Market Design Considerations for Scarcity Pricing: A Stochastic Equilibrium Framework

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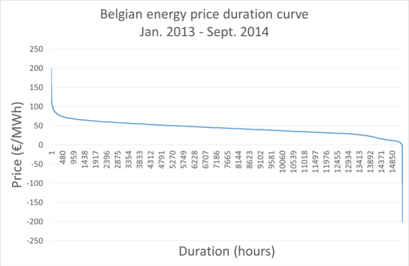
Workshop on Electricity Systems of the Future
Mathematics of Energy Systems
Isaac Newton Institute, Cambridge

Outline

Outline

A Paradox of Highly Renewable Systems

Gas and oil units are (i) the most flexible, and (ii) the least profitable



	Inv. cost (€/MWh)	Marg. cost (€/MWh)	Min load cost (€/MWh)	Energy market profit (€/MWh)	Profit (€/MWh)
Biomass	27.9	5.6	0	35.6	7.7
Nuclear	31.8	7.0	0	34.2	2.4
Gas	5.1	50.2	20	0.1	-5
Oil	1.7	156.0	20	0	-1.7

Motivation for Scarcity Pricing

- Scarcity pricing: a real-time demand for reserve capacity, determined by loss of load probability
  - introduces a *non-volatile* real-time price for reserve capacity
  - affects the real-time price of energy
- Definition of flexibility for *this* talk:
  - Secondary reserve: reaction in a few seconds, full response in 7.5 minutes
  - Tertiary reserve: available within 15 minutes

  such as can be provided by
  - combined cycle gas turbines
  - demand response

The CREG Scarcity Pricing Studies

- **First study (2015)**: How would electricity prices change if we introduce ORDC (Hogan, 2005) in the Belgian market?
- **Second study (2016)**: How does scarcity pricing depend on
  - Strategic reserve
  - Value of lost load
  - Restoration of nuclear capacity
  - Day-ahead (instead of month-ahead) clearing
- **This talk**: **Third study (2017)**: Can we take a US-inspired design and plug it into the existing European market?
- **ELIA parallel runs (2018)**: ELIA (Belgian TSO) releases report on the simulation of scarcity prices in the Belgian market for 2017
- **New scarcity adder incentive (2019)**: By October 2019, ELIA will be posting adders publicly

Scarcity Pricing Adder Formula

In its simplest form, the scarcity pricing adder is computed as

$$(VOLL - \hat{MC}(\sum_g p_g)) \cdot LOLP(R),$$

where $\hat{MC}(\sum_g p_g)$ is the incremental cost for meeting an additional increment in demand, R is the available reserve

- More frequent, lower amplitude price spikes
- Price spikes can occur even if regulator mitigates bids of suppliers in order to mitigate market power
- Can co-exist with capacity mechanisms, perceived as no-regret measure for improving the energy-only market

Illustration from Texas: July 30, 2015

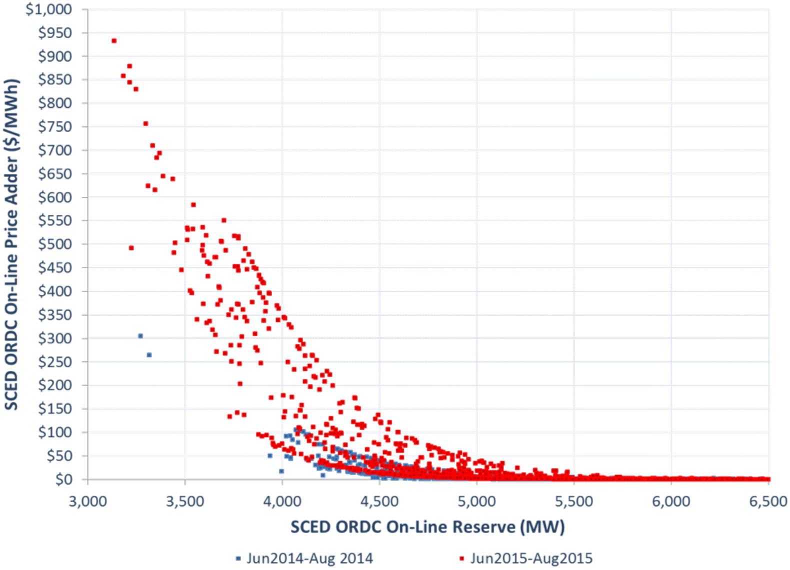
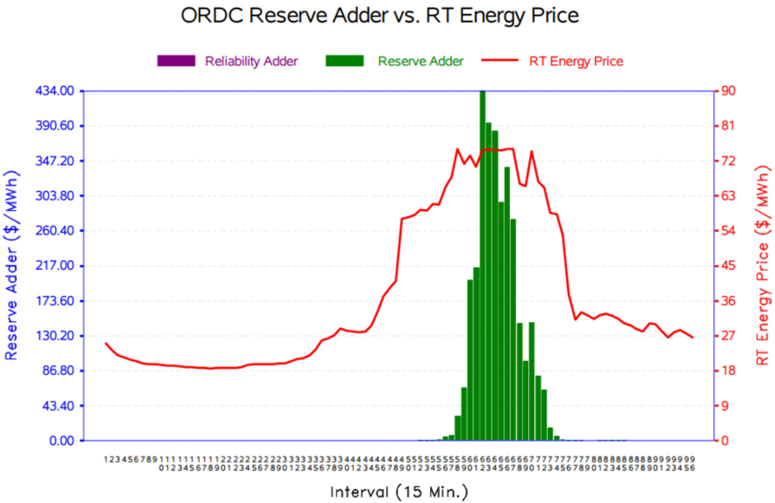


Illustration from Texas: July 30, 2015

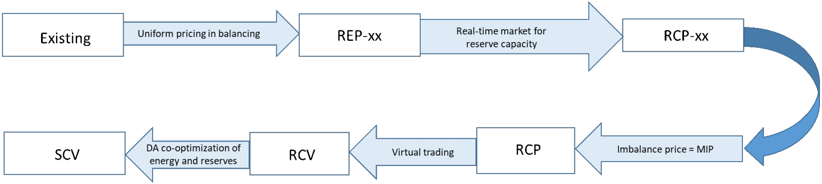


Focus of this Presentation

Focus of this presentation: in order to *back-propagate* the scarcity signal

- When should
- Do we need a *real-time reserve market*?
- Do we need *virtual bidding*? *day-ahead* reserve auctions be conducted? Before, during, or after the clearing of the energy market?

A Possible Evolution of the Belgian Market



The Models in the Evolution Chain

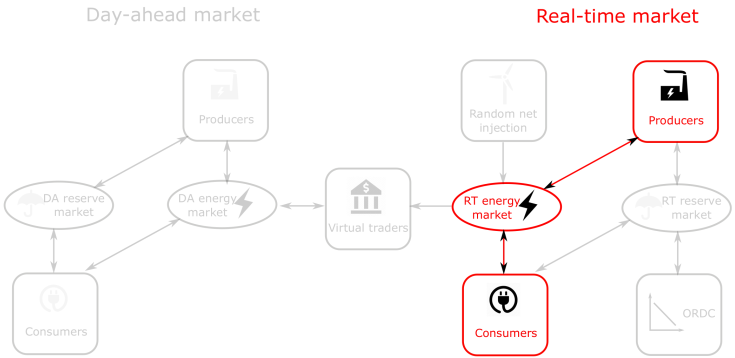
	Simultaneous DA energy and reserves	RT reserve market	Virtual trading
SCV	✓	✓	✓
RCV		✓	✓
RCP		✓	
REP			

The dilemmas of the market design:

- **S**imultaneous day-ahead clearing of energy and reserve, or **R**eserve first (S/R)?
- **C**learing of energy and reserve in real time, or **E**nergy only (C/E)?
- **V**irtual trading, or **P**hysical trading only (V/P)?

Outline

Energy-Only Real-Time Market



Notation

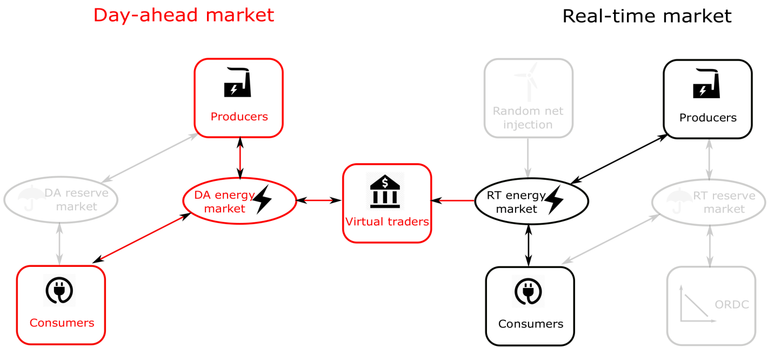
- Sets
  - Generators: G
  - Loads: L
- Parameters
  - Bid quantity of generators: P_g^+
  - Bid quantity of loads: D_l^+
  - Bid price of generators: C_g
  - Bid price of loads: V_l
- Decisions
  - Production of generators: p_g^{RT}
  - Consumption of loads: d_l^{RT}
- Dual variables
  - Real-time energy price: λ^{RT}

Model

Just a *merit-order* dispatch model:

$$
\begin{aligned}
& \max \sum_{l \in L} V_l \cdot d_l^{RT} - \sum_{g \in G} C_g \cdot p_g^{RT} \\
& p_g^{RT} \leq P_g^+, g \in G \\
& d_l^{RT} \leq D_l^+, l \in L \\
(\lambda^{RT}) : \quad & \sum_{g \in G} p_g = \sum_{l \in L} d_l \\
& p_g, d_l \geq 0, g \in G, l \in L
\end{aligned}
$$

Energy-Only in Real Time and Day Ahead



Additional Notation

- Decisions
  - Day-ahead energy production of generator: p_g^{DA}
  - Day-ahead energy consumption of load: d_l^{DA}
- Dual variables
  - Day-ahead energy price: λ^{DA}

Model

Generator profit maximization:

$$\max \lambda^{DA} \cdot p_g^{DA} + (\Pi_g^{RT} - \lambda^{RT} \cdot p_g^{DA})$$

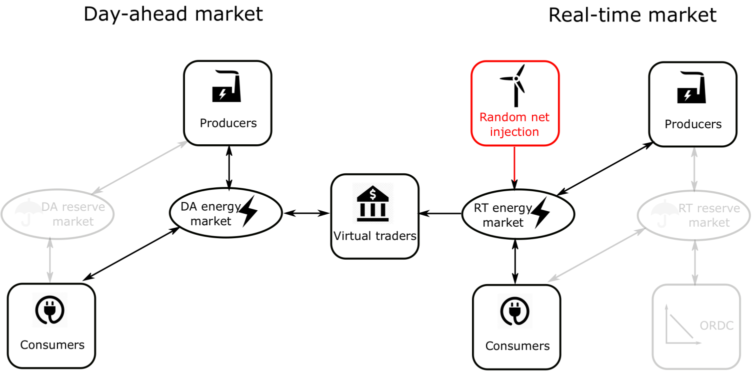
where $\Pi_g^{RT} = (\lambda^{RT} - C_g) \cdot p_g^{RT}$ is the real-time profit

Similarly for loads

Market equilibrium:

$$\sum_{g \in G} p_g^{DA} = \sum_{l \in L} d_l^{DA}$$

Adding Uncertainty in Real Time



Additional Notation

- Sets
  - Set of uncertain real-time outcomes (e.g. renewable supply forecast errors, demand forecast errors): Ω
- Parameters
  - Real-time profit of agent: $\Pi_{g,\omega}^{RT}$
- Functions
  - Risk-adjusted profit of random payoff: $\mathcal{R}_g : \mathbb{R}^\Omega \to \mathbb{R}$

Model

Generator profit maximization:

$$\max \lambda^{DA} \cdot p_g^{DA} + \mathcal{R}_g(\Pi_{g,\omega}^{RT} - \lambda_\omega^{RT} \cdot p_g^{DA}),$$

where

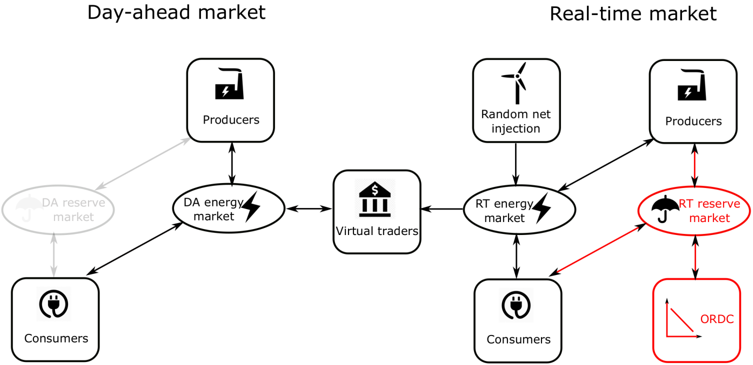
$$\Pi_{g,\omega}^{RT} = (\lambda_\omega^{RT} - C_g) \cdot p_{g,\omega}^{RT}$$

Similarly for load maximization

Day-ahead market equilibrium:

$$\sum_{g \in G} p_g^{DA} = \sum_{l \in L} d_l^{DA}$$

Reserve Capacity in Real Time



Additional Notation

- Sets
  - ORDC segments: RL
- Parameters
  - ORDC segment valuations: V_l^R
  - ORDC segment capacities: D_l^R
  - ramp rate: R_g
- Decisions
  - Real-time demand for reserve capacity: $d_{l,\omega}^{R,RT}$
  - Real-time supply of reserve capacity: $r_{g,\omega}^{RT}$
- Dual variables
  - Real-time price for reserve capacity: $\lambda^{R,RT}$

Model

Real-time trading of energy *and* reserve for outcome $\omega \in \Omega$:

$$\max \sum_{l \in RL} V_l^R \cdot d_l^{R,RT} + \sum_{l \in L} V_l \cdot d_l - \sum_{g \in G} C_g \cdot p_g$$

$$(\lambda^{RT}): \quad \sum_{g \in G} p_g^{RT} = \sum_{l \in L} d_l^{RT}$$

$$(\lambda^{R,RT}): \quad \sum_{g \in G \cup L} r_g^{RT} = \sum_{l \in RL} d_l^{R,RT}$$

$$p_g^{RT} \leq P_{g,\omega}^+, r_g^{RT} \leq R_g, p_g^{RT} + r_g^{RT} \leq P_{g,\omega}^+, g \in G$$

$$d_l \leq D_l^+, r_l^{RT} \leq R_l, r_l^{RT} \leq d_l^{RT}, l \in L$$

$$d_l^{R,RT} \leq D_l^R, l \in RL$$

$$p_g^{RT}, r_g^{RT} \geq 0, g \in G, d_l^{RT}, r_l^{RT} \geq 0, l \in L, d_l^{R,RT} \geq 0, l \in RL$$

Remarks

Suppose that a given generator g

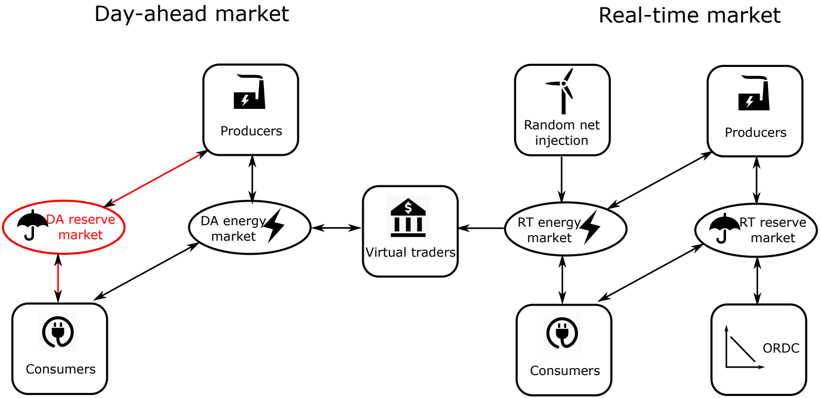
- is simultaneously offering energy ($p_g^{RT} > 0$) and reserve ($r_g^{RT} > 0$)
- is not constrained by ramp rate ($r_g^{RT} < R_g$)

We have the following linkage between the energy and reserve capacity price:

$$\lambda_\omega^{RT} - C_g = \lambda_\omega^{R,RT}$$

This no-arbitrage relationship is the *essence of scarcity pricing*

Reserve Capacity in Day Ahead



Additional Notation

- Decisions
  - Day-ahead supply of reserve capacity: r_g^{DA}
- Dual variables
  - Day-ahead price for reserve capacity: $\lambda^{R,DA}$

Model

Generator profit maximization:

$$\max \lambda^{DA} \cdot p_g^{DA} + \lambda^{R,DA} \cdot r_g^{DA} +$$
$$\mathcal{R}_g(\Pi_{g,\omega}^{RT} - \lambda_\omega^{RT} \cdot p_g^{DA} - \lambda_\omega^{R,RT} \cdot r_g^{DA}),$$

where

$$\Pi_{g,\omega}^{RT} = (\lambda_\omega^{RT} - C_g) \cdot p_{g,\omega}^{RT} + \lambda_\omega^{R,RT} \cdot r_{g,\omega}^{RT}$$

Similarly for load profit maximization

Day-ahead market equilibrium:

$$\sum_{g \in G} p_g^{DA} = \sum_{l \in L} d_l^{DA}, \sum_{g \in G \cup L} r_g^{DA} = 0$$

To Summarize

We have arrived at our first target model: **SCV**

- **S**imultaneous day-ahead clearing of energy and reserve
- **C**oordinated trading of energy and reserve in real time
- **V**irtual trading

Back-Propagation of Prices

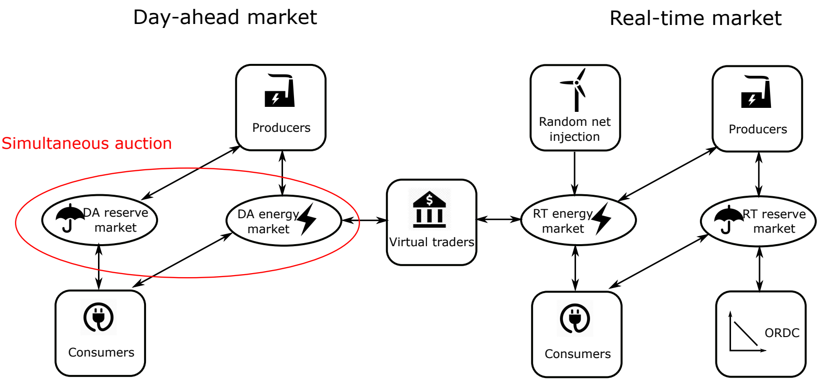
The first-order conditions with respect to day-ahead energy and reserve decisions yields no-arbitrage conditions that explain how real-time prices *back-propagate* to forward markets:

$$\lambda^{DA} = \sum_{\omega \in \Omega} q_{g,\omega} \cdot \lambda_{\omega}^{RT}$$

$$\lambda^{R,DA} = \sum_{\omega \in \Omega} q_{g,\omega} \cdot \lambda_{\omega}^{R,RT}$$

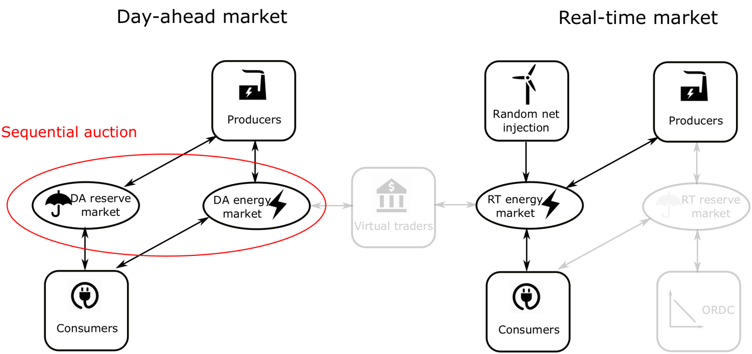
where q_g is the risk-neutral probability measure of agent g

US Market


Day-ahead market
Real-time market
Simultaneous auction
Producers
DA reserve market
DA energy market
Consumers
Virtual traders
Random net injection
Producers
RT energy market
RT reserve market
Consumers
ORDC

Outline

Belgian Market



Moving from Virtual to Physical Trading

It is easy to replace *virtual trading* (V) with *physical trading (P)*, by introducing *physical constraints* in the day-ahead model

For example, for generators:

$$p_g^{DA} + r_g^{DA} \leq P_g^+$$
$$r_g^{DA} \leq R_g$$
$$r_g^{DA} \geq 0$$

Moving from **C**oordinated Clearing of Real-Time Energy and Reserve to **E**nergy-Only Trading

It is similarly easy to switch from real-time *clearing of energy and reserve* to *energy-only trading* by switching between co-optimization and merit order dispatch in real time

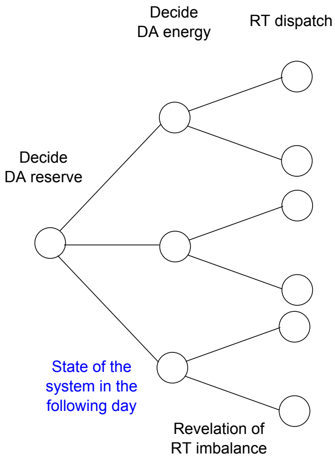
Moving from **S**imultaneous Day-Ahead Clearing to **R**eserve First

Qualitatively, we want to capture the difference between the following:

- *Simultaneous auctioning*: system operator co-optimizes, taking into account all the relevant *inter-dependencies* of power production and reserve capacity
- *Sequential auctioning*: agents determine opportunity costs on the basis of *possibly inaccurate forecasts* of the *system state* for the following day

We formulate the problem as a multistage stochastic equilibrium by *nesting* risk functions (Philpott, 2016)

Sequence of Events



Type of day: assessment of the TSO for what quantity of operating reserve will be required for the following day

In line with current effort of ELIA to transition towards *dynamic reserve sizing and procurement* in the day ahead (De Vos, 2018)

Populating the Tree with Data

Denote a given node as (t, ω), where t is stage and ω is outcome

No specific random vector is revealed in stage 2, instead the *system state*:

- Node (2, 1): Low-risk day
- Node (2, 2): Medium-risk day
- Node (2, 3): High-risk day

In stage 3, renewable supply P^{+}_{wind} is revealed:

- Node (3, 1): 111 MW; node (3, 2): 101 MW
- Node (3, 3): 156 MW; node (3, 4): 56 MW
- Node (3, 5): 206 MW; node (3, 6): 6 MW

Some Additional Features of the European Model

For the case study, we introduce some additional features:

- Two types of reserve (secondary and tertiary) that are *substitutable*
- **Inelastic** requirements for reserve capacity *after* activation
- Penalties on deviations between day-ahead and real-time energy production

The European Model

- In the following, the European market equilibrium model is presented from the point of view of generators:
  - real-time energy market
  - day-ahead energy exchange
  - day-ahead reserve capacity auction
- Loads are modeled similarly
- Market clearing conditions are added where appropriate

Generator profit maximization:

$$
\begin{aligned}
(PE^{G,RT}_{g,\omega,\omega'}):\quad & \max_{p^{RT},s^{RT,+},s^{RT,-}} \lambda^{RT}_{\omega'} \cdot p^{RT}_{g,\omega'} - C_g \cdot p^{RT}_{g,\omega'} \\
& -\epsilon^{+}_{g} \cdot s^{RT,+}_{g,\omega,\omega'} - \epsilon^{-}_{g} \cdot s^{RT,-}_{g,\omega,\omega'} \\
(\alpha^{G,RT,+}_{g,\omega,\omega'}):\quad & p^{RT}_{g,\omega'} \le P^{RT,+}_{g,\omega'} \cdot y_{g,\omega} \\
(\alpha^{G,RT,-}_{g,\omega,\omega'}):\quad & -p^{RT}_{g,\omega'} \le -P^{RT,-}_{g,\omega'} \cdot y_{g,\omega} \\
(\beta^{G,F,RT}_{g,\omega}):\quad & r^{F,DA}_{g} - r^{F,RT}_{g,\omega} \le 0 \\
(\beta^{G,S,RT}_{g,\omega}):\quad & r^{S,DA}_{g} - r^{S,RT}_{g,\omega} \le 0 \\
(\gamma^{G,RT,+}_{g,\omega,\omega'}):\quad & p^{RT}_{g,\omega'} - p^{DA}_{g,\omega} - s^{RT,+}_{g,\omega,\omega'} \le 0 \\
(\gamma^{G,RT,-}_{g,\omega,\omega'}):\quad & p^{DA}_{g,\omega} - p^{RT}_{g,\omega'} - s^{RT,-}_{g,\omega,\omega'} \le 0 \\
& p^{RT}_{g,\omega'}, s^{RT,+}_{g,\omega,\omega'}, s^{RT,-}_{g,\omega,\omega'} \ge 0
\end{aligned}
$$

A Gap in the Existing EU Balancing Design

- In Belgium today, it is clear what balancing service providers need to be able to deliver *before* activation
- But system scarcity is measured by leftover capacity *after* activation
- There are plausible arguments for
  - dropping the constraints $\beta^{F/S}$: why should we carry protection after we have eliminated imbalances?
  - including the constraints $\beta^{F/S}$: the end of one imbalance interval marks the beginning of a new one
- The presence or absence of these constraints has **major** implications for real-time prices

Day-Ahead Energy Exchange in the European Model

$$
\begin{aligned}
(PE_{g,\omega}^{G,DA,2}): \quad & \max_{y,p^{DA}} \lambda_{\omega}^{DA} \cdot p_{g,\omega}^{DA} + \\
& \mathcal{R}2_g(\Pi_{g,\omega'}^{RT}(y,p^{DA}) - \lambda_{\omega'}^{RT} \cdot p_g^{DA}) - K_g \cdot y_{g,\omega} \\
(\delta_{g,\omega}): \quad & y_{g,\omega} \leq 1 \\
(\alpha_{g,\omega}^{G,DA,+}): \quad & p_{g,\omega}^{DA} + r_g^{F,DA} + r_g^{S,DA} \leq P_g^{DA,+} \cdot y_{g,\omega} \\
(\alpha_{g,\omega}^{G,DA,-}): \quad & -p_{g,\omega}^{DA} \leq -P_g^{DA,-} \cdot y_{g,\omega} \\
& y_{g,\omega}, p_{g,\omega}^{DA} \geq 0
\end{aligned}
$$

$$
\begin{aligned}
(PE_g^{G,DA1}) \quad & \max_{r^{F,DA}, r^{S,DA}} \tilde{\lambda}^{R,F,DA} \cdot r_g^{F,DA} + \lambda^{R,S,DA} \cdot r_g^{S,DA} \\
& + \mathcal{R}1_g(\Pi_{g,\omega}^{DA}(r^{F,DA}, r^{S,DA})) \\
(\beta_g^{G,F,DA}) : \quad & r_g^{F,DA} \leq R_g^F \\
(\beta_g^{G,S,DA}) : \quad & r_g^{S,DA} \leq R_g^S \\
& r_g^{F,DA}, r_g^{S,DA} \geq 0
\end{aligned}
$$

Outline

Case Study Setup

- We simulate the Belgian market for September 2015 - March 2016
- We assume risk-neutral agents
- We solve the equilibrium problems using a stochastic optimization equivalent

Energy Price

Design	Summary	Price
SCV	US design	33.29
RCV	Allow virtual trading	34.36
RCP	Remove imbalance penalties	34.36
RCP-0.1	Trade real-time reserve	34.36
REP-0.1	EU design extreme 2	27.60
REP-0.1-inel.	EU design extreme 1	45.42
Hist. DA	Historical day-ahead	38.87
Hist. RT	Historical real-time	35.26

Observations

- **Validation**: REP-0.1 and REP-0.1-inelastic (proxies of Belgian market) envelope the historically observed day-ahead and real-time energy prices
- The requirement of whether or not to hold reserve capacity *after* the activation of reserve has a **major** impact on prices

Secondary Reserve Prices

Design	Summary	Price DA	Price RT
SCV	US design	15.34	14.57
RCV	Allow virtual trading	15.78	15.69
RCP	No imbalance penalties	15.78	15.65
RCP-0.1	Trade real-time reserve	15.79	15.15
REP-0.1	EU design extreme 2	1.42	N/A
REP-0.1-inel.	EU design extreme 1	26.90	N/A
Historical		9.59	N/A

Tertiary Reserve Prices

Design	Summary	Price DA	Price RT
SCV	US design	11.27	10.50
RCV	Allow virtual trading	10.54	10.54
RCP	No imbalance penalties	10.59	10.52
RCP-0.1	Trade real-time reserve	10.67	10.17
REP-0.1	EU design extreme 2	1.42	N/A
REP-0.1-inel.	EU design extreme 1	26.90	N/A
Historical		5.27	N/A

Profits

	SCV	RCV	RCP	RCP-0.1	REP-0.1	REP-0.1-inel.
G1	*6.44*	*7.37*	*7.37*	*7.40*	**2.59**	16.15
G2	19.59	20.66	20.68	20.79	15.07	31.80
G3	*7.02*	*8.06*	*8.06*	*8.09*	**2.64**	19.03
G4	10.48	12.04	12.04	12.08	**3.84**	28.62
G5	19.96	21.05	21.07	21.18	15.45	32.26
G6	*7.23*	*8.29*	*8.30*	*8.32*	**2.66**	19.42
G7	20.36	21.43	21.45	21.56	15.82	32.57
G8	19.50	20.56	20.58	20.69	14.93	31.67

- Profitable plants (normal font): profits above 8.66 €/MWh
- Break-even plants (*italic* font): profits 6.03 - 8.66 €/MWh
- Non-viable plants (**bold** font): profits below 6.03 €/MWh

Observations

- Removing the requirement of carrying reserve after activation (REP-0.1) places 4 out of 8 units in a non-viable financial position
- The introduction of a real-time market for reserve capacity (RCP and RCP-0.1) restores 3 of these units to breaking even, and 1 of them to covering its investment costs comfortably

Making Sense of the Results

A major difficulty with the absence of a real-time reserve market is that it becomes difficult to value reserve precisely:

$$\lambda^{R,DA} = \beta_g^{G,DA} + \mathbb{E}[\alpha_{g,\omega}^{G,DA}]$$

where

- $\alpha_{g,\omega}^{G,DA}$: ramp rate constraint multiplier
- $\beta_g^{G,DA}$: capacity constraint multiplier

If we are forced to carry the full amount of reserve after activation, the scarcity signal is *too* strong:

$$\lambda^{R,DA} = \beta_g^{G,DA} + \mathbb{E}[\alpha_{g,\omega}^{G,DA}] + \mathbb{E}[\beta_{g,\omega'}^{G,RT}]$$

where

- $\beta_{g,\omega'}^{G,RT}$: multiplier associated to requirement of carrying real-time reserve capacity *after* activation

Making Sense of the Results

The real-time ORDC automates this calculation in a self-correcting fashion, and arbitrage propagates this price to the day-ahead market, thereby signaling investment in reserve capacity in case of tight system conditions:

$$\lambda^{R,DA} = \beta_g^{G,DA} + \mathbb{E}[\alpha_{g,\omega}^{G,DA}] + \mathbb{E}[\lambda_{\omega'}^{R,RT}]$$

Conclusions of the Belgian Case Study

Our recommendations to the Belgian regulatory commission:

- Introducing a real-time market for reserve capacity is the **top priority**
- Virtual trading and simultaneous clearing of day-ahead energy and reserves are less crucial in a **risk-neutral** setting

Thank You for Your Attention

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