

# Flexibility services in the electrical system

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# Outline

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The European electrical system

Flexibility in electrical system

Flexibility in

- the day-ahead energy market

- the reserve market

- the distribution network

Flexibility from

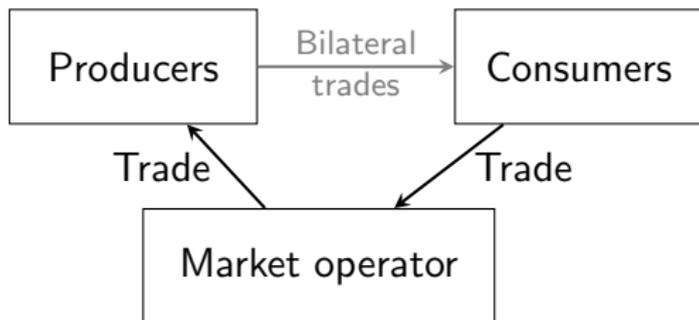
- heat pumps

- a price signal in the distribution network

Conclusion

# Producers, consumers and the market

Electricity is a commodity which main roles are:



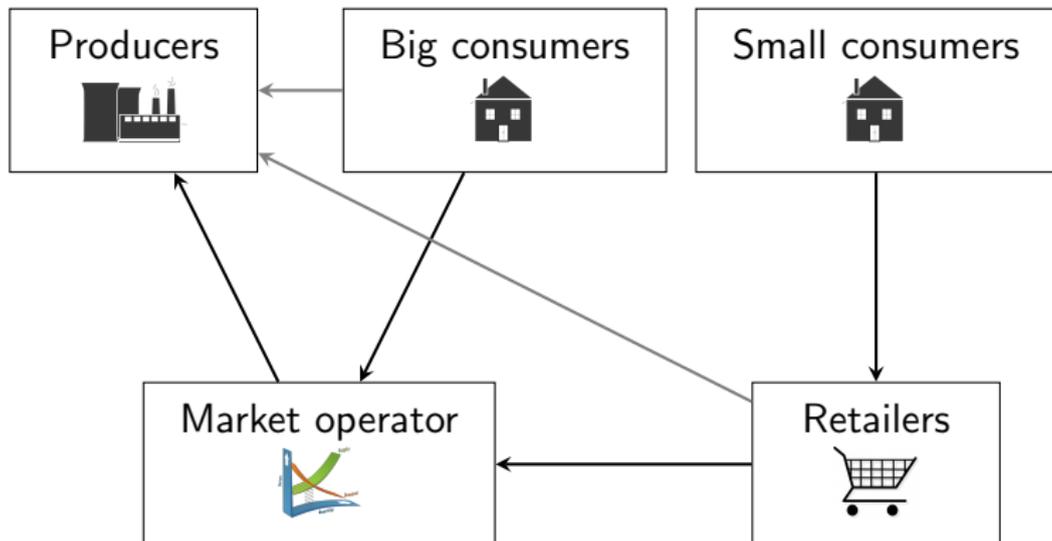
The most common market is the day-ahead energy market.



# Electricity retailers

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**Small consumers** do not buy their electricity individually but make use of the services of **intermediation** provided by **retailers** .



# The network

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Once traded, electricity needs to be conveyed. The physical link is called the network.

The network is divided into 2 layers:

- ▶ The **distribution** network operated by the **Distribution System Operator (DSO)** .  
*Low-voltage < 1kV & medium-voltage < 36kV*
- ▶ The **transmission** network operated by the **Transmission System Operator (TSO)** .  
*High-voltage > 36kV*



# Imbalance

One of the most important task of the TSO  is to maintain the **balance** at every moment between **production and consumption**.

This **equilibrium** is first **ensured on the trades** with the obligation for each participant to submit a **planning** of production and consumption called **baseline**.

The **baselines** are **provided** by **Balancing Responsible Parties (BRP** ) which may regroup multiple actors.

*To access to the network, every user of the network needs a BRP.*

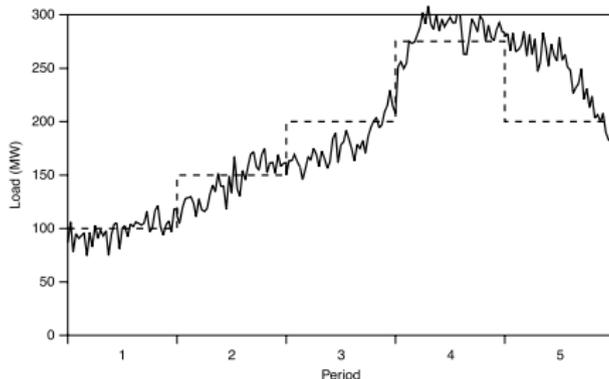
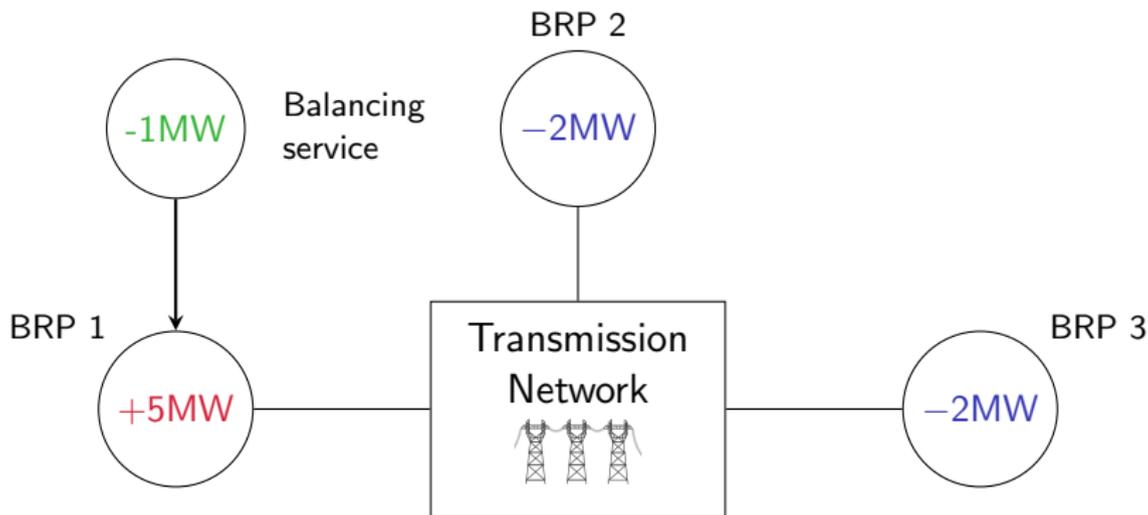


Figure: Example of baseline and realization.

# Balancing responsibilities

In real-time, **realizations** may **deviate** from **baselines**. The **TSO**  is responsible to **compensate** the overall **imbalance**.

Due to the unbundling of the electrical system, the **TSO**  **does not own production or consumption** assets and must **contract and activates balancing services** according to the needs of the system.



Imbalance of the system: **+1MW**

# Imbalance price

The **most expensive** activated service **defines** the **imbalance price** which serves as a basis for the **payment or compensation** of BRPs in imbalance.

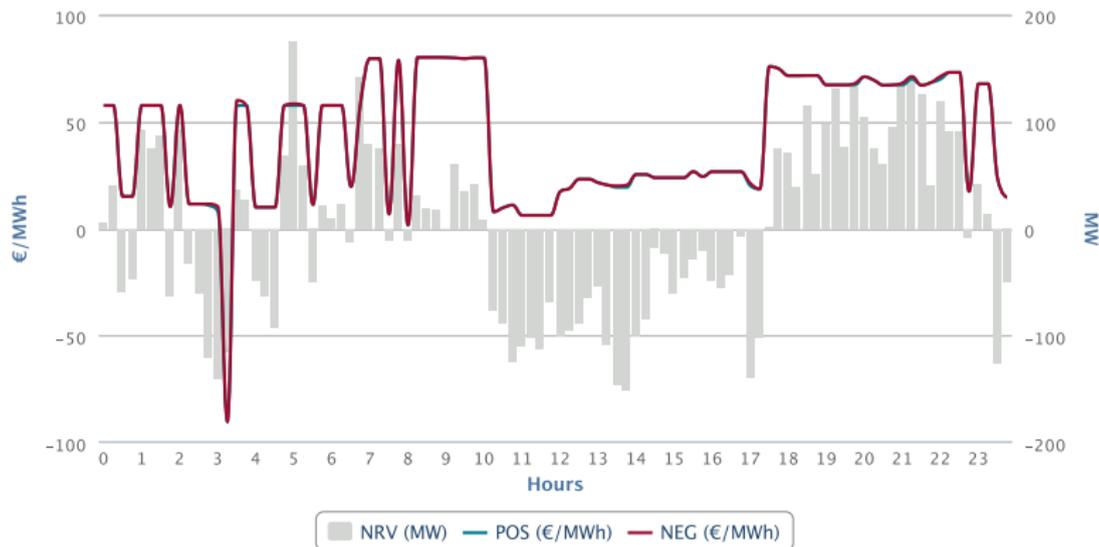


Figure: Imbalance prices on June 1, 2015 of Elia, the Belgian TSO.

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# Definition of the flexibility

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**Flexibility** in electrical system is the **modification** of the **production** or **consumption** in **reaction** to an activation **signal** to provide a **service**.

*e.g. a gas unit producing 25MW asked to produce 1MW more.*

The actor providing flexibility is called in this work a **Flexibility Service Provider (FSP** ).

The needs for flexibility can be triggered by:

- ▶ the loss of a production unit,
- ▶ an unexpected over-production of a wind turbine,
- ▶ a congestion in a line of the network, etc.

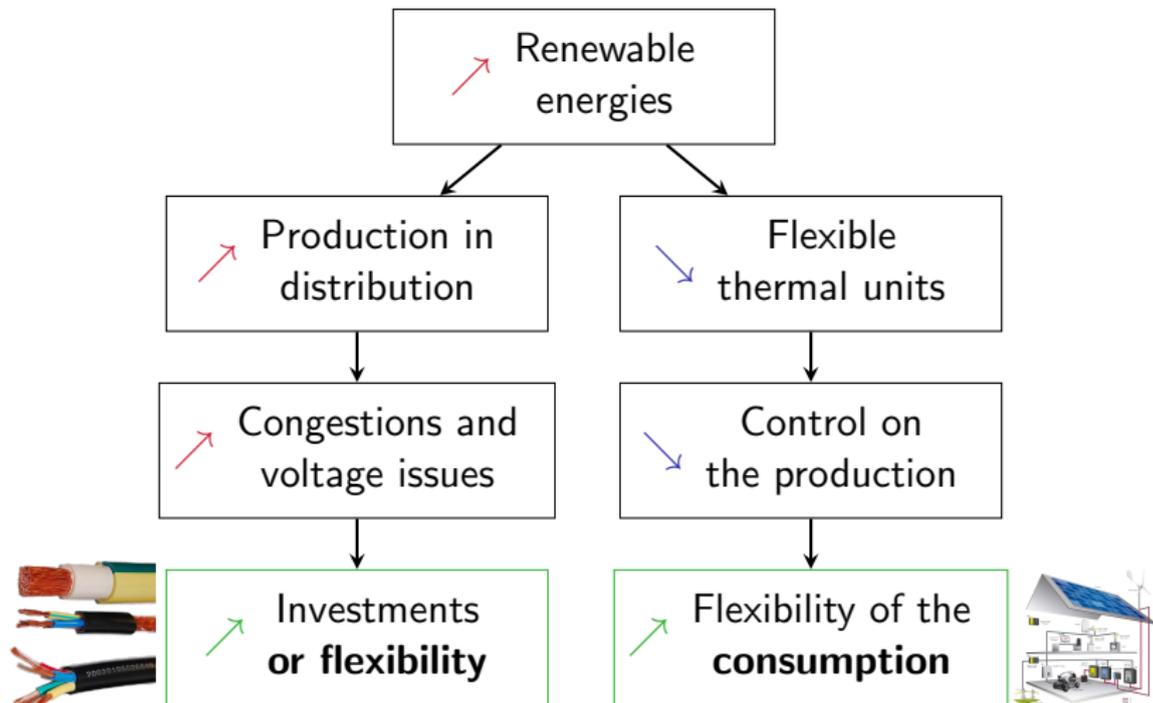


# Changes of the electrical system

The current electrical system is extremely reliable.

*“Why looking at flexibility since **everything is already working?**”*

The electrical system is changing from its traditional conception.



# Renewable energy curtailment

Production units may change their output to provide flexibility.

Flexibility	Thermal unit	Wind turbine
↗ modulation	↗ fuel	-
↘ modulation	↘ fuel	↻ blades pitch

To provide an **upward modulation**, a production unit runs **below its maximum power**.

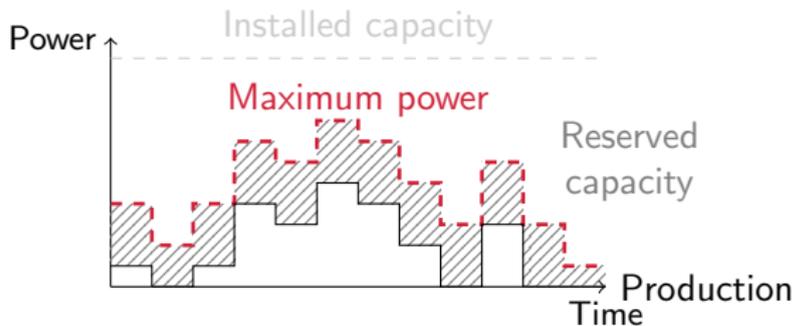


Figure: Wind turbine production plan with reserved capacity.

**Reserving** capacity on a wind turbine is equivalent to throwing away this **free energy**.

# Flexibility of the consumption

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A large part of the **consumption** can be **controlled**.

*e.g. electrical heaters, air-conditioners, industrial consumption, etc.*

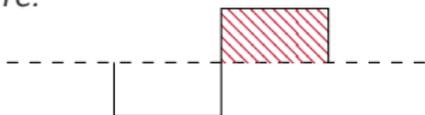
The control of loads gives rise to **new challenges**:

- ▶ Developing solutions which considers the **constraints** of all **processes behind** the electrical consumption.

*e.g. getting flexibility from heat pumps.*

- ▶ Integrating the **payback effect** coming from the modulation of energy consumption into flexibility **services**.

*If the consumption of a fridge decreases for 1h, the temperature inside the fridge rises. In the 2<sup>sd</sup> hour, the fridge consumes more to restore the temperature.*

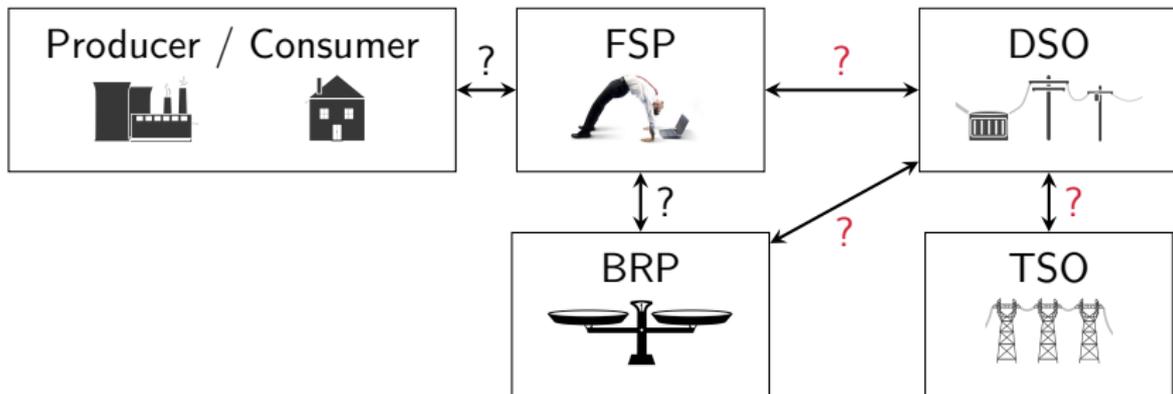


- ▶ Determining the **cost** to provide the flexibility.

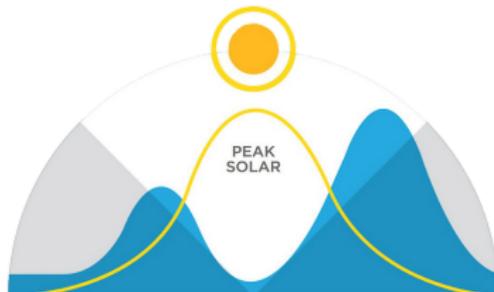
# Flexibility in distribution networks

The DSO may resort to different **options** to obtain flexibility:

- ▶ Using **flexibility services** in the distribution network.



- ▶ Changing the **distribution network tariffs** to shift consumption.



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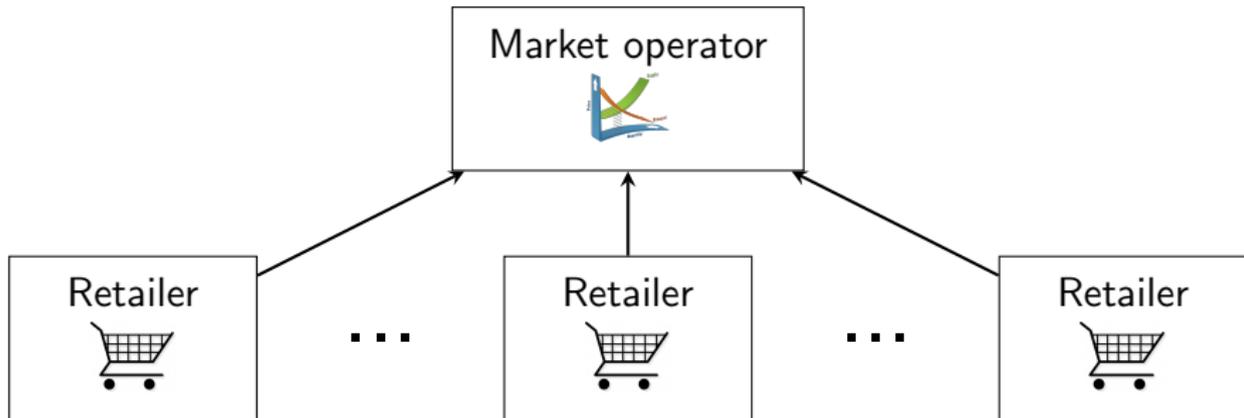
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# Retailers and day-ahead energy market

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We study the system ...

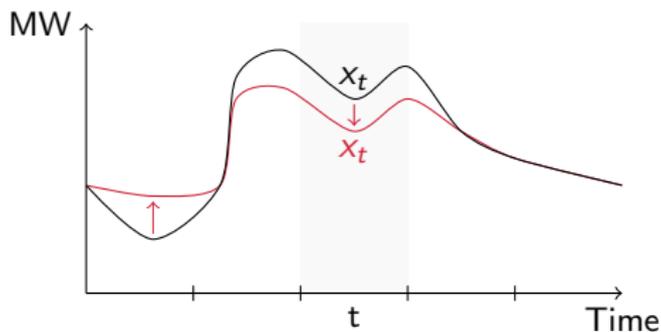


... using **game theory**, in particular **congestion games**.

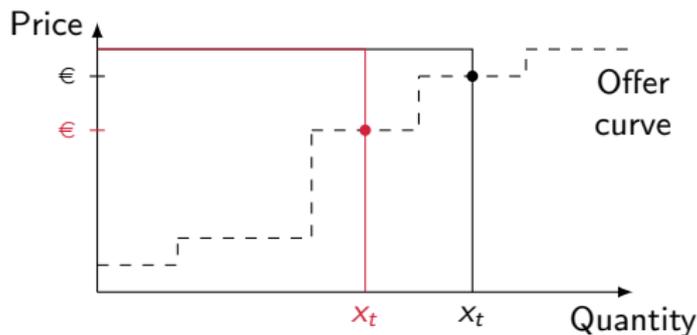
Each retailer with flexible consumption can **choose** its **consumption** in each hour to **minimize** the **cost** of buying its energy.

# Shifting demand according to energy prices

Changing the consumption profile...

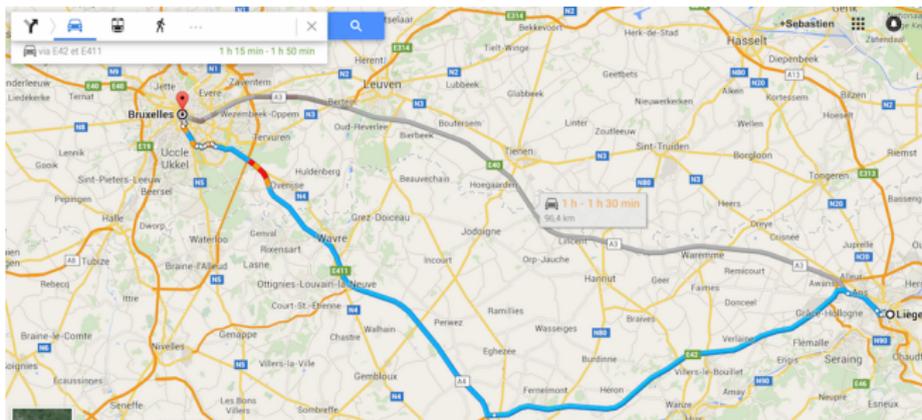


... affects the energy prices.

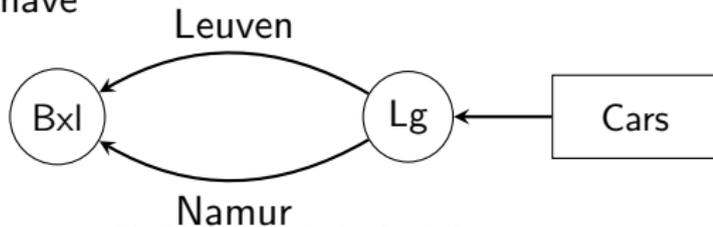


# Congestion game

An example of congestion game is the **car trip Liège-Bruxelles**. The more cars there are on the road, the more time it takes. At **7 am**, the **time taken is identical** for the two paths. This situation is a **Nash equilibrium**.

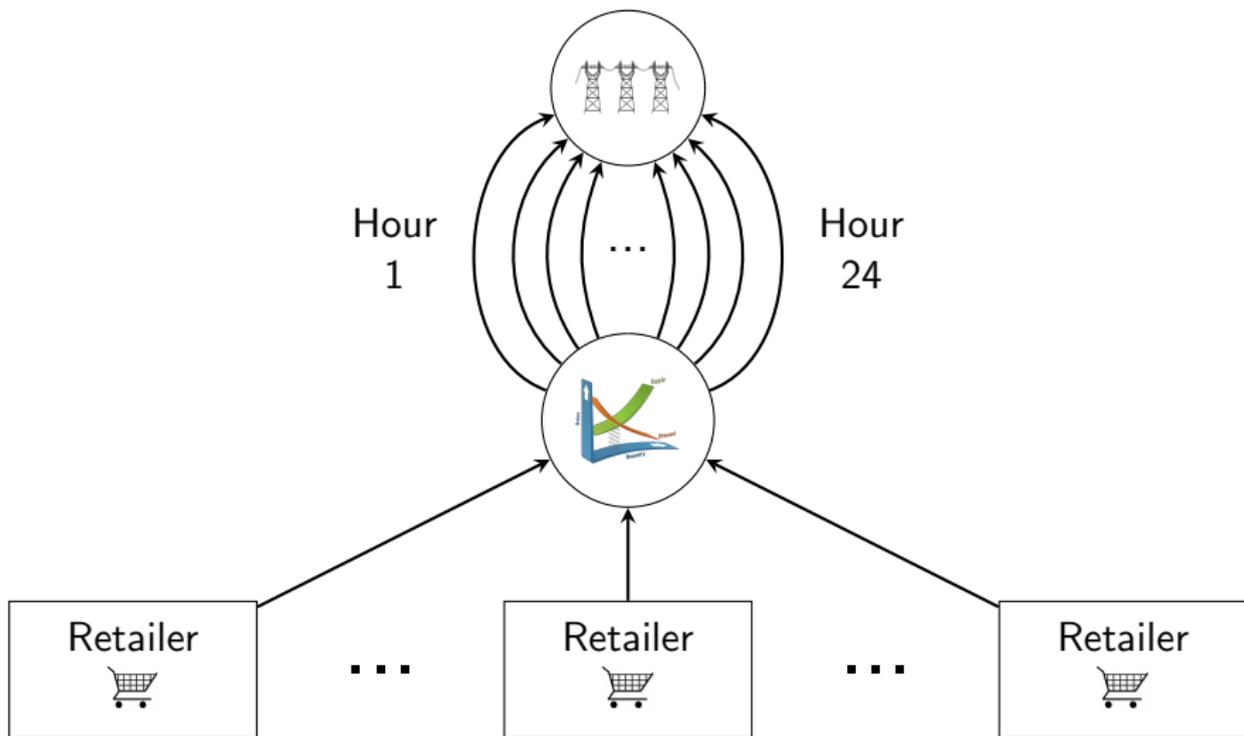


Schematically we have



# Retailers-market system as a congestion game

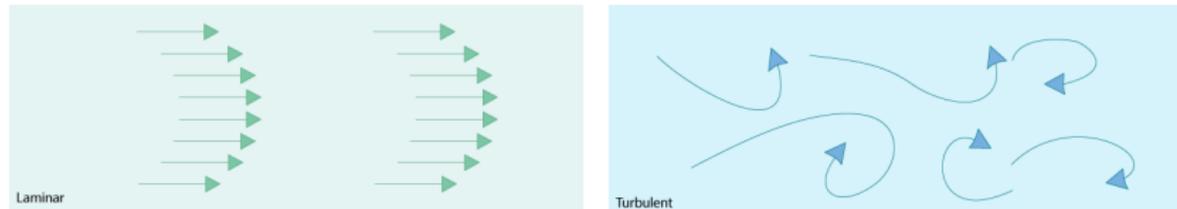
The **mapping** of the retailers-market system as a congestion game is:



# Results

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We define and work on a **particular regime** of the game: the **laminar** flow, valid if retailers are “big enough”.



## Contributions

If the Nash equilibrium is laminar, we obtain

- ▶ a bound on the **ratio maximum/minimum market price**,
- ▶ a bound on the ratio of the **total system cost** at the Nash equilibrium and the optimal one,
- ▶ the **price of flexibility**, i.e. the cost of shifting energy away from a given hour.

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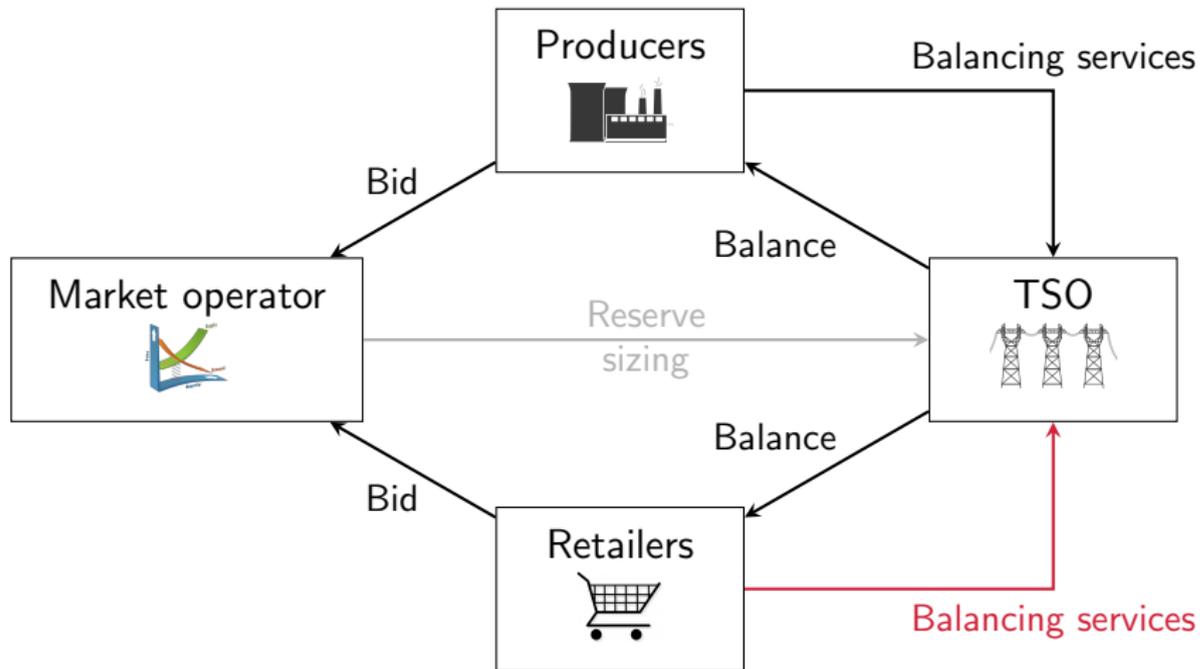
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# Impact of load flexibility on the reserve market

What is the **impact** of a **retailer** controlling flexible consumption on the day-ahead **energy market** and on the secondary **reserve market**?



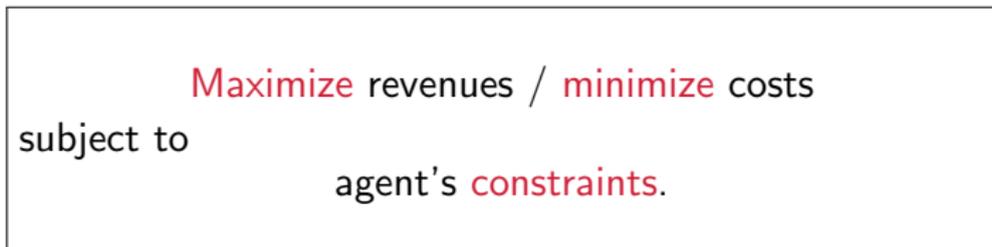
# Agent-based modeling

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Each actor is modeled individually in an **agent-based system**.



The behavior of the actors are given by **optimization problems**.

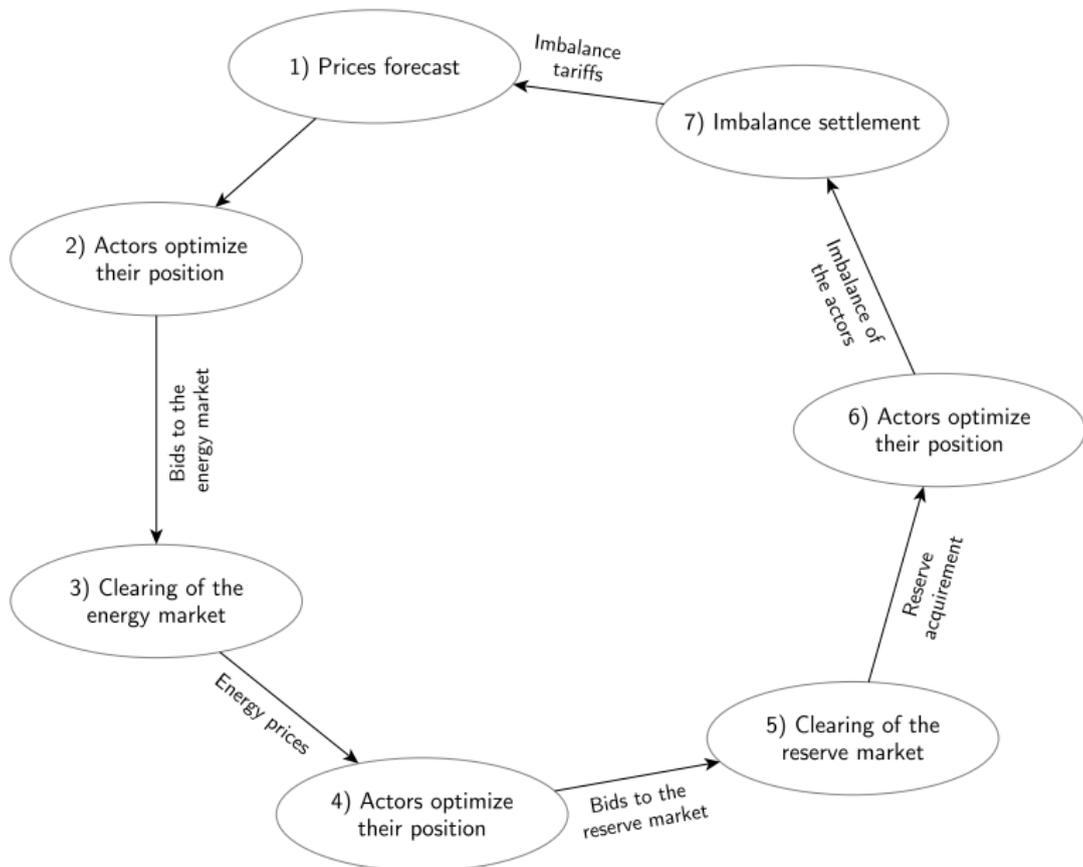


This kind of models allows to

- ▶ **model individually** each actor and observe their **reaction** in the **complete** modeled **system**,
- ▶ to highlight and understand **unpredicted behaviors** of the actors.

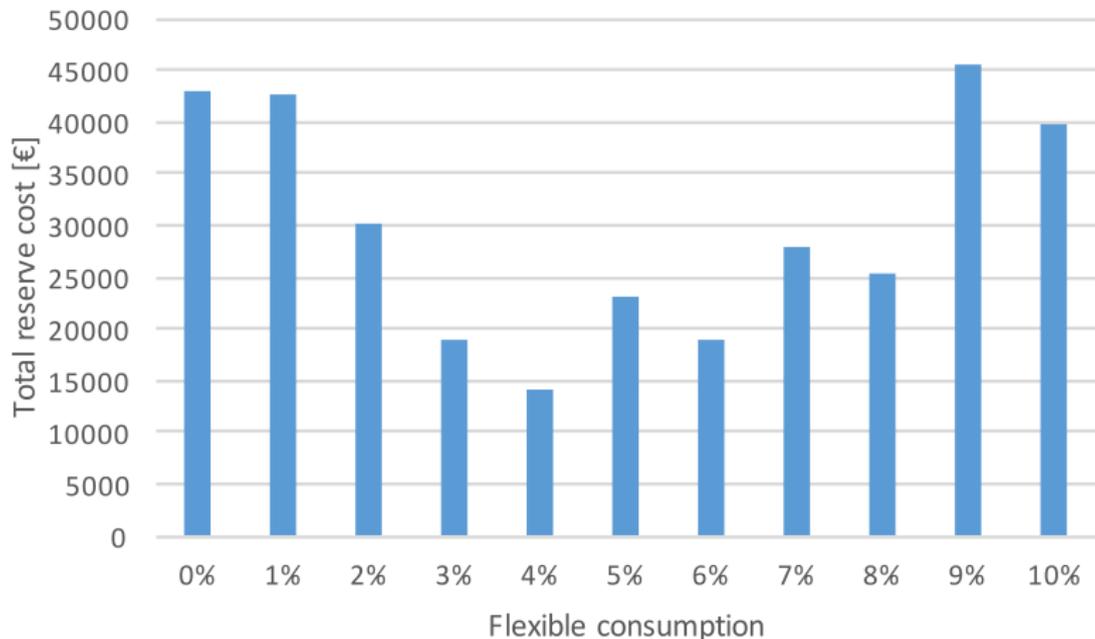
# General view of the simulated system

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# Results

Drastic **reduction** of the reserve **procurement costs** even though the **total cost** increases above 4% of flexible consumption.



Reserve services provided by the consumption are **less efficient** due to the **payback effect**.

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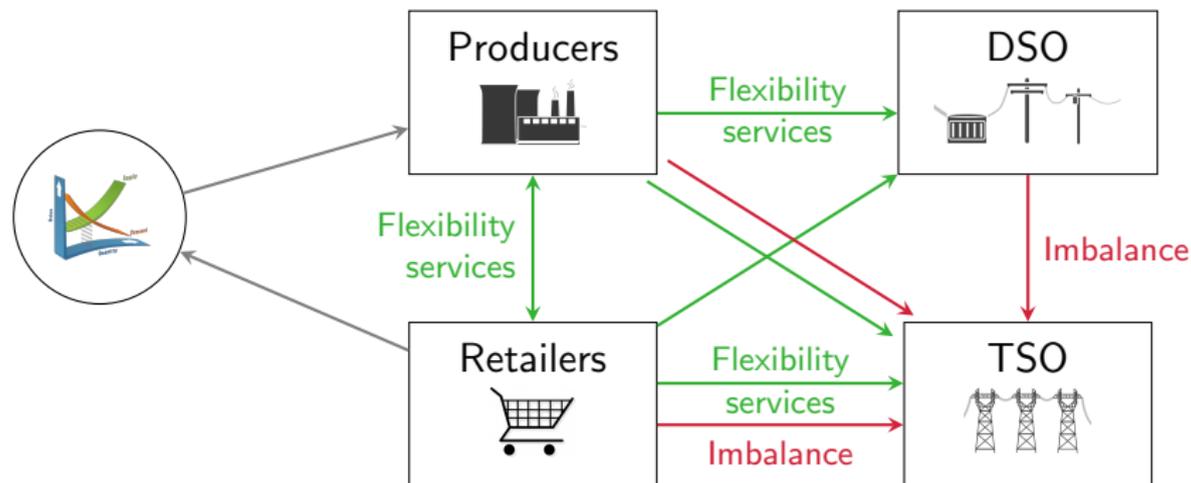
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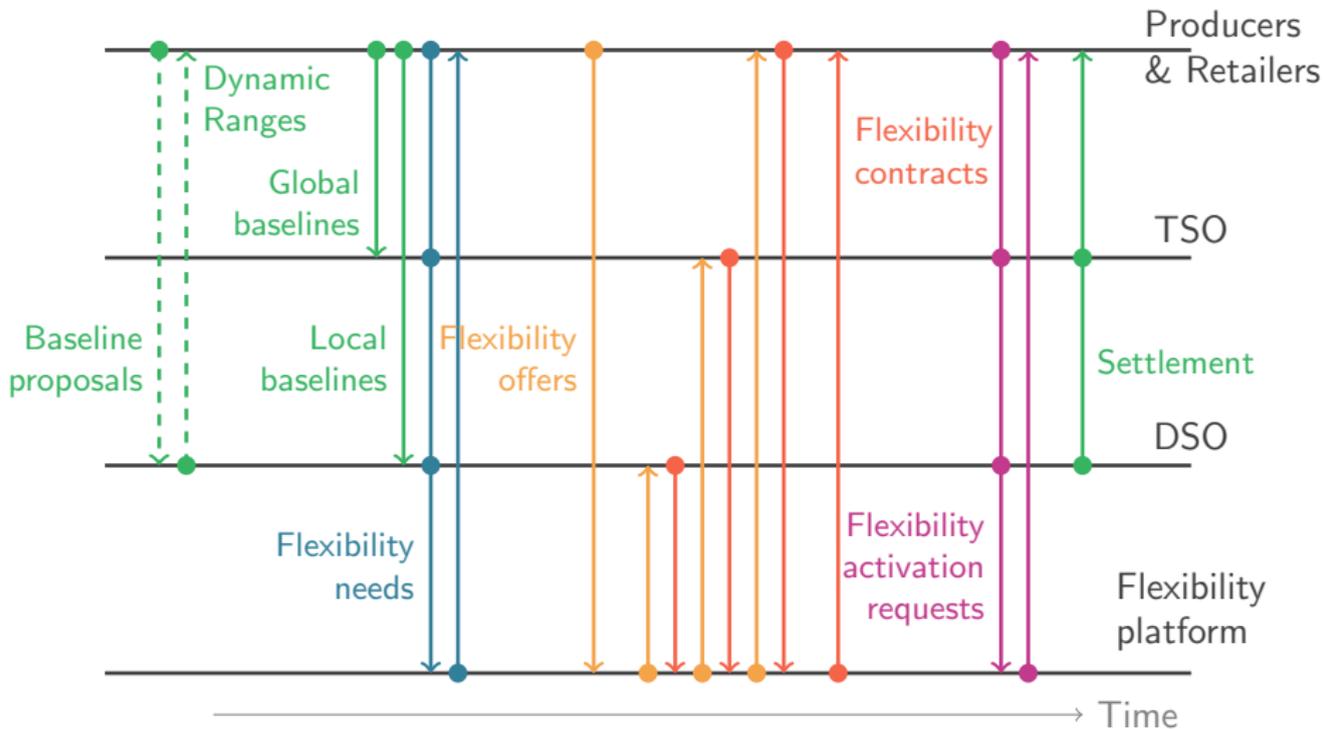
# Active distribution network management

Flexibility in the **distribution network** is mostly **unused** up to now and could solve local **congestion** problems.

There is a need of a **framework detailing** the **interactions** needed to exchange flexibility.



# Timeline of the interaction between the agents



**Figure:** To each arrow corresponds an exchange of information whose source is given by the dot and the destination by the arrow head.

# DSIMA: an open-source testbed

The testbed to evaluate interaction models is available as an **open source** code at the address

<http://www.montefiore.ulg.ac.be/~dsima>

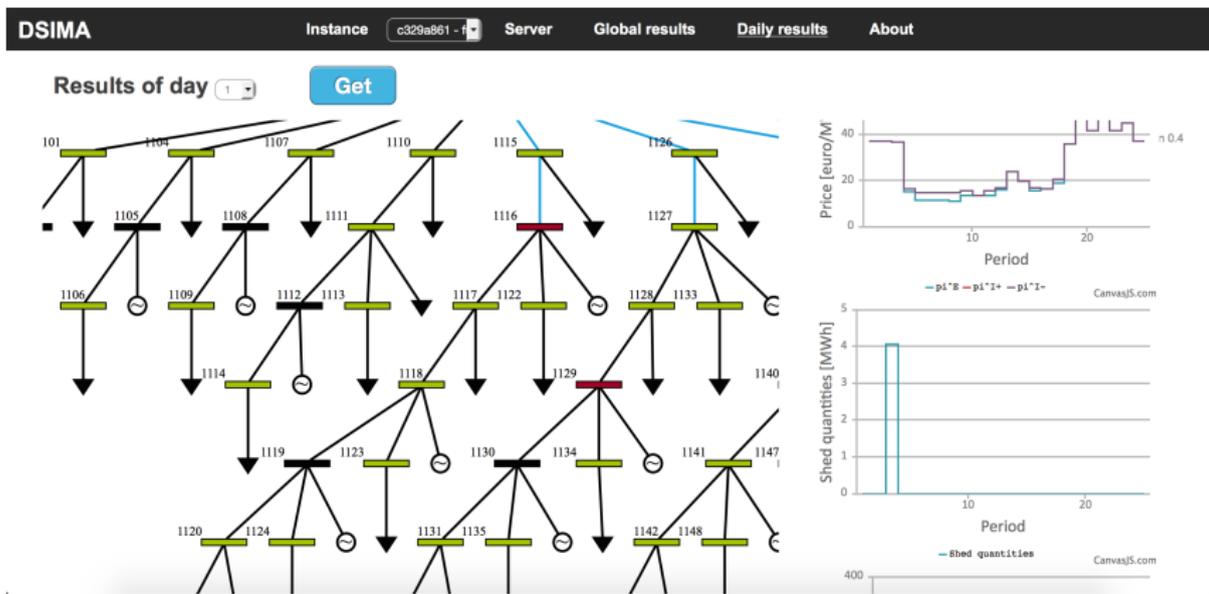


Figure: Screenshot of the user interface.

# Interaction models

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DSIMA allows **comparing quantitatively** different interaction models. In the thesis, **six interaction models** are studied.

These interaction models are differentiated by

1. their type of **access contract** to the distribution network,
2. their **financial compensation** of flexibility services.

**Table:** Summary of the parameters of 4 of the studied interaction models.

<b>Interaction model</b>	<b>Access type</b>	<b>Financial compensation</b>
Model 1	unrestricted	–
Model 2	restricted	–
...		
Model 5	unrestricted	bids & imbalance
Model 6	dynamic	–

# Results

Results obtained on a 75 bus network for a representative 2025 year.

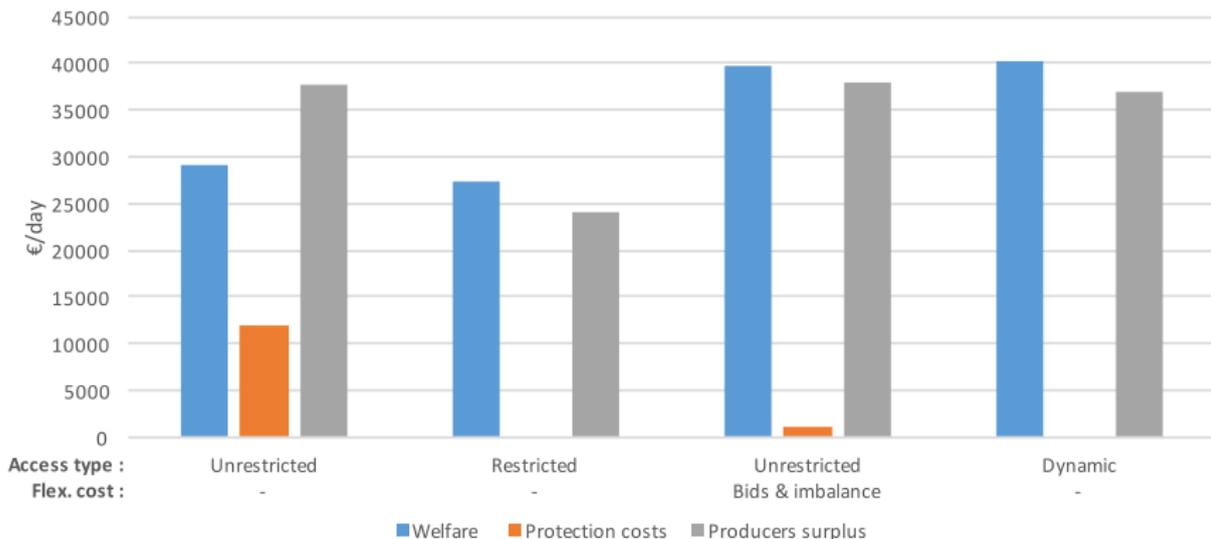


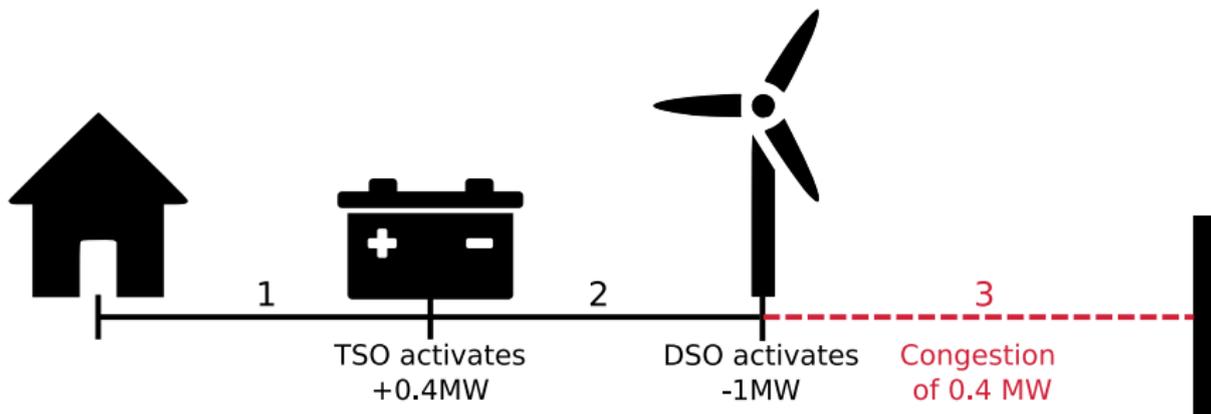
Figure: Quantitative comparison of four interaction models.

Protection costs reflect the cost of shedding of production or consumption due to problems in the management of the system.

# Coordination problem

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Assume that the DSO predicts that the power flow will exceed the capacity of the line 3 by 1MW. To solve this issue, the DSO curtails a wind turbine by 1MW.



At the same time, assume that the TSO asks a storage unit to inject 0.4MW. These activations lead to a remaining congestion of 0.4MW.

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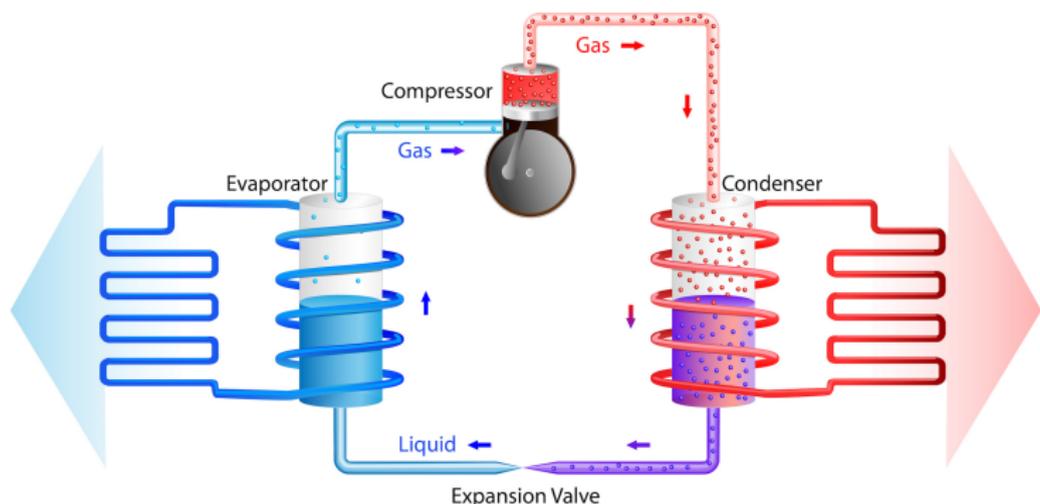
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# Flexibility from heat pumps

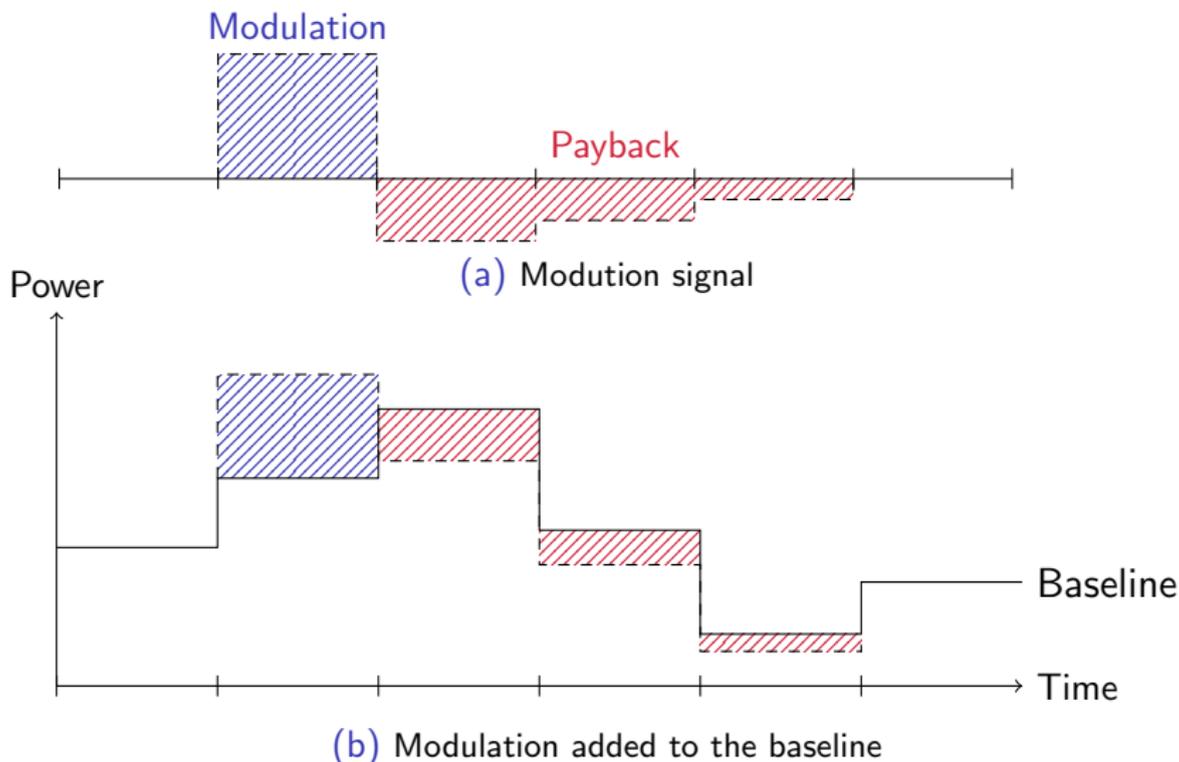


This **electrical energy** consumed by the heat pump is converted into **heat** which is **stored** by the **building** and, depending on its thermal inertia, allows consumption to be shifted.



# A flexibility service considering payback

This flexibility service consists in a modulation in one quarter followed by a well **defined** and **limited** energy **payback** in the following hour.



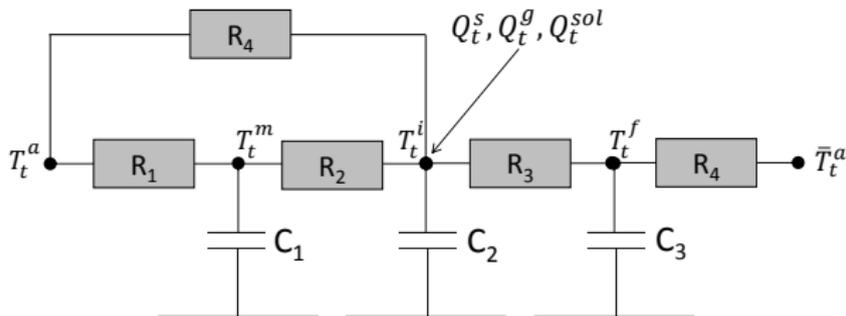
# Optimization of the baseline

Minimize energy cost

subject to

- ▶ thermal state transition model,
- ▶ state constraints,
- ▶ power limitations,
- ▶ heat pump constraints.

using an accurate thermal model of the building and the heat pump.



# Optimization of the modulation

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To obtain the maximum flexibility in quarter  $t$ , solve

**Maximize** flexibility available in quarter  $t$

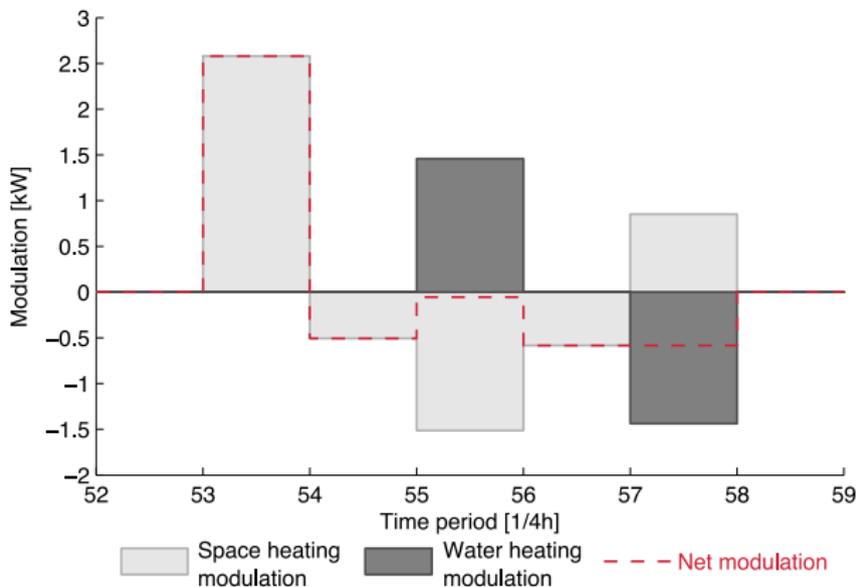
subject to

- ▶ thermal state transition model,
- ▶ state constraints,
- ▶ power limitations,
- ▶ heat pump constraints,
- ▶ **payback limited on  $k$  quarters.**

Accurately defining this payback is the key element that **allows** flexibility to be **used** in one quarter **without** risking **creating other issues** afterwards.

# Results

A modulation of **2.5 kW** with a payback of 1 hour provided by space heating from a **4.3 kW heat pump**. Domestic hot water counterbalances space heating to limit deviations during payback.



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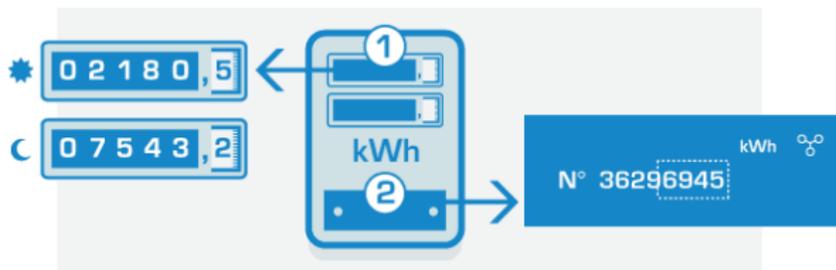
Conclusion

# Price signal in the distribution network

The DSO may use the **tariff of distribution** as a price signal to **shift the consumption** and alleviate problems in its network.



This solution has the major advantage that the **infrastructure is already in place** with the system of **off-peak and on-peak tariffs**.



In Belgium, there are **night-only meters** that switch on **electric boilers and heaters** only during off-peak periods.

# Problem statement

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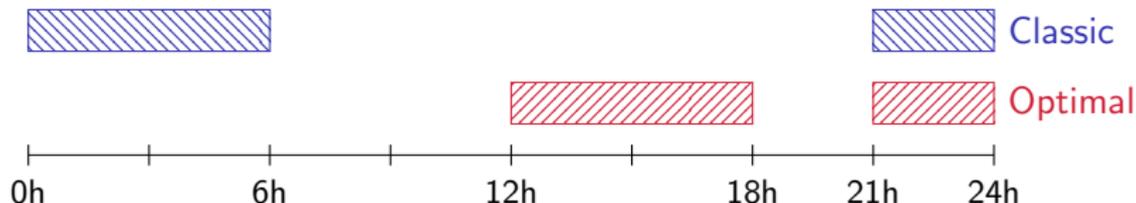
Find the best **off-peak hours pattern** by solving

**Minimize** energy costs  
**and** photovoltaic curtailment costs

subject to

- ▶ distribution network model and constraints,
- ▶ automatic tripping of solar panels,
- ▶ a fixed number of off-peak hours, etc.

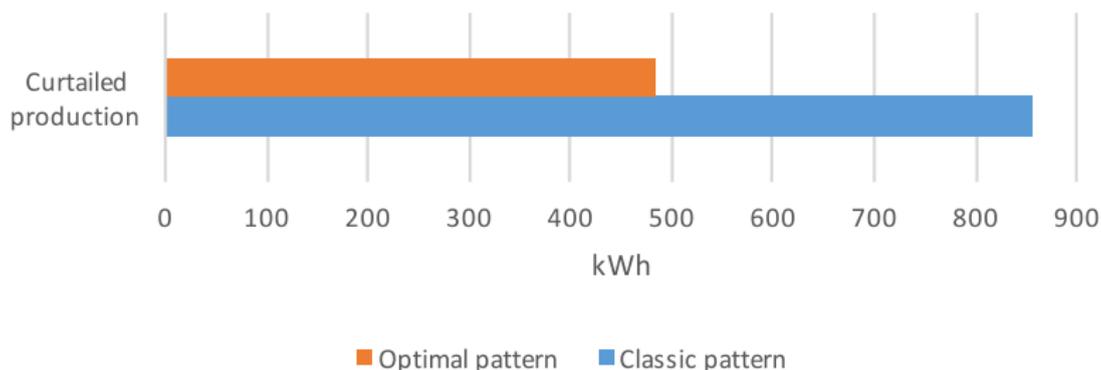
## Examples of off-peak patterns



# Results

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The test case is a **sunny summer day** on a 108 buses medium-voltage network with **5040 houses**. 5.7% of houses are equipped with night-only meters and **30% with PV panels** of 6 kW.



This is therefore a **good short-term solution** to increase the amount of renewable energy produced in the distribution network.

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# Summary

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This thesis assesses impacts of exchanging **flexibility** in the electrical system and analyzes the resulting **complex interactions**.

The **modeling techniques** used to carry the analysis are

- ▶ game theory,
- ▶ agent-based modeling,
- ▶ optimization.

The **impacts** on different parts of the electrical **system** are presented:

- ▶ the day-ahead energy market,
- ▶ the secondary reserve,
- ▶ the distribution system.

Methods to **obtain flexibility from** the **consumption** are broached:

- ▶ direct control of a portfolio of heat pumps,
- ▶ dynamic pricing to control electric heaters and boilers.

# Discussion

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This thesis strengthens the state of the art by formalizing the interactions needed to use flexibility in the European electrical system.

This work could be continued along two major lines:

- ▶ doing **further academic researches**:
  - ▶ more detailed models,
  - ▶ other modelization techniques,
  - ▶ compare investments in flexibility and in the network,
  - ▶ etc.



- ▶ going from **theory to practice**.

# Discussion

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This work could be continued along two major lines:

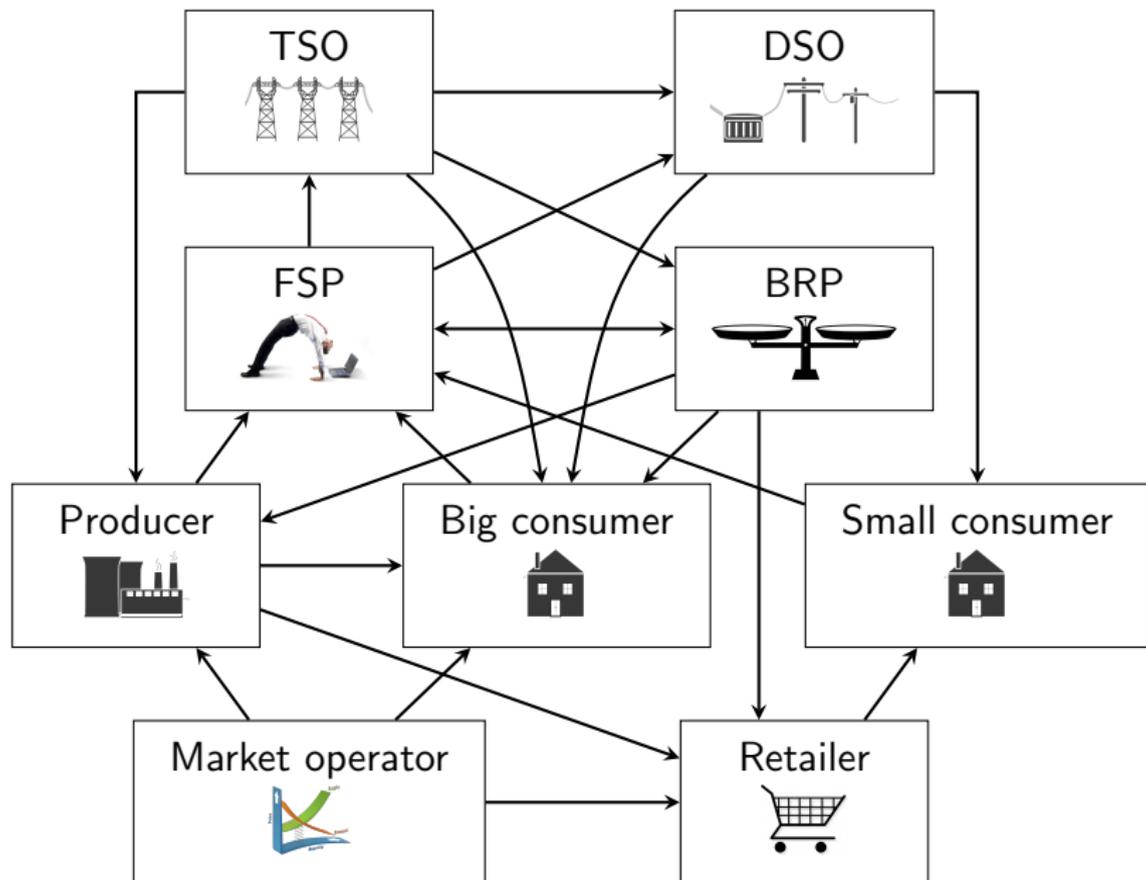
- ▶ doing **further academic researches**:
- ▶ going from **theory to practice**. There already are
  - ▶ many applied projects on flexibility,
  - ▶ an increasing number of flexible consumption devices,
  - ▶ algorithms able to coordinate these flexible loads.



My opinion is that one important **remaining step** to perform is to **complete** the **regulation** of flexibility in the electrical system.

Fortunately, many regulators of various countries of the European electrical system are **currently writing** this legislation.

# Conclusion



## Further information

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in the thesis:

S. Mathieu, "Flexibility services in the electrical system,"  
PhD thesis, University of Liège, 2016

and in the corresponding papers:

- ▶ S. Mathieu, Q. Louveaux, D. Ernst, *et al.*, "Dsim: A testbed for the quantitative analysis of interaction models within distribution networks," *Sustainable Energy, Grids and Networks*, vol. 5, pp. 78 –93, 2016, ISSN: 2352-4677. DOI: 10.1016/j.segan.2015.11.004
- ▶ E. Georges, B. Cornélusse, D. Ernst, *et al.*, "Direct control service from residential heat pumps aggregation with specified payback," in *Proceedings of the 19th Power Systems Computation Conference (PSCC)*, IEEE, 2016
- ▶ Q. Louveaux and S. Mathieu, "Electricity markets with flexible consumption as nonatomic congestion games," in *Submitted*, 2016
- ▶ L. Merciadri, S. Mathieu, D. Ernst, *et al.*, "Optimal assignment of off-peak hours to lower curtailments in the distribution network," in *Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2014 5th IEEE/PES*, IEEE, 2014
- ▶ S. Mathieu, Q. Louveaux, D. Ernst, *et al.*, "A quantitative analysis of the effect of flexible loads on reserve markets," in *Proceedings of the 18th Power Systems Computation Conference (PSCC)*, IEEE, 2014.