Scarcity Pricing Market Design Considerations

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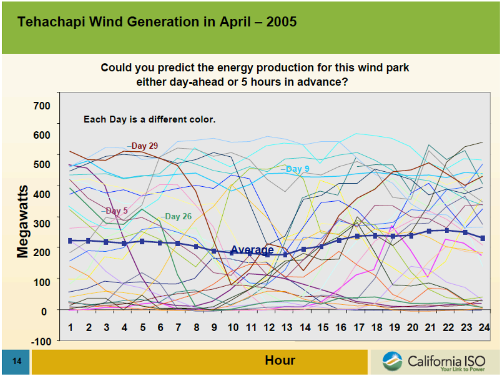
Outline

Outline

Challenges of Renewable Energy Integration



Renewable energy integration

- depresses electricity prices
- requires flexibility due to (i) uncertainty, (ii) variability, (iii) non-controllable output

Motivation for Scarcity Pricing

- Scarcity pricing: adjustment to price signal of *real-time* electricity markets in order to compensate *flexible* resources
- Definition of flexibility for *this* talk:
  - Secondary reserve: reaction in a few seconds, full response in 7 minutes
  - Tertiary reserve: available within 15 minutes

  such as can be provided by
  - combined cycle gas turbines
  - demand response
- We will not be addressing sources of flexibility for which scarcity pricing is not designed to compensate (e.g. seasonal renewable supply scarcity)

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
- **Third study (2017)**: Can we take a US-inspired design and plug it in to the existing European market?

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

- $VOLL$ is the value of lost load
- $\hat{MC}(\sum_g p_g)$ is the incremental cost for meeting an additional increment in demand
- R is the amount of capacity that can respond within an imbalance interval
- $LOLP : \mathbb{R}_+ \to [0, 1]$ is the loss of load probability

Generator Example

Assume the following inputs:

- Day-ahead energy price: λPDA = 20 €/MWh
- Day-ahead reserve price: λRDA = 65 €/MWh
- Real-time marginal cost of marginal unit: 80.3 €/MWh
- Real-time reserve price: λRRT = 3.9 €/MWh
- Real-time energy price: λPRT = 84.2 €/MWh
- Generator capacity: P_g^+ = 125 MW

Forward Reserve Awarded, Not Deployed

Settlement type	Formula	Price [€/MWh]	Quantity [MW]	Cash flow [€/h]
DA energy	$\lambda PDA \cdot pDA$	20	$pDA = 0$	0
DA reserve	$\lambda RDA \cdot rDA$	65	$rDA = 25$	1625
RT energy	$\lambda PRT \cdot (pRT - pDA)$	80.3	$pRT = 100$	8030
Total				9655

Table: Without Adder

Settlement type	Formula	Price [€/MWh]	Quantity [MW]	Cash flow [€/h]
DA energy	$\lambda PDA \cdot pDA$	20	$pDA = 0$	0
DA reserve	$\lambda RDA \cdot rDA$	65	$rDA = 25$	1625
RT energy	$\lambda PRT \cdot (pRT - pDA)$	84.2	$pRT = 100$	8420
RT reserve	$\lambda RRT \cdot (rRT - rDA)$	3.9	$rRT = 25$	0
Total				10045

Table: With Adder

Forward Reserve Awarded And Deployed

Settlement type	Formula	Price [€/MWh]	Quantity [MW]	Cash flow [€/h]
DA energy	$\lambda PDA \cdot pDA$	20	$pDA = 0$	0
DA reserve	$\lambda RDA \cdot rDA$	65	$rDA = 25$	1625
RT energy	$\lambda PRT \cdot (pRT - pDA)$	80.3	$pRT = 125$	10037.5
Total				11662.5

Table: Without Adder

Settlement type	Formula	Price [€/MWh]	Quantity [MW]	Cash flow [€/h]
DA energy	$\lambda PDA \cdot pDA$	20	$pDA = 0$	0
DA reserve	$\lambda RDA \cdot rDA$	65	$rDA = 25$	1625
RT energy	$\lambda PRT \cdot (pRT - pDA)$	84.2	$pRT = 125$	10525
RT reserve	$\lambda RRT \cdot (rRT - rDA)$	3.9	$rRT = 0$	-97.5
Total				12052.5

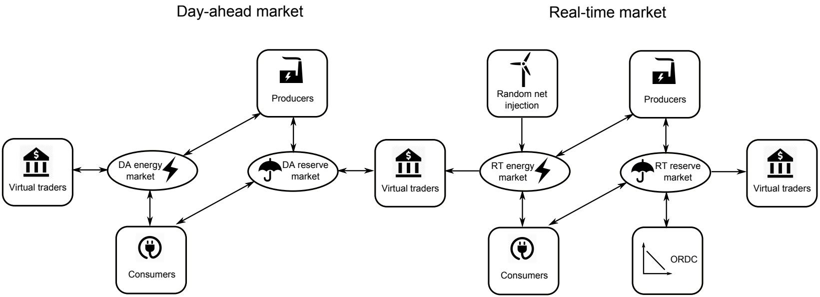
Table: With Adder

Focus of this Presentation

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

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

Methodology



The Eight Models

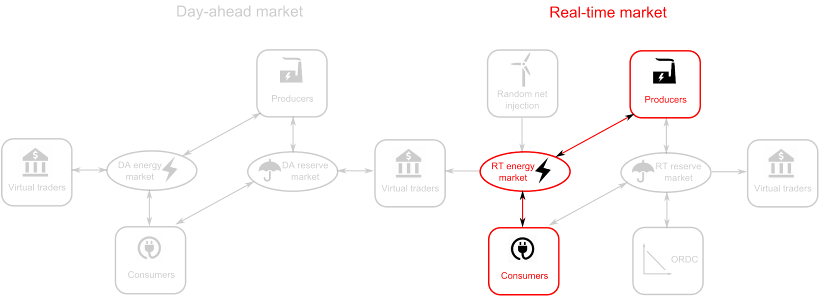
	Simultaneous DA energy and reserves	RT co-optimization of energy/reserve	Virtual trading
SCV	✓	✓	✓
SCP	✓	✓	
SEV	✓		✓
SEP	✓		
RCV		✓	✓
RCP		✓	
REV			✓
REP			

The dilemmas of the market design:

- **S**imultaneous day-ahead clearing of energy and reserve, or **R**eserve first (S/R)?
- **C**ooptimization 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: pRT_g
  - Consumption of loads: dRT_l
- Dual variables
  - Real-time energy price: λRT

Just a *merit-order* dispatch model:

$$\max \sum_{l \in L} V_l \cdot dRT_l - \sum_{g \in G} C_g \cdot pRT_g$$

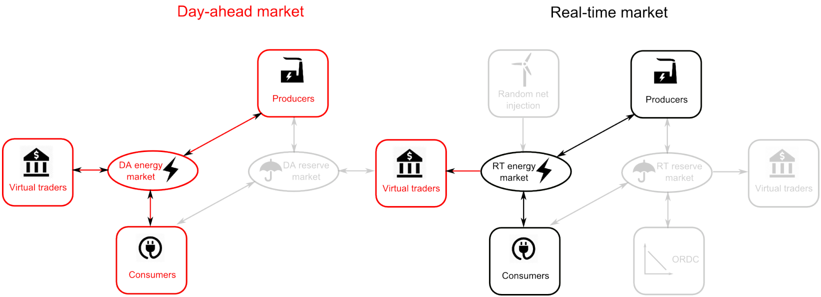
$$pRT_g \leq P_g^+, g \in G$$

$$d_l \leq D_l^+, l \in L$$

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

$$p_g, d_l \geq 0, g \in G, l \in L$$

Energy-Only in Real Time and Day Ahead



Additional Notation

- Decisions
  - Day-ahead energy production of generator: pDA_g
  - Day-ahead energy consumption of load: dDA_l
- Dual variables
  - Day-ahead energy price: λDA

Model

Generator profit maximization:

$$\max \lambda DA \cdot pDA_g + \lambda RT \cdot (pRT_g - pDA_g) - C_g \cdot pRT_g$$
$$pRT_g \leq P_g^+$$
$$pRT_g \geq 0$$

Load profit maximization:

$$\max -\lambda DA \cdot dDA_l + V_l \cdot dRT_l - \lambda RT \cdot (dRT_l - dDA_l)$$
$$dRT_l \leq D_l^+$$
$$dRT_l \geq 0$$

Market equilibrium:

$$\sum_{g \in G} pRT_g = \sum_{l \in L} dRT_l$$
$$\sum_{g \in G} pDA_g = \sum_{l \in L} dDA_l$$

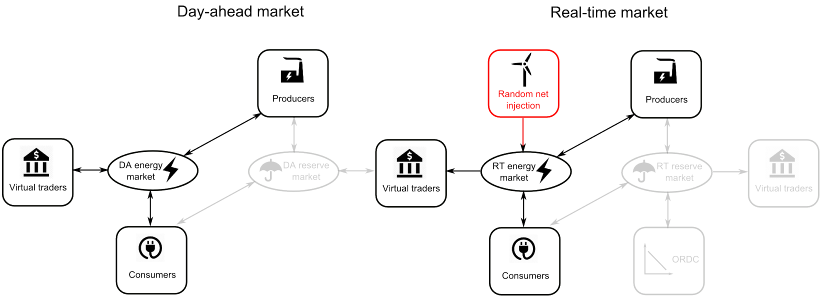
Remarks

- **Back-propagation**: from KKT conditions of profit maximization, we have

$$\lambda DA = \lambda RT$$

- In fact, day-ahead and real-time parts of the model can be completely *decoupled*
- We have introduced **virtual trading**: agents can take positions in the day-ahead market which do not correspond to their physical characteristics

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: $\Pi RT_{g,\omega}$
- Functions
  - Risk-adjusted profit of random payoff: $\mathcal{R}_g : \mathbb{R}^\Omega \to \mathbb{R}$

Model

Generator profit maximization:

$$\max \lambda DA \cdot pDA_g + \mathcal{R}_g(\Pi RT_{g,\omega} - \lambda RT_\omega \cdot pDA_g),$$

where

$$\Pi RT_{g,\omega} = (\lambda RT_\omega - C_g) \cdot pRT_{g,\omega}$$

Load profit maximization:

$$\max -\lambda DA \cdot dDA_l + \mathcal{R}_l(\Pi RT_{l,\omega} + \lambda DA_\omega \cdot dDA_l)$$

where

$$\Pi RT_{l,\omega} = (V_l - \lambda RT_\omega) \cdot dRT_{l,\omega}$$

Day-ahead market equilibrium:

$$\sum_{g \in G} pDA_g = \sum_{l \in L} dDA_l$$

Modeling the Risk Function $\mathcal{R}$

How do we model attitude of agent towards risk, $\mathcal{R}$?

Let's consider the *conditional value at risk*, *CVaR*

- Parameters
  - Percent of poorest scenarios considered in evaluation of risked payoff: α_g
  - Probability of outcome ω: p_ω
- Variables
  - Conditional value at risk: $CVaR_g$
  - Value at risk: VaR_g
  - Auxiliary variable for determination of risk-adjusted real-time payoff: $u_{g,\omega}$
- Dual variables:
  - Risk-neutral probability of agent: $q_{g,\omega}$

Modeling the Risk Function $\mathcal{R}$ (cont.)

There exists a *linear programming formulation* of $\mathcal{R}$

For example, the generator problem reads:

$$
\begin{aligned}
& \max \lambda DA \cdot pDA_g + CVaR_g \\
& CVaR_g = VaR_g - \frac{1}{\alpha_g} \sum_{\omega} p_\omega \cdot u_{g,\omega} \\
(q_{g,\omega}) : \quad & u_{g,\omega} \geq VaR_g - (\Pi RT_{g,\omega} - \lambda RT_\omega \cdot sDA_g) \\
& u_{g,\omega} \geq 0
\end{aligned}
$$

Remarks

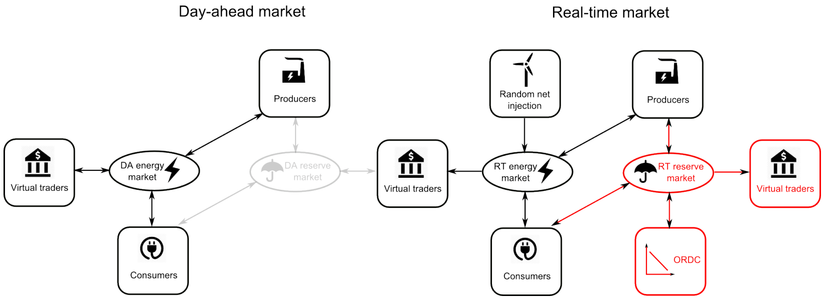
- Two possible interpretations of profit ΠRT:
  - *Correct* interpretation: λRT_ω and $\Pi RT_{g,\omega}$ are *parameters* for day-ahead profit maximization
  - *Incorrect* interpretation: λRT_ω and $\Pi RT_{g,\omega}$ are *variables* for day-ahead profit maximization
  - The two interpretations produce a different result
    - $\max(\mathcal{R}[\max])$ is different from $\max(\mathcal{R})$
    - Second model can produce out-of-merit dispatch in real time
- Day-ahead price can be potentially different from average real-time price:

$$\lambda DA = \mathbb{E}_{Q_g}[\lambda RT_\omega] = \sum_{\omega \in \Omega} q_{g,\omega} \cdot \lambda RT_\omega, \forall g \in G \cup L$$

- But if there is a single risk-neutral agent with an infinitely deep pocket, then

$$\lambda DA = \mathbb{E}[\lambda RT_\omega] = \sum_{\omega \in \Omega} p_\omega \cdot \lambda RT_\omega$$

Reserve Capacity in Real Time



Additional Notation

- Sets
  - ORDC segments: RL
- Parameters
  - ORDC segment valuations: MBR_l
  - ORDC segment capacities: DR_l
  - ramp rate: R_g
- Decisions
  - Real-time demand for reserve capacity: $dRRT_{l,\omega}$
  - Real-time supply of reserve capacity: $rRT_{g,\omega}$
- Dual variables
  - Real-time price for reserve capacity: λRRT

Model

Real-time co-optimization of energy and reserve for outcome $\omega \in \Omega$:

$$\max \sum_{l \in RL} MBR_l \cdot dRRT_l + \sum_{l \in L} V_l \cdot d_l - \sum_{g \in G} C_g \cdot p_g$$

$$(\lambda RT): \quad \sum_{g \in G} pRT_g = \sum_{l \in L} dRT_l$$

$$(\lambda RRT): \quad \sum_{g \in G \cup L} rRT_g = \sum_{l \in RL} dRRT_l$$

$$pRT_g \leq P^+_{g,\omega}, rRT_g \leq R_g, pRT_g + rRT_g \leq P^+_{g,\omega}, g \in G$$

$$d_l \leq D^+_l, rRT_l \leq R_l, rRT_l \leq dRT_l, l \in L$$

$$dRRT_l \leq DR_l, l \in RL$$

$$pRT_g, rRT_g \geq 0, g \in G, dRT_l, rRT_l \geq 0, l \in L, dRRT_l \geq 0, l \in RL$$

Remarks

Suppose that a given generator g

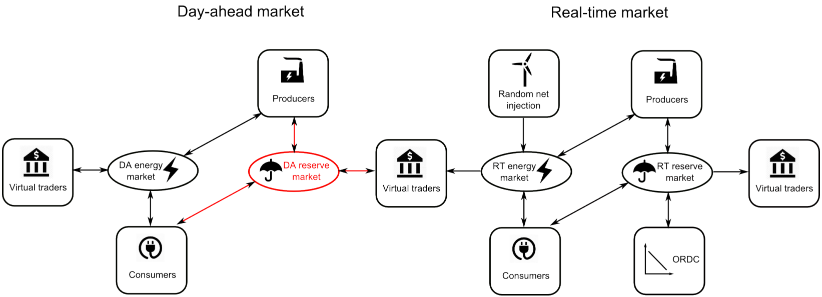
- is simultaneously offering energy ($pRT_g > 0$) and reserve ($rRT_g > 0$)
- is not constrained by ramp rate ($rRT_g < R_g$)

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

$$\lambda RT_\omega - C_g = \lambda RRT_\omega$$

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

Reserve Capacity in Day Ahead



Additional Notation

- Decisions
  - Day-ahead supply of reserve capacity: rDA_g
- Dual variables
  - Day-ahead price for reserve capacity: λRDA

Model

Generator profit maximization:

$$\max \lambda DA \cdot pDA_g + \lambda RDA \cdot rDA_g + \mathcal{R}_g(\Pi RT_{g,\omega} - \lambda RT_\omega \cdot pDA_g - \lambda RRT_\omega \cdot rDA_g),$$

where

$$\Pi RT_{g,\omega} = (\lambda RT_\omega - C_g) \cdot pRT_{g,\omega} + \lambda RRT_\omega \cdot rRT_{g,\omega}$$

Load profit maximization:

$$\max -\lambda DA \cdot dDA_l + \lambda RDA \cdot rDA_l + \mathcal{R}_l(\Pi RT_{l,\omega} + \lambda RT_\omega \cdot dDA_l - \lambda RRT_\omega \cdot rDA_l),$$

where

$$\Pi RT_{l,\omega} = (V_l - \lambda RT) \cdot dRT_l + \lambda RRT \cdot rRT_{l,\omega}$$

Day-ahead market equilibrium:

$$\sum_{g \in G} pDA_g = \sum_{l \in L} dDA_l, \quad \sum_{g \in G \cup L} rDA_g = 0$$

Remarks

- No need to explicitly introduce ORDC in day-ahead market:

$$\lambda RDA = \mathbb{E}_{Q_g}[\lambda RRT_\omega] = \sum_{\omega \in \Omega} q_{g,\omega} \cdot \lambda RRT_\omega, \forall g \in G \cup L$$

  and λRRT is already augmented by ORDC in real-time market
- Should the day-ahead auction explicitly impose physical constraints? This is linked to the question of *virtual trading*:
  - \+ Imposing explicit physical constraints may move us away from the pure financial market equilibrium
  - \- Simple examples indicate that the equilibrium solution may require unrealistic liquidity in the day-ahead market

To Summarize

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

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

Outline

Numerical Illustration

Consider the following market bids:

- Blast furnace: 323 MW @ 38.13 €/MWh
- Renewable: 106 MW @ 35.71 €/MWh
- Gas-oil: 5 MW @ 85 €/MWh
- LVN: 212 MW @ 315 €/MWh
- Demand: 100 MW (inelastic)

Percent of worst-case scenarios considered in CVaR:

- Blast furnace: $\alpha = 20\%$
- Renewable: $\alpha = 30\%$
- Gas-oil: $\alpha = 50\%$
- LVN: $\alpha = 70\%$
- Demand: $\alpha = 90\%$

Summary Statistics

Consider the scenario tree of the previous section with *equal transition probabilities* at every stage

	λDA	λRDA	λRT_{S1}	λRT_{S2}	λRRT_{S1}	λRRT_{S2}	Welfare
SCV	47.9	11.1	35.7	63.1	0	25	1,001,800
SCP	55.3	18.2	35.7	63.1	0	25	1,005,260
SEV	37.1	0	35.7	38.1	NA	NA	996,369
SEP	37.4	0.4	35.7	38.1	NA	NA	996,556
RCV	47.9	12.8	35.7	63.1	0	25	1,001,950
RCP	50.6	25.0	35.7	63.1	0	25	1,007,120
REV	37.1	0	35.7	38.1	NA	NA	996,329
REP	37.4	0.3	35.7	38.1	NA	NA	996,452

Outline

Conclusions

	S/R	C/E	V/P	Preliminary observations
SCV	✓	✓	✓	Theoretical first-best, large (long and short) positions in DA reserve market
SCP	✓	✓		Mitigates DA reserve exposure with minor effect on DA-RT price convergence
SEV	✓		✓	Not reasonable: degenerates to energy-only market without reserve market
SEP	✓			Weak DA reserve capacity signal, not the result of back-propagation of RT price
RCV		✓	✓	Inflation of DA reserve price due to uncertainty regarding TSO reserve needs
RCP		✓		Highest DA reserve price
REV			✓	Same weakness as SEV
REP				Same attributes as SEP

Perspectives

- Multiple periods
- Multiple reserve types
  - Differentiate *secondary* and *tertiary*
  - Differentiate *upward* and *downward*
- Unit commitment (per work of De Maere and Smeers)
- Additional features: pumped hydro, imports/exports
- Practical questions:
  - width of ORDC
  - effects of switch every 4 hours on volatility of RT price
- Computational challenges: regularized decomposition of equilibrium models seems promising

Thank You for Your Attention

For more information:

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