Eneday 2019 Dresden

Modelling of imports and exports for the German electricity system

Timona Ghosh, Johannes Kochems, Benjamin Grosse und Joachim Müller-Kirchenbauer
Department of Energy and Resource Management, Technical University of Berlin

Key-Words:

- Power exchange
- Export, import
- Modellierung
- Interconnectors
- Capacity
- Fundamental model
- Energy system analysis

Abstract: There is an increasing need for flexibility due to the growing share of fluctuating renewable energies and the progressing integration of the European power market. Thus, an adequate depiction of imports and exports within models of electricity systems is essential. So far, however, a systematization of existing modeling approaches is missing as well as a modelling approach that addresses the discrepancy between very detailed flow-based models and simplified approaches based on fixed net transfer capacities. Therefore, this paper develops such a systematization and an approach that addresses the gap between model complexity and model accuracy by introducing a new control parameter for the variations of the "level of detail". In addition, a detailed analysis of the available transfer capacities for each border between Germany and its electrical neighbours is carried out.

Table of Content

1 Introduction

Due to the progressing integration of the European internal electricity market since the liberalization, the representation of imports and exports in models for the electricity system and for submarkets of the electricity sector continues to gain importance. Power market models, which approximate market results of the spot market by mapping fundamental influencing factors, are widespread in the research landscape. Many of these fundamental models use the rationality of the merit order to determine a cost-minimal dispatch of power plant capacities to cover the demand for electricity. Here the electricity exchange with foreign countries can be modelled in different ways. So far, there is no systematization of existing modelling approaches in the research landscape, although many different approaches are applied for modelling imports and exports. In addition, there are few publications that present the approaches used in a transparent manner. From the few publications and the experience of the authors, however, it can be concluded that there is a gap between a very detailed and complex modelling of load flow-based capacity allocation and a simple mapping using rigid NTC approaches.

Therefore, this paper presents a systematization of existing and possible approaches for modelling imports and exports. In addition, a model approach with variable complexity is proposed in order to adequately address the conflict between model complexity and computing time. The focus is on a methodical outline of the approach. First results using an incomplete test data set are also presented.

2 State of Research and Systematization of Existing Modelling Approaches

In the following, the fundamentals of allocating and calculating capacity are briefly presented. Furthermore, an overview of modelling approaches for imports and exports in existing German power market models is given.

2.1 Capacity allocation and calculation

The combination of physical transfer capacities and commercial trade across national borders can be carried out through **explicit or implicit capacity auctions**. Implicit auctions combine trading of capacities and energy in a joint auction. The resulting electricity price, therefore, consists of the price for the capacity usage right and the price for electricity [1, p. 239]. In an explicit capacity auction, in addition to the Energy Only Market auction, a separate auction for the transmission capacity is held in which electricity volumes are contracted. [2, p. 11f]

Both explicit and implicit capacity auctions are currently being held at most electrical interconnection points in Europe. There are two types of implicit auctions, both of which are used in Europe. In **market splitting** (also known as **zonal pricing**), an area is initially regarded as a single coherent market. However, the market areas can be temporarily divided into already predefined zones. In **market coupling**, certain administratively defined markets or market areas are handled separately. An implicit auction is conducted between the market areas. If enough transmission capacity is available, the prices align completely, resulting in an identical price P_{MC}. If this is not the case, prices only converge to the extent that available commercial capacity is exhausted, as illustrated in Figure 2.1 for two market areas A and B. This results in prices P'_A and P'_B. Without an exchange prices P_A und P_B would establish [2, p. 12]

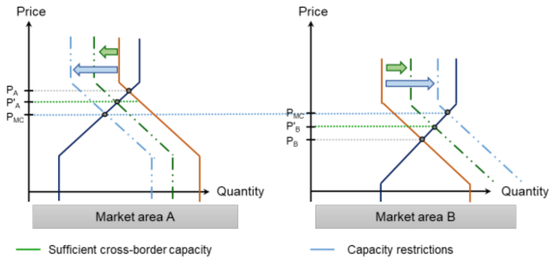

Figure 2.1: The principle of market coupling (Own illustration based on [3, p. 23] und [4, p. 2])

Depending on the border and the type of market coupling, there are currently two main methods for calculating the available transfer capacity: the model based on Net Transfer Capacities – **NTC model** (also known as Available Transfer Capacities or ATC model) and the flow-based capacity allocation within the flow-based market coupling – **FBMC**. The calculations are based on static and dynamic elements (see [5]–[9]).

TTC *(Total Transfer Capacity)* describes the maximum capacity available for the electricity exchange between two network operators without endangering the "(n-1)-security" of the network.

NTC *(Net Transfer Capacity)* describes the available capacity for commercial transactions and is calculated as the difference between TTC and **TRM** *(Transmission Reliability Margin).* TRM is the safety margin that network operators always must have available to directly or indirectly support other countries. Two neighbouring network operators calculate their NTC values based on this principle. The minimum of the two values is set as theoretical maximum capacity for the border between the two network operators.

ATC *(Available Transfer Capacity)* describes the available capacity for commercial transactions after deduction of energy transactions that have already taken place.

The maximum available capacity is determined before the closure of the market. Since the entire available transmission capacity between two market areas is used in the price formation, the NTC values contribute to the trading price of the respective electricity exchanges [10, p. 28ff].

Key problems of the NTC approach are the inflexible definition of transmission capacity and the lacking consideration of existing bottlenecks within market areas. In order to take this into account, so-called technical profiles were introduced at many borders, which extend the existing NTC calculation methodology. Technical profiles represent the dependency of the transmission capacity on additional factors such as wind forecasts. They are designed to maximize NTC values so that the unplanned deviations are less pronounced [11, p. 5].

As of October 2018, the German market area is connected to most of its neighbours by the European Multi-Regional Coupling based on the NTC methodology. On the day-ahead markets of the Central Western European (CWE) region, i.e. on the borders with France and the Netherlands, FBMC was introduced in 2015. While in the NTC model the relationship between physical and commercial flows is strongly simplified, the flow-based capacity allocation uses a more detailed model where load flows of the entire network are considered [12]. The allocation of the interconnector capacities takes place simultaneously with the market clearance. This means that bottleneck capacities are allocated to transmission lines with the greatest welfare gain. In addition, better forecasting qualities, reduced price differences between market areas and a decrease in the general price level are achieved. [13, p. 22], [14, p. 4ff], [15, p. 26]

Two factors are decisive for FBMC calculations: **Power Transfer Distribution Factors (PTDFs)**, i.e. the distribution of power flows and **Remaining Available Margins (RAM)**. In the CWE region they are implemented as follows (see [15] – [17]).

The flow-based capacity calculation starts with the creation of the Base Case, which is based on the **Congestion Forecasts** of the transmission system operators (TSOs) for their region **two days before delivery (D2CF)**, representing every hour of the delivery day. The D2CFs of the TSOs are combined to form a Base Case, where imports and exports add up to zero. In addition, **critical branches** are determined. These are transmission lines or transformers on which cross-border trade has an extraordinary effect. In the next step, the PTDFs related to a zone are calculated. **Generation Shift Keys** are relevant here. They show how a change within a zone is distributed to the nodes within the zone. Then the PTDFs for the critical branches are calculated, which describe the influence of a changed trade balance on the critical section. For that purpose, it is calculated how the current flow between two nodes would change if the generation in one zone increases either in the normal operating mode or the (n-1) case. This is then analyzed for all other zones and combinations of outages. This way a PTDF matrix is created.

Finally, for each critical branch the RAM under critical outages is determined. This sets the maximum commercial flow through a critical transmission line and is calculated as follows:

$$\mathrm{RAM} = \mathrm{F_{max}} - \mathrm{F_{ref'}} - \mathrm{FRM} - \mathrm{FAV}$$

The maximum permitted effective power flow of a critical branch is described by $\mathrm{F_{max}}$. $\mathrm{F_{ref'}}$ represents all commercial transactions that are traded outside the day-ahead market. The *Flow Reliability Margin* (FRM) is a safety margin. Several simplifications and assumptions are also used in the FBMC for the calculation, which is why it is necessary to be able to take unplanned deviations into account. The *Final Adjustment Value* (FAV) represents such a further adjustment value. It allows network operators to include additional positive or negative transmission capacity for a critical branch that is not included in the previous FBMC calculation.

2.2 Existing modelling approaches

Most existing power market models use fundamental models to represent neighbouring countries and an NTC methodology to depict imports and exports. Thereby, power plant fleets of Germany's neighbouring countries or throughout Europe are simplified and the transmission capacity between countries is represented by fixed NTC values.

The Öko-Institut's Power-Flex-EU model uses a simplified fundamental approach in which each transmission line between Germany and its neighbouring countries is represented by a fixed NTC value. [18]

The NEMO III model of RWTH Aachen uses a detailed network flow model in which the European electricity system is simulated in several stages. In the first stage, the electricity exchange between countries is determined by a network simulation based on a simplified European power plant fleet and maximum NTC values. The maximum NTC values are real historical values, which have been adjusted by planned expansion measures. [19]

DIW Berlin's dynElmod model uses two different methods to represent imports and exports. The first approach depicts the network with fixed NTC values, neglecting loop-flows, with the advantage of lower computational time and less necessary data. In the second approach, a simplified FBMC algorithm is applied. [20]

In model EMMA (European Electricity Market Model) of the Neon Neue Energieökonomik GmbH a linear optimization model is used, which optimizes the dispatch within the calculations of the short-term equilibrium. The interconnector capacity is considered in the calculation using fixed ATC values. [21]

3 Methodology

For modelling imports and exports, a multi-level analysis approach was applied, which is based on following elements:

- a systematization of existing approaches for modelling imports and exports (Chapter 3.1),
- an analysis of cross-border capacity and capacity expansion plans (Chapter 3.3), and
- the development of a modular model for modelling imports and exports (Chapter 3.4).

The developed model consists of three sub-modules: the Transfer Capacity Calculation, the Power Price Calculation and the Cross-border Exchange Optimization. The electricity market model referred to in the following as European comprises Germany and its electrical neighbours and thus Norway, Denmark East and West, Sweden, Poland, the Czech Republic, Austria, Switzerland and the Benelux states. Different data inputs are required for each module, which are described in Chapter 3.2. Figure 3.1 gives an overview of the methodological approach and the path of the analyses.

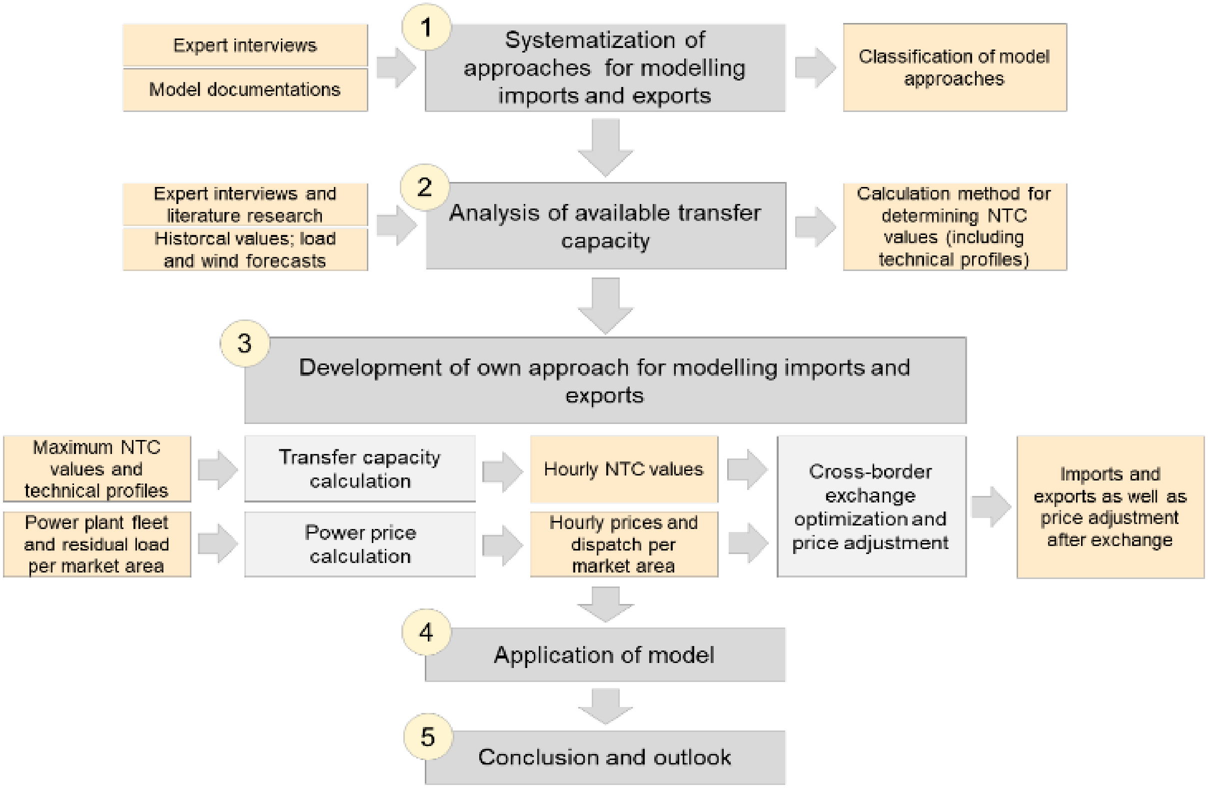

Figure 3.1: Overview of the methodology and conducted analyses (Own illustration)

3.1 Systematization of existing modelling approaches

To select a suitable approach for modelling imports and exports, a categorization of possible modelling approaches was developed. For this purpose, twelve interviews were conducted with experts from research institutions, universities and companies that have implemented their own electricity market models. In addition, the available model documentation was considered. Both served as basis for categorizing possible models.

3.2 Input data

The calculation of the interconnector's transmission capacity is based on the maximum capacity of a transmission line and (time-variable) NTC values. For this purpose, expert interviews, research on websites of the TSOs and historical NTC values were conducted. The NTC values for the interconnector to Sweden are published as Market Coupling Capacities by Nord Pool. “Forecasted Transfer Capacities - Day Ahead” from the ENTSO-E Transparency Platform were used for borders to Denmark East and West, the Czech Republic and Switzerland. The ENTSO-E Transparency Platform also publishes wind forecasts for Germany and wind and load forecasts for TenneT's control area.

The calculation of electricity prices for 2016 requires publicly available historical data from Germany and its neighbouring countries. Day-ahead load and renewable electricity forecasts are also available on the ENTSO-E Transparency Platform. Information about the German power plant fleet by plant unit are based on data from the Power Plant List and the

Power Plant Closure Notifications from the German Federal Network Agency (BNetzA), the Open Power System Data Platform, the Power Plant List of the World Resources Institute, the Electricity Network Development Plan 2030 as well as studies conducted at the Department of Energy and Resource Management, the Technical University of Berlin and the Department of Petroleum and Natural Gas Engineering at the Technical University of Clausthal. The data for the foreign power plant fleet originate from a set compiled by Hofmann et al. [22]. The available data were extended by the efficiencies using a methodology developed at our Department that is based on [23] and [24]. The marginal costs per fuel were calculated using variable costs and fuel prices presented in Table 7.1 in the appendix. They represent our own compilation of publicly available data and the average CO_2 certificate price for 2016.

Data quality and availability is essential for determining the transmission capacity and validating the model with the help of a test data set. It has a strong impact on the quality of the results. Information to determine hourly NTC values and reasons for their reduction are only available to a limited extent.

3.3 Analysis of available transfer capacity

The aim of the conducted analysis is to find a suitable way to calculate the NTC values in the model for each individual border to an electrical neighbour (see Figure 3.2). Thereby, the maximum annual capacity between 2015 and 2030 for Germany's neighbouring countries is determined and a methodology for calculating time-variable NTC values is developed.

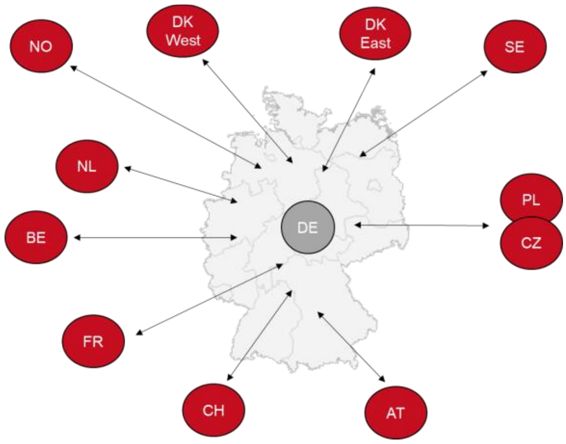

Figure 3.2: Germany and its electrical neighbours (Own illustration)

To describe the maximum transfer volume that can be made available to the market, the maximum annual NTC value of a border is chosen as starting point. In the next step, reasons for a reduction of NTC values by the TSOs are examined. For some borders, TSOs publish information so that either through a general description or a published technical profile a traceability of the calculations is ensured. Usually, however, the TSOs' publications are not extensive enough to determine one's own calculation method. In this case, publicly available approximations are used, in particular the System Analyses of the TSOs for 2017 and 2018 published by the BnetzA [25, 26]. In addition, further information on adjustments of the NTCs were collected through interviews with experts at the TSOs.

To forecast the development of NTC values until 2030, grid expansions and additions must be considered. This is done in the next step based on the ENTSO-E's 10-Year Network Development Plan 2014 [27], BNetzA's Establishing Requirements 2017-2030 [28] and information published by the TSOs. Usually, the increase in transmission capacity is indicated as *Grid Transfer Capability* (GTC) in MW and increments take place at the same time for import and export. The GTC value describes the expected performance of a power line for cross-border electricity transmission [27, p. 438]. Regardless of the type of transmission, it can be assumed that the maximum NTC value increases by the GTC value through the extension of transmission capacity. In addition to the grid extension, further agreements between German and foreign TSOs or governments with an influence on future commercial transmission capacities are considered. Finally, the annual maximum NTCs for each electrical neighbour are presented. Increases become effective in the year in which the transmission line becomes available for the first time for the entire year.

The results of the previous steps are crucial for the last part of the analyses. At this point, the maximum NTCs for import and export between 2015 and 2030 are summarized for each neighbouring country and a calculation method for the time-variable NTC values is determined.

3.4 Model description

The model consists of three separate modules. The first module (Transfer Capacity Calculation) determines the capacity of the interconnectors for a given year. The next module (Power Price Calculation) calculates isolated power prices of a country. The last module (Cross-border Exchange Optimization) optimizes the exchange between national electricity systems based on the results of the first and second module. It returns the German power price, considering the calculated import and export flows. For this purpose, the control parameter d (“level of detail") is introduced, which considerably reduces the computing time and allows to run the model with variable precision regarding the resolution of the merit order in the neighbouring country. Figure 3.3 summarizes the modules and their relationship to each other.

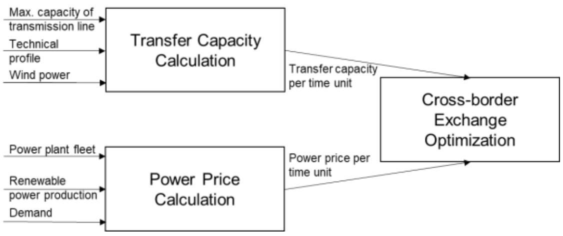

Figure 3.3: Structure of implemented model (Own illustration)

The model itself is implemented in Python. For the Cross-border Exchange Optimization module the framework oemof (open energy modelling framework) was used, which allows a representation of a complex energy system as a directed (bipartite) graph with nodes (vertices) and weighted edges, for which a system cost minimization is carried out. For the analytical solution, this framework relies on the Python package Pyomo. [29, p. 18–22].

The principle of determining the time-variable NTC values within the Transmission Capacity Calculation module was described in Chapter 3.3. Country-specific power prices are calculated using a fundamental model for the electricity market, which optimizes the use of power plants according to the merit order principle. A simplified linear approach was used for testing purposes.

The Cross-border Exchange Optimization module is the central part of the model. It combines the functions of the other two modules and in doing so calculates German import and export flows. First of all, the year to be considered is defined as well as the desired level of the control parameter d, which determines the number of desired supply nodes. This is explained in detail hereafter. The next step is the optimization of the power system, whereby hourly electricity prices are calculated after cross-border exchanges.

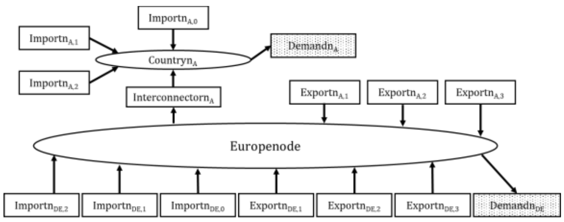

Figure 3.4: Exemplary structure of the Cross-border Exchange Optimization module for Germany and a country A with a “level of detail” of three (Own illustration)

In the Cross-border Exchange Optimization module (see Figure 3.4), the demand of each neighbouring country A is represented by a demand node. A time series of the forecasted total demand of the corresponding year is passed to the node. It is defined that the demand always must be completely supplied. Each neighbouring country has its own country node to which the demand node and part of the supply nodes – the import nodes – of that country are connected. A country node is basically a busbar collecting inputs and outputs for a country A. $\mathrm{Importn}_{A,0}$ generates electricity at the equilibrium price prior to exchange p_{GG} and thus represents the price in country A without considering imports or exports. In addition, on the supply side, a lower or increased demand in country A due to imports or exports from a neighbouring country must be taken into account. If the electricity price in another European country is currently lower than in country A, country A will import electricity, which will reduce the electricity price in A. This case is approximated in the model by (d-1) additional supply nodes, of which each offers a certain amount of electricity at a lower price than p_{GG}. They are referred to in the following as $\mathrm{Importn}_{A,i}$. The maximum supply of the import node with the lowest price is:

$$Supply(Importn_{A,(d-1)}) = Demand_A - (d-1) * Capacity_{A,Import}/d$$

An even lower supply must not be considered, since the maximum export capacity determines the maximum share of power generation that can be covered by foreign countries. Thus, the demand of country A exceeding the capacity of the interconnector always has to be met by a production in country A and hence by the import node with the lowest price. Additional $\mathrm{Importn}_{A,i}$ equally to $\mathrm{Importn}_{A,0}$ have a maximum supply of $\mathrm{Capacity}_{A,Export}$ / d. As a result, all import nodes of a country add up to the demand of country A. This makes sure that within A congestions are not possible at any time.

If the power price in a European country is higher in the considered time step compared to country A, country A will export electricity to that country. It is accompanied by an increased demand and a higher electricity price in A. This is considered by d further supply nodes, which are referred to as $\mathrm{Exportn}_{A,i}$. Their overall sum corresponds to the total transfer capacity for imports from a German point of view. The maximum supply offered by a node determines its price and does not necessarily have to be retrieved in the model. This means that a supply node can supply at its maximal capacity or less. Its price, however, remains unchanged.

The maximum export from the European countries to country A results from the restriction of the interconnectors and is described by the node $\mathrm{Interconnectorn}_{A}$. It is linked to the $\mathrm{Countryn}_{A}$ on one side. On the other side, there is a connection to the so called Europenode which equals the German country node. The maximum flow via $\mathrm{Interconnectorn}_{A}$ is defined as the maximum NTC value of the respective time period and does not have to be retrieved completely. The export nodes of country A are directly connected to the Europenode, as they cover an additional demand from abroad.

Germany's import and export nodes are generated analogously to the methodology described for country A. However, as there are no restrictions to transmit electricity within Germany and the capacity restrictions to foreign countries are already represented by the nodes of the neighbouring countries, the German supply nodes are directly connected to the Europenode. In addition, a supply by Germany exceeding the total capacity of all supply nodes must be considered. Therefore, Germany's export node with the maximum price has an unlimited capacity.

$\mathrm{Capacity}_{A,Import}$ and $\mathrm{Capacity}_{A,Export}$ are determined for each time step by the Transfer Capacity Calculation module. The price of the supply nodes is determined by the Power Price Calculation module. $\mathrm{Importn}_{A,0}$ has the equilibrium price p_{GG} and is determined by the residual load of a period and the merit order. For the power prices of the other supply nodes, the residual load is shifted by the cumulative supply of the respective supply nodes.

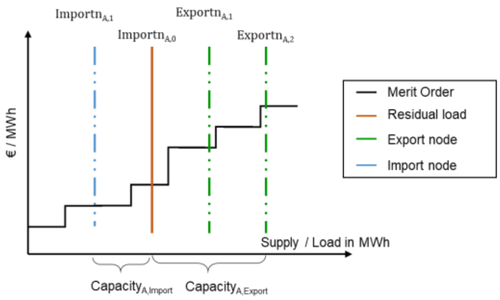

Figure 3.5: Exemplary illustration of the Power Price Calculation module for a time period t with a "level of detail" of two (Own illustration)

Figure 3.5 illustrates the power price calculations for country A with a "level of detail" d=2. It demonstrates how the use of import and export nodes takes into account a lower demand with a lower price or an increased demand with a higher price. The graph also shows that between $\mathrm{Exportn}_{A,1}$ and $\mathrm{Exportn}_{A,2}$ a part of the merit order or one or more power plants with the same marginal costs are skipped and thus their price is not considered in the overall model. This makes clear that at a higher "level of detail" d, more stages of the power prices are considered, which increases the accuracy of the overall calculations of the Cross-border Exchange Optimization module. Thus, the control parameter d controls the accuracy of the considered merit order around the country-specific equilibrium price (before imports and exports).

Once the calculations have been completed and the components of the power market model have been generated, the solution to the optimization model is determined with the aim of minimizing overall costs. All demands are covered by the cheapest supply nodes that are restricted by their maximum supply. As a result, cost-optimal flows are calculated for all time steps of the corresponding year.

In the final step, the German power prices are recalculated, adjusted by import and export flows. The decisive factor for the price calculation is the modified demand in Germany. For each time unit, the following total is calculated: $\sum_{i=(d-1)}^{i=d} Supplyn_{\mathrm{DE,i}}$. With this new demand time series the Power Price Calculation module is executed again. This finally determines the resulting German power prices.

4 Results and Discussion

In the following, the systematization of possible approaches for modelling imports and exports are presented. Subsequently, an overview of the transmission capacities is given, and first results of our own calculations are presented. Finally, a critical assessment of the model is carried out.

4.1 Systematization of existing modelling approaches

In general, price forecasting models for power markets can be divided into fundamental, statistical and hybrid approaches [30, p. 80]. An additional option is to use historical real values. Based on this, the following categorization for modelling imports and exports of an electricity system is proposed (see Figure 4.1).

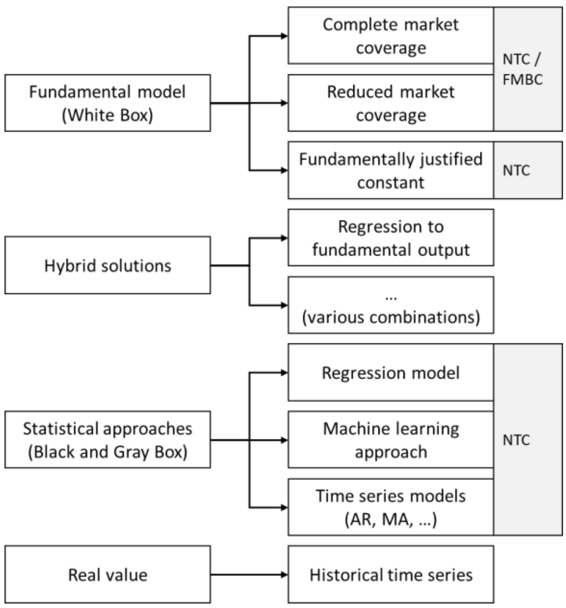

Figure 4.1: Overview of possible approaches for modelling imports and exports (Own illustration)

Fundamental models

Fundamental models (see Figure 4.1) generally provide a comprehensive picture of the market structure, while using physical-technical and economic relationships between power supply and demand within a country [31, p. 1042]. They are based on a detailed data framework of (fundamental) input data. Most of the considered research institutions and companies in Germany use this model type. The main reason is that it also describes the relationship between and the situation in the neighbouring countries. Existing models differ regarding their degree of detail in country coverage, their modelling of transfer capacities between two countries or regions and their time horizon. Neighbouring regions can either be depicted modelling every single power plant unit, every power plant or power plant fleets in technological terms, and the regions can include either only Germany's direct electrical neighbours or entire Europe. As general subcategories for modelling the exchange between two market areas with a fundamental approach **a complete market coverage**, a **reduced** or simplified (geographical) **market coverage** and a **constant justified by fundamental input factors** can be identified.

Statistical Models

Statistical models (see Figure 4.1) use historical prices or other exogenous factors to forecast future developments [31, p. 1049]. For this purpose, many different approaches can be used. Our research has shown that statistical models are rarely used in Germany. Most models try to depict Europe or an entire region. Therefore, they do not analyze historical individual cross-border electricity flows in detail. For modelling imports and exports within a statistical model, three possible implementations were identified. In a **regression model based on historical data**, correlations between past commercial import or export flows and other parameters are used to forecast future trade flows. A possible extension of this approach and improvement regarding structure preservation can be offered by **machine learning approaches**, which however require extensive data inputs. Furthermore, other methods based on **time series analyses** can be considered to represent stochastic influences. Nevertheless, such approaches were not identified in our research.

Hybrid models

Hybrid models (see Figure 4.1) combine fundamental and statistical approaches. Therefore, they can not be clearly assigned to one of the two categories. That is why, it is difficult to provide a further subdivision and a general description of the advantages and disadvantages [31, p. 1040]. One option is to combine a fundamental and a regression approach. Thereby, the regression is used to define an upper and lower limit for import and export flows and a simplified fundamental model improves the results. In addition, various other characteristics are conceivable.

Real values

It is also possible to completely outsource the exchanges between market areas and to approximate them based on historical time series. This approach shows similarities with a fundamentally justified constant.

Classification of the developed approach

The model described in this paper can be assigned to the group of fundamental models with a reduced market coverage for modelling foreign power plants.

4.2 Transfer capacity

The analyses of available transfer capacities between Germany and its electrical neighbours show that only few publications describe the hourly calculations or reductions of NTC values in detail. Nevertheless, the broad evaluated range of sources made it possible to determine an approximate solution to calculate the NTC values to all electrical neighbours.

The calculations for the countries of the CWE region - Switzerland, the Netherlands and France - are based on a (previously) used technical profile, the so-called “C-Function”. According to experts it still represents a good approximation despite the introduction of FBMC [32, p. 37]. Similarly, for Denmark West, the technical profile is approximated by using the methodology of the TSOs' System Analyses [25, p. 61], [26, p. 41]. However, estimating the hourly transmission capacity for Poland, the Czech Republic and Sweden is challenging due to the lack of available information. Therefore, fixed NTC values had to be used. Austria, Norway and Belgium are also modelled using fixed NTC values as the criteria for reducing the available transfer capacity will become clear only after the separation of the electricity price zones and the completion of the planned power lines. Denmark East, however, can be approximated with the help of fixed NTC values, as most of the time the whole capacity is offered. The following graph summarizes the NTC calculation methods.

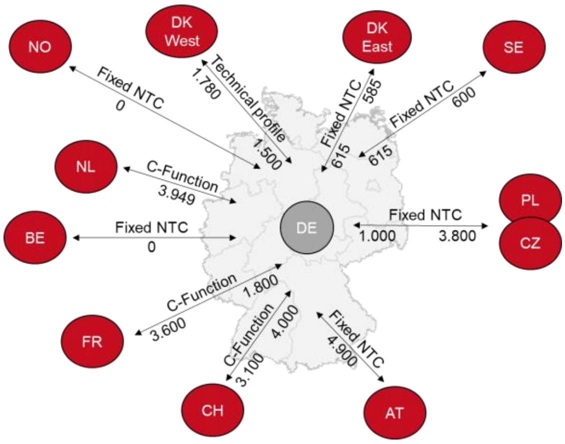

Figure 4.2: Methods for calculating cross-border transfer capacity and maximum NTC value per electrical neighbour (Own analysis)

During the analyses, several additional aspects were examined, such as planned extensions of power lines, constructions of phase-shifting transformers or the introduction of FBMC planned in some market areas. In most cases, specific information from public sources was available, which made it possible to estimate future maximum NTC values until 2030. The maximum NTC values assumed for the model that resulted from the analyses, are summarized in the appendix for all electrical neighbours (see Table 7.2).

The following table assesses the results for four neighbouring regions of Germany for 2016 based on the Mean Absolute Error (MAE) and the percentage of calculated NTCs with a certain maximum deviation. The number of hours in 2016 in which the calculated value matches the actual NTC value is determined, considering a possible deviation of ±5 % or ±10 %. Results show major differences in quality with MAEs between 0 and 383 MW depending on the market area. Reasons for this can be found in a detailed analysis of the respective market areas. HVDC lines, for instance, are generally easy to control and usually the entire transfer capacity can be offered. Nevertheless, due to frequent grid congestion at Sweden's west coast, the offered capacity of the HVDC line at this border has to be reduced frequently [33, p. 5f]. Physical flows in HVAC lines are generally less controllable, which is why not all thermal capacity is available on the market [33, p. 933ff]. However, large differences can be identified in this regard, in particular due to grid congestion between northern and southern Germany.

Due to the particularly good availability of data, NTC values for the market areas DK East, DK West, Sweden and Switzerland are shown below as examples. Where data availability allowed, a comparison was carried out in a similar way for the other market areas.

Table 4.1: Assessment of determined NTC values

	Market Area	Mean Absolute Error [MW]	Percentage of calculated values with maximum deviation of ±10 % from actual value	Percentage of calculated values with maximum deviation of ±5 % from actual value
Import from	DK East	63	88,8 %	88,8 %
	DK West	383	6,3 %	2,9 %
	SE	202	50,5 %	47,4 %
	CH	0	100 %	100 %
Export to	DK East	63	89,3 %	89,3 %
	DK West	208	52,1 %	41,4 %
	SE	264	25,8 %	22,4 %
	CH	300	35,7 %	29,0 %

Source: Own calculations based on [35]

4.3 Power prices with / without import and export

The Cross-border Exchange Optimization module is the core of the implemented model. Its results are presented in the following based on a preliminary test data set. A comparison of historical prices of the German-Austrian market area with the calculated power prices shows for 2016 with the control parameter set at a "level of detail" of two a MAE of 6.93 €/MWh. In addition, Figure 4.3 illustrates that the model frequently tends to underestimate electricity prices, as calculated results are below actual prices in almost 64% of the time periods. The average forecasted electricity price for the entire year is with 25.97 €/MWh as well below the average actual day-ahead prices of

28.98 €/MWh. The model also appears to underestimate overall price spreads. Reasons for that could be that non-availability of capacities and production below the determined variable costs are not considered. The use of different "levels of detail" shows no significant changes in the results of the test data sets.

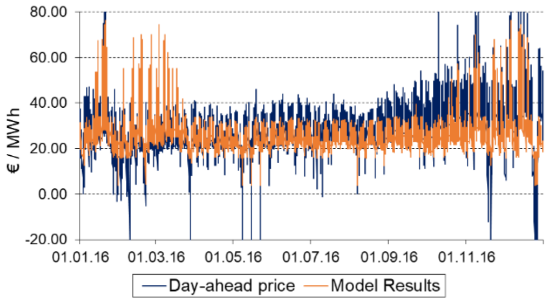

Figure 4.3: Results of the Cross-border Exchange Optimization module compared to the German-Austrian day-ahead prices for 2016 in the range -20 €/MWh to 80 €/MWh (Own illustration based on [35])

It should be noted, that the comparison was carried out with preliminary test data sets. These indicate a considerable need for enhancement, which will be presented based on their three main limitations. First, considerable gaps, particularly in the publicly available data on foreign power plant fleets, have become apparent. In addition, in particular in countries with a high proportion of hydroelectric power plants, other fossil-fuel power plants were only considered to a very limited extent. Assuming variable costs of 1.125 €/MWh for water (see Table 7.1), this leads to a significant underestimation of the production costs of electricity for example in Switzerland or Sweden. This has a corresponding influence on the calculations of the adjusted German electricity price.

Second, the test data sets include estimated efficiencies for power plants. Thus, the same type of power plants often have the same efficiency and hence at constant assumed fuel prices the same marginal costs. This illustrates in particular why higher "levels of detail" did not achieve better results. On the one hand, due to the same marginal costs, the number of segments of the merit order is reduced and at the same time becomes valid for a larger load range (see Figure 3.5). On the other hand, the cost gap between the individual segments increases. This means that either all import and export nodes, regardless of the control parameter d, offer their electricity at the same price (since all are within the same segment of the merit order), or the electricity price of some import or export nodes is significantly higher or lower.

Third, the variable costs of the power plants have been considered only approximately although they are an important element of the test data sets. An enhancement would be a detailed calculation of fuel prices, which, in addition to actual costs on the European raw material market and expected fluctuations, also considers transportation costs to respective power plants.

Due to these limitations, the results only confirm a basic functioning of the model with the corresponding test data sets. It is not possible to draw conclusions about quality and accuracy of model results and the chosen model approach. The developed methodology of the "level of detail" is an essential simplification on which the model is based but has the advantage of a considerable reduction in computing time. It can be assumed that if the control parameter d is set to a high level of detail, the results of the developed model are only slightly worse compared to an approach that considers all power plants as individual components.

4.4 Assessment of approach

The systematization developed in this paper made it for the first time possible, to present the various approaches for modelling imports and exports in power market models in a lucid manner. This is helpful for recognizing strengths and weaknesses of existing approaches, for identifying research gaps and for developing one's own model.

Determining the available transfer capacity as carried out in the second step of the analysis is crucial for the model and ensures an hourly resolution of the NTC values as result. Due to the expandable data availability a precise forecast is challenging and there is a high degree of uncertainty with regard to forecasting future NTCs. First, there could be possible delays in the grid expansion or shortcoming in determining the exact influence of a new transmission line on the available transfer capacity without considering detailed grid data. Second, the expansion of the German domestic network was not taken into account. This could lead to increases in future available import and export capacity. The model, however, assumes a uniform, congestion-free German market area with no failure or planned maintenances of transmission lines. Finally, a change in the policy framework may lead to an increase or decrease in NTC values, which cannot be adequately reflected in the projections. In particular, this concerns the ongoing implementation of the Commission Regulation establishing a *Guideline on Capacity Allocation and Congestion Management* (CACM) [36, p. 49] as well as in future effective agreements on the Power Market Regulation. The latter regulate by Article 14 that 70 % of the net cross-border transfer capacity must be available for cross-border electricity trade, considering safety limits and deducting constraints [37].[1]

Nevertheless, a good approximation for modelling transfer capacities was developed in this work. It goes beyond frequently used simple representations with static values in other works, but at the same time is accompanied by a moderate computational effort.

The developed overall model closes the gap between very complex and highly simplified models. Furthermore, it is possible to transfer the model to other frameworks and model formulations, since no specific functions were used. A significant advantage is the reduced computing time with a low and variable complexity, which is achieved by using a merit order model and introducing a variable control parameter, the "level of detail". Thereby only the relevant part of the merit order is considered more closely. However, this is accompanied by the fact that only discrete steps of the merit order are considered, so that not all power plants with their marginal costs are included in the price calculation. The fundamental criticism of the merit order model when used for long-term forecasts is the lack of dynamic adaptability and the associated poor robustness in the event of structural changes in the power market [38, p. 3162]. In addition, only variable costs of power plants are considered. Nevertheless, overall results of merit order models are of good quality.

The main challenge for accurate forecasts of imports and exports, however, is the quality of publicly available data that is used as input.

5 Conclusion and Further Research Demand

In the following, central results of the analyses for modelling imports and exports in the German electricity system are summarized. Subsequently, further research demand is stated.

5.1 Conclusion

This analysis proposes a systematization of existing and possible approaches for modelling imports and exports in power market models. This way, the existing research gap in this field is closed. In addition, an analysis of the available commercial transfer capacities between Germany and its electrical neighbours is carried out. Based on the analyses, an own fundamental model with reduced (simplified) market coverage is developed and tested. The developed model consists of three modules: a module for calculating the maximum transmission capacities available for commercial exchanges based on of time-variable NTCs, a module for calculating electricity prices using country-specific supply curves (merit orders) and an integrated optimization module for the European electricity market. The model approach addresses the conflict between computing time and model complexity by a variably adjustable control parameter, the "level of detail" d. This ultimately makes it possible to vary the degree of detail of the country-specific merit order, which is available at maximum in a block-sharp resolution.

[1] At the time of publication, the relevant Trilogue result and the approval of the responsible ITRE Committee were available. The final text of the regulation has not been adopted yet.

To demonstrate its functionality, the model is tested with preliminary test data sets. Furthermore, the resulting transmission capacities are compared with the real values. Preliminary results lead to a MAE of 6.93 €/MWh for the electricity price in Germany in 2016 with a "level of detail" d of two and tend to indicate an underestimation of real prices.

5.2 Outlook

To allow continuous further enhancement and refinement of the developed model, a test with a high-quality and comprehensive data set should be carried out. In addition, it is reasonable to extend the model with further technologies as well as inflexibilities and dynamic behaviour of power plants. In case of a very high accuracy requirement, the use of a corresponding transmission network model is recommended. This makes it possible to implement a load flow-based approach as it is likely that in future FBMC will be introduced beyond the CWE region [39, p. 16]. Moreover, a corresponding redispatch model could be used in this way to identify network congestion within a country and to adjust market results.

It also should be analyzed whether the fundamental approach could be reasonably supplemented by statistical approaches - and thus turn into a hybrid model. If information regarding actual transfer capacities become publicly available, neuronal networks could be trained. It can be expected that they have a high validity regarding the predicted transfer capacities and at the same time reduce the computational effort in the model. This clearly would lead to advantages regarding runtime, which, however, would be accompanied by increased preparation time for parameterization of the model.

6 References

[1] W. Ströbele, W. Pfaffenberger, und M. Heuterkes, *Energiewirtschaft*, 3., überarb. u. aktualisierte Aufl. München: Oldenbourg, 2012.

[2] V. Böckers, J. Haucap, und U. Heimeshoff, *Benefits of an Integrated European Electricity Market*, Bd. No 109. Düsseldorf: Düsseldorf Institute for Competition Economics (DICE), 2013.

[3] E. Hauser, U. Klann, K. Grashof, U. Leprich, M. Luxenburger, und M. Sabatier, „Weiterentwicklung des Marktdesigns und der Netzregulierung zur Transformation des Stromsystems (‚Trans-Sys-D')", 2014.

[4] S. Kumar und D. Most, „Cross border commercial flow of electricity for Germany", gehalten auf der 14th International Conference on the European Energy Market (EEM), Dresden, 2017, p. 1–6.

[5] ETSO, „Procedures for cross-border transmission capacity assessments", 2001.

[6] EnBW, „Allgemeines Modell zur Berechnung der Gesamtübertragungskapazität und der Sicherheitsmarge der EnBW Transportnetze AG", 2012.

[7] Elia, „Transmission capacity at borders", 2018.

[8] TenneT, „Bestimmung der Übertragungskapazität an auktionierten Grenzkuppelstellen der TenneT TSO GmbH", 2015.

[9] Amprion, „Berechnung von regelblocküberschreitenden Übertragungskapazitäten zu internationalen Partnernetzen", 2015.

[10] B. Cornélusse, „How the European day-ahead electricity market works", 2017.

[11] TransnetBW, „Allgemeines Modell zur Berechnung der Gesamtübertragungskapazität und der Sicherheitsmarge der TransnetBW GmbH", 2015.

[12] BNetzA, „Market Coupling - Marktkopplung der europäischen Stromgroßhandelsmärkte", 2016.

[13] ACER und CEER, „Annual Report on the Results of Monitoring the Internal Electricity and Gas Markets in 2016", 2017.

[14] Amprion, TenneT, und TransnetBW, „Genehmigungsantrag zur lastflussbasierten Kapazitätsberechnung (FBKB) in der CWE-Region gemäß Art. 15 Abs. 2 EU-VO 714/2009", 2014.

[15] K. van den Bergh, J. Boury, und E. Delarue, „The Flow-Based Market Coupling in Central Western Europe", *The Electricity Journal*, Bd. 29, Nr. 1, p. 24–29, 2016.

[16] Amprion, „Exemplarisches Beispiel für eine lastflussbasierte Kapazitätsberechnung (FBKB)", 2015.

[17] KU Leuven Energy Institute, „Cross-border electricity trading: towards flow-based market coupling“, 2015.

[18] H. Hermann *u. a.*, „Klimaschutz im Stromsektor 2030 - Vergleich von Instrumenten zur Emissionsminderung“, 2017.

[19] H. Natemeyer *u. a.*, „Weiterführende Analysen zur Ermittlung erforderlicher Ausbaumaßnahmen des deutschen Übertragungsnetzes ‚NEMO III‘“, 2014.

[20] C. Gerbaulet und C. Lorenz, „dynELMOD: A Dynamic Investment and Dispatch Model for the Future European Electricity Market“, 2017.

[21] L. Hirth, „The European Electricity Market Model EMMA - Model documentation“. 2017.

[22] H.-P. Beck, B. Engel, L. Hofmann, R. Menges, T. Turek, und H. Weyer, „Eignung von Speichertechnologien zum Erhalt der Systemsicherheit“, efzn, Goslar, Studie, März 2013.

[23] K. Heuck, K.-D. Dettmann, und D. Schulz, *Elektrische Energieversorgung: Erzeugung, Übertragung und Verteilung elektrischer Energie für Studium und Praxis*. Wiesbaden: Vieweg + Teubner, 2010.

[24] J. Egerer *u. a.*, „Electricity Sector Data for Policy-Relevant Modeling: Data Documentation and Applications to the German and European Electricity Markets“. 2014.

[25] 50Hertz, Amprion, TenneT, und TransnetBW, „Abschlussbericht - Systemanalysen 2017“, 2017.

[26] 50Hertz, Amprion, TenneT, und TransnetBW, „Abschlussbericht - Systemanalysen 2018“, 2018.

[27] ENTSO-E, „10-Year Network Development Plan 2014“, 2014.

[28] BNetzA, „Bedarfsermittlung 2017-2030“, 2017.

[29] S. Hilpert, C. Kaldemeyer, U. Krien, S. Günther, C. Wingenbach, und G. Plessmann, „The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling“, *Energy Strategy Reviews*, Bd. 22, p. 16–25, Nov. 2018.

[30] J. Borchert, R. Schemm, und S. Korth, *Stromhandel*, 1. Auflage. Stuttgart: Schäffer-Poeschel, 2006.

[31] R. Weron, „Electricity price forecasting“, *International Journal of Forecasting*, Bd. 30, Nr. 4, p. 1030–1081, 2014.

[32] 50Hertz, Amprion, TenneT, und TransnetBW, „Ergebnisdokumentation“, 2015.

[33] Svenska Kraftnät, „Swedish Interconnectors“, 2018.

[34] D. Oeding und B. R. Oswald, Hrsg., *Elektrische Kraftwerke und Netze*, 8th ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2016.

[35] ENTSO-E, „ENTSO-E Transparency Platform“, 2018.

[36] EU-Kommission, *Verordnung (EU) 2015/ 1222 der Kommission - vom 24. Juli 2015 - zur Festlegung einer Leitlinie für die Kapazitätsvergabe und das Engpassmanagement*. p. 49.

[37] Committee on Industry, Research and Energy (ITRE-Ausschuss), *Provisional Agreement Resulting from interinstitutional negotiations. Subject: Proposal for a regulation of the European Parliament and of the Council on the internal market for electricity (recast)(COM(2016)0861 – C8-0492/2016 – 2016/0379 (COD))*. 2019.

[38] Y. He, M. Hildmann, F. Herzog, und G. Andersson, „Modeling the Merit Order Curve of the European Energy Exchange Power Market in Germany“, *IEEE Trans. Power Syst.*, Bd. 28, Nr. 3, p. 3155–3164, 2013.

[39] ENTSO-E, „Annual Report 2017, Final Version“, 2018.

7 Appendix

Table 7.1: Overview of assumed fuel prices, variable costs and CO_2 emissions per fuel typ

Fuel type	Fuel price in €/MWh	Variable cost in €/MWh	CO_2 em-missin in t/MWh
Water	0.000	1.125	0.000
Ura-nium	3.446	3.890	0.000
Lignite	1.368	4.750	0.407
Hard coal	9.770	5.370	0.337
Natu-ral Gas	23.290	1.828	0.201
Oil	43.987	3.950	0.294
Waste	15.457	11.300	0.000
Bio-mass	30.300	11.300	0.147

Table 7.2: Defined maximum NTCs for import and export from 2015 to 2030 (Own calculation based on [35])

		2015	2020	2025	2030
Import from:	CH	4.000	4.000	4.000	4.000
	NL	2.449	4.249	4.249	4.249
	FR	1.800	1.800	1.800	1.800
	CZ	1.800	2.400	2.400	2.400
	PL	1.400	1.600	1.600	1.600
	AT	4.900	4.900	7.805	7.805
	DK W	1.780	1.780	2.500	2.500
	DK O	585	585	585	585
	SE	600	600	600	1.300
	NO	0	0	1.400	1.400
	BL	0	0	1.000	1.000
Export to:	CH	2.000	3.100	3.400	3.400
	NL	2.449	4.249	4.249	4.249
	FR	3.000	3.600	3.600	3.600
	CZ	1.000	1.600	1.600	1.600
	PL	0	200	900	900
	AT	4.900	4.900	7.805	7.805
	DK W	1.500	1.500	2.500	2.500
	DK O	615	615	615	615
	SE	615	615	615	1.315
	NO	0	0	1.400	1.400
	BL	0	0	1.000	1.000