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Abstract

Distribution system operators are expected to procure flexibility when it is cheaper than expanding their distribution grid. How to integrate these flexibility markets in the existing sequence of electricity markets is an important open issue in the evolution of electricity markets in Europe. In this paper, we investigate four market sequencing options: (1) the nodal wholesale market that includes network constraints (WNC); (2) the zonal wholesale market without network constraints followed by an integrated redispatch market to remedy the network congestion at transmission and distribution level created by the wholesale market in a coordinated way (WIR); (3) the zonal wholesale market followed by separate flexibility, redispatch and balancing markets in that order, which implies that congestion at distribution level is treated before congestion at transmission level (WFRB); and (4) the zonal wholesale market followed by separate redispatch, flexibility and balancing markets in that alternative order, which implies that congestion at transmission level is managed before congestion at distribution level (WRFB). We analyse how changing the market sequence can impact the strategic behaviour of flexibility providers, here represented by a Balancing Responsible Party (BRP). We introduce a bi-level model in which the strategic BRP in the upper-level acts as a first mover that anticipates the effect of its offers on the market outcome of the lower-level optimization problems. In analogy with the inc-dec game triggered by redispatch markets, we find that flexibility markets can trigger new games. These games will be difficult to detect by regulators as they can be performed by relatively small players. We observe that the WNC market design clearly outperforms the other sequencing options, but there is no clear second best among the alternatives WIR, WFRB, and WRFB.

1. Introduction

With the uptake of distributed energy resources, the European energy scene experienced significant changes over the last decades. Also in the coming years, a further transformation is expected due to the deployment of new, flexible technologies that come from the electrification of the transport, building and industry sector. As most of these new technologies will be connected to the distribution network, Distribution System Operators (DSOs) face a major network integration challenge. A recent study by Eurelectric and E.DSO shows that DSOs in Europe will in total need to invest 375-425 €bn in their networks between 2020 and 2030 (Eurelectric, et al., 2020). Luckily, due to their flexible characteristics, these new technologies do not only contribute to this DSO challenge, but could also be part of the solution. The active management of flexible resources by DSOs for the operation and planning of their distribution networks has the potential to significantly decrease future network investments (BMWi et al., 2014; Enedis & ADEeF, 2017). For this reason, DSOs are expected from the Clean Energy Package to procure flexibility in a market-based way when it is cheaper than expanding their distribution network. Different pilots and research projects on flexibility markets do already exists today (European Commission, 2021; Schittekatte & Meeus, 2020), but overall, the integration of these flexibility markets in the existing sequence of European electricity markets remains an important open issue (Meeus, 2020; Pollitt & Anaya, 2020). We were inspired by two streams of literature to contribute to this discussion.

The first stream relates to market sequencing options which are often referred to as alternative TSO-DSO coordination schemes because they imply different levels of cooperation between the Transmission System Operator (TSO) and DSOs. While congestion management by DSOs is rather new, TSOs have already been procuring flexible resources for balancing services and congestion management for a longer time. As both TSOs and DSOs will consider flexibility for congestion management, a debate around TSO-DSO coordination has been growing in Europe (Hadush & Meeus, 2018). Accordingly, TSO and DSO associations ENTSO-E and E.DSO came out with a common vision on this subject (CEDEC et al., 2019). This TSO-DSO report proposes three market models: a separate approach for congestion management, a coordinated scheme between system operators for congestion management and a coordinated scheme for congestion management and balancing services. Likewise, the coordination between TSOs and DSOs has been studied in publications by academics. Burger et al. (2019) focus on the coordination between DSOs and balancing authorities, while Gerard et al. (2018) analyse the idea of an independent market operator to facilitate the coordination between TSOs and DSOs. Besides that, Vicente-Pastor et al. (2019) examine the performance of coordination schemes between DSOs, TSOs and retailers hedging against network usage tariffs, and Le Cadre et al. (2019) model the competition between DSOs and TSOs when accessing flexibility under different coordination schemes. Several authors referred to the strategic behaviour of market parties, but it has not yet been modelled extensively. Therefore, the main contribution of this paper is to model this strategic behaviour under the alternative market sequencing options.

For our modelling approach, we were inspired by a second stream of literature on the inc-dec game, which is a profitable strategic arbitrage trading between an inter-zonal electricity market and an intra-zonal congestion management market. This game was first discovered during the California market crisis where it played an important role in the creation of the crisis (Harvey & Hogan, 2001; Stoft, 1998). As a result, inc-dec gaming is often used as an argument in favour of nodal pricing, which is a concept that was first promoted by Schweppe et al. (1998). In the literature on the inc-dec game, two approaches are used to compare the performance of redispatch markets and nodal pricing. In the first approach, the Nash equilibrium between all (strategic) market players is solved analytically. Dijk & Willems (2011) find that redispatch markets are an inefficient tool for congestion management compared to nodal pricing and Holmberg & Lazarczyk (2015) obtain similar findings, adding that this market set up might give inefficient investments signal for generators. In Hirth & Schlecht (2019), the intuition behind nodal pricing and the inc-dec game is explained by a simple, theoretical example of a network with two transmission nodes. In the second approach, the strategic behaviour of the market players is formulated by bi-level equilibrium model. Sarfati et al. (2019) numerically show the inefficient character of the inc-dec game and Sarfati & Holmberg (2020) confirm these findings while proposing a new real-time market design to mitigate the inc-dec game. To the best of our knowledge, the literature on the inc-dec game does not yet consider the recent developments in distribution networks with flexibility markets, which is the focus of this paper.

In this paper, we combine the literature on market sequencing options and the second approach of the literature on the inc-dec game to examine the integration of flexibility markets in the sequence of electricity markets. The strategic behaviour of a market player, here represented by a Balancing Responsible Party (BRP), can typically be captured by a bi-level optimization problem where the strategic BRP in the upper-level acts as a first mover that anticipates the effect of its offer on the market outcome of the lower-level optimization problems. Here it must be noted that we will focus our analysis on a single strategic player and we will not consider the equilibrium between multiple strategic agents. The number of lower-levels treated in the model depends on the analysed market sequencing option. The following four sequencing options are considered in our paper: (1) the nodal wholesale market that includes network constraints; (2) the zonal wholesale market without network constraints followed by a redispatch market to remedy the network congestion at transmission and distribution level created by the wholesale market in a coordinated way; (3) the zonal wholesale market followed by separate flexibility, redispatch and balancing markets in that order, which implies that congestion at distribution level is treated before congestion at transmission level; and (4) the zonal wholesale market followed by separate redispatch, flexibility and balancing markets in that alternative order, which implies that congestion at transmission level is managed before congestion at distribution level.

Five main sections follow this introduction. Section 2 provides an overview of the different versions of the model, its mathematical formulation and the analysed performance parameters. In Section 3, the results based on the reference power system and perfect competition are presented. Section 4 discusses the different types of games that emerge under the alternative sequencing options. Section 5 analyses the impact of market structure on the performance of sequencing options with a Monte Carlo simulation and Section 6 discusses the limitations of the model. Finally, we summarize our main findings in the conclusion.

2. Methodology

In this section, we provide an overview of the different versions of our model and give the mathematical formulation of its five main building blocks: the BRP, the wholesale market, the TSO redispatch market, the DSO flexibility market and the TSO balancing market. We end this section by discussing the performance parameters that will be analysed to compare the alternative market sequencing options.

2.1. Overview of the different versions of the model and their solution methods

A schematic overview of the relation between the different market parties and the sequencing options can be found in Figure 1. The numbers in Figure 1 refer to the respective equations in the mathematical formulation of Section 2.2 to Section 2.6.

Market sequence (a) WNC, also called Wholesale market with Network Constraints, is characterised by a nodal wholesale market that considers transmission and distribution network constraints during the market clearing. Option (b) WIR or Wholesale market with Integrated Redispatch market consists of two markets: a zonal wholesale market followed by an integrated redispatch market where transmission and distribution constraints are managed in a coordinated way. Congestion at transmission and distribution level is treated separately in sequencing options (c) WFRB and (d) WRFB that are respectively called Wholesale market with Flexibility, Redispatch and Balancing markets, and Wholesale market with Redispatch, Flexibility and Balancing markets. Here it is assumed that the DSO is not responsible for the imbalance created in the flexibility market, but that this is covered in the TSO balancing market. Both options consist of four markets that can be placed in a different sequence. In the case of WFRB, a zonal wholesale market is followed by separate flexibility, redispatch and balancing markets in that order, which implies that congestion at distribution level is treated before congestion at transmission level. In the case of WRFB, a zonal wholesale market is followed by separate redispatch, flexibility and balancing markets in that alternative order, which implies that congestion at transmission level is managed before congestion at distribution level.

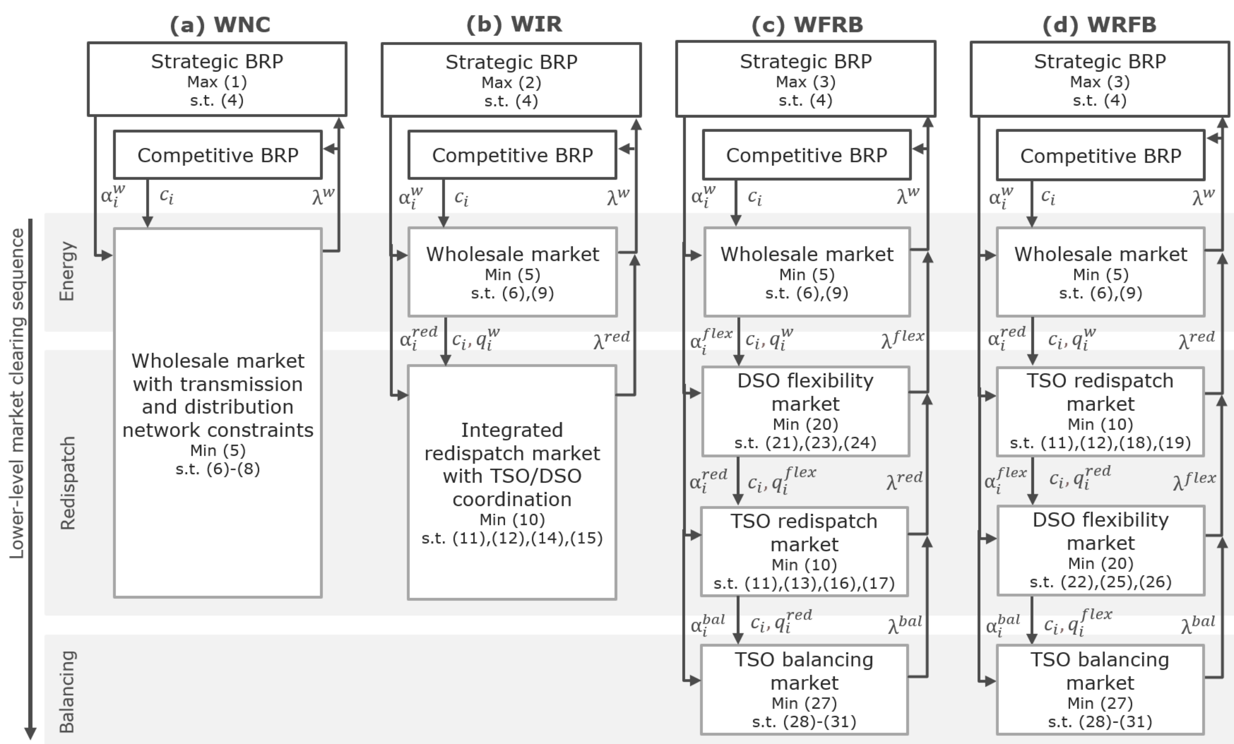

Figure 1: Schematic overview of the model including references to the optimization problems (1) – (31) of the market players (cf. Section 2.2 – 2.6) for (a) WNC the nodal wholesale market with integrated transmission and distribution network constraints; (b) WIR the zonal wholesale market followed by an integrated redispatch market; (c) WFRB the zonal wholesale market followed by separate flexibility, redispatch and balancing markets; and (d) WRFB the zonal wholesale market followed by separate redispatch, flexibility and balancing markets.

For each sequencing option, we model perfect competition as the reference case and compare this to a situation where a strategic BRP is the first mover in the market. As a result, there are eight versions of the model studied in this paper, all analysed for a single timestep. Depending on the analysed market structure, the model is solved in different ways. In the case of perfect competition, the lower-level market can be solved as a Mixed Complementarity Problem (MCP) using the PATH solver. In the case of market power, the bi-level problem is formulated as a Mathematical Program with Equilibrium Constraints (MPEC) as shown in Ruiz et al. (2012) and Sarfati et al. (2018). Note here, that we limit our analysis to a single strategic player and we do not develop the Equilibrium Problem with Equilibrium Constraints (EPEC) formulated in those publications. The MPEC formulation can be found in Annex A and contains two sources of non-linearities: the objective function of the BRP in the upper-level and the complementarity slackness conditions of the KKT conditions in the lower-level. Due to the sequential characteristic of the lower-level problem, the objective function of the BRP can only be linearised in the case of WNC by using the strong duality theorem and complementary slackness conditions (Nasrolahpour et al., 2018). The non-linearities in the lower-level are linearised using the big-M method (Fortuny-Amat & McCarl, 1981). In the case of WNC, the model is solved as a Mixed Integer Problem (MIP) using CPLEX in GAMS and in the case of WIR, WFRB and WRFB, the model is solved as a Mixed Integer Non Linear Problem (MINLP) using COENNE in GAMS. In order to validate the solutions of the MINLP, different starting points were analysed.

2.2. Balancing Responsible Party (BRP)

Depending on the analysed market structure, the generation units will be divided among the competitive and the strategic BRP. A selection of the generation sources is allocated to the strategic BRP, and all other units are included in the portfolio of the competitive BRP.

The competitive BRP offers its marginal cost to each market and cannot decide on the bid price ꟾ ᵢ. As a result, the perfect competitive case can be simplified to a single-level model that contains all markets of the selected sequencing option. The different mathematical formulations of the markets can be found in Sections 2.3 – 2.6.

In the case of the strategic BRP, the bid price ꟾ ᵢ becomes an important decision variable and is used as a tool to maximize the profits of its generation portfolio ɱ. Because the strategic BRP acts as a first mover, the model is solved as a bi-level optimization model that contains the following equations in the upper-level. The objective functions for sequencing options WNC (1), WIR (2), WFRB (3) and WRFB (3) consist of two effects. First, the BRP tries to maximize its income on each market, which is reflected by the product of the market price ‗ and the hourly generation ή for each unit in the BRP portfolio. Second, the BRP aims to minimize its generation costs, which is equivalent to the product of the marginal costs ῶ and hourly generation ή for all units in the strategic BRP portfolio. It must be noted that in the case of WNC, nodal prices are considered in the objective function by including a condition that the generation unit must be located at the appropriate node n in the set of nodes ɰ. Finally, as shown in (4), the strategic bid price must be positive and is limited by the price cap of the market ɺ. In future notations, the subscript of the bid price changes depending on the market it is offered to.

-ÁØ ꞁ ῶ ή WNC (1)

-ÁØ ꞁ ῶ ή ῶ ꞁ ή ꞁ ῶ ή WIR (2)

-ÁØ ꞁ ῶ ή ῶ ꞁ ή ῶ ꞁ ή ꞁ ῶ ή ꞁ ῶ ή WFRB, WRFB (3)

π ɺ ɺ ꞁ ɱ WNC, WIR, WFRB, WRFB (4)

2.3. Wholesale market

The wholesale market is represented by an independent market clearing agent that minimizes total generation costs while satisfying all technical and market clearing constraints. In this way, the wholesale market price ł and the hourly generation ή of each generation unit can be determined.

The objective function of the market clearing agent (5) consists of two parts. First, the cost minimization of all competitive units in the set ɱ that offer their marginal price ώ to the market. Second, the cost minimization of all strategic units that offer their selected bid price to the market. While is a decision variable of the upper-level problem, the market clearing agent perceives the bid offer as a parameter. The objective function is subjected to the technical constraints of the generation units (6) and the market clearing constraint. The latter is dependent on the analysed market clearing sequence. In the case of WNC, network constraints are treated in the wholesale market and prices are created locally. The power balance at each bus is expressed in (7), where the dual variable ł reflects the price at each node and the parameter Ὀ expresses the electricity demand. The capacity limits of the network lines can be found in (8), where m counts over the neighbouring nodes of the analysed node n in the set g. In the case of sequencing options WIR, WRFB and WFRB, no network constraints are treated and the wholesale market clearing constraint is represented by (9), with dual variable ł expressing the zonal price.

-ÉÎ ώή ... łή WNC, WIR, WFRB, WRFB (5)

Subject to

π ή ή ... t ... t ... WNC, WIR, WFRB, WRFB (6)

Ὀ ... ή ... Ὀ ... π ... ł ... WNC (7)

π Ὀ Ὀ ... t ... t ... g WNC (8)

Ὀ ... ή ... π ... ł ... Ë WIR, WFRB, WRFB (9)

2.4. TSO redispatch market

In the redispatch market, the TSO acts as a market clearing agent that tries to minimize redispatching costs while satisfying generation and network capacity constraints. In this way, the upwards and downwards redispatch market prices and , and the hourly upwards and downwards generation ή and ή of each power unit are determined.

Each term of the objective function (10) is characterised by two parameters: the behaviour of the BRP (competitive or strategic) and the direction of the market (upwards or downwards). The influence of the behaviour of the BRP is similar to the wholesale market as the TSO observes marginal costs ώ of competitive players and bid offers ł from strategic players. The direction of the market determines the sign of the generation costs terms. In the upwards market, the TSO will activate the cheapest units (positive sign), while in the downwards market the most expensive units will be activated first (minus sign).

The technical constraints of the generation sources are dependent on the wholesale market outcome and the analysed market sequence. It is assumed that, due to its location, a generation unit can never participate to both the upwards and downwards redispatch market at the same time. All units that can participate in the upwards redispatch market are indicated with the set [illegible] and all units located in the downwards redispatch market are indicated by the set [illegible]. The upwards generation unit is limited by the available generation capacity after the wholesale market clearing (11) for sequencing options WIR, WFRB and WRFB. The amount of downwards generation in WIR (12), WFRB (13) and WRFB (12) is limited by the previous activation of the generation units in the wholesale (and flexibility) market.

The network capacity constraints can be represented by the power balance at each node and the capacity limits of the appropriate network lines. They vary along market sequencing options as the redispatch market is preceded by different markets and other network constraints must be considered. In the case of WIR, both network constraints at transmission and distribution level are considered. Therefore, (14) and (15) are calculated for all nodes in network. The nodal power balances in the case of WFRB and WRFB can be found in (16) and (18) respectively. In principle, the redispatch market must only solve congestion at the transmission level. However, in the case of WFRB, where the flexibility market takes place before the redispatch market, it must be assured that no new congestion is created at distribution level, and again the line capacity between all nodes must be guaranteed (17). In the case of WRFB, the flexibility market only takes place in a next step. Therefore, only the line capacity constraints at transmission level must be considered and (19) is only valid if both node n and m are located at the transmission network defined by the set [illegible].

[illegible] WIR, WFRB, WRFB (10)

Subject to

[illegible] WIR, WFRB, WRFB (11)

[illegible] WIR, WFRB (12)

[illegible] WFRB (13)

[illegible] WIR (14)

[illegible] WIR (15)

[illegible] WFRB (16)

[illegible] WFRB (17)

[illegible] WRFB (18)

[illegible] WRFB (19)

2.5. DSO flexibility market

The flexibility market, that appears in WFRB and WRFB, is a downwards market in which the DSO tries to minimize congestion management costs (20). Similar as before, the DSO observes strategic bid offers [illegible] and marginal costs bids [illegible], and the sign of the generation costs is negative as the DSO turns down the most expensive bids first.

As different markets precede the flexibility market, the generation capacity constraints differ slightly between the sequencing options WFRB (21) and WRFB (22). The network capacity constraints are again represented by the power balance at each node (23) & (25), and the capacity limits of the appropriate network lines (24) & (26). The capacity limits of all distribution network lines are to be taken into account in the flexibility market. However, in the case of WRFB where the redispatch market takes place before the redispatch market, no additional congestion can be created at transmission level. As a result, the line capacity constraint of (24) is valid for all transmission lines. In the case of WFRB, congestion at transmission level is still to be solved in sequential markets. Therefore, only the line capacity constraints at distribution level must be considered and (26) is only valid for all lines connected between two nodes n, m that are not both located at the transmission network.

[illegible] WFRB, WRFB (20)

Subject to

[illegible] WFRB (21)

[illegible] WRFB (22)

[illegible] WFRB (23)

[illegible] WFRB (24)

[illegible] WRFB (25)

[illegible] WRFB (26)

2.6. TSO balancing market

Lastly, the balancing market, that is present in market sequences WFRB and WRFB, is characterized by the TSO as market clearing agent that tries to solve the imbalance created in the flexibility market at minimum costs. Similar to the previously discussed markets, the objective function (27) tries to minimize activation costs of the bids received from the strategic and competitive BRP.

As the balancing market is always last in sequence, the generation constraint (28) is valid for both WFRB and WRFB. The amount of balancing units that must be generated is determined by the amount of imbalance, which is equal to the amount of activated flexibility bids (29). This time, no network constraints can be violated. Therefore, the nodal balances and line capacity limits for all network nodes are shown in (30) and (31).

[illegible] WFRB, WRFB (27)

Subject to

[illegible] WFRB, WRFB (28)

[illegible] WFRB, WRFB (29)

[illegible] WFRB, WRFB (30)

[illegible] WFRB, WRFB (31)

2.7. Performance parameters

When analysing the results in the next sections, we will use the following two parameters to evaluate the performance of the alternative market sequencing options: generation costs and total cost towards consumers.

The generation costs (32) – (34) equal the total costs of all dispatched generators at the end of the market sequence. As demand is fully inelastic in our numerical example, this criteria relates to the total welfare created during the market sequence.

Generation costs = [illegible] WNC (32)

Generation costs = [illegible] WIR (33)

Generation costs = [illegible] WFRB, WRFB (34)

The total cost towards consumers represents the final cost of energy and congestion management paid by consumers. In the case of WNC (35), these costs consist of two parts: the price paid by consumers for energy in the local wholesale markets and the congestion rent. In the case of WIR (36), WFRB (37) and WRFB (37), the total cost towards consumers is equal to the price paid by consumers for energy in the zonal wholesale market and the costs created in the markets for congestion management. By analysing the total cost towards consumers, we can examine the effect of strategic behaviour on the internal welfare allocation between producers and consumers.

Total cost towards consumers = [illegible] WNC (35)

Total cost towards consumers = [illegible] WIR (36)

Total cost towards consumers = [illegible] WFRB, WRFB (37)

3. Perfect competitive reference case

In what follows, we introduce the reference power system we use for our numerical example, and we discuss its market outcome under perfect competition.

3.1. Reference power system

The reference power system builds further on the power system design of Hirth & Schlecht (2019), which started from a one-hour snapshot of the German transmission network. In what follows, we first describe the network parameters, and then the load and generation parameters.

First, the network parameters. A schematic outline of the examined network is shown in Figure 2. The network contains two transmission nodes: one in the North (N) and one in the South (S). The nodes are connected by a transmission line with a maximum capacity F_{NS}^{max} of 29.5 GW. This value is an adjustment to the transmission line capacity of 30 GW in Hirth & Schlecht (2019) in order to avoid numerical issues in the model, which will be explained in more detail at the end of this section. We added two distribution nodes to transmission node (N). The first distribution node (n1) is connected by a network line with maximum capacity F_{n1N}^{max} of 9.75 GW. The second distribution node (n2) in connected to the transmission level with a network line that has an overly-designed capacity, such that it always remains uncongested. As a result, our model treats transmission node (N) and distribution node (n2) as one location. Note finally that a simplified representation of the network is considered that leaves out transmission losses, distribution losses and voltage limits.

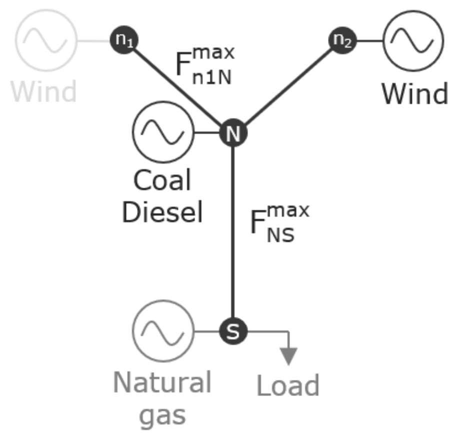

Figure 2: The reference power network

Second, the load and generation parameters. The merit order curve with the marginal costs of all generation units is shown in Figure 3. By using the same grey-scale of the network in Figure 2, the graph indicates the location and technology type of each power plant. At the distribution node (n1), 10 wind farms of 1 GW at 1 €/MWh and 5 wind farms of 1 GW at 2 €/MWh are located. The uncongested distribution node (n2) contains 5 wind farms of 1 GW and marginal cost of 2€/MWh. Next, the transmission node in the North connects coal and diesel fired power plants to the network. The coal plants have 20 incremental generation units of 1 GW ranging from 21 €/MWh up to 40 €/MWh and the diesel plants contain 5 incremental bids of 1 GW ranging from 66 €/MWh and 70 €/MWh. Last, the transmission node in the South contains natural gas fired power plants with 25 incremental bids of 1 GW between 45 €/GWh and 65 €/MWh. It must be noted that under strategic behaviour, BRPs can offer self-chosen price offer α instead of marginal costs to the market. The maximum value of the bid price α^{max} is 3000 €/MWh, which equals the maximum price in the day-ahead market determined by ACER (Meeus, 2020).

There is only one load source present in the reference power system which is located at the transmission node in the South. As a result, the North can be characterized as an export-constrained area and the South as an import-constrained area. The demand D is inelastic and equal to 49.25 GW. An adjustment is made to the value used in Hirth & Schlecht (2019) to avoid numerical issues: if the demand curve intersects the generation curve at a vertical step, an infinite amount of solutions to the model could be found. By slightly adjusting the rounded values of F_{NS}^{max}, F_{n1N}^{max} and D, an intersection on the horizontal step of the offer curve can be assured and a single solution to the market clearing can be guaranteed.

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