling, 42nd IAEE International Conference, 29.05.2019, Montreal

Analysis Focusing on Drivers of the German Export Capability

The regression analysis performed confirms that the export capability of Germany depends on the wind penetration in Germany **(see Figure 20). Accordingly, German export capabilities decrease with an increasing wind penetration.**

However, **the supply situation in France appears to also impact the export capability of Germany, as lower export capabilities are obtained with a decreasing share of nuclear generation in France.** Consequently, it is not only excess wind generation in Germany, but also supply scarcity in France that negatively influences German export capabilities.

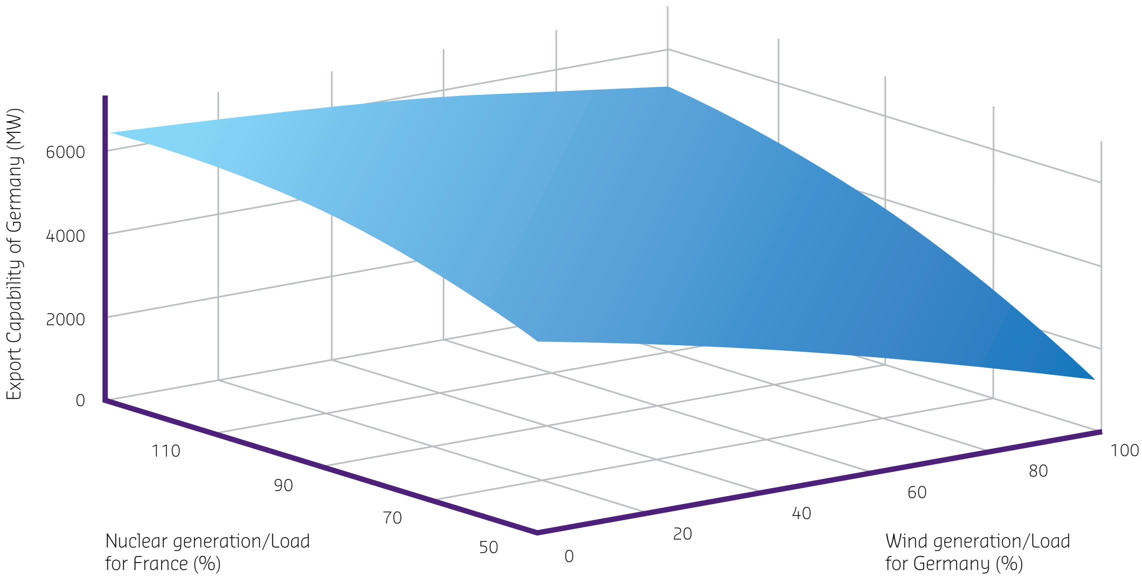


Figure 20: Regression on the export capability of Germany in CWE (Maximum Net Position) relative to wind penetration in Germany and nuclear generation in France

The results of the regression for commercial cross-border flows mirror this effect. As Figure 21 shows, high export flows from Germany to France are obtained for situations with high wind penetration in Germany and a high share of nuclear generation in France, reducing north-south congestion in the CWE region (see blue circle).

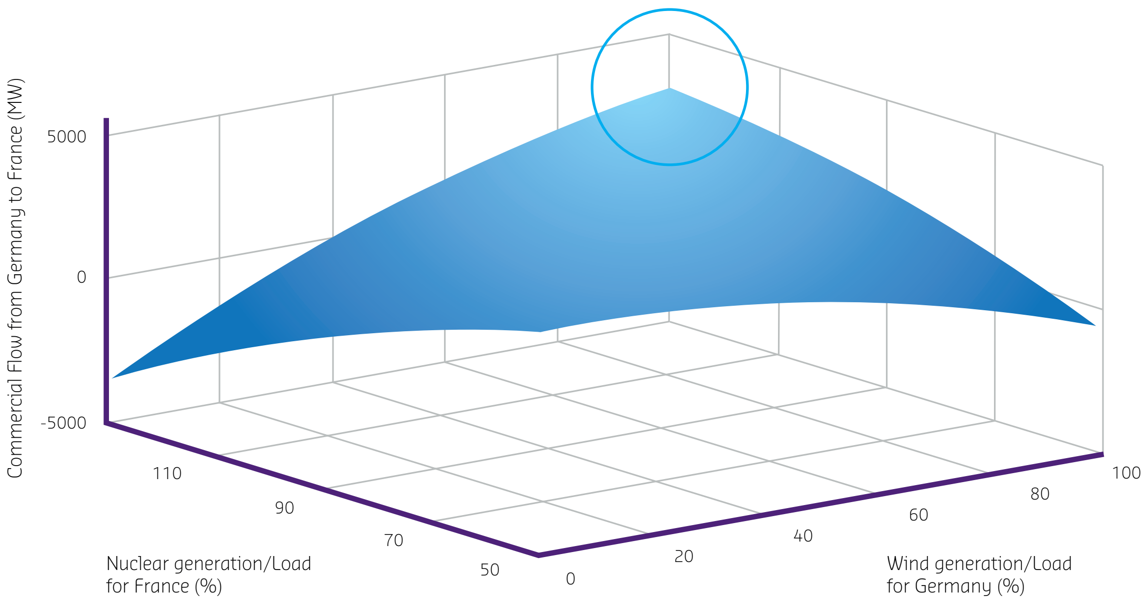


Figure 21: Regression on the commercial flow from Germany to France (day-ahead bilateral exchange) relative to wind penetration in Germany and share of nuclear generation in France

Analysis Focusing on Drivers of Belgian Import Capability

Regarding the import capability of Belgium, the regression analysis performed shows that the impact of the German wind penetration is of a comparably high level to the impact of the share of nuclear generation in Belgium (see blue circles in Figure 22).

Accordingly, the import capabilities of Belgium decrease with an increasing German wind penetration but are also negatively impacted by an increasing share of Belgian nuclear generation.

The strong impact of the local nuclear generation on Belgium's import capability might be explained by the distribution of nuclear power plants, which are located mostly at the borders of Belgium. Consequently, high shares of nuclear generation in Northern and Southern Belgium coincide with lower import capabilities from neighbouring countries since Belgian generators are using the Belgian grid to supply demand. In contrast, a high wind penetration in Germany in combination with a high nuclear generation share in Belgium leads to a lower regional imbalance and hence results in higher import capabilities of Belgium (see decreasing centre in Figure 22).

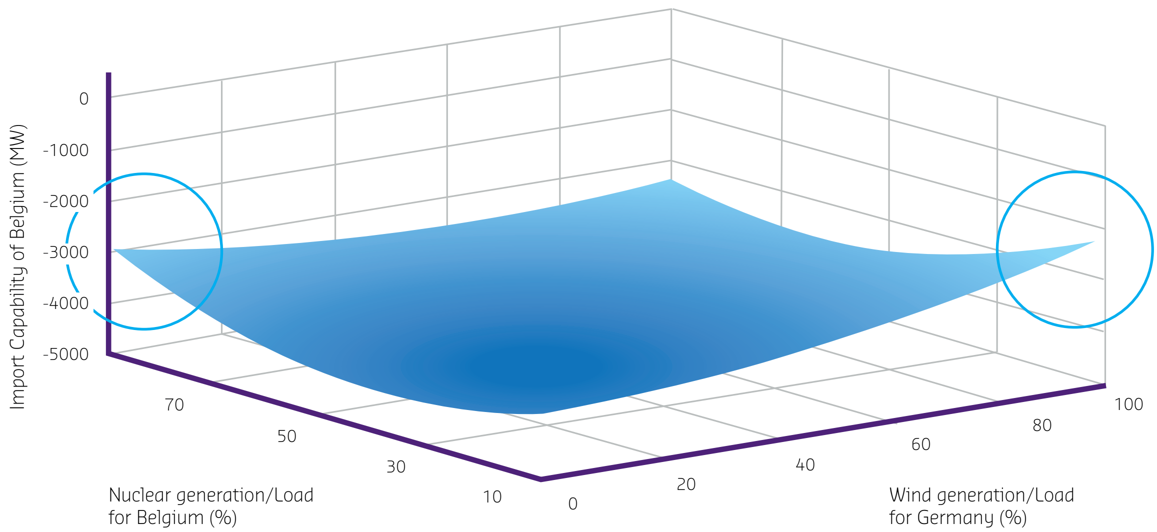


Figure 22: Regression on the import capability of Belgium in CWE (maximum net position) relative to wind penetration in Germany and nuclear generation in Belgium

To summarise, the statistical analysis confirms the intuitive reasoning by which an increasing regional imbalance of supply and demand leads to grid congestion and lower commercial exchange capabilities in the CWE region.

9. Conclusion and Outlook

The report emphasises:

- TSOs are drivers of the integration of the entire European energy market.
- TSOs are enablers of the European energy transition.
- Amprion is highly committed to supporting cross-border trades.
- Amprion cooperates strongly and steadily with TSOs of the CWE region and beyond.
- Due to its central location in Europe, Amprion serves as an important electricity transit zone.

The high level of commitment shown by Amprion in the past years is set to continue:

While the new interconnector between Germany and the Netherlands went live in 2018, Amprion is largely committed to continuing the grid development. To facilitate the integration of wind energy into the system and to ensure the transportation of an increasing amount of transfer flows from northern CWE borders to the south, Amprion is continuously enhancing its internal grid and building new interconnectors. The interconnector ALEGro that is currently being built will be the first interconnection between Germany and Belgium and is also part of the EU list of Projects of Common Interest, showing its high importance for the European integrated market. This 90-kilometre-long connection will be able to transmit about 1,000 MW. The project applies innovative technology: direct current transmission at a voltage level of 320 kV. ALEGro is scheduled to become operational in Q2/2020 and will make the European electricity network even more secure and powerful. Through two new offshore windfarm grid connection points in 2028 and 2029, Amprion will further facilitate the integration of offshore wind energy and facilitate its transmission to the load centres located in the west and south of Europe.

Amprion is highly committed to the ongoing activities in the capacity calculation region Core. One of the main current deliverables of the Core project (consisting of the previously separated regions CWE and CEE) is the implementation of a flow-based capacity calculation and allocation at all Core borders for the day-ahead and intraday timeframes.

In regard of the substantial increase in renewable energy in the future, Amprion is working on intelligent concepts to ensure grid security. Amprion recently started (together with Open Grid Europe) to investigate intelligent sector coupling concepts considering power to gas units.

Amprion continuously supports the integration of renewable energy and the ongoing development towards a European integrated market while ensuring grid security.

Appendix

In the following, the underlying impact analysis of fundamental factors on the CWE Flow-based Market Coupling are described, while the main findings are shown in section 8.

The procedure implemented can be divided into three major steps: (I.) Definition of dependent and explanatory variables, (II.) Principal Component Analysis and (III.) Local polynomial regression.

(I.) First, based on the design of the FB MC in CWE, relevant dependent and explanatory variables are identified. Different sets of dependent variables are formed by the outcomes of the subsequent stages of the capacity allocation process, i. e. commercial transaction constraints and resulting cross-border power flows. The explanatory variables comprise variables describing the generation and load situation in the CWE region. Due to the focus on spot markets in the day-ahead timeframe, forecasts of the respective variables are considered.

$$\hat{p}_t = \frac{\widehat{W}_t}{\hat{L}_t} \qquad (1)$$

where $\widehat{W}_t$ is the wind power production forecast and $\hat{L}_t$ the load forecast for Germany. While the German power system is characterised by a high share of variable wind power production, in France the conventional generation (mainly nuclear) and load situation is considered to also impact the market coupling.

$$\hat{c}_t = \frac{N_t}{\hat{L}_t} \qquad (2)$$

where N_t is the generation from nuclear plants and $\hat{L}_t$ the load forecast for France. Further variables like the generation and load situation in Belgium and the Netherlands can be included accordingly. All these variables are available in hourly resolution in the dataset under consideration for the period from May 2015 to May 2018.

(II.) Second and where necessary, the complexity of the multivariate data is reduced using principal component analysis (PCA). In particular when analysing a large number of flows, the dimensionality of the problem increases, which is why the subsequent statistical regression is employed on a reduced basis of the original dataset. In order to identify the principal components Y_i (PCs) accounting for most of the variance in the flow dataset, the covariance matrix of the centred flows is computed and eigenvectors according to the corresponding eigenvalues are selected. The original flows $\tilde{X}_t$ can then be written as a linear combination of the PCs Y_i plus an error term ε_t. In order to account for the effect of the explanatory variables (see first step) the coefficients α_i of the PCs are allowed to vary as functions of the explanatory variables u_t with $u_t = [\hat{p}_t, \hat{c}_t]$:

$$\tilde{X}_t = \sum_{i=1}^{n} \alpha_i (u_t) Y_i + \varepsilon_t \qquad \forall t \qquad (3)$$

(III.) Third, local polynomial regression is applied to study the dependence structure between generation and load patterns and respective sets of dependent variables, i. e. export capabilities and commercial cross-border flows (cf. Zugno et al. (2013)[25]).

[25] M. Zugno, P. Pinson and H. Madsen (2013): Impact of Wind Power Generation on European Cross-Border Power Flows, in IEEE Transactions on Power Systems, 28 (4)

The results of the PCA (step II.) applied to the commercial cross-border flows reveal that most of the original variance can be explained by a limited number of PCs (see Table 2). Consequently, selecting the first i PCs allows a similar statistical representation of the original flow dataset to be achieved and the size of the problem to be reduced.

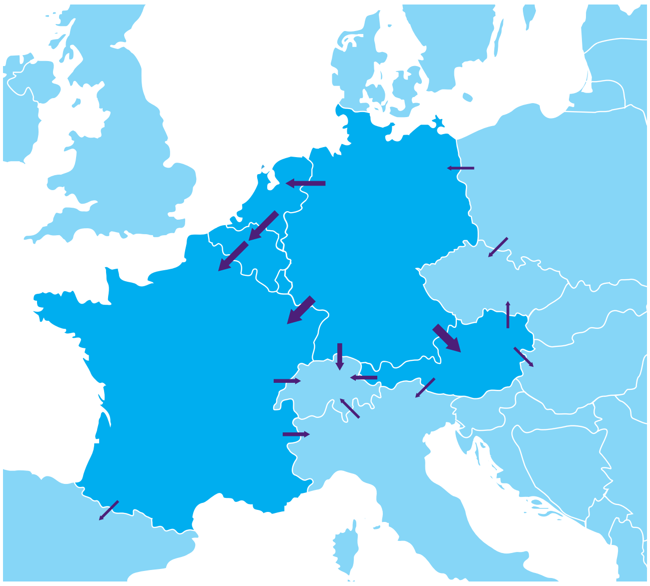
Table 2: Fraction of variance explained by the principal components for commercial cross-border flows

PRINCIPAL COMPONENT (PC)	INDIVIDUAL FRACTION OF VARIANCE [%]	CUMULATIVE FRACTION OF VARIANCE [%]
1	29.2	29.2
2	17.1	46.3
3	13.7	60.0
4	10.7	70.7
5	8.0	78.8
6	6.1	84.9
7	3.6	88.4
8	3.5	91.9

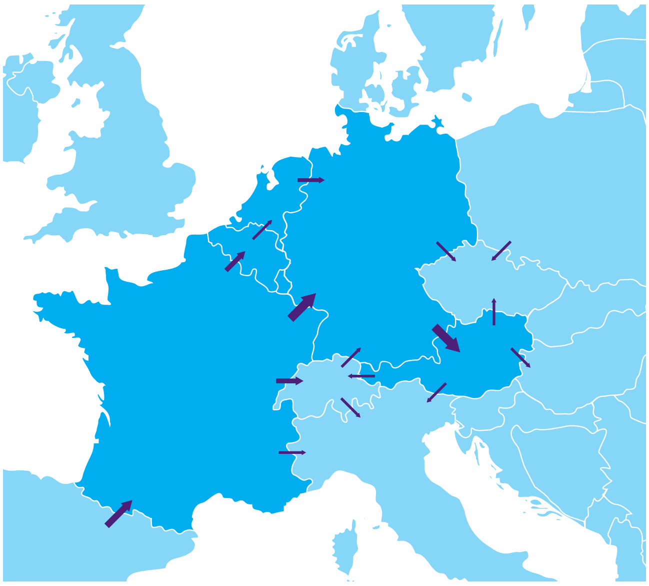
Figure 23 provides further insight into the characteristics of the first four PC, which in total explain more than 70% of the variance. PC 1 is mainly described by commercial flows directed from Germany to France and Austria. Moreover, flows from Germany to France via the Netherlands and Belgium can be observed. While the commercial flows of the first PC are mainly driven by the German infeed, PC 2 and 3 show different characteristics and seem to be mainly impacted by the generation in France. PC 4 seems to be determined by the generation situation on the hydro-dominated countries in the Alps. Furthermore, PC 2, 3 and 4 indicate transit flows from France.

The analysis shows that the exchanges in CWE can be explained to a large extent (PC1 with a variance of 30%) by the German RES infeed. However, further exchange characteristics (PC2 – 4 with a cumulative variance of 40%) cannot be explained by the RES infeed in Germany but seem to be determined by the generation situation in France and the dispatch of hydro plants in the Alpine countries.

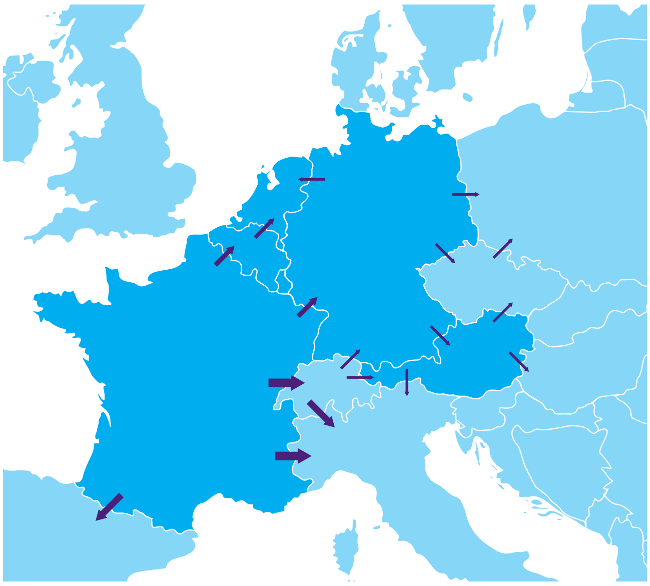
PC1: **29.2 %**



PC2: **17.1 %**



PC3: **13.7 %**



PC4: **10.7 %**

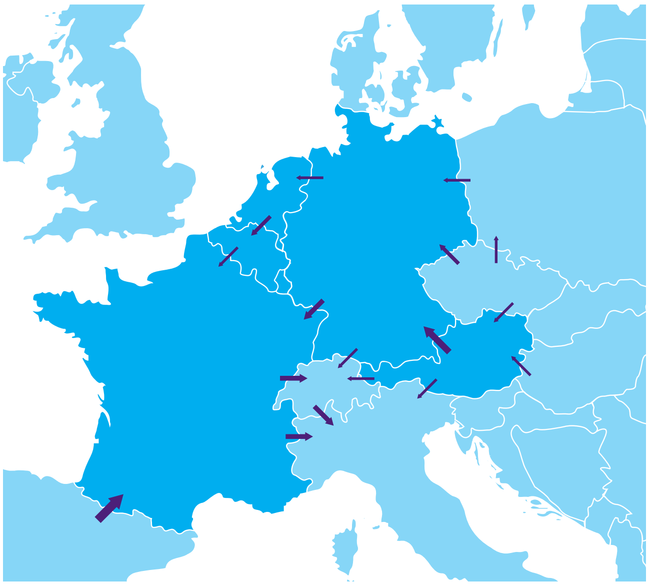


Figure 23: Map of CWE showing the weights of the commercial cross-border flows in the Principal Component 1, 2, 3 and 4

PC coefficient = 0.1

PC coefficient = 0.2

PC coefficient = 0.3

PC coefficient = 0.4

PC coefficient = 0.5

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List of Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
CACM	Capacity Allocation and Congestion Management
CB	Critical Branch
CBCO	Critical Branch Critical Outage
CCR	Capacity Calculation Region
CEE	Central Eastern Europe
CWE	Central Western Europe
D2CF	Two-Days-Ahead Congestion Forecast
DACF	Day-Ahead Congestion Forecast
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FAV	Final Adjustment Values
FB MC	Flow-Based Market Coupling
FCA	Forward Capacity Allocation
Fmax	Maximum Allowable Power Flow
FRM	Flow Reliability Margins
FTR	Financial Transmission Right
GSK	Generation Shift Key
Imax	Maximum Current on a Critical Network Element
JAO	Joint Allocation Platform
NRAs	National Regulatory Authorities
NTC	Net Transfer Capacity
PC	Principal Component
PCA	Principal Component Analysis
PTDFs	Power Transfer Distribution Factors
RAM	Remaining Available Margin
RES	Renewable Energy Sources
SPAIC	Standard Procedure for Assessing the Impact of Changes
TSO	Transmission System Operator

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