

Energy Systems Integration & Modeling Group Working Paper Series No. ESIM2021-05

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Last update: May 18, 2021

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Strategic behaviour in flexibility markets: new games and sequencing options

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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 upperlevel 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 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 α_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 α_i becomes an important decision variable and is used as a tool to maximize the profits of its generation portfolio Ω_s . 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 λ and the hourly generation q_i 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 c_i and hourly generation q_i 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 Ψ_n . Finally, as shown in (4), the strategic bid price must be positive and is limited by the price cap of the market α_i^{max} . In future notations, the subscript of the bid price changes depending on the market it is offered to.

$$\begin{aligned} & \max \sum_{i \in \Omega_s} (\lambda_{(n:i \in \Psi_n)}^w - c_i) q_i^w \\ & \text{WNC (1)} \\ & \max \sum_{i \in \Omega_s} (\lambda^w - c_i) q_i^w + \sum_{i \in \Omega_s} (c_i - \lambda^{red,do}) q_i^{red,do} + \sum_{i \in \Omega_s} (\lambda^{red,up} - c_i) q_i^{red,up} \end{aligned}$$

$$\begin{aligned} & \text{WIR (2)} \end{aligned}$$

$$\operatorname{Max}\sum_{i\in\Omega_{s}}^{\operatorname{red}, y} (\lambda^{w} - c_{i})q_{i}^{w} + \sum_{i\in\Omega_{s}}^{\operatorname{red}, y} (c_{i} - \lambda^{flex})q_{i}^{flex} + \sum_{i\in\Omega_{s}}^{\operatorname{red}, do} (c_{i} - \lambda^{red, do})q_{i}^{red, do} + \sum_{i\in\Omega_{s}}^{\operatorname{red}, up} (\lambda^{red, up} - c_{i})q_{i}^{red, up} + \sum_{i\in\Omega_{s}}^{\operatorname{red}, up} (\lambda^{bal} - c_{i})q_{i}^{bal}$$

$$\operatorname{WFRB}, \operatorname{WRFB}(3)$$

WNC, WIR, WFRB, WRFB (4)

 $0 \leq \alpha_i \leq \alpha_i^{max} \ \forall i \in \Omega_s$

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 λ^w and the hourly generation q_i^w 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 Ω_c that offer their marginal price c_i to the market. Second, the cost minimization of all strategic units that offer their selected bid price α_i to the market. While α_i 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 λ_n^w reflects the price at each node and the parameter D_k 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 Θ_n . In the case of sequencing options WIR, WRFB and WFRB, no network constraints are treated and the wholesale market clearings are treated and the wholesale market constraints are treated and the wholesale market clearing a node of the analysed node n in the set Θ_n . 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 λ^w expressing the zonal price.

$$\operatorname{Min}\sum_{i\in\Omega_{c}}c_{i}q_{i}^{w}+\sum_{i\in\Omega_{s}}\alpha_{i}^{w}q_{i}^{w}$$
WNC, WIR, WFRB, WRFB (5)

Subject to

$$0 \le q_i^w \le q_i^{cap} ; \quad \mu_i^{w,min}, \mu_i^{w,max} \quad \forall i$$
WNC, WIR, WFRB, WRFB (6)

$$\sum_{k \in \Psi_n} D_k - \sum_{i \in \Psi_n} q_i^w + \sum_{m \in \Theta_n} F_{nm} = 0 \quad ; \quad \lambda_n^w \quad \forall n$$

$$0 \le F_{nm} \le F_{nm}^{max} \quad ; \quad \mu_{nm}^{Fmin}, \mu_{nm}^{Fmax} \quad \forall n, \forall m \in \Theta_n$$
WNC (8)

$$\sum_{k} D_{k} - \sum_{i} q_{i}^{W} = 0 \quad ; \quad \lambda^{W} \quad \forall i, \forall k$$
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 $\lambda_n^{red,up}$ and $\lambda_n^{red,do}$, and the hourly upwards and downwards generation $q_i^{red,up}$ and $q_i^{red,do}$ 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 c_i of competitive players and bid offers α_i^{red} 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 $\Omega_{red,up}$ and all units located in the downwards redispatch market are indicated by the set $\Omega_{red,do}$. 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 $\Psi_{n,trans}$.

$$\operatorname{Min}\sum_{i\in\Omega_{s}}\alpha_{i}^{red,up}q_{i}^{red,up} + \sum_{i\in\Omega_{c}}c_{i}q_{i}^{red,up} - \sum_{i\in\Omega_{s}}\alpha_{i}^{red,do}q_{i}^{red,do} - \sum_{i\in\Omega_{c}}c_{i}q_{i}^{red,do}$$
WIR, WFRB, WRFB (10)

$$0 \le q_i^{red,up} \le q_i^{cap} - q_i^w ; \quad \mu_i^{rup,min}, \mu_i^{rup,max} \quad \forall i$$

$$0 \le q_i^{red,do} \le q_i^w ; \quad \mu_i^{rdo,min}, \mu_i^{rdo,max} \quad \forall i$$
WIR, WRFB (12)

$$0 \le q_i^{res,do} \le q_i^w - q_i^{flex} ; \quad \mu_i^{rdo,min}, \mu_i^{rdo,max} \quad \forall i$$
WFRB (13)

$$\sum_{k \in \Psi_n} D_k - \sum_{i \in \Psi_n} q_i^w - \sum_{i \in \Psi_n} q_i^{red,up} + \sum_{i \in \Psi_n} q_i^{red,do} + \sum_{m \in \Theta_n} F_{nm} = 0; \lambda_n^{red,up} \forall n \in \Psi_{red,up}, \lambda_n^{red,do} \forall n \in \Psi_{red,do}$$
 WIR (14)

$$0 \le F_{nm} \le F_{nm}^{max} ; \quad \mu_{nm}^{Fmin}, \mu_{nm}^{Fmax} \forall n, \forall m \in \Theta_n$$

$$WIR (15)$$

$$\sum F_{nm} = \sum red un \sum$$

$$\sum_{k \in \Psi_n} D_k - \sum_{i \in \Psi_n} q_i^w - \sum_{i \in \Psi_n} q_i^{red,up} + \sum_{i \in \Psi_n} q_i^{red,do} + \sum_{i \in \Psi_n} q_i^{flex} + \sum_{m \in \Theta_n} F_{nm}^{max} = 0 \quad ; \quad \lambda_n^{red,up} \forall n \in \Psi_{red,up}, \lambda_n^{red,do} \forall n \in \Psi_{red,do}$$
WFRB (16)

$$0 \le F_{nm} \le F_{nm}^{max}$$
; $\mu_{nm}^{Fmin}, \mu_{nm}^{Fmax} \forall n, \forall m \in \Theta_n$ WFRB (17)

$$\sum_{k \in \Psi_n} D_k - \sum_{i \in \Psi_n} q_i^w - \sum_{i \in \Psi_n} q_i^{red,up} + \sum_{i \in \Psi_n} q_i^{red,do} + \sum_{m \in \Theta_n} F_{nm}^{max} = 0; \lambda_n^{red,up} \forall n \in \Psi_{red,up}, \lambda_n^{red,do} \forall n \in \Psi_{red,do} \text{ WRFB (18)}$$

$$0 \le F_{nm} \le F_{nm}^{max} ; \quad \mu_{nm}^{Fmin}, \mu_{nm}^{Fmax} \quad \forall n, m \in \Psi_{n, trans}, \forall m \in \Theta_n$$
WRFB (19)

2.5. DSO flexibility market

Subject to

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 α_i^{res} and marginal costs bids c_i , 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.

$$\operatorname{Min} - \sum_{i \in \Omega_s} \alpha_i^{flex} q_i^{flex} - \sum_{i \in \Omega_c} c_i q_i^{flex}$$
WFRB, WRFB (20)

Subject to

$$0 \le q_i^{flex} \le q_i^w \; ; \; \mu_i^{flex,min}, \mu_i^{flex,max} \; \forall i \in \Omega_s, \Omega_c \tag{WFRB(21)}$$

$$0 \le q_i^{flex} \le q_i^w + q_i^{res,up} - q_i^{res,do}; \ \mu_i^{flex,min}, \mu_i^{flex,max} \ \forall i \in \Omega_s, \Omega_c$$

$$WRFB (22)$$

$$\sum_{k \in \Psi_n} D_k - \sum_{i \in \Psi_n} q_i^w + \sum_{i \in \Psi_n} q_i^{flex} + \sum_{m \in \Theta_n} F_{nm}^{max} = 0 \quad ; \quad \lambda_n^{flex} \quad \forall n$$
WFRB (23)

 $0 \leq F_{nm} \leq F_{nm}^{max}$; μ_{nm}^{Fmin} , $\mu_{nm}^{Fmax} \forall n \notin \Psi_{n,trans}$, $\forall m \in \Theta_n$

$$\sum_{k \in \Psi_n} D_k - \sum_{i \in \Psi_n} q_i^w - \sum_{i \in \Psi_n} q_i^{red,up} + \sum_{i \in \Psi_n} q_i^{red,do} + \sum_{i \in \Psi_n} q_i^{flex} + \sum_{m \in \Theta_n} F_{nm}^{max} = 0 \quad ; \quad \lambda_n^{flex} \quad \forall n$$
WRFB (25)

 $0 \le F_{nm} \le F_{nm}^{max}$; $\mu_{nm}^{Fmin}, \mu_{nm}^{Fmax} \forall n, \forall m \in \Theta_n$ 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).

$$\begin{split} & \operatorname{Min} \sum_{i \in \Omega_s} \alpha_i^{bal} q_i^{bal} + \sum_{i \in \Omega_c} c_i q_i^{bal} & \operatorname{WFRB}, \operatorname{WFRB} (27) \\ & \operatorname{Subject to} & \\ & 0 \leq q_i^{bal} \leq q_i^{cap} - q_i^w - q_i^{red,up} + q_i^{red,do} + q_i^{flex} ; \quad \mu_i^{bal,min}, \mu_i^{bal,max} \quad \forall i \in \Omega_s, \Omega_c & \\ & \sum_i q_i^{bal} - \sum_i q_i^{flex} = 0 ; \quad \mu_i^{bal} \quad \forall i \in \Omega_s, \Omega_c & \\ \end{split}$$

WFRB (24)

$$\sum_{k \in \Psi_n} D_k - \sum_{i \in \Psi_n} q_i^w - \sum_{i \in \Psi_n} q_i^{red,up} - \sum_{i \in \Psi_n} q_i^{bal} + \sum_{i \in \Psi_n} q_i^{red,do} + \sum_{i \in \Psi_n} q_i^{flex} + \sum_{m \in \Sigma_n} F_{nm}^{max} = 0 \quad ; \quad \lambda_n^{bal} \quad \forall n$$

$$WFRB, WRFB (30)$$

$$WFRB, WRFB (31)$$

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 =
$$\sum_{i} c_{i} q_{i}^{w}$$
 WNC (32)

 $\text{Generation costs} = \sum_{i} c_{i} q_{i}^{w} - \sum_{i} c_{i} q_{i}^{red,do} + \sum_{i} c_{i} q_{i}^{red,up}$

Generation costs =
$$\sum_{i} c_i q_i^w - \sum_{i} c_i q_i^{red,do} + \sum_{i} c_i q_i^{red,up} - \sum_{i} c_i q_i^{flex} + \sum_{i} c_i q_i^{bal}$$
 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 =
$$\sum_{k} \lambda_{(n:k \in \Psi_n)}^w D_k - \sum_{n} \lambda_n^w \left(\sum_{(k:n \in \Psi_n)} D_k - \sum_{(i:n \in \Psi_n)} q_i \right)$$
 WNC (35)

Total cost towards consumers =
$$\sum_{i} \lambda^{w} q_{i}^{w} - \sum_{i} \lambda^{red,do} q_{i}^{red,do} + \sum_{i} \lambda^{red,up} q_{i}^{red,up}$$
WIR (36)

Total cost towards consumers =
$$\sum_{i} \lambda^{w} q_{i}^{w} - \sum_{i} \lambda^{red,do} q_{i}^{red,do} + \sum_{i} \lambda^{red,up} q_{i}^{red,up} - \sum_{i} \lambda^{flex} q_{i}^{flex} + \sum_{i} \lambda^{bal} q_{i}^{bal}$$
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.

WIR (33)

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 \in /MWh and 5 wind farms of 1 GW at 2 \in /MWh are located. The uncongested distribution node (n2) contains 5 wind farms of 1 GW and marginal cost of 2 \in /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 \in /MWh up to 40 \in /MWh and the diesel plants contain 5 incremental bids of 1 GW ranging from 66 \in /MWh and 70 \in /MWh. Last, the transmission node in the South contains natural gas fired power plants with 25 incremental bids of 1 GW between 45 \notin /GWh and 65 \in /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 \in /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.



Figure 3: Merit order and demand curve of the reference power system. The intersection of the merit order and demand curve shows the price of the zonal wholesale market under the WIR, WFRB and WRFB market sequence.

3.2. Market outcome under perfect competition

In what follows, two characteristics of the market outcome under perfect competition are discussed in detail: the functioning of the wholesale market and the functioning of the markets for congestion management.

We start with the functioning of the wholesale market. Depending on the sequencing option, the wholesale market clearing will produce congestion or not. In the case of WNC, where distribution and transmission constraints are considered during the wholesale market clearing, nodal prices make sure that no congestion is created. In the local market of node (n1), 9.75 GW of wind farms are activated at a nodal price of 1€/MWh. In the local market of node (n2) and (N), 5 GW of wind farms and 14.75 GW of coal plants are selected at a nodal price of 35 €/MWh. Finally, the remaining demand is produced by 19.75 GW of natural gas units at a price of $60 \notin MWh$ in the local market of node (S). The diverging nodal prices indicate that the Northern distribution and transmission nodes are limited in their export capacity and imply that congestion rents are collected by the market operator. In the case of WIR, WFRB and WRFB, the wholesale market creates congestion as the market operation does not consider network constraints. The market price of 50 €/MWh, which is uniform over the whole reference power system, can be found in Figure 3 at the intersection of the demand and merit order curve. The demand is fulfilled by 20 GW of wind farms, 20 GW of coal power plants and 9.25 GW of natural gas units. By analysing the location of the activated generation units, the amount of congestion at distribution and transmission level can be found. In the reference power system, 5.25 GW and 10.5 GW of congestion must be solved at distribution and transmission level respectively. We will now analyse in more detail how this congestion is managed in the WIR, WFRB and WRFB market sequence.

Figure 4 shows the case of WIR, where the congestion management is organized in a coordinated way by both system operators. To solve all the congestion at distribution level, at least 5.25 GW of wind plants at node (n1) must be selected in the downwards market. Due to the topology of the reference power

network, this already solves part of the congestion at transmission level. The remaining overcapacity at transmission level is managed by selecting the most expensive generation units in the downwards redispatch market. In this case, 5.25 GW of coal power plants are turned off. The overall price of the downwards integrated redispatch market is set to $1 \notin /MWh$ by the wind power plant. It must be noted that this low downwards redispatching price is characteristic to the WIR market sequence and our numerical example. As the downward activation of wind units at the congested distribution node is necessary to solve all network congestion, these units will always set the market price equal or below $2\notin /MWh$. In order to balance the downwards redispatch market at a price of $60 \notin /MWh$.



Figure 4: Functioning of the markets for congestion management after the zonal wholesale market clearing in the WIR market sequence under perfect competition and the reference power system.

Figure 5 shows the case of WFRB in which the overcapacity of the distribution line is considered first. The congestion at distribution level is solved in the DSO flexibility market by curtailing 5.25 GW of wind farms at a price of $1 \notin$ /MWh. It must be noted that we assume that the DSO does not have to balance its flexibility market but that this is managed in the balancing market at the end of the market sequence. Next, a downwards and upwards redispatch market are organised to solve the remaining congestion at transmission level. In the downwards market, 5.25 GW of coal power plants are selected at a market price of $35 \notin$ /MWh and 5.25 GW of natural gas units are activated in the upwards redispatch market at a price of $55 \notin$ /MWh. Finally, the imbalance is settled by the natural gas power plant at a price of $60 \notin$ /MWh.

Figure 6 shows the functioning of the markets for congestion management in the WRFB market sequence in which the overcapacity of the transmission line is considered first. To solve all congestion at transmission level, 10.5 GW of coal unit are selected in the downwards redispatch market at a market price of $30 \notin$ /MWh and 10.5 GW of natural gas units are activated in the upwards redispatch market at a price of $60 \notin$ /MWh. As in our numerical example the TSO redispatch market does not affect the congestion at distribution level, an additional 5.25 GW of wind units at node (n1) must be curtailed in the DSO flexibility market. Finally, the imbalance is solved in the balancing market by the remaining available coal bids at a price of $35 \notin$ /MWh.



Figure 5: Functioning of the markets for congestion management after the zonal wholesale market clearing in the WFRB market sequence under perfect competition and the reference power system.



Figure 6: Functioning of the markets for congestion management after the zonal wholesale market clearing in the WRFB market sequence under perfect competition and the reference power system.

In Table 1, the results of the performance parameters are summarized for the alternative market sequencing options and perfect competition. The following three trends can be observed. First, we find that each market sequence results in the same generation costs. This implies that, despite being activated in a different way, the final dispatch of the four market sequencing options is the same. Second, we observe that although market prices and quantities of congestion management markets vary, the costs for congestion management in the WIR, WFRB and WRFB market sequence are similar. Finally, we find that under perfect competition, the costs towards consumer are lowest under the nodal pricing of the WNC market sequence. In the following sections, we will analyse whether this performance order changes when considering strategic behaviour of flexibility providers.

WNC WIR WFRB WRFB Generation costs [k€] 1426.00 1426.00 1426.00 1426.00 Wholesale market clearing [k€] 2955.00 2463.50 2463.50 2463.50 + congestion management [k€] -1069.00 619.50 414.75 493.50 (congestion rent) (redispatch costs) (redispatch costs) (redispatch costs)

3082.00

2877.25

1886.00

 Table 1: Overview of generation costs and total cost towards consumers for the alternative market sequencing options under perfect competition.

4. Strategic behaviour with old and new games

= Total cost towards consumers [k€]

In this section, we illustrate the strategic behaviour that occurs in our numerical example based on the following four BRP portfolios: two coal units of 24-25 €/MWh, two natural gas units of 45-46 €/MWh, two natural gas units of 57-58 €/MWh and two diesel units of 67-68 €/MWh. Each portfolio was selected from an extensive analysis of 22 samples in which subsequently two and five generation units of the same technology and location where allocated to the strategic BRP portfolio. The combination of these samples could be reduced to the different games analysed in this section.

Table 2 shows the performance parameters under perfect competition and the four BRP portfolios for each sequencing options. At least six types of strategic behaviour could be identified and are indicated by their respective roman numeral. While the first three games are already known in existing literature (and therefore referred to as old games), the last three games cover new games that arise in the market sequencing options when considering congestion management at distribution level. Overall, the six types of strategic behaviour can be divided into three categories: (1) games where the strategic BRP drives up prices within the market; (2) games where the strategic BRP creates and solves additional congestion between two markets; and (3) games where the strategic BRP anticipates its relevance in the total market sequence and pursues activation in the most profitable market(s). In our numerical example, game types I. and II. belong to category (1) and (2) respectively, and the other games classify under category (3). It must be noted that additional types, categories and classifications of games could be found when analysing alternative market sequences or different power systems. We will now explain in more detail the six types of games that appeared in our numerical example.

I. The price-setter game, which occurs when the BRP is in a dominant enough position to drive up market prices. This game can be played in all four sequencing options by the strategic BRP with two natural gas units of 57-58 €/MWh. In the different sequencing options, the BRP offers the unit with a marginal cost of 58 €/MWh to the available market at a price that is higher than its marginal cost and just above the

2956.00

expected market price. As a results, part of the generation quantity of this unit is now replaced by more expensive generation unit and the market clears at a higher price. The inefficient dispatch increases generation costs, and the higher market price creates additional costs towards consumers that are proportional to the increase in market price and the size of the market.

II. The underbidding game via the wholesale market and downwards (integrated) redispatch market, which is also known as the decremental strategy of the inc-dec game. The strategic BRP with two diesel units of 67-68 €/MWh can exercise this game in sequencing options WIR, WFRB and WRFB. In this game, the BRP offers both units to the wholesale market at a price that is lower than its marginal costs and below the expected market price. As a result, both units become activated in the wholesale market and create additional congestion at transmission level that has to be managed in the remainder of the market sequence. As the BRP has the most expensive units available in the downwards redispatch market, the created congestion will be solved by activating these units downwards again. The price of the downwards redispatch market, however, is set by the coal units that are required to manage the remaining congestion at transmission level. As a result, the BRP makes additional profits, by virtually turning its units on and off again, that are proportional to the number of strategic units and price difference between the wholesale and downwards redispatch market. The underbidding game does not impact the generation costs but influences the total cost towards consumers as the wholesale market price decreases and the amount of congestion at transmission level increases. The combination of these two effects increases the total cost towards consumers in WIR market sequences but lowers the costs in the WFRB and WRFB market sequence.

Game type (I-VI) Generation costs [k€] Total cost towards consumers [k€]	Perfect competition	Strategic coal units 24-25 €/MWh	Strategic natural gas units 45-46 €/MWh	Strategic natural gas units 57-58 €/MWh	Strategic diesel units 67-68 €/MWh
WNC	1426.00 1886.00	1426.00 1886.00	1426.00 1886.00	l. 1426.50 1905.75	1426.00 1886.00
WIR	1426.00 3082.00	V. 1449.50 3082.00	III. 1426.00 3180.50	l. 1426.50 3092.50	II. 1426.00 3101.50
WFRB	1426.00 2877.25	1426.00 2877.25	IV. 1426.00 2986.25	l. 1426.50 2882.50	II. 1426.00 2818.75
WRFB	1426.00 2956.00	VI. 1426.00 2935.00	III. 1426.00 3054.50	l. 1426.50 2966.50	II. 1426.00 2917.50

Table 2: Game type, generation costs and total cost towards consumers under perfect competition and the fourBRP portfolios for the different market sequencing options.

Old games

- I. Price-setter game
- II. Underbidding game via the wholesale market and downwards (integrated) redispatch market

III. Overbidding game via the wholesale market and upwards (integrated) redispatch market

New games

- IV. Overbidding game via the wholesale market, upwards redispatch market, and balancing market
- V. Overbidding game within the downwards integrated redispatch market
- VI. Overbidding game via the downwards redispatch market and balancing market

III. The overbidding game via the wholesale market and upwards (integrated) redispatch market, which is also known as the incremental strategy of the inc-dec game. This game can be performed by a strategic BRP with two natural gas units of 45-46 €/MWh in the WIR and WRFB market sequence. In this game, the BRP anticipates the high market price in the upwards redispatch market and chooses to offers both units to the wholesale market at a price that is higher than its marginal costs and above the expected market price. As a result, both units are no longer activated in the wholesale market but are selected in the following, upwards redispatch market. Due to this behaviour, the BRP makes additional profits that are proportional to the number of strategic units and price difference between the wholesale and upwards redispatch market. The behaviour of the BRP does not impact the generation costs, but creates higher costs towards consumers as the wholesale market price increases.

IV. The overbidding game via the wholesale market, upwards redispatch market, and balancing market, which is a variation to the overbidding game in III. that arises because flexibility markets are considered in the market sequence. This game was carried out by a strategic BRP with two natural gas units of 45-46 €/MWh in the WFRB market sequence. In this game, the BRP anticipates the high market price of the balancing market at the end of the market sequence and chooses to offer both units to the wholesale market and the upwards redispatch market at a price that is higher than its marginal costs and above the expected market prices. As a result, both units are no longer activated in the wholesale market and upwards redispatch market but are selected in the final, balancing market to solve the imbalance created in the flexibility market. Due to this behaviour, the BRP makes additional profits that are proportional to the number of strategic units and price difference between the wholesale and the balancing market. This game is dispatched efficiently and does not create additional generation costs, but increases the total cost towards consumers due to higher prices in the wholesale and upwards redispatch market.

V. The overbidding game within the downwards integrated redispatch market, which occurs when the BRP can take advantage of low market prices that are set by other, competitive generators. The strategic BRP with two coal units of 24-25 €/MWh can exercise this game in the WIR market sequence. In the downwards integrated redispatch market, the BRP offers both units at a price that is higher than its marginal costs and above the most expensive expected offer to the market. As a results, both units are now activated downwards and the BRP makes additional profits that are proportional to the number of strategic units and price difference between the wholesale and downwards redispatch market. In our numerical example, this price difference will always be large as the downwards redispatch market of the WIR market sequence is characterised by a very low market price set by the wind farms at the congested distribution node (see Section 3.2). As the BRP prevents the downwards activation of other, more expensive natural gas units, this game results in an inefficient dispatch and higher generation costs. The total cost towards consumers remains the same as the game is played within the same market and does not affect market prices or the amount of created congestion.

VI. The overbidding game via the downwards redispatch and balancing market, which is a variation to the inc-dec game that occurs because flexibility markets are considered in the sequence of electricity markets. This game can be performed by the strategic BRP with two coal units of $24-25 \notin$ /MWh in the WRFB market sequence. In this case, the BRP offers both units to the downwards redispatch market at a price that is higher than its marginal costs and above the most expensive expected offer to the market. As a result, both units are turned-off in the downwards redispatch market and become available in the balancing market at the end of the market sequence where they are re-activated to solve the imbalance created by the flexibility market. By virtually turning its units off and on again, the BRP can make additional profits

that are proportional to the number of strategic units and price difference between the downwards redispatch and the balancing market. The strategic behaviour does not impact the generation costs but creates lower costs towards consumers as higher prices in the downwards redispatch market causes that system operators can recuperate part of their congestion management costs.

When looking at the overall trends of Table 2, the following two findings emerge. First, we find that the WNC market sequence is most resistive to strategic behaviour and has better performance parameters than the other market sequences. Second, it seems that for the other market sequences, the influence of strategic behaviour is largest in sequencing option WIR and better results are obtained in the case of WFRB. This finding, however, must be interpreted carefully as we only illustrate a limited amount of BRP portfolios and power system configurations in this section. To analyse the effect of taking into account all different types and sizes of BRP portfolios of the reference power system, we perform a Monte Carlo simulation in the next section.

5. Impact of market structure on the performance of sequencing options

In what follows, we introduce how we ran the Monte Carlo simulation, and we discuss the three main observations that can be made based on the results summarized in Table 3.

For each run of the Monte Carlo simulation, a random portfolio is allocated to the strategic BRP and the total cost towards consumers of the market sequence are calculated. For our numerical example this implies that the strategic BRP can own up to 70 of the available generation units and the remaining units are submitted to the market sequence at marginal cost. For each sequencing option, 1000 runs of the Monte Carlo simulation are performed. This results in 1000, 984, 884 and 965 feasible data points of total cost towards consumers for WNC, WIR, WFRB and WRFB respectively.

Strategic BRP size [-]	Me Ave			
# runs [-]	WNC	WIR	WFRB	WRFB
Perfect	1886.00	3082.00	2877.25	2956.00
competition	1886.00	3082.00	2877.25	2956.00
1 – 5	1895.75	3082.00	2877.25	2956.00
# 65	1898.57	3102.20	2893.12	2969.93
6 - 10	1925.50	3141.38	2916.00	2996.50
# 84	5390.24	4441.53	3136.42	3769.56
11 – 15	1974.75	3230.88	3004.00	3080.25
# 89	20963.75	12052.77	5977.40	11624.56
16 - 20	60000.25	32096.75	3200.00	28951.25
# 87	55641.36	24569.56	12274.83	19955.65

Table 3: Median and average total cost towards consumers from the Monte Carlo simulation for each market sequencing option and different strategic BRP sizes. Below the BRP size, the amount of runs of the Monte Carlo simulation that fall under this BRP size are specified.

Table 3 shows the median and average total cost towards consumers for each market sequence and different BRP sizes. Below the BRP size, the amount of runs of the Monte Carlo simulation that fall under this BRP size are specified. The following three observations can be made. First, we find that even small strategic players can exercise strategic behaviour and on average increase the total cost towards consumers. As the strategy of the BRP can consist of various games and can hold small volumes, detecting this behaviour will be difficult in reality. Second, we find that in analogy with the previous section, the

WNC market sequence outperforms the other market sequencing options when BRP size are smaller or equal to 15. The higher average costs towards consumers in this sequence with BRP sizes 6-10 and 10-15 indicate that for some runs, the BRP is in a dominant enough position to perform the price-setter game in the some of the local markets up to the maximal bid price. The lower median costs however, shows that these high prices only occur in exceptional cases and the WNC market sequence is the best market sequencing option under small strategic BRP sizes. Third, we observe that when the BRP size becomes larger than 16 units, the price-setter game starts to occur in all four market sequences, and median and average costs towards consumers become highest in the WNC market sequence. This shows a disadvantage of nodal pricing compared to the other market sequencing options that was not yet identified in other contributions. We can explain this difference by looking at the model set-up. In this paper, we start from an MPEC model that has no strict limitations on the strategic bid price. Sarfati et al. (2019) and Sarfati & Holmberg (2020), on the other hand, use an EPEC model with a limiting bid price cap in order to make the model solvable. The difference in price cap and the number of strategic players considered in the model can explain the diverging findings. Although the WNC market sequence performs weakly under large strategic BRP sizes, the conclusion on the performance of this sequencing option still holds since it make sense to filter out larger BRP sizes as they cover extreme cases that will be easy to detect by regulators and therefore less frequently occur in reality.

6. Limitations of the model

In this section, we illustrate five limitations of the model that can lead to overestimations or underestimations of the impact of strategic behaviour.

Examples of overestimations include the reservation of flexibility, the risk averse behaviour of the BRP and demand response. First, the reservation of flexible resources is not considered in our model but is known to reduce market power issues. Note that reservation can also have negative effects, which is why we have reduced the level of reservation in the balancing market. Second, the strategic BRP has no sense of risk averseness in our model, while in reality uncertainty and imperfect information will make it harder for the BRP to exercise its market power. The possibility to be fined for strategic behaviour can also motivate market parties to refrain from the games we illustrated in this paper. Finally, we did not consider that demand is increasingly becoming elastic which can help to solve congestion via demand response and reduce the possibility for market parties to exercise market power.

Examples of underestimations include the analysed reference power system and the strategic behaviour of system operators. First, our analysis is limited because only a single, static power system is considered while in reality various network topologies exist, with characteristics that can change over hours of the day, seasons and weather conditions. We found that including more expensive power plants, such as biogas, at the distribution node (n1) results in additional new games that are variations of the underbidding strategy using the flexibility market. Note, however, that changing the power system might also result in less opportunities for strategic behaviour. Lastly, we did not consider the strategy behaviour of the system operators. Two types of conflict of interest between system operators can be observed in Table 4. First, both system operators minimize their congestion management costs if the other system operator is responsible for the imbalance. Second, system operators might have interest in different sequencing options. In this example, the TSO always prefers the WFRB market sequence while the DSO favours the WRFB market sequence when it is responsible for the imbalance.

Table 4: Total congestion management costs of the TSO and DSO under the WFRB and WRFB market sequence anddifferent balancing cost allocations.

(a) Balancing costs allocated to TSO.		(b) Balancing co	(b) Balancing costs allocated to DSO.			
Total congestion			Total congestion			
management costs [k€]	WFRB	WRFB	management costs [k€]	WFRB	WRFB	
TSO	420.00	498.75	TSO	105.00	315.00	
DSO	-5.25	-5.25	DSO	309.75	178.50	

7. Conclusions

In this paper we analysed four market sequencing options that consider network congestion at transmission and distribution level in the context of strategic flexibility providers. We formulated a MCP and MPEC model to capture competitive and strategic behaviour in the alternative markets sequences. A reference power system was defined to illustrate the wholesale market and congestion management functioning of the sequencing options and to discover old and new games triggered by redispatch and flexibility markets. Finally, the performance of the four sequencing options was examined under different market structures and the main limitations of our model were specified. In what follows, we highlight our two main findings and their practical relevance.

First, we found that in analogy with the inc-dec game triggered by redispatch markets, flexibility markets can create new games among flexibility providers. In this paper, six types of old and new games were identified and divided into three categories of strategic behaviour: driving up prices within the market, creating and solving additional congestion between two markets, and pursuing activation in the most profitable market(s) of the total market sequence. We also observed that these bidding strategies will be hard to detect in reality as they can be performed by relatively small strategic players and are highly dependent on the considered power system and market sequencing option. This is of practical relevance for market surveillance, as regulators that have the mandate to perform market oversight activities need to be aware of these new games that might occur to be able to detect them.

Second, we observed that the WNC market design is more resistant to strategic behaviour and performs better than the other market sequencing options, but can experience great distortions by the price-setter game of large strategic players. Besides that, we found no clear second best under the alternatives WIR, WFRB, or WRFB as their relative performance is sensitive to the market structure and dependent on the analysed power system. These findings are of practical relevance for the debate on how to integrate distribution network constraints in the current sequence of electricity markets.

Acknowledgments and funding

The PhD of Ellen Beckstedde is supported by the EUniversal project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864334. We would like to thank Tomás Gómez San Román, Dirk Van Hertem and Kenneth Bruninx for their valuable feedback on an earlier version of the paper. Additionally, we extend thanks to the participants of the ESIM group meeting and Vlerick-FSR research seminar where earlier results of the research were presented.

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$$\begin{split} F_{n1N}^{max} &- \sum_{i \in n1} q_i^w = 0 \ ; \ \lambda_{n1}^w \ \text{free} \\ 0 &\leq c_i - \lambda_{n1}^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in n1 \\ 0 &\leq q_i^{cap} - q_i^w \perp \mu_i^{w,max} \geq 0 \ ; \ \forall i \in n1 \\ -F_{n1N}^{max} + F_{NS}^{max} - \sum_{i \in N, n2} q_i^w = 0 \ ; \ \lambda_{n2,N}^w \ \text{free} \\ 0 &\leq c_i - \lambda_{n2,N}^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in n2, N \\ 0 &\leq q_i^{cap} - q_i^w \perp \mu_i^{w,max} \geq 0 \ ; \ \forall i \in n2, N \\ -F_{NS}^{max} + \sum_{k \in S} D_k - \sum_{i \in S} q_i^w = 0 \ ; \ \lambda_S^w \ \text{free} \\ 0 &\leq c_i - \lambda_S^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in S \\ 0 &\leq q_i^{cap} - q_i^w \perp \mu_i^{w,max} \geq 0 \ ; \ \forall i \in S \end{split}$$

A.2. Strategic behaviour in the WNC market sequence (MPEC) Upper-level:

$$\begin{split} &\operatorname{Min}\sum_{i\in\Omega_{s}}\left(c_{i}-\lambda_{(n\,:\,i\in\Psi_{n})}^{w}\right)\,q_{i}^{w}\\ &0\leq\alpha_{i}^{w}\leq\alpha_{i}^{max}\;\;;\;\;\forall i\in\Omega_{s} \end{split}$$

Lower-level:

$$\begin{split} F_{n1N}^{max} &- \sum_{i \in n1} q_i^w = 0 \ ; \ \lambda_{n1}^w \ \text{free} \\ 0 &\leq c_i - \lambda_{n1}^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in \Omega_c, n1 \\ 0 &\leq \alpha_i^w - \lambda_{n1}^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in \Omega_s, n1 \\ 0 &\leq q_i^{cap} - q_i^w \perp \mu_i^{w,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n1 \\ -F_{n1N}^{max} + F_{NS}^{max} - \sum_{i \in N, n2} q_i^w = 0 \ ; \ \lambda_{N,n2}^w \ \text{free} \\ 0 &\leq c_i - \lambda_{n2,N}^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in \Omega_c, n2, N \\ 0 &\leq \alpha_i^w - \lambda_{n2,N}^w + \mu_i^{w,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n2, N \\ 0 &\leq q_i^{cap} - q_i^w \perp \mu_i^{w,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n2, N \\ -F_{NS}^{max} + \sum_{k \in S} D_k - \sum_{i \in S} q_i^w = 0 \ ; \ \lambda_S^w \ \text{free} \\ 0 &\leq c_i - \lambda_S^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in \Omega_c, S \\ 0 &\leq \alpha_i^w - \lambda_S^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in \Omega_c, S \\ 0 &\leq \alpha_i^{cap} - q_i^w \perp \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \in \Omega_s, S \\ 0 &\leq q_i^{cap} - q_i^w \perp \mu_i^{w,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, S \\ 0 &\leq q_i^{cap} - q_i^w \perp \mu_i^{w,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, S \end{split}$$

A.3. Perfect competition in the WIR market sequence (MCP)

• Wholesale market

$$\sum_{k} D_{k} - \sum_{i} q_{i}^{w} = 0 \; ; \; \lambda^{w} \operatorname{free}$$

$$\begin{aligned} 0 &\leq c_i - \lambda^w + \mu_i^{w,max} \perp q_i^w \geq 0 \ ; \ \forall i \\ 0 &\leq q_i^{cap} - q_i^w \perp \mu_i^{w,max} \geq 0 \ ; \ \forall i \end{aligned}$$

• Downwards integrated redispatch market:

$$\begin{split} F_{n1N}^{max} &- \sum_{i \in n1} q_i^w + \sum_{i \in n1} q_i^{red,do} = 0 \ ; \ \lambda^{red,do} \ \text{free} \\ -F_{n1N}^{max} &+ F_{NS}^{max} - \sum_{i \in n2,N} q_i^w + \sum_{i \in n2,N} q_i^{red,do} = 0 \ ; \ \lambda \ \text{free} \\ 0 &\leq -c_i + \lambda^{red,do} + \mu_i^{rdo,max} \perp q_i^{red,do} \geq 0 \ ; \ \forall i \in n1 \\ 0 &\leq -c_i + \lambda + \mu_i^{rdo,max} \perp q_i^{red,do} \geq 0 \ ; \ \forall i \in n2,N \\ 0 &\leq q_i^w - q_i^{red,do} \perp \mu_i^{rdo,max} \geq 0 \ ; \ \forall i \in n1, n2,N \end{split}$$

• Upwards integrated redispatch market:

$$\begin{split} -F_{NS}^{max} + \sum_{k \in S} D_k - \sum_{i \in S} q_i^w - \sum_{i \in S} q_i^{red,up} &= 0 \ ; \ \lambda_S^{red,up} \ \text{free} \\ 0 &\leq c_i - \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in S \\ 0 &\leq q_i^{cap} - q_i^w - q_i^{red,up} \perp \mu_i^{rup,max} \geq 0 \ ; \ \forall i \in S \end{split}$$

A.4. Strategic behaviour in the WIR market sequence (MPEC) Upper-level:

$$\begin{split} \text{Min } \sum_{i \in \Omega_s} (c_i - \lambda^w) q_i^w + \sum_{i \in \Omega_s} (\lambda^{red, do} - c_i) q_i^{red, do} + \sum_{i \in \Omega_s} (c_i - \lambda^{red, up}) q_i^{red, up} \\ & 0 \leq \alpha_i^w \leq \alpha_i^{max} \ ; \ \forall i \in \Omega_s \\ & 0 \leq \alpha_i^{red, do} \leq \alpha_i^{max} \ ; \ \forall i \in \Omega_s \\ & 0 \leq \alpha_i^{red, up} \leq \alpha_i^{max} \ ; \ \forall i \in \Omega_s \end{split}$$

Lower-level:

• Wholesale market:

$$\sum_{k} D_{k} - \sum_{i} q_{i}^{w} = 0 ; \ \lambda^{w} \text{ free}$$
$$0 \leq c_{i} - \lambda^{w} + \mu_{i}^{w,max} \perp q_{i}^{w} \geq 0 ; \ \forall i \in \Omega_{c}$$
$$0 \leq \alpha_{i}^{w} - \lambda^{w} + \mu_{i}^{w,max} \perp q_{i}^{w} \geq 0 ; \ \forall i \in \Omega_{s}$$
$$0 \leq q_{i}^{cap} - q_{i}^{w} \perp \mu_{i}^{w,max} \geq 0 ; \ \forall i \in \Omega_{c}, \Omega_{s}$$

• Downwards integrated redispatch market:

$$\begin{split} F_{n1N}^{max} &- \sum_{i \in n1} q_i^w + \sum_{i \in n1} q_i^{red,do} = 0 \ ; \ \lambda^{red,do} \ \text{free} \\ &- F_{n1N}^{max} + F_{NS}^{max} - \sum_{i \in n2,N} q_i^w + \sum_{i \in n2,N} q_i^{red,do} = 0 \ ; \ \lambda \ \text{free} \\ &0 \leq -c_i + \lambda^{red,do} + \mu_i^{rdo,max} \perp q_i^{red,do} \geq 0 \ ; \ \forall i \in \Omega_{c}, n1 \\ &0 \leq -\alpha_i^{red,do} + \lambda^{red,do} + \mu_i^{rdo,max} \perp q_i^{red,do} \geq 0 \ ; \ \forall i \in \Omega_{s}, n1 \\ &0 \leq -c_i + \lambda + \mu_i^{rdo,max} \perp q_i^{red,do} \geq 0 \ ; \ \forall i \in \Omega_{c}, n2, N \\ &0 \leq -\alpha_i^{red,do} + \lambda + \mu_i^{rdo,max} \perp q_i^{red,do} \geq 0 \ ; \ \forall i \in \Omega_{s}, n2, N \\ &0 \leq q_i^w - q_i^{red,do} \perp \mu_i^{rdo,max} \geq 0 \ ; \ \forall i \in \Omega_{c}, \Omega_{s}, n1, n2, N \end{split}$$

• Upwards integrated redispatch market:

$$\begin{split} -F_{NS}^{max} + \sum_{k \in S} D_k - \sum_{i \in S} q_i^w - \sum_{i \in S} q_i^{red,up} &= 0 \ ; \ \lambda_S^{red,up} \ \text{free} \\ 0 &\leq c_i - \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in \Omega_c, S \\ 0 &\leq \alpha_i^{red,up} - \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in \Omega_s, S \\ 0 &\leq q_i^{cap} - q_i^w - q_i^{red,up} \perp \mu_i^{rup,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, S \end{split}$$

A.5. Perfect competition in the WFRB market sequence (MCP)

• Wholesale market:

$$\sum_{k} D_{k} - \sum_{i} q_{i}^{w} = 0 ; \lambda^{w} \text{ free}$$
$$0 \le c_{i} - \lambda^{w} + \mu_{i}^{w,max} \perp q_{i}^{w} \ge 0 ; \forall i$$
$$0 \le q_{i}^{cap} - q_{i}^{w} \perp \mu_{i}^{w,max} \ge 0 ; \forall i$$

• Flexibility market:

$$\begin{split} F_{n1N}^{max} &- \sum_{i \in n1} q_i^w + \sum_{i \in n1} q_i^{flex} = 0 \ ; \ \lambda^{flex} \ \text{free} \\ 0 &\leq -c_i + \lambda^{flex} + \mu_i^{flex,max} \perp q_i^{flex} \geq 0 \ ; \ \forall i \in n1 \\ 0 &\leq q_i^w - q_i^{flex} \perp \mu_i^{flex,max} \geq 0 \ ; \ \forall i \in n1 \end{split}$$

• Downwards redispatch market:

$$\begin{split} -F_{n1N}^{max} + F_{NS}^{max} - \sum_{i \in \mathbb{N}, n2} q_i^w + \sum_{i \in n1, n2, N} q_i^{red, do} &= 0 \ ; \ \lambda^{red, do} \ \text{free} \\ 0 &\leq -c_i + \lambda^{red, do} + \mu_i^{rdo, max} \perp q_i^{red, do} \geq 0 \ ; \ \forall i \in n1, n2, N \\ 0 &\leq q_i^w - q_i^{flex} - q_i^{red, do} \perp \mu_i^{rdo, max} \geq 0 \ ; \ \forall i \in n1 \\ 0 &\leq q_i^w - q_i^{red, do} \perp \mu_i^{rdo, max} \geq 0 \ ; \ \forall i \in n2, N \end{split}$$

• Upwards redispatch market:

$$\begin{split} -F_{n1N}^{max} + F_{NS}^{max} - \sum_{k \in S} D_k + \sum_{i \in S} q_i^w + \sum_{i \in S} q_i^{red,up} - \sum_{i \in n1} q_i^w &= 0 \ ; \ \lambda_S^{red,up} \ \text{free} \\ 0 &\leq c_i + \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in S \\ 0 &\leq q_i^{cap} - q_i^w - q_i^{red,up} \perp \mu_i^{rup,max} \geq 0 \ ; \ \forall i \in S \end{split}$$

• Balancing market:

$$\begin{split} -F_{n1N}^{max} &- \sum_{i \in n2, N, S} q_i^{bal} + \sum_{i \in n1} q_i^w - \sum_{i \in n1} q_i^{red, do} = 0 \ ; \ \lambda^{bal} \ \text{free} \\ F_{n1N}^{max} &- F_{NS}^{max} - \sum_{i \in n2, N} q_i^{bal} + \sum_{i \in n2, N} q_i^w - \sum_{i \in n1, n2, N} q_i^{red, do} = 0 \ ; \ \lambda \ \text{free} \\ 0 &\leq c_i - \lambda^{bal} - \lambda + \mu_i^{bal, max} \perp q_i^{bal} \geq 0 \ ; \ \forall i \in n2, N \\ 0 &\leq q_i^{cap} - q_i^w + q_i^{red, do} - q_i^{bal} \perp \mu_i^{rup, max} \geq 0 \ ; \ \forall i \in n2, N \\ 0 &\leq c_i - \lambda^{bal} + \mu_i^{bal, max} \perp q_i^{bal} \geq 0 \ ; \ \forall i \in S \\ 0 &\leq q_i^{cap} - q_i^w - q_i^{red, up} - q_i^{bal} \perp \mu_i^{rup, max} \geq 0 \ ; \ \forall i \in S \end{split}$$

A.6. Strategic behaviour in the WFRB market sequence (MPEC) Upper-level:

$$\begin{split} \operatorname{Min} \sum_{i \in \Omega_{s}} (c_{i} - \lambda^{w}) q_{i}^{w} + \sum_{i \in \Omega_{s}} (\lambda^{flex} - c_{i}) q_{i}^{flex} + \sum_{i \in \Omega_{s}} (\lambda^{red, do} - c_{i}) q_{i}^{red, do} + \sum_{i \in \Omega_{s}} (c_{i} - \lambda^{red, up}) q_{i}^{red, up} + \sum_{i \in \Omega_{s}} (c_{i} - \lambda^{bal}) q_{i}^{bal} \\ & 0 \leq \alpha_{i}^{w} \leq \alpha_{i}^{max} ; \quad \forall i \in \Omega_{s} \\ & 0 \leq \alpha_{i}^{flex} \leq \alpha_{i}^{max} ; \quad \forall i \in \Omega_{s} \\ & 0 \leq \alpha_{i}^{red, do} \leq \alpha_{i}^{max} ; \quad \forall i \in \Omega_{s} \\ & 0 \leq \alpha_{i}^{red, up} \leq \alpha_{i}^{max} ; \quad \forall i \in \Omega_{s} \\ & 0 \leq \alpha_{i}^{bal} \leq \alpha_{i}^{max} ; \quad \forall i \in \Omega_{s} \end{split}$$

Lower-level:

• Wholesale market:

$$\sum_{k} D_{k} - \sum_{i} q_{i}^{w} = 0 \; ; \; \lambda^{w} \text{ free}$$
$$0 \leq c_{i} - \lambda^{w} + \mu_{i}^{w,max} \perp q_{i}^{w} \geq 0 \; ; \; \forall i \in \Omega_{c}$$
$$0 \leq \alpha_{i}^{w} - \lambda^{w} + \mu_{i}^{w,max} \perp q_{i}^{w} \geq 0 \; ; \; \forall i \in \Omega_{s}$$
$$0 \leq q_{i}^{cap} - q_{i}^{w} \perp \mu_{i}^{w,max} \geq 0 \; ; \; \forall i \in \Omega_{c}, \Omega_{s}$$

• Flexibility market:

$$\begin{split} F_{n1N}^{max} &- \sum_{i \in n1} q_i^w + \sum_{i \in n1} q_i^{flex} = 0 \ ; \ \lambda^{flex} \ \text{free} \\ 0 &\leq -c_i + \lambda^{flex} + \mu_i^{flex,max} \perp q_i^{flex} \geq 0 \ ; \ \forall i \in \Omega_c, \text{n1} \\ 0 &\leq -\alpha_i^{flex} + \lambda^{flex} + \mu_i^{flex,max} \perp q_i^{flex} \geq 0 \ ; \ \forall i \in \Omega_s, \text{n1} \\ 0 &\leq q_i^w - q_i^{flex} \perp \mu_i^{flex,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, \text{n1} \end{split}$$

• Downwards redispatch market:

$$\begin{split} -F_{n1N}^{max} + F_{NS}^{max} - \sum_{i \in n2,N} q_i^w + \sum_{i \in n1,n2,N} q_i^{red,do} &= 0 \ ; \ \lambda^{red,do} \ free \\ 0 &\leq -c_i + \lambda^{red,do} + \mu_i^{rdo,max} \perp q_i^{red,do} \geq 0 \ ; \ \forall i \in \Omega_c, n1, n2, N \\ 0 &\leq -\alpha_i^{red,do} + \lambda^{red,do} + \mu_i^{rdo,max} \perp q_i^{red,do} \geq 0 \ ; \ \forall i \in \Omega_s, n1, n2, N \\ 0 &\leq q_i^w - q_i^{flex} - q_i^{red,do} \perp \mu_i^{rdo,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n1 \\ 0 &\leq q_i^w - q_i^{red,do} \perp \mu_i^{rdo,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n2, N \end{split}$$

• Upwards redispatch market:

$$\begin{split} -F_{n1N}^{max} + F_{NS}^{max} - \sum_{k \in S} D_k + \sum_{i \in S} q_i^w + \sum_{i \in S} q_i^{red,up} - \sum_{i \in n1} q_i^w &= 0 \ ; \ \lambda^{red,up} \ \text{free} \\ 0 &\leq c_i + \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in \Omega_c, S \\ 0 &\leq \alpha_i^{red,up} + \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in \Omega_s, S \\ 0 &\leq q_i^{cap} - q_i^w - q_i^{red,up} \perp \mu_i^{rup,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, S \end{split}$$

• Balancing market:

$$\begin{split} -F_{n1N}^{max} - \sum_{i \in n2, N, S} q_i^{bal} + \sum_{i \in n1} q_i^w - \sum_{i \in n1} q_i^{red, do} &= 0 \ ; \ \lambda^{bal} \ \text{free} \\ F_{n1N}^{max} - F_{NS}^{max} - \sum_{i \in n2, N} q_i^{bal} + \sum_{i \in n2, N} q_i^w - \sum_{i \in n1, n2, N} q_i^{red, do} &= 0 \ ; \ \lambda \ \text{free} \end{split}$$

$$\begin{split} 0 &\leq c_i - \lambda^{bal} - \lambda + \mu_i^{bal,max} \perp q_i^{bal} \geq 0 \ ; \ \forall i \in \Omega_c, n2, N \\ 0 &\leq \alpha_i^{bal} - \lambda^{bal} - \lambda + \mu_i^{bal,max} \perp q_i^{bal} \geq 0 \ ; \ \forall i \in \Omega_s, n2, N \\ 0 &\leq q_i^{cap} - q_i^w + q_i^{red,do} - q_i^{bal} \perp \mu_i^{rup,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n2, N \\ 0 &\leq c_i - \lambda^{bal} + \mu_i^{bal,max} \perp q_i^{bal} \geq 0 \ ; \ \forall i \in \Omega_c, S \\ 0 &\leq \alpha_i^{bal} - \lambda^{bal} + \mu_i^{bal,max} \perp q_i^{bal} \geq 0 \ ; \ \forall i \in \Omega_s, S \\ 0 &\leq q_i^{cap} - q_i^w - q_i^{red,up} - q_i^{bal} \perp \mu_i^{rup,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, S \end{split}$$

A.7. Perfect competition in the WRFB market sequence (MCP)

• Wholesale market:

$$\begin{split} &\sum_{k} D_{k} - \sum_{i} q_{i}^{w} = 0 \ ; \ \lambda^{w} \, \text{free} \\ &0 \leq c_{i} - \lambda^{w} + \mu_{i}^{w,max} \perp q_{i}^{w} \geq 0 \ ; \ \forall i \\ &0 \leq q_{i}^{\text{cap}} - q_{i}^{w} \perp \mu_{i}^{w,max} \geq 0 \ ; \ \forall i \end{split}$$

• Downwards redispatch market:

$$\begin{split} F_{NS}^{max} &- \sum_{i \in n1, n2, N} q_i^w + \sum_{i \in n1, n2, N} q_i^{red, do} = 0 \ ; \ \lambda^{red, do} \ free \\ 0 &\leq -c_i + \lambda^{red, do} + \mu_i^{rdo, max} \perp q_i^{red, do} \geq 0 \ ; \ \forall i \in n1, n2, N \\ 0 &\leq q_i^w - q_i^{red, do} \perp \mu_i^{rdo, max} \geq 0 \ ; \ \forall i \in n1, n2, N \end{split}$$

• Upwards redispatch market:

$$\begin{split} &-F_{NS}^{max} + \sum_{k \in S} D_k - \sum_{i \in S} q_i^w - \sum_{i \in S} q_i^{red,up} = 0 \ ; \ \lambda_S^{red,up} \ \text{free} \\ & 0 \leq c_i - \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in S \\ & 0 \leq q_i^{cap} - q_i^w - q_i^{red,up} \perp \mu_i^{rup,max} \geq 0 \ ; \ \forall i \in S \end{split}$$

• Flexibility market:

$$\begin{split} F_{n1N}^{max} + \sum_{i \in n1} q_i^{red,do} - \sum_{i \in n1} q_i^w + \sum_{i \in n1} q_i^{flex} &= 0 \ ; \ \lambda^{flex} \ \text{free} \\ 0 &\leq -c_i + \lambda^{flex} + \mu_i^{flex,max} \perp q_i^{flex} \geq 0 \ ; \ \forall i \in n1 \\ 0 &\leq q_i^w - q_i^{red,do} - q_i^{flex} \perp \mu_i^{flex,max} \geq 0 \ ; \ \forall i \in n1 \end{split}$$

• Balancing market:

$$\begin{split} -F_{n1N}^{max} &- \sum_{i \in n2, N, S} q_i^{bal} + \sum_{i \in n1} q_i^w - \sum_{i \in n1} q_i^{red, do} = 0 \ ; \ \lambda^{bal} \ \text{free} \\ & 0 \leq c_i - \lambda^{bal} + \mu_i^{bal, max} \perp q_i^{bal} \geq 0 \ ; \ \forall i \in n2, N, S \\ & 0 \leq q_i^{cap} - q_i^w + q_i^{red, do} - q_i^{bal} \perp \mu_i^{rup, max} \geq 0 \ ; \ \forall i \in n2, N \\ & 0 \leq q_i^{cap} - q_i^w - q_i^{red, up} - q_i^{bal} \perp \mu_i^{rup, max} \geq 0 \ ; \ \forall i \in S \end{split}$$

A.8. Strategic behaviour in the WRFB market sequence (MPEC) Upper-level:

$$\begin{split} \operatorname{Min} \sum_{i \in \Omega_s} (c_i - \lambda^w) q_i^w + \sum_{i \in \Omega_s} (\lambda^{red, do} - c_i) q_i^{red, do} + \sum_{i \in \Omega_s} (c_i - \lambda^{red, up}) q_i^{red, up} + \sum_{i \in \Omega_s} (\lambda^{flex} - c_i) q_i^{flex} + \sum_{i \in \Omega_s} (c_i - \lambda^{bal}) q_i^{bal} \\ 0 \le \alpha_i^w \le \alpha_i^{max} ; \quad \forall i \in \Omega_s \end{split}$$

$$\begin{split} 0 &\leq \alpha_i^{red,do} \leq \alpha_i^{max} ; \ \forall i \in \Omega_s \\ 0 &\leq \alpha_i^{red,up} \leq \alpha_i^{max} ; \ \forall i \in \Omega_s \\ 0 &\leq \alpha_i^{flex} \leq \alpha_i^{max} ; \ \forall i \in \Omega_s \\ 0 &\leq \alpha_i^{bal} \leq \alpha_i^{max} ; \ \forall i \in \Omega_s \end{split}$$

Lower-level:

• Wholesale market:

$$\begin{split} &\sum_{k} D_{k} - \sum_{i} q_{i}^{w} = 0 \ ; \ \lambda^{w} \, \text{free} \\ &0 \leq c_{i} - \lambda^{w} + \mu_{i}^{w,max} \perp q_{i}^{w} \geq 0 \ ; \ \forall i \in \Omega_{c} \\ &0 \leq \alpha_{i}^{w} - \lambda^{w} + \mu_{i}^{w,max} \perp q_{i}^{w} \geq 0 \ ; \ \forall i \in \Omega_{s} \\ &0 \leq q_{i}^{\text{cap}} - q_{i}^{w} \perp \mu_{i}^{w,max} \geq 0 \ ; \ \forall i \in \Omega_{c}, \Omega_{s} \end{split}$$

• Downwards redispatch market:

$$\begin{split} F_{NS}^{max} &- \sum_{i \in n1, n2, N} q_i^w + \sum_{i \in n1, n2, N} q_i^{red, do} = 0 \ ; \ \lambda^{red, do} \ free \\ 0 &\leq -c_i + \lambda^{red, do} + \mu_i^{rdo, max} \perp q_i^{red, do} \geq 0 \ ; \ \forall i \in \Omega_c, n1, n2, N \\ 0 &\leq -\alpha_i^{red, do} + \lambda^{red, do} + \mu_i^{rdo, max} \perp q_i^{red, do} \geq 0 \ ; \ \forall i \in \Omega_s, n1, n2, N \\ 0 &\leq q_i^w - q_i^{red, do} \perp \mu_i^{rdo, max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n1, n2, N \end{split}$$

• Upwards redispatch market:

$$\begin{split} &-F_{NS}^{max} + \sum_{k \in S} D_k - \sum_{i \in S} q_i^w - \sum_{i \in S} q_i^{red,up} = 0 \ ; \ \lambda_S^{red,up} \ \text{free} \\ & 0 \leq c_i - \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in \Omega_c, S \\ & 0 \leq \alpha_i^{red,up} - \lambda^{red,up} + \mu_i^{rup,max} \perp q_i^{red,up} \geq 0 \ ; \ \forall i \in \Omega_s, S \\ & 0 \leq q_i^{cap} - q_i^w - q_i^{red,up} \perp \mu_i^{rup,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, S \end{split}$$

• Flexibility market:

$$\begin{split} F_{n1N}^{max} + \sum_{i \in n1} q_i^{red,do} &- \sum_{i \in n1} q_i^w + \sum_{i \in n1} q_i^{flex} = 0 \ ; \ \lambda^{flex} \ \text{free} \\ 0 &\leq -c_i + \lambda^{flex} + \mu_i^{flex,max} \perp q_i^{flex} \geq 0 \ ; \ \forall i \in \Omega_c, n1 \\ 0 &\leq -\alpha_i^{flex} + \lambda^{flex} + \mu_i^{flex,max} \perp q_i^{flex} \geq 0 \ ; \ \forall i \in \Omega_s, n1 \\ 0 &\leq q_i^w - q_i^{red,do} - q_i^{flex} \perp \mu_i^{flex,max} \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n1 \end{split}$$

• Balancing market:

$$\begin{split} -F^{max}_{n1N} &- \sum_{i \in n2, N, S} q^{bal}_i + \sum_{i \in n1} q^w_i - \sum_{i \in n1} q^{red, do}_i = 0 \ ; \ \lambda^{bal} \ \text{free} \\ & 0 \leq c_i - \lambda^{bal} + \mu^{bal, max}_i \perp q^{bal}_i \geq 0 \ ; \ \forall i \in \Omega_c, n2, N, S \\ & 0 \leq \alpha^{bal}_i - \lambda^{bal} + \mu^{bal, max}_i \perp q^{bal}_i \geq 0 \ ; \ \forall i \in \Omega_s, n2, N, S \\ & 0 \leq q^{cap}_i - q^w_i + q^{red, do}_i - q^{bal}_i \perp \mu^{rup, max}_i \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, n2, N \\ & 0 \leq q^{cap}_i - q^w_i - q^{red, up}_i - q^{bal}_i \perp \mu^{rup, max}_i \geq 0 \ ; \ \forall i \in \Omega_c, \Omega_s, S \end{split}$$



On the authors:

Ellen Beckstedde (ellen.beckstedde@vlerick.com) KU Leuven Department of Mechanical Engineering Division Applied Mechanics and Energy Conversion Celestijnenlaan 300 - post box 2421 B-3001 Leuven (Heverlee), Belgium and Vlerick Business School, Vlerick Energy Centre Bolwerklaan 21 B-1210 Brussels, Belgium

Leonardo Meeus (leonardo.meeus@vlerick.com)

Florence School of Regulation Robert Schuman Centre for Advanced Studies, European University Institute Via Boccaccio 121 I-50133 Florence, Italy and Vlerick Business School, Vlerick Energy Centre Bolwerklaan 21 B-1210 Brussels, Belgium

Erik Delarue (erik.delarue@kuleuven.be)

KU Leuven Department of Mechanical Engineering Division Applied Mechanics and Energy Conversion Celestijnenlaan 300 - post box 2421 B-3001 Leuven (Heverlee), Belgium and EnergyVille Thor Park 8310 B-3600 Genk, Belgium

On the research group:

More information about the Energy Systems Integration & Modeling Group can be found here.