Modeling Cross-Border Interactions of EU Balancing Markets: a Focus on Scarcity Pricing

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Abstract

The goal of scarcity pricing is to reflect more accurately the incremental value of reserve capacity in real-time operations, and thereby create a more favorable environment for investment in resources that can offer reserve services to the system. Scarcity pricing has recently been expanded in various US markets, and is being increasingly considered as a viable option forward for EU market design. The consideration of scarcity pricing by certain EU member states raises the question of how a unilateral implementation of the mechanism might affect neighboring markets. We present a simple stochastic equilibrium model for understanding the effects of a unilateral implementation of scarcity pricing on a two-zone illustrative example. We focus specifically on the implications of scarcity pricing on balancing market equilibrium and the back-propagation of scarcity adders in day-ahead markets. We comment on the insights derived from the model, and their institutional relevance.

Keywords: balancing markets; reserve markets; stochastic equilibrium; scarcity pricing; ORDC

1. Introduction

Although the US and EU electricity market designs differ considerably, both systems share a need for a market design that is capable of signaling a need for investment in "flexible" resources. Flexible resources, in the context of this chapter, are resources that are capable of offering balancing services in the form of reserves. Scarcity pricing is a market design that has been proposed for addressing this need. The design becomes especially relevant in a regime of large-scale renewable energy and distributed resource integration, where the system should become increasingly capable to adapt to the highly variable, largely unpredictable, and largely uncontrollable fluctuations of net demand.

The transposition of the scarcity pricing design from the US to the EU market requires a careful consideration of the commonalities and differences among the two market architectures. The common points and differences of these markets are analyzed in detail by Papavasiliou et al. (2019), and are not repeated here. Instead, the appendix of the present chapter, which is sourced from Papavasiliou et al. (2019), provides a glossary of market design terms that are related to the Belgian and Texas markets, as representative market design models of a typical EU and US design, respectively. The remainder of this chapter focuses on the specific topic of neighboring market interactions in the case of a unilateral implementation of scarcity pricing.

1.1. Scarcity Pricing in US Markets

Scarcity pricing (Hogan, 2005; Stoft, 2002) is a market mechanism for improving the valuation of reserve capacity. In US parlance, the mechanism corresponds to the introduction of an elastic demand curve in real-time markets that trade energy and reserves. This demand curve reflects the incremental value of reserve capacity in terms of improving system security. This demand curve is referred to as an **operating reserve demand curve**, abbreviated as **ORDC**. The mechanism becomes especially valuable in reflecting the real-time value of reserve capacity in regimes of large-scale renewable energy integration, and serves to attract various forms of "flexible" capacity to the system. The term flexible here refers to resources that can offer operating reserve, and includes demand response, combined cycle gas turbines, and other technologies that can respond rapidly to abrupt and unpredictable variations in system conditions.

The effect of introducing this demand curve in real-time market clearing is the emergence of a price signal, or ORDC adder, which is effectively a price for real-time reserve capacity, as well as an adder to the system lambda, i.e. an add-on to the real-time energy price. Although an ideal implementation of the mechanism would entail a real-time co-optimization of energy and reserves, in which case the adder would emerge automatically by virtue of the presence of the ORDC, the mechanism can also be implemented by an ex-post computation of the adder as a function of remaining reserve capacity in the system. Therefore, the real-time co-optimization of energy and reserves is not essential to the implementation of the mechanism (although the presence of a real-time market for reserve capacity *is* essential, as we discuss subsequently). Through appropriate market design, this real-time adder is back-propagated to forward (e.g. day-ahead) markets for reserve capacity. This back-propagation may rely on virtual trading, a day-ahead co-optimization of energy and reserves, or an internalization of opportunity costs (Papavasiliou et al., 2019).

1.2. Scarcity Pricing in EU Markets

In EU parlance, scarcity pricing amounts to (i) an introduction of the scarcity adder to the imbalance price, which affects the settlement of balancing responsible parties, and (ii) an introduction of the scarcity adder for settling the availability of real-time reserve capacity, which affects balancing service providers.

Scarcity pricing has recently gained traction among EU market design stakeholders. This is reflected in two important EU legal articles, the European Commission Electricity Balancing Guideline (EBGL), and the European Parliament Clean Energy Package (CEP). Concretely, article 44(3) of the EBGL and article 20(3) of the CEP refer to a **shortage pricing function**, as a mechanism that individual EU transmission system operators may decide to implement unilaterally.

The implementation of scarcity pricing in Belgium has been studied by Papavasiliou and Smeers (2017), Papavasiliou et al. (2018), and Papavasiliou et al. (2019). These investigations led to an ex-post simulation, by the Belgian transmission system operator ELIA, of the scarcity prices that would have transpired in Belgium in 2017 assuming the scarcity pricing mechanism had been in place for that year (ELIA, 2018). Since October 2019, the Belgian TSO publishes scarcity prices publicly online for information purposes, one day after real-time operations.

One important complication for the implementation of scarcity pricing in EU market design is that the EU lacks a real-time market for reserve capacity. This means that reserve imbalances are not settled in real time (for example, free bids are not remunerated in real time for the sake of being simply present and protecting the system). Reserve capacity is traded in forward (typically day-ahead) reserve capacity auctions, but not in real time. This creates serious, if not insurmountable, difficulties with the back-propagation of scarcity prices, since balancing service providers who sell reserve capacity in forward reserve markets are not liable for buying back that capacity against a real-time price if that reserve capacity is activated for providing balancing energy. Article 44.3 of the EBGL offers a possible way out by allowing a scarcity pricing function which can be decided unilaterally by TSOs. Such a scarcity pricing function can be designed in such a way as to emulate the effects of a real-time market for reserve capacity. This is not the focus of the present chapter, but it is an important institutional consideration related to the implementation of scarcity pricing.

1.3. Cross-Border Considerations

In light of the fact that article 44.3 of the EBGL allows for a unilateral implementation of scarcity pricing, the Belgian regulatory authority has raised questions about the cross-border effects of scarcity pricing. Concretely, suppose that Belgium implements the mechanism, whereas neighboring zones do not. How should the settlement exactly work out? And what could one expect in terms of balancing energy prices and day-ahead energy and reserve prices in neighboring zones?

We address these questions in the present chapter using a stochastic equilibrium model which is based on previous work by Papavasiliou et al. (2019). The origins of the stochastic equilibrium model draw from Ralph and Smeers (2015). Stochastic equilibrium has been applied in a context of capacity expansion planning in previous research, see Ehrenmann and Smeers (2011) for related applications.

Note that the stochastic equilibrium model that we present in this chapter does not require risk averse agents in order to provide useful insights. It can also provide useful insights in the case were all agents are risk neutral, because it explains the mechanism by which agents arbitrage real-time prices against day-ahead prices. Thus, the stochastic equilibrium framework provides a quantitative approach to explaining the back-propagation of energy and reserve prices in forward (e.g. day-ahead) markets when a change is introduced to the real-time market design (e.g. via the introduction of a scarcity adder). Further note that the stochastic equilibrium framework is, in a sense, required. The market model that we consider in this chapter features a missing market: the Dutch TSO does not trade reserve capacity in real time. The representation of this market incompleteness is impossible via an equivalent optimization model (Harker, 1993).

1.4. Structure of the Chapter

In the following section we present the stochastic equilibrium model that we employ. In section 3 we apply the model to a simple two-zone example which attempts to emulate, in rough strokes, the interaction of Belgium with the Netherlands. The model is purely conceptual, and is used for understanding concepts as opposed to providing a realistic market simulation. Nevertheless, the model provides interesting insights. These insights and their institutional implications are discussed in section 4. Section 5 concludes the chapter, and indicates promising areas of further analysis.

2. The Stochastic Equilibrium Model

In order to understand the basic principles of a unilateral implementation of scarcity pricing, we present in this section a transmission constrained stochastic equilibrium model. We will specifically assume (i) a uniform pricing of energy for BSPs and BRPs (both in Belgium as well as abroad), and (ii) a pricing of reserve capacity for BSPs (only in Belgium). Although the uniform pricing of energy for BSPs and BRPs in this stylized model deviates from actual practice in EU balancing market design, it is the first step in understanding the general principles. We proceed with the description of the model.

2.1. Real Time

Real-time Balancing Platform

We represent the function of the real-time platform (e.g. MARI) as a maximization of the value of available capacity. We use an ATC model between the two zones, so the only variable decided by the platform is the transportation of power from the Belgian zone to the Dutch zone. We assume an ATC model for the platform.

$$max_e \sum_{k=(m,n)\in K} (\rho_n - \rho_m) \cdot e_k$$
$$(\lambda_k^+): e_k \leq ATC_k^+, k \in K$$
$$(\lambda_k^-): -e_k \leq -ATC_k^-, k \in K$$

The KKT conditions are described as follows:

$$\rho_m - \rho_n + \lambda_k^+ - \lambda_k^- = 0, k = (m, n) \in K$$
$$0 \leq \lambda_k^+ \perp ATC_k^+ - e_k \geq 0, k \in K$$
$$0 \leq \lambda_k^- \perp e_k - ATC_k^- \geq 0, k \in K$$

The formulation is indicating that, if there is congestion in the m-to-n direction, then the price in location n is higher than the price in location m.

Generators in the Netherlands

Generators solve the following profit maximization, for every $g \in G_{NL}$:

$$max_p(\rho_{n(g)} - C_g) \cdot p_g$$
$$(\mu 1_g): p_g \leq P_g^+$$
$$p_g \geq 0$$

The KKT conditions are given as follows:

$$0 \leq \mu 1_g \perp P_g^+ - p_g \geq 0$$
$$0 \leq p_g \perp C_g - \rho_{n(g)} + \mu 1_g \geq 0$$

The notation $n(g)$ indicates the zone at which resource g is located.

Generators in Belgium

Generators in Belgium solve the following profit maximization, for every $g \in G_{BE}$:

$$max_{p,r}(\rho_{n(g)} - C_g) \cdot p_g + \rho_{n(g)}^R \cdot r_g$$
$$(\mu 1_g): p_g + r_g \leq P_g^+, k \in K$$
$$(\mu 2_g): r_g \leq R_g$$
$$p_g, r_g \geq 0$$

The KKT conditions are given as follows:

$$0 \leq \mu 1_g \perp P_g^+ - p_g - r_g \geq 0$$
$$0 \leq \mu 2_g \perp R_g - r_g \geq 0$$
$$0 \leq p_g \perp C_g - \rho_{n(g)} + \mu 1_g \geq 0$$
$$0 \leq r_g \perp -\rho_{n(g)}^R + \mu 1_g + \mu 2_g \geq 0$$

Loads

Loads solve the following profit maximization, for every $l \in L$:

$$max_d(V_l - \rho_{n(l)}) \cdot d_l$$
$$(\nu_l): d_l \leq D_{l\omega}^+$$
$$d_l \geq 0$$

The KKT conditions are given as follows:

$$0 \leq \nu_l \perp D_{l\omega}^+ - d_l \geq 0$$
$$0 \leq d_l \perp -V_l + \rho_{n(l)} + \nu_l \geq 0$$

It is straightforward to offer reserve provision to the load model, but does not affect the insights of the model.

Belgian Network Operator

The Belgian network operator is interested in reliability, procured in the form of reserve capacity through a demand curve.

$$max_{d^R} \sum_{l \in RL_{BE}} \left(V_l^R - \rho_{n(l)}^R\right) \cdot d_l^R$$
$$(\mu_l^R): d_l^R \leq D_l^{R,+}, l \in RL_{BE}$$
$$d_l^R \geq 0, l \in RL_{BE}$$

where RL_{BE} is the set of ORDC segments of the Belgian TSO.

The KKT conditions are given as follows:

$$0 \leq \mu_l^R \perp D_l^{R,+} - d_l^R \geq 0$$
$$0 \leq d_l^R \perp -V_l^R + \rho_{n(l)}^R + \mu_l^R \geq 0$$

Market Clearing

The energy market clearing conditions are described as follows for every $z \in Z$:

$$\sum_{l \in L_z} d_l + \sum_{k=(z,\cdot)} e_k - \sum_{g \in G_z} p_g - \sum_{k=(\cdot,z)} e_k = 0$$

Note that there are no explicit market clearing conditions for transmission rights.

The reserve market clearing condition for Belgium is described as follows:

$$\sum_{l \in RL_{BE}} d_l^R - \sum_{g \in G_{BE}} r_g = 0$$

2.2. Day Ahead

Day-Ahead Market Clearing Platform

The day-ahead market clearing platform (EUPHEMIA) maximizes the day-ahead value of the network by solving the following optimization (analogous to the balancing platform in real time):

$$max_e \sum_{k=(m,n) \in K} (\rho_n - \rho_m) \cdot e_k$$
$$(\lambda_k^+): e_k \leq ATC_k^+, k \in K$$
$$(\lambda_k^-): -e_k \leq -ATC_k^-, k \in K$$

The KKT conditions are described as follows:

$$\rho_m - \rho_n + \lambda_k^+ - \lambda_k^- = 0, k = (m,n) \in K$$
$$0 \leq \lambda_k^+ \perp ATC_k^+ - e_k \geq 0, k \in K$$

$$0 \leq \lambda_k^- \perp e_k - ATC_k^- \geq 0, k \in K$$

Generators in Belgium

The real-time profit is used for formulating the day-ahead generator profit maximization. This parameter is computed once the real-time model has been solved. The real-time profit is expressed as follows for each $g \in G_{BE}$:

$$\Pi_{g\omega}^{RT} = \left(\rho_{BE,\omega}^{RT,*} - C_g\right) \cdot p_{g\omega}^* + \rho_\omega^{R,RT,*} \cdot r_{g\omega}^*,$$

where $p_{g\omega}^*$ and $r_{g\omega}^*$ are the optimal solutions of the real-time model, and where $\rho_{z,\omega}^{RT,*}$ and $\rho^{R,RT,*}$ is the equilibrium real-time energy price and real-time reserve price respectively.

Each generator $g \in G_{BE}$ solves the following problem:

$$max_{p,r,VaR,u}\, \rho_{n(g)} \cdot p_g + \rho_{n(g)}^R \cdot r_g + VaR_g - \frac{1}{\alpha_g} \sum_{\omega \in \Omega} P_\omega \cdot u_{g\omega}$$

$$\left(q_{g\omega}\right): u_{g\omega} \geq VaR_g - (\Pi_{g\omega}^{RT} - \rho_{n(g),\omega}^{RT,*} \cdot p_g - \rho_\omega^{R,RT,*} \cdot r_g)$$

$$\left(\mu 2_g\right): r_g \leq R_g$$

$$u_{g\omega} \geq 0$$

The KKT conditions can be expressed as follows for every $g \in G_{BE}$:

$$0 \leq u_{g\omega} \perp \frac{P_\omega}{\alpha_g} - q_{g\omega} \geq 0, \omega \in \Omega$$

$$\left(p_g\right): \sum_{\omega \in \Omega} q_{g\omega} \cdot \rho_{n(g),\omega}^{RT,*} - \rho_{n(g)} = 0$$

$$0 \leq r_g \perp \sum_{\omega \in \Omega} q_{g\omega} \cdot \rho_{n(g),\omega}^{RT,*} - \rho_{n(g)}^R + \mu 2_g \geq 0$$

$$\left(VaR_g\right): \sum_{\omega \in \Omega} q_{g\omega} = 1$$

$$0 \leq q_{g\omega} \perp u_{g\omega} - VaR_g + \Pi_{g\omega}^{RT} - \rho_{n(g),\omega}^{RT,*} \cdot p_g - \rho_\omega^{R,RT,*} \cdot r_g \geq 0, \omega \in \Omega$$

$$0 \leq \mu 2_g \perp R_g - r_g \geq 0$$

Note that we allow for virtual trading of energy, but not of reserves, since we introduce a ramp rate constraint for units, which limits the amount of day-ahead reserve capacity that they can trade.

Generators in the Netherlands

Dutch generators $g \in G_{NL}$ only access the energy market in real time:

$$\Pi_{g\omega}^{RT} = \left(\rho_{NL,\omega}^{RT,*} - C_g\right) \cdot p_{g\omega}^*.$$

The day-ahead optimization of Dutch generators is expressed as follows, for every $g \in G_{NL}$:

$$max_{p,r,VaR,u}\, \rho_{n(g)} \cdot p_g + \rho^R_{n(g)} \cdot r_g + VaR_g - \frac{1}{\alpha_g} \sum_{\omega \in \Omega} P_\omega \cdot u_{g\omega}$$

$$(q_{g\omega}): u_{g\omega} \geq VaR_g - (\Pi^{RT}_{g\omega} - \rho^{RT,*}_{n(g),\omega} \cdot p_g)$$

$$(\mu 2_g): r_g \leq R_g$$

$$u_{g\omega} \geq 0$$

The KKT conditions can be expressed as follows for every $g \in G_{NL}$:

$$0 \leq u_{g\omega} \perp \frac{P_\omega}{\alpha_g} - q_{g\omega} \geq 0, \omega \in \Omega$$

$$(p_g): \sum_{\omega \in \Omega} q_{g\omega} \cdot \rho^{RT,*}_{n(g),\omega} - \rho_{n(g)} = 0$$

$$0 \leq r_g \perp -\rho^R_{n(g)} + \mu 2_g \geq 0$$

$$(VaR_g): \sum_{\omega \in \Omega} q_{g\omega} = 1$$

$$0 \leq q_{g\omega} \perp u_{g\omega} - VaR_g + \Pi^{RT}_{g\omega} - \rho^{RT,*}_{n(g),\omega} \cdot p_g \geq 0, \omega \in \Omega$$

$$0 \leq \mu 2_g \perp R_g - r_g \geq 0$$

Loads

As in the case of generators, we need to first compute real-time profits for all $l \in L$, $\omega \in \Omega$:

$$\Pi^{RT}_{l\omega} = \left(V_l - \rho^{RT,*}_{n(l),\omega}\right) \cdot d^*_{l\omega}.$$

Loads solve the following profit maximization in all zones, i.e. for all $l \in L$:

$$max_{d,VaR,u} - \rho_{n(l)} \cdot d_l + VaR_l - \frac{1}{\alpha_l} \sum_{\omega \in \Omega} P_\omega \cdot u_{l\omega}$$

$$(q_{l\omega}): u_{l\omega} \geq VaR_l - (\Pi^{RT}_{l\omega} + \rho^{RT,*}_{n(l),\omega} \cdot d_l)$$

$$u_{l\omega} \geq 0$$

The KKT conditions are expressed as follows for all $l \in L$:

$$0 \leq u_{l\omega} \perp \frac{P_\omega}{\alpha_l} - q_{l\omega} \geq 0, \omega \in \Omega$$

$$(d_l): \rho_{n(l)} - \sum_{\omega \in \Omega} q_{l\omega} \cdot \rho^{RT,*}_{n(l),\omega} = 0$$

$$0 \leq r_g \perp -\rho^R_{n(g)} + \mu 2_g \geq 0$$

$$(VaR_l): \sum_{\omega \in \Omega} q_{l\omega} = 1$$

$$0 \leq q_{l\omega} \perp u_{l\omega} - VaR_l + \Pi^{RT}_{l\omega} + \rho^{RT,*}_{n(l),\omega} \cdot d_l \geq 0, \omega \in \Omega$$

It is straightforward to offer reserve provision to the load model, but does not affect the insights of the model.

Network Operator

The network operator of each zone $z \in Z$ solves the following for procuring day-ahead reserve capacity:

$$max_{d^R} \sum_{l \in RL_z} \left(V_l^R - \rho_{n(l)}^R\right) \cdot d_l^R$$

$$(\mu_l^R): d_l^R \leq D_l^{R,+}, l \in RL_z$$

$$d_l^R \geq 0, l \in RL_z$$

where RL_{BE} is the set of ORDC segments of the Belgian TSO.

The KKT conditions are given as follows:

$$0 \leq \mu_l^R \perp D_l^{R,+} - d_l^R \geq 0$$

$$0 \leq d_l^R \perp -V_l^R + \rho_{n(l)}^R + \mu_l^R \geq 0$$

Note that the behavior of the network operator is notably different from that of the market agents. The network operator is represented in the day-ahead market with a day-ahead demand curve, which is fundamentally different from the producers and consumers, who do not incur any physical cost or benefit in the day ahead, but rather engage in a purely financial position.

Market Clearing

The following day-ahead energy market clearing condition c

$$\sum_{l \in L_z} d_l + \sum_{k=(z,\cdot)} e_k - \sum_{g \in G_z} p_g - \sum_{k=(\cdot,z)} e_k = 0$$

Transmission rights are not traded explicitly, but rather implicitly within the day-ahead market clearing platform, so we represent this implicit trading through the maximization of network value in the day-ahead platform.

We also have the following market clearing condition for day-ahead reserve capacity for every zone $z \in Z$:

$$\sum_{l \in RL_z} d_l^R - \sum_{g \in G_z} r_g = 0$$

3. Application on a Two-Zone System

We consider a stylized two-zone example, with the two zones connected by a link of limited capacity. We limit our analysis to a two-zone model in order to understand the effects that are at play. The model is depicted in the following Figure. The available transfer capacity of the link in both directions is assumed to be equal to 1000 MW.

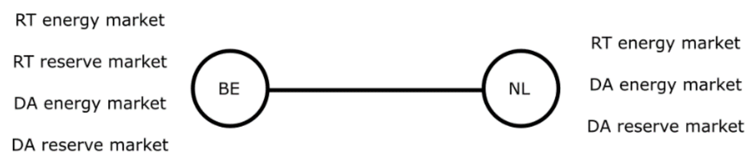

Fig. 1. The two-zone test system that is analyzed in section 3.

The system consists of the capacities described in the following table[1]. The valuation of the consumers in each zone is assumed equal to 8300 €/MWh, which is the estimate of the Belgian Federal Bureau for the value of lost load in Belgium (Papavasiliou et al., 2018). We assume a demand of 13.1 GW for the Netherlands, and a demand of 8.2 GW for Belgium in the base scenario.

Table 1. Generation resources in the example of section 3.

Name	Capacity (MW)	Marginal cost (€/MWh)	Zone
CoalNL	3400	35	NL
GasNL	5400	65	NL
RenewableNL	5000	0	NL
NucBE	5000	7	BE
OtherBE	3000	40	BE
GasBE	1000	70	BE

We introduce uncertainty into the model by considering two different scenarios:

1. A scenario where neither system is experiencing scarcity.
2. A scenario where the Belgian system is experiencing scarcity, and the Dutch one is not. We want this scenario to correspond to a situation where Belgium uses Dutch reserves, and we want to understand how these activated reserves should be paid for. We consider a case in which the link is not congested in our numerical simulations, although the model is general enough to also represent the case of a congested link.

We will assume that scarcity originates from variations in net demand, as opposed to loss of generation capacity. We present net demand scenarios in the following table. These scenarios cover cases 1 and 2 above.

Table 2. Scenarios in the stochastic model.

Scenario	Demand BE (MW)	Demand NL (MW)	Probability
Base	8200	13100	0.99
Scarcity	9100	13100	0.01
Scarcity section 3.5	8900	13700	0.01

In the following sections, we build the model incrementally, and analyze the equilibrium outcomes by adding one feature at a time. This allows us to understand the effect of each market design component. Specifically, in section 3.1 we consider a market that only trades energy in real time. In section 3.2 we introduce a market for real-time reserve capacity **only** in Belgium. In section 3.3 we introduce a day-ahead energy market, and analyze the back-propagation of energy prices. In section 3.4, we introduce a day-ahead reserve market, and analyze the formation of day-ahead reserve prices. In section 3.5 we consider a scenario of scarcity which captures the focus of our analysis: what happens when the Belgian system is so tight that it needs to rely on neighboring balancing energy to the extent of depleting the neighboring markets' resources?

[1] Dutch gas units are assumed to be newer and more efficient than Belgian gas units.

3.1. Market for Real-Time Energy in Both Zones

We first consider the equilibrium in each of the scenarios of the previous table. The results of the market clearing are presented in the following table.

Table 3. Market clearing results for the model of section 3.1.

	Base	Scarcity	Scarcity section 3.5
Energy price NL (€/MWh)	65	70	70
Energy price BE (€/MWh)	65	70	70
CoalNL prod (MW)	3400	3400	3400
GasNL prod (MW)	4900	5400	5400
RenewableNL prod (MW)	5000	5000	5000
NucBE prod (MW)	5000	5000	5000
OtherBE prod (MW)	3000	3000	3000
GasBE prod (MW)	0	400	800
Flow NL-BE (MW)	200	700	100

In the base scenario, the equilibrium energy price is 65 €/MWh in both zones. The flow is 200 MW along the interconnector, from NL to BE, however the link is not congested, and this explains the equal prices. The marginal resource is gas in the Netherlands. In the scarcity scenario, the equilibrium energy price is 70 €/MWh in both zones. The flow is 700 MW along the interconnector, from NL to BE, however the link is not congested, and this explains the equal prices. The marginal resource is gas in Belgium. In the scarcity scenario of section 3.5, the equilibrium energy price is again 70 €/MWh. The marginal resource is gas in Belgium, and the import of power from the Netherlands is 100 MW, since this scenario involves higher demand in the Netherlands and lower demand in Belgium, relative to the scarcity scenario of the third column of the table. The scarcity scenario of section 3.5 exhibits similar behavior, with Dutch gas units being marginal, and with less imports from the Netherlands to Belgium.

3.2. Market for Real-Time Reserve Capacity in Belgium but not in the Netherlands

We introduce next a real-time ORDC for Belgium, but not for the Netherlands. We construct this ORDC by using three segments, which we present in the following table. Note that the valuation for reserve capacity beyond RL3 is 0 €/MWh.

Table 4. Reserve demand curve (ORDC) for the Belgian real-time reserve market.

ORDC segment	Width (MW)	Valuation (€/MWh)
RL1	200	8000
RL2	100	20
RL3	100	8

The results of the market clearing are presented in the following table.

Table 5. Market clearing results for the model of section 3.2.

	Base scenario	Scarcity scenario
Energy price NL (€/MWh)	65	70
Energy price BE (€/MWh)	65	70
Reserve price BE (€/MWh)	8	8
CoalNL prod (MW)	3400	3400
GasNL prod (MW)	4900	5400

RenewableNL prod (MW)	5000	5000
NucBE prod (MW)	5000	5000
OtherBE prod (MW)	3000	3000
GasBE prod (MW)	0	400
Flow NL-BE (MW)	200	700
Reserve BE (MW)	350	350

The energy price is consistent with the reserve price in Belgium. Note that the reserve price is non-zero, and equal to 8 €/MWh in both scenarios. The non-zero reserve price can be understood from the point of view of the gas units in Belgium, which are offering both reserve and energy. On the reserve service, the Belgian gas unit is earning a positive profit, and is indeed limiting its supply of reserve due to its ramp limit. The unit is indifferent about how much energy to offer in the energy market, since the profit margin of the energy market is zero, which is consistent with the fact that the Belgian gas unit is producing a non-zero quantity. Effectively, the reserve price is set from the ORDC, since at 350 MW we are in the interior of the third segment of the ORDC, which is valued at 8 €/MWh.

Note that we assume that the Dutch market does not have a market for real-time reserve capacity, hence the table does not have a "Reserve NL" row. On the other hand, the Belgian market can source real-time energy from the Netherlands.

3.3. Day-Ahead Energy Market

Having introduced real-time markets for energy for both zones and a real-time market for reserve in Belgium, we now introduce virtual trading and a day-ahead energy market in both zones. For this purpose, we rely on a risk measure for agents. We use Conditional Value at Risk (CVaR), for which risk neutrality is a special case (whereby the risk coefficient α_g is equal to 1 for all agents, and the risk-neutral probability $q_{g\omega}$ is equal to the physical probability measure P_ω for all scenarios and all agents). The formulation is explained in section 2. The results of the model are presented in the following table.

Table 6. Market clearing results for the model of section 3.3.

	Base scenario real time	Scarcity scenario real time	Day-ahead
Energy price NL (€/MWh)	65	70	65.05
Energy price BE (€/MWh)	65	70	65.05
Reserve price BE (€/MWh)	8	8	N/A
CoalNL prod (MW)	3400	3400	3284.9
GasNL prod (MW)	4900	5400	5317.4
RenewableNL prod (MW)	5000	5000	4917.2
NucBE prod (MW)	5000	5000	3683.1
OtherBE prod (MW)	3000	3000	376.8
GasBE prod (MW)	0	400	22.1
Flow NL-BE (MW)	200	700	304.7
Reserve BE (MW)	350	350	N/A

The result of the equilibrium is a day-ahead energy price of 65.05 €/MWh for both zones, which is the weighted average of the real-time energy prices. Note that we have assumed virtual trading implicitly in our model, in the sense that the day-ahead production / demand of producers / consumers is not limited by physical limitations related to the maximum production or consumption capacity of these resources. Mathematically, this is represented by the fact that the day-ahead generator model of the Belgian generators does not include a constraint of the type $p_g + r_g \leq P_g^+$. Note, however, that Belgian generators are not allowed to trade reserve capacity virtually, which means mathematically that we impose the constraint $r_g \leq R_g$ in the day-ahead model of the Belgian generators. We have observed in previous work (Papavasiliou et al., 2019) that the virtual trading assumption has minor implications for the equilibrium outcome in the risk-neutral case.

3.4. Day-Ahead Reserve Market

We now proceed to introduce a day-ahead market for reserve capacity to the model. Note that we now have a different reserve market for each zone. We assume that the day-ahead reserve capacity auctions are conducted simultaneously with the day-ahead energy auctions. In practice, reserve capacity auctions precede the auctioning of energy in the Belgian market. We have shown in previous analysis (Papavasiliou et al., 2019) that the sequential and simultaneous clearing produce similar outcomes in risk-neutral models.

All operating reserve demand curves in this model (day-ahead reserve demand curve of Belgium and Netherlands, as well as real-time reserve demand curve of Belgium) are assumed to follow the specifications of Table 4. The results of the model are presented in the following table. In practice, the existing day-ahead reserve demand curves in Belgium are essentially inelastic (in the sense that the Belgian TSO sets hard reserve requirements). The model can be easily adapted to handle inelastic day-ahead reserve requirements by adapting the parameters of Table 4 accordingly.

Note that there is no "transportation" of reserve capacity, which means that each zone can only satisfy its local reserve requirements with its local reserve resources. We comment on this assumption in the sequel. The results of the model are presented in the following table.

Table 7. Market clearing results for the model of section 3.4.

	Base scenario real time	Scarcity scenario real time	Day-ahead
Energy price NL (€/MWh)	65	70	65.05
Energy price BE (€/MWh)	65	70	65.05
Reserve price BE (€/MWh)	8	8	8
Reserve price NL (€/MWh)	N/A	N/A	8
CoalNL prod (MW)	3400	3400	3284.9
GasNL prod (MW)	4900	5400	5317.4
RenewableNL prod (MW)	5000	5000	4917.2
NucBE prod (MW)	5000	5000	3683.1
OtherBE prod (MW)	3000	3000	376.8
GasBE prod (MW)	0	400	22.1
Flow NL-BE (MW)	200	700	304.7
Reserve BE (MW)	350	350	326.1
Reserve NL (MW)	N/A	N/A	350

The Belgian and Dutch day-ahead reserve price becomes 8 €/MWh. There are 326.1 MW of reserve sourced from Belgium, and 350 MW of reserve sourced from the Netherlands. The day-ahead equilibrium of the Belgian reserve capacity market is illustrated in the following figure. The situation is identical for the Dutch market.

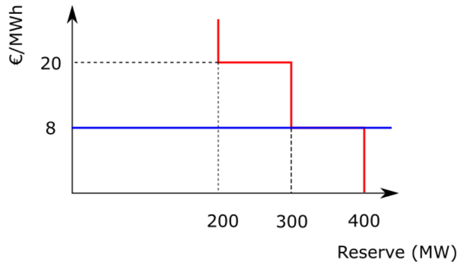

Fig. 2. The day-ahead reserve market equilibrium for the Belgian market (identical for the Dutch market). The red curve represents the demand curve of the TSO for reserve capacity. The blue curve represents the supply curve of BSPs for reserve capacity. Due to quantity indeterminacy, any clearing quantity between 300 and 400 MW is a valid day-ahead equilibrium.

The non-zero reserve price is driving the reserve supply to 350 MW in the Netherlands, which is the ramp rate of the gas units in the Dutch system. From the point of view of Dutch resources, this is consistent with generator incentives, because every MW offered in the day-ahead reserve market represents a posit profit margin for Dutch units. The reserve supply in Belgium is 326.1 MW, which is consistent with Belgian gas units' incentives, since Belgian reserve providers are indifferent between selling the reserve capacity in the day-ahead reserve price, or in the average real-time reserve price. Note that we assume, in this model, that Dutch generators which offer reserves are not held accountable for holding this capacity available in real time. We have shown in previous work (Papavasiliou et al., 2019) that this can lead to a significant under-valuation of reserves in the Netherlands (compared to a scarcity pricing mechanism, or compared to the obligation of carrying this reserve capacity in real time).

3.5. Leaning on Dutch Resources

We proceed to analyze a situation in which the Dutch system is tight to the point of having leftover capacity which is less than its day-ahead reserve requirement. We specifically consider a case where the demand in the scarcity scenario is 8900 MW in Belgium and 13700 MW in the Netherlands, as shown in Table 2. The reason that this choice of values is interesting is that (i) it avoids the unrealistic case where Belgian capacity is exceeded by Belgian demand, while (ii) leaving only 100 MW of reserve available in the Netherlands and 100 MW in Belgium. This implies that we expect tension between the provision of reserve in Belgium, and the Netherlands, and we are interested in understanding where the market equilibrates under such conditions. The results of the model are presented in the following table.

Table 8. Market clearing results for the model of section 3.5.

	Base scenario real time	Scarcity scenario real time (model)	Scarcity scenario real time (platform)	Day-ahead
Energy price NL (€/MWh)	65	90.3	70	65.25
Energy price BE (€/MWh)	65	90.3	70	65.25
Reserve price BE (€/MWh)	8	20.3	N/A	8.12
Reserve price NL (€/MWh)	8	N/A	N/A	8
CoalNL prod (MW)	3400	3400	3400	6756.5
GasNL prod (MW)	4900	5400	5400	7334.8
RenewableNL prod (MW)	5000	5000	5000	6990.4
NucBE prod (MW)	5000	5000	5000	8444.1
OtherBE prod (MW)	3000	3000	3000	7057
GasBE prod (MW)	0	800	800	5774.6

Flow NL-BE (MW)	200	100	100	59.6
Reserve BE (MW)	350	200	N/A	300
Reserve NL (MW)	N/A	N/A	N/A	350

We obtain the following results from the model: a real-time energy price of 65 €/MWh in the base scenario, for both zones; a real-time energy price of 90.3 €/MWh in the scarcity scenario, for both zones; and a day-ahead reserve price of 8 €/MWh in the Netherlands and 8.12 €/MWh in Belgium. The 20.3 €/MWh price for real-time reserve capacity in Belgium under the scarcity scenario is compatible with the leftover reserve capacity in Belgium. Concretely, since 200 MW of reserve remain available in Belgium, any reserve price between 20 €/MWh and 8000 €/MWh is compatible with the Belgian real-time operating reserve demand curve.

The effect of the tighter situation, therefore, is to lift reserve prices slightly in the day-ahead market for Belgium, whereas the price in the Netherlands is not affected. Note that the remainder of real-time reserve capacity in the Netherlands is zero (since all of its balancing capacity is used to cover the needs of Belgium), but this is anyways consistent with the loose definition of reserve as capacity that is only sold in the day ahead without any real-time obligation to keep any of it available after activation. It is also interesting to note that any excess capacity that remains in the system is available in Belgium, *not* the Netherlands: the Belgian gas units keep 200 MW of reserve available in real time. Thus, Belgium is relying on foreign resources to cover its real-time energy needs, and the 200 MW of excess reserve that are available throughout the entire system are actually reserved for Belgium.

In column 4 of the table, we have repeated the results of column 4 of Table 3. We now label these results as "Scarcity scenario real time (platform)". These are the results that would have been produced by a balancing platform (e.g. PICASSO or MARI) under truthful bidding. Since such platforms do not co-optimize energy and reserves, the prices that emerge may not be consistent with a co-optimization of energy and reserve. In section 4.1 we discuss how articles 18.4(d) and 44.3 of the EBGL could be invoked to remedy this effect.

We compare the equilibrium solution to what would occur in a business-as-usual case in which Belgium does not operate a real-time market for reserve capacity. The results are presented in the following table.

Table 9. Business-as-usual results for the model of section 3.5.

	Base scenario real time	Scarcity scenario real time	Day-ahead
Energy price NL (€/MWh)	65	70	65.05
Energy price BE (€/MWh)	65	70	65.05
Reserve price BE (€/MWh)	N/A	N/A	8
Reserve price NL (€/MWh)	N/A	N/A	8
CoalNL prod (MW)	3400	3400	2954
GasNL prod (MW)	4900	5400	4659.2
RenewableNL prod (MW)	5000	5000	4317.8
NucBE prod (MW)	5000	5000	4603.5
OtherBE prod (MW)	3000	3000	2773.6
GasBE prod (MW)	0	800	346.4
Flow NL-BE (MW)	200	100	-27.6
Reserve BE (MW)	N/A	N/A	350
Reserve NL (MW)	N/A	N/A	350

In this case, the day-ahead reserve capacity price amounts to 8 €/MWh for both Belgium and the Netherlands.

4. Discussion

4.1. Equilibrium Model Solutions versus Actual Platform Outcomes

The equilibrium model that we present in this chapter assumes a co-optimization of reserve and energy in Belgium in real time. In practice, a balancing platform will receive bids from BSPs and dispatch on the basis of these bids without performing such an endogenous co-optimization. This can be represented in our model by using the results of the platform as hard constraints in the real-time equilibrium. Concretely, we would need to enforce that, for the models which include reserve capacity in real time (sections 3.2 – 3.5) that the real-time production and market clearing prices should obey the results of the model of section 3.1. This can be enforced as a hard constraint in principle, and we can observe from the results of sections 3.1 – 3.4 that it holds anyway for our specific instance.

In the general case, this additional requirement may result in an infeasible equilibrium model, in the sense that the outcome of the balancing platform may be incompatible with a real-time co-optimization of energy and reserves. This is the case, for example, in Table 8, where we observe that the real-time energy price in Belgium and the Netherlands in the model is 90.3 €/MWh, whereas the balancing platform would produce a price of 70 €/MWh. Forcing the price in the stochastic equilibrium model to 70 €/MWh is infeasible.

Even if the a balancing platform which does not trade energy cannot reproduce the result of a co-optimization of energy and reserve, scarcity pricing can be emulated indirectly, by an ex post settlement. Concretely, article 18.4(d) of the EBGL attributes a BSP to an associated BRP, and article 44.3 of the EBGL allows the possibility of introducing an additional settlement mechanism separate from imbalance settlement. Scarcity pricing can therefore be implemented by (i) introducing the scarcity adder to the imbalance settlement (see article 52.2(d) of the EBGL), payable by BRPs, (ii) keeping the platform settlement price for activated energy, and (iii) introducing two terms, related to the real-time value of balancing energy and to reserve capacity imbalance, as foreseen by article 44.3 of the EBGL.

4.2. Institutional Considerations

An underlying institutional concern of this analysis has been to understand how the proposed mechanism should interact with neighboring BSPs and BRPs. Note that this is in fact not a concern, according to the design considered in our model. The balancing platforms will produce a *local* zonal energy price for each BSP in the market. Zones which apply scarcity pricing settle their BRPs (and the associated BSPs of each BRP) according to the standard scarcity pricing formulas (Papavasiliou et al., 2019), whereas zones which do not apply scarcity pricing are not affected. Concretely, Dutch resources will pay the Dutch zonal price, and therefore they are *not* directly affected by the adder settlements (even if the adder may have an effect on the equilibrium outcome of the balancing platform). The fact that Dutch resources are being activated in order to address a Belgian scarcity incident is not at odds with the fact that these Dutch resources are supplying their balancing energy in the Dutch zone, and the balancing platforms produce a price for this balancing energy.

There is no need for violating the merit order of the balancing platform in order to arrive to the equilibrium outcome of section 3.5. It is indeed true that, with a marginal cost of 70 €/MWh for Belgian gas units, one would expect that a balancing price of 90.4 €/MWh would result in an activation of these units. Instead, these units are kept as spare reserve capacity. Nevertheless, this can happen if the Belgian gas units incorporate the opportunity cost of using up their real-time reserve capacity into their balancing offer to the balancing platform, which is effectively what the equilibrium model is capturing. If neighboring Dutch BSPs are not exposed to real-time markets for reserve capacity in the Netherlands, they anyways would not internalize the cost of delivering this reserve in real time to their day-ahead reserve capacity auction bids.

This discussion underscores the importance of applying scarcity pricing for reserve imbalance settlements (equivalently, putting in place a real-time market for reserve capacity), and not limiting the application of the adder as an add-on to imbalance charges. Indeed, if scarcity adders would only be limited to add-ons on the imbalance price, then one could envision that Belgian BSPs might lower their marginal price so that they would be selected at the expense of imported bids from foreign BSPs. This would raise a concern among foreign NRAs as a violation of the (common) merit order: if the scarcity adder is applicable if the import potential is not fully used, then the perception is that Belgian BSPs push away foreign BSPs. By contrast, the application of scarcity pricing, as it is intended, for settling not only real-time energy *but also* real-time reserve capacity, would eliminate the interest for Belgian BSPs to mark down their bids, since whatever Belgian BSPs gain on the margin from providing balancing energy is balanced off from using up reserve capacity during activation. What remains is the incentive for Belgian BSPs to internalize the real-time adders in their day-ahead reserve capacity bids, which would serve towards back-propagating real-time scarcity adders to day-ahead reserve prices in Belgium.

5. Conclusions and Perspectives

We can draw the following conclusions from our analysis of the simplified model:

- A unilateral implementation of ORDC in Belgium does not affect the day-ahead reserve price of the Netherlands.
- A unilateral implementation of ORDC in Belgium increases the day-ahead reserve price in Belgium.
- A unilateral implementation of ORDC in Belgium increases the real-time energy price in the Netherlands under conditions of scarcity.
- The approach appears to be compatible with the provisions of the EBGL:
    - Only Belgian resources are affected by the settlement, therefore there is no application of an adder on foreign balancing resources.
    - The merit order of the balancing platform (e.g. MARI) is respected, opportunity costs can be incorporated by Belgian resources in their balancing offers.

For the moment, it is not possible for Belgium to procure reserve capacity in the day-ahead time frame from neighboring zones, e.g. the Netherlands. It will be possible to procure reserve capacity in the future from neighbors (though there is no hard date yet) according to article 33 of the EBGL by joining a balancing cooperation region. Joining a balancing cooperation region requires using one of the techniques that are described in articles 40-43 of the EBGL, which amounts to either (i) a so-called co-optimized allocation of cross-zonal capacity or (ii) a so-called market-based allocation. Either of the two aforementioned techniques will determine what part of cross-zonal capacity in the day ahead will be reserved for exchanging balancing capacity. This allocation of balancing capacity and cross-zonal transmission capacity would take place before the day-ahead energy market in case of market-based allocation; in case of co-optimized allocation it will take place during the day-ahead energy market. In future work, therefore, we are interested in developing equilibrium models that inform how settlements should be arranged when Dutch generators can sell reserve capacity to Belgium in the day ahead. This includes a clarification of the roles and responsibilities related to the procurement of transmission rights for delivering the reserve capacity.

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Acronyms

ATC:	Available Transfer Capacity
BE:	Belgium
BRP:	Balancing Responsible Party
BSP:	Balancing Service Provider
CEP:	Clean Energy Package
EBGL:	Electricity Balancing Guideline
NL:	Netherlands
ORDC:	Operating Reserve Demand Curve

TSO: Transmission System Operator

Nomenclature

Sets

K: Set of zonal model links

G: Set of generators

L: Set of loads

Z: Set of zones

RL: Set of reserve loads

Parameters

ATC_k^+, ATC_k^-: ATC capacity in upward and downward direction

P_g^+: Capacity of generator g

R_g^+: Ramp limit of generator g

D_l^+: Capacity of consumer l

C_g: Marginal cost of generator g

V_l: Valuation of load l

V_l^R: Valuation of reserve slice l

$D_l^{R,+}$: Capacity of reserve slice l

α_g: Risk aversion coefficient of agent g

P_ω: Probability of scenario ω

$\rho_{z\omega}^{RT,*}$: Equilibrium real-time energy price in zone z in scenario ω

$\rho_\omega^{R,RT,*}$: Equilibrium real-time reserve price in Belgium in scenario ω

$\rho_z^{DA,*}$: Equilibrium day-ahead energy price in zone z

$\rho_z^{R,DA,*}$: Equilibrium day-ahead reserve price in zone z

$d_{l\omega}^{R,RT,*}$: Real-time reserve demand of Belgian TSO in scenario ω for reserve segment l

Primal variables

e_k: Transported power along zonal link k

p_g: Production of generator g

d_l: Demand of consumer l

d_l^R: Reserve demand of slice l

Dual variables

λ_k^+, λ_k^-: Flowgate capacity limit dual variables

$\rho_{z,\omega}^{RT}$: Real-time energy price in zone z in scenario ω

ρ_z^R: Reserve price in zone z

ρ_z: Energy price in zone z

$\mu 1_g$: Dual of generator g capacity constraint

$\mu 2_g$: Dual of generator g ramp constraint

ν_l: Dual of consumer l capacity constraint

μ_l^R: Dual of reserve slice l capacity constraint

$q_{g\omega}$ Risk-adjusted probability of scenario ω for agent g

References

Stoft, S., 2002. Power System Economics. IEEE Press and Wiley Interscience.

Ehrenmann, A., Smeers, Y., 2011. Stochastic Equilibrium Models for Generation Capacity Expansion. Vol. 163 of Stochastic Optimization Methods in Finance and Energy, International Series in Operations Research and Management Science, Part 2. Springer, pp. 273–310.

ELIA, "Study report on Scarcity Pricing in the context of the 2018 discretionary incentives", December 20, 2018.

Harker, Patrick T. Lectures on computation of equilibria with equation-based methods. CORE, Université Catholique de Louvain, 1993.

Hogan, W. W., September 2005. On an 'energy only' electricity market design for resource adequacy. Tech. rep., Center for Business and Government, JFK School of Government, Harvard University.

A. Papavasiliou, Y. Smeers. Remuneration of Flexibility under Conditions of Scarcity: A Case Study of Belgium, the Energy Journal, vol. 38, no. 6, pp. 105-135, 2017.

A. Papavasiliou, Y. Smeers, G. Bertrand. An Extended Analysis on the Remuneration of Capacity under Scarcity Conditions, Economics of Energy and Environmental Policy, vol. 7, no. 2, 2018.

A. Papavasiliou, Y. Smeers, G. de Maere d'Aertrycke, Study on the general design of a mechanism for the remuneration of reserves in scarcity situations, June 6, 2019.

Ralph, D., Smeers, Y., 2015. Risk trading and endogenous probabilities in investment equilibria. SIAM Journal on Optimization 25 (4), 2589–2611.

Appendix A. An example appendix

The following glossary provides short definitions of specific terms that are used in the Texas and Belgium market, and points out correspondences whenever relevant.

Adjustment period (Texas): a process following the day-ahead market and before reliability unit commitment in Texas day-ahead operations, where schedules of individual generators are adjusted in order to allow for self-commitment and outages.

Automatic frequency restoration reserve / aFRR (Belgium): Synonym, and most recent terminology for, secondary reserve.

Available regulation capacity / ARC (Belgium): A function operated by ELIA which computes the amount of capacity which can be made available for responding in the upward and downward direction within 15 minutes.

Balancing responsible party / BRP (Belgium): Entity in the Belgian market which is responsible for arriving to real time with a forward financial position that exactly matches its net physical position.

Balancing service provider / BSP (Belgium): Entity in the Belgian market that offers secondary and/or tertiary reserves.

Base point deviations (Texas): These are deviations of resources during their real-time dispatch from the energy and ancillary services set-points that have been instructed by the system operator.

Continuous intraday market (Belgium): An energy market that operates after the day-ahead auction and until 45 minutes before real time, with a continuous matching of bids on a bilateral first-come-first-serve basis.

Current operating plan / COP (Texas): The hourly on/off, technical minimum, technical maximum, and ancillary service obligation schedule of individual generators in the Texas day-ahead market. This is the analog of nominations in the Belgian market.

Coordination of the Injection of Production Units / CIPU contract (Belgium): A legacy classification of conventional units (as opposed to newer renewable or demand-side resources) in the Belgian system, along with an associated set of rules that govern the operation of these units.

Day-ahead reliability unit commitment / DRUC (Texas): The day-ahead process that includes TSA and RUC.

EUPHEMIA (Belgium): The algorithm that is used for clearing the European day-ahead power exchange.

Energy bids (Texas): Demand-side bids in the ERCOT day-ahead market that are submitted by QSEs for buying energy.

Energy-only offers (Texas): Supply-side bids in the ERCOT day-ahead market that are submitted by QSEs for selling energy.

Free bids (Belgium): Bids for upward and downward regulation which are submitted to the Belgian real-time market by resources that have not pre-committed their capacity as reserve.

Frequency control reserve / FCR (Belgium): Synonym, and most recent terminology for, primary reserve.

Independent system operator / ISO (Texas): ERCOT, the entity which operates the electric power system and electricity market of Texas, including the day-ahead and real-time reserve and energy markets.

Intraday price coupling of regions / IDPCR (Belgium): A continuous auction that trades energy after the day-ahead market and before real time.

Load frequency control / LFC (Texas): Automatic control that is sent every 4 seconds to resources that are providing regulation in the Texas market, triggered by frequency deviations. This is the analog of primary reserve in the Belgian system.

Locational marginal prices / LMP (Texas): Marginal value of locational power balance constraint in the SCED.

Manual frequency restoration reserve / mFRR (Belgium): Synonym, and most recent terminology for, tertiary reserve.

Minimum contingency level / MCL (Texas): The minimum amount of reserve capacity, below which the ORDC adder produces a real-time price equal to VOLL.

Market information system / MIS (Texas): The information technology platform that is used in the ERCOT market in order to map postings related to market operations.

Net regulation volume / NRV (Belgium): The energy that ELIA dispatches in order to cope with system imbalance.

Nomination (Belgium): The day-ahead procedure whereby the set-point, technical maximum and quantity of offered reserve of individual resources are declared by the owners to the system operator.

Paradoxically rejected bids / PRB (Belgium): Bids in the day-ahead power exchange which may be rejected, even if activating them would result in a profit for these resources.

Pool (Texas): The organization of the day-ahead market in Texas whereby the non-convex costs and operating constraints of generators are represented explicitly in the day-ahead market bids.

Portfolio bidding (Belgium): The practice whereby market participants enter the day-ahead power exchange with a bid representing a portfolio of resources, as opposed to an individual generator or load.

Power exchange (Belgium): EPEX Spot, the entity which operates the Belgian day-ahead energy market, and the actual operation of trading energy in the day-ahead time frame.

Primary reserve /R1 (Belgium): Reserve in the Belgian market that needs to react within 3 seconds. This is the analog of regulation in the Texas market.

Proactive balancing (Europe): The notion that BRPs freeze their schedules hours in advance of real time, with the TSO taking over balancing of the system from that point onwards.

Qualified scheduling entities / QSE (Texas): Market entities that manage generation resources and load resources.

Reactive balancing (Europe): The notion that BRPs should be responsible for balancing their perimeter right up to real time operations, with the TSO providing advance indicators that can help BRPs balance their perimeter, and with the TSO only handling any remaining imbalances.

Reliability unit commitment (Texas): A process which is executed in the day-ahead time frame after the Texas day-ahead market in order to commit additional units beyond those committed by the day-ahead market, in case the ISO assesses that this is needed in order to ensure reliable operations.

Reserve price adders (Texas): The adder computed by the ORDC methodology. This corresponds to the Belgian scarcity adder.

Real-time online reserve price adder / RTORPA (Texas): The amount of reserve capacity that can be made available in a horizon of 30 minutes, as measured every five minutes by the results of a SCED run.

Real-time offline reserve price adder / RTOFFPA (Texas): The amount of reserve capacity that can be made available in a horizon of 60 minutes, as measured every five minutes by the results of a SCED run.

Real-time reserve price for online reserve / RTRSVPOR (Texas): The average of RTORPA over a 15-minute interval, used for settlement purposes.

Real-time reserve price for offline reserve / RTRSVPOFF (Texas): The average of RTRSVPOFF over a 15-minute interval, used for settlement purposes.

Real-time settlement point prices (Texas): The result of combining locational marginal prices with reserve price adders, which is used for paying activated reserves.

Reliability must run / RMR units (Texas): Resources that are required to run in real time for reliability reasons, independently of the outcome of the day-ahead market.

Reservation (Belgium): The procurement of reserve capacity by the TSO in auctions that take place before the day-ahead energy market.

Responsive reserve service / RRS (Texas): Reserve that needs to be made available within 30 minutes in the Texas market. This is the analog of tertiary reserve in the Belgian market, in the sense that it is the slowest type of operating reserve.

R3 flexible (Belgium): A type of tertiary reserve product offered in the Belgian market which has less stringent delivery conditions than standard tertiary reserve.

R3 standard (Belgium): The reference tertiary reserve product that is offered in the Belgian market.

Secondary reserve / R2 (Belgium): Reserves that need to be activated within 7.5 minutes in the Belgian market. This is similar to responsive reserves in the Texas market, in these sense that this is the fastest operating reserve.

Security constrained economic dispatch / SCED (Texas): A real-time dispatch model that is run in the Texas market every five minutes.

Self-commitment (Texas): The decision to commit a unit independently of the result of the day-ahead market. Self-commitment typically takes place in the adjustment period after the day-ahead market, and resources that are self-committed are not guaranteed a make-whole payment for their fixed and startup costs.

Shift factor (Texas): Output produced by the network security analysis function of ERCOT, which is added to the system lambda in order to determine the LMP.

Strategic reserve (Belgium): An emergency measure used in Belgium for keeping units that are intended to be mothballed as available backup capacity in order to overcome adequacy issues during winter months.

System imbalance: The discrepancy between injections and offtakes of power which produce deviations from reference frequency.

Tertiary reserve / R3 (Belgium): Reserves that need to be activated within 15 minutes in the Belgian market. This is similar to the Texas non-spinning reserve, in the sense that it is the slowest operating reserve.

Three-part supply offers (Texas): Supply-side bids in the ERCOT day-ahead market that are submitted by QSEs for selling energy and are associated to individual generators.

Transmission security analysis / TSA (Texas): Part of the DRUC process which generates input for RUC by screening contingencies.

Transmission service provider / TSP (Texas): TSPs are responsible for operating and monitoring transmission resources (lines, transformers, buses).

Transmission system operator / TSO (Belgium): ELIA, the entity which operates the Belgian electric power system.

Two-settlement system (Texas): An accounting system for treating day-ahead financial transactions followed by physical real-time injections/withdrawals of power. The two-settlement system can be viewed in two identical ways. (i) Agents buy out their *entire* financial position at the real-time price, and are also paid the real-time price for their entire physical production/withdrawal. (ii) Equivalently, agents are paid the real-time price for the difference between their physical injection/withdrawal and their position in the forward day-ahead market.