# Study Committee C5

## Electricity Markets & Regulations

10604

# SPATIOTEMPORAL EFFECTS OF NODAL MARGINAL PRICING

Tatiana VASKOVSKAYA

V.A. Trapeznikov of Institute of Control Sciences of Russian Academy of Sciences

OJSC "Trading System Administrator of Wholesale Electricity Market Transactions "

## Introduction

- Locational marginal pricing allows optimal scheduling of generators while delivering power under constraints
- Price signals are necessary for effective usage of available and emerging resources during
  - creation of the conditions for new market participants
  - integration of wholesale and retail markets

## Motivation

- A lot of effort is dedicated to formulating mathematical models and algorithms. OPF problem has been considerably tangled
- However, the possibility of intuitively explaining LMP and shadow prices of binding constraints through marginal resources meets serious challenges

## Methodology

- The approach is based on marginal resources' respond to changes in the system
- The responses are price-bonding factors (PBF) or price linkages to marginal resources
- Locational marginal prices are the sum of PBFs multiplied by resources' marginal costs

## Framework

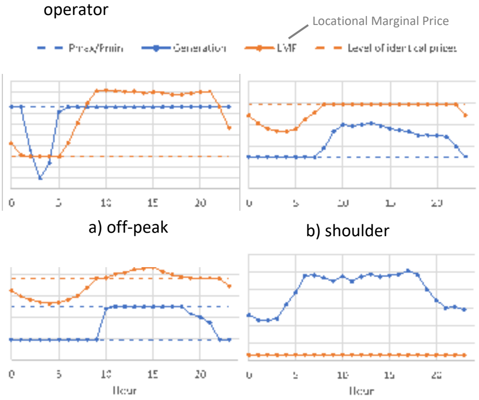
- AC OPF framework for day-ahead market with transmission, voltage, ramping, limited energy, and storage constraints
- The power system of 10 000 nodes, 16 000 branches
- Daily calculations in 24-hour time intervals

## Conclusion

- Multi-period AC optimal power flow shapes a spatiotemporal structure of locational marginal pricing
- We give an intuitive understanding of how marginal resources are exploited
- We examine four combinations of different constraints in real pricing situations
- Ramping, limited energy, and storage constraints are intertemporal and connect different time intervals
- Transmission and voltage constraints are locational but create price signals due to rescheduling of resources through intertemporal constraints
- Thus , LMPs will be formed by prices of marginal resources from different time intervals

## 1. Limited Energy Resources (LER)

- Has limited overall energy = area under scheduling plot is constant
- Generation at certain hour is a choice of the market operator




a) off-peak

b) shoulder

c) peak and shoulder

d) full-day

When generation is constant LMPs differ. When generation differs LMPs are identical

- LMPs are flattened by LER throughout hours = LER is not interested in changing its output.
- LMPs are identical only at LER's node
- LER is either sets prices or has active limited energy constraint
- In the latter case it rather collects prices of other marginal resources

## Discussion

- LER reallocates marginal resources to fit its optimality
- LER transfers prices from one hour to another
- LER maintain two modes simultaneously:
  - price-taking mode when LMP is formed by other resources.
  - price-forming mode when LER sets the price taken from other hours

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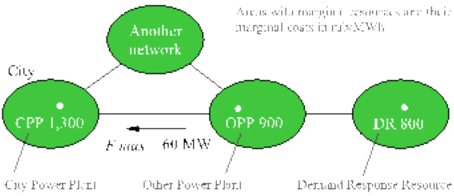
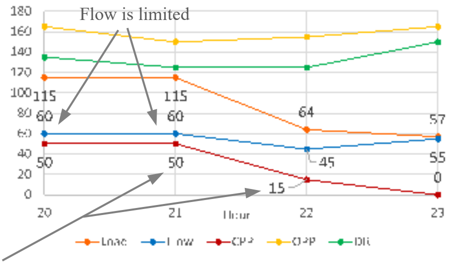
## 2. Ramping Constraints

- To meet a ramp-down rate, a generator need to reschedule its output with help of closest infra- and extramarginal resources
- Marginal resources from the adjacent time interval participate in forming LMPs



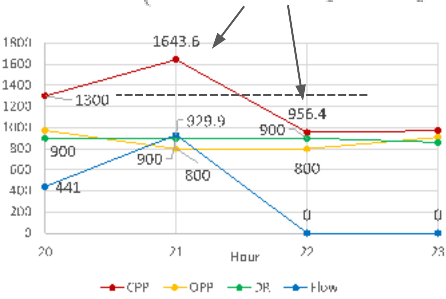

The city load, flow to the city, and marginal resources' output, MW




Ramp-down rate prevents reducing CPP's output

LMP at marginal resources' nodes and shadow price of flow to the city, rub/MWh

$$\begin{cases} LMP_{CPP,21} = C_{gh} + v \\ LMP_{CPP,22} = C_{gh} - v \end{cases} \text{ or } \sum_h LMP_{i,h} = \sum_h C_{gh}$$




### Why LMP at CPP at hour 21 is so high?

Adding 1 MW leads to

- **Two times** increasing of CPP's output by 1 MW at hours 21 and 22 due to ramping constraint
- Decreasing OPP's output by 0.828 MW and increasing load of DR by 0.264 MW to balance CPP's changes at hour 22

$$LMP = 1{,}300 \cdot 2 - 900 \cdot 0.828 - 800 \cdot 0.264 = 1{,}643.6\ \frac{rub}{MWh}$$

### What is shadow price of ramping constraint?

Removing 1 MW from ramp-down rate leads to

- Increasing CPP's output by 1 MW at hour 22 — we can't abandon CPP at hour 21 due to transmission constraint
- Same changes in OPP's and DR's output

$$v = 1{,}300 \cdot 1 - 900 \cdot 0.828 - 800 \cdot 0.264 = 343.6\ \frac{rub}{MWh}$$

### Why shadow price of transmission constraint at hour 21 is so high?

Removing 1 MW from transmission capacity leads to

- Increasing CPP's output by 1.252 MW at hour 21 — we supplied 0.252 through another network
- Alike changes in OPP's and DR's output at hour 22 as in the case of LMP at CPP's node

**We repeat it again** for hour 22 due to ramping constraint

$$\sigma = 1{,}300 \cdot 1.252 - 900 \cdot 0.959 - 800 \cdot 0.353 + 1{,}300 \cdot 1.252 - 900 \cdot 0.990 - 800 \cdot 0.361 = 929.9\ \frac{rub}{MWh}$$

### Discussion

A generator with an insufficient ramp-down rate produces

- a peak price higher than any marginal cost in the system
- a doubled shadow price of a transmission constraint

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## 3. Energy Storage Systems (ESS)

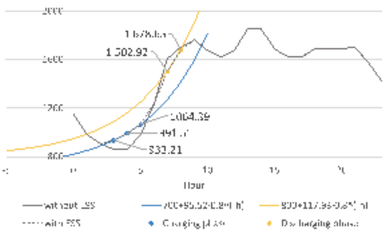
- ESS is like LER with two periods of flattened prices – charging and discharging
- If ESS has storing inefficiency, prices are identical on a logarithmic scale — to provide equality of selling and buying profits in absolute terms.

Round trip efficiency

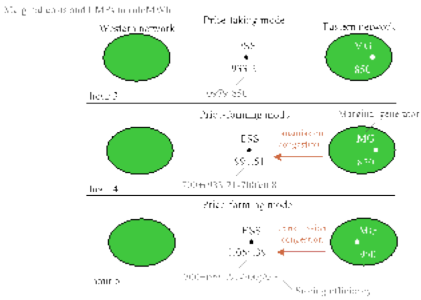
$$\left(LMP_{t,t_1} - C_{t,t_1}\right)\eta_s^{t_1}\eta = \left(LMP_{t,t_2} - C_{t,t_2}\right)\eta_s^{t_2}$$

Bid/offer price — Storing efficiency

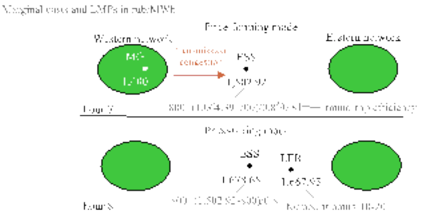
LMP at ESS's node, rub/MWh




Charging hours with bid price 700 rub/MWh




Discharging hours with offer price 800 rub/MWh



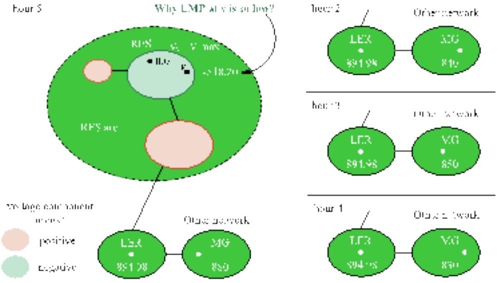

### What is LMP at ESS's node at hour 4?

Adding 1 MW leads to

- Inability to deliver power from MG with cost 850 rub/MWh
- Reducing consumption of ESS by 1 MW with cost 700 rub/MWh
- Decreasing ESS's generation at hour 8 by $1 \cdot 0.8^4 \cdot 0.81 = 0.332$ MW with cost 800 rub/MWh
- Increasing LER's output at hour 8 by 0.334 MW with LMP 1,667.95 rub/MWh

$$LMP_4 = \underbrace{\left(700 - 800 \cdot 0.8^4 \cdot 0.81\right)}_{\text{ESS's contribution}} + \underbrace{1{,}667.95 \cdot 0.334}_{\text{LER's contribution}} = 991.51 \frac{rub}{MWh}$$

## 4. Voltage Constraints




- Negative price at node *v* reflects the excess of reactive power.
- It is formed by RES with zero cost minus cost of MGs at hours 2–5 which outputs decreased after adding 1 MW at node *v*

### Discussion

- Due to the voltage constraint active power from RES redistributes to LER and other MG for the considered hour and other hours of LER's schedule
- Voltage component eliminates the contribution of marginal resources in a local area to LMPs outside.

### Discussion

- ESS' pricing is like LER. However, ESS contributes to price formation with bidding prices while LER only redispatches the power of other resources
- Transmission constraint employs marginal resources from further time periods when ESS discharges.