Smart Regulation for Distribution Networks: Modelling New Local Electricity Markets and Regulatory Frameworks for the Integration of Distributed Electricity Generation Resources

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LIÈGE université

The lost mountain

(a) Year – 1900

The lost mountain

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(b) Year – 2013

Figure 1: *Extracted from* del Valle Melendo, J., 2014. El cambio climático: reflexiones tras la cumbre de Varsovia. Pre-bie3, (1), p.29.

Global warming

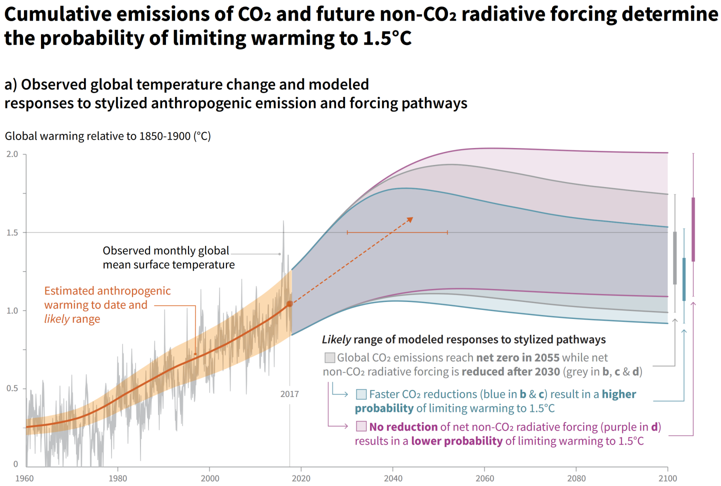

Figure 2: *Extracted from* IPCC report 2018: Summary for Policymakers.

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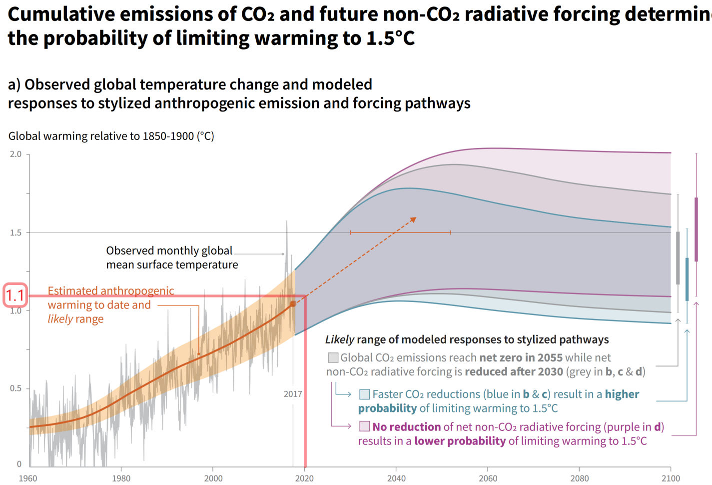

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Energy Transition

Energy consumption comes from mainly three sources:

- transport sector;
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- electricity sector.

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Energy transition == Paradigm shift

Pathway toward the transformation of the global energy sector from fossil-based systems of energy consumption and production to a zero-carbon system.[a]

[a] International Renewable Energy Agency (IRENA) – https://www.irena.org/energytransition

Energy Transition

Energy consumption comes from mainly three sources:

- transport sector;
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- electricity sector $\Rightarrow$ **decarbonisation of this sector**

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Decarbonisation of the power sector

From conventional to renewable

- Large, conventional power plants (coal, gas) replaced by renewable alternatives (wind, hydro, solar);
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From centralised to decentralised

- Large power plants far from the consumption centers replaced by small renewable alternatives closer to them;
- Decentralised effort deploying small production units (e.g. rooftop solar photovoltaic).

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Outline of the presentation

1. Decentralisation of the electricity sector and challenges
2. Objectives
3. Part I
   - The role of the distribution system operator
   - Metering technology & Tariff design
   - A tariff simulator
   - Results & Policy recommendations
4. Part II
   - New decentralised electricity markets
   - Flexibility services
   - A market design for renewable energy communities
   - Insights on decentralised electricity markets
5. Conclusion & Outlook

Decentralisation of the power sector and challenges

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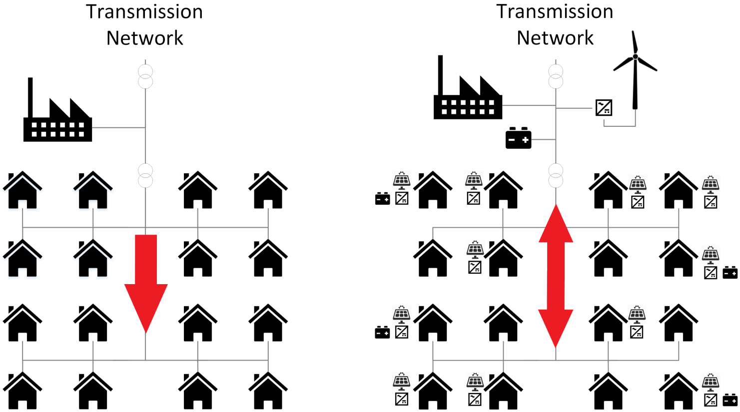

Figure 3: Distribution network – from passive (left) to active (right).

Decentralisation of the power sector and challenges

Technical challenges:

- under-/ over-voltages;
- energy losses.

Regulatory challenges (concerning distribution networks):

- how to pay for the use of the distribution network;
- establish ground rules for new local electricity markets.

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- how to pay for the use of the distribution network; **Part I**
- establish ground rules for new local electricity markets. **Part II**

Objectives

Part I

Assess the qualitative and quantitative impacts of the decentralisation of the power sector on the economic sustainability of distribution networks.

Part II

Design and implement new consumer-centric electricity markets.

The role of the DSO

The role of the DSO

Distribution networks are operated by DSOs[1], these entities:

- operate and maintain the electricity distribution system;
- reinforce the network if necessary;
- ensure the electricity delivery considering some technical constraints;
- DSOs draw revenues from users charges and must break-even.

Design of the revenue collection of the DSO

- economic sustainability of the DSO;
- avoidance of potential regulatory failures.

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How to value the DSO service is not clear.

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The role of the DSO

Example of regulatory failure

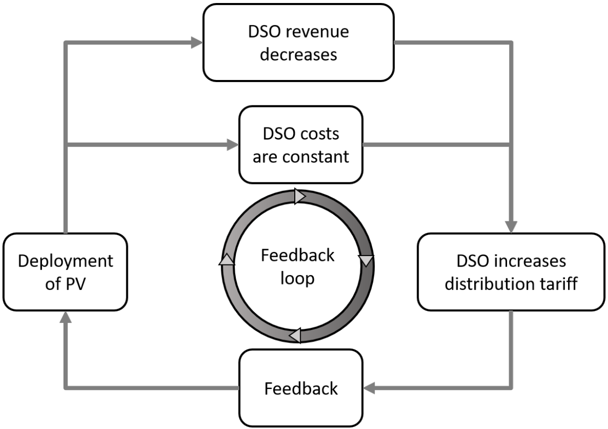

Figure 4: Death spiral of the utility – DSO fee increases owing to PV[2] installations being deployed.

[2] **PV:** Solar photovoltaic.

Metering technology & Tariff design

Metering technology & Tariff design

Any DER[3] installation (e.g. PV) is connected to the distribution network with a metering device:

- Records electricity exchanges (consumption and injection) between the DER installation and the grid;

Types of metering technology

- Net-metering: records imports running forward and exports running backward – both signs are associated with the same price signal.
- Net-purchasing (or net-billing): records imports and exports independently – each sign can have a different price signal associated.

[3] **DER:** Distributed (renewable) energy resources.

Metering technology & Tariff design

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- pay-per-energy or **volume fees**: unit of energy (€/kWh);
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- pay-per-connection or **fixed fees**: connection point (€/connection).

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Note: this fee pays for the distribution service, not the energy nor the power.

Tariff simulator

Tariff simulator

How to find the **right** combination among the various options of metering technology and tariff design? How is **right** defined?

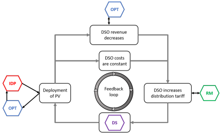
- it depends on our particular objective;
- trade-offs may emerge.

Tariff simulator

Inputs

- metering technology;
- tariff design;
- traditional consumers;
- potential and actual prosumers.

Computational tool



Outputs

Predictions (trajectories) of:

- PV penetration over time;
- total PV and battery capacities deployed per prosumer;
- overall electricity costs for consumers and prosumers.

Tarif simulator

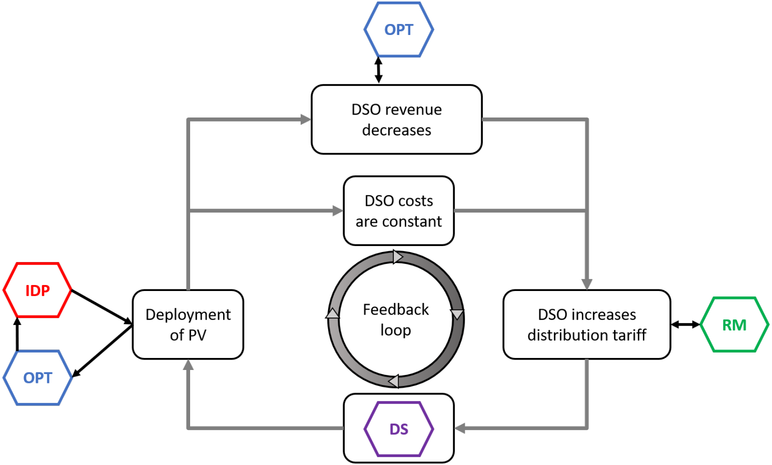
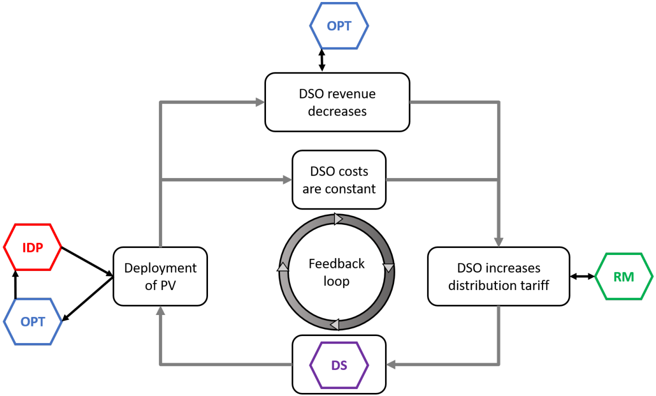
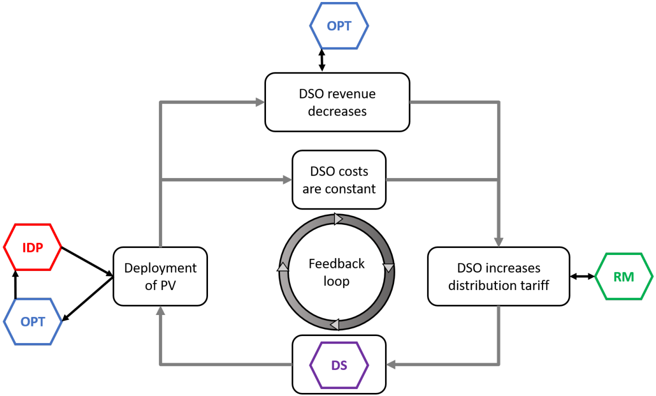


Figure 5: Diagram of the tariff simulator.

Tarif simulator

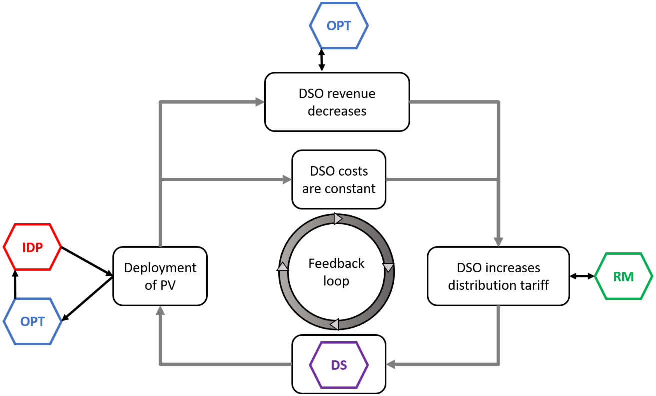


Tarif simulator



Gradually deploy PV installations

Tarif simulator



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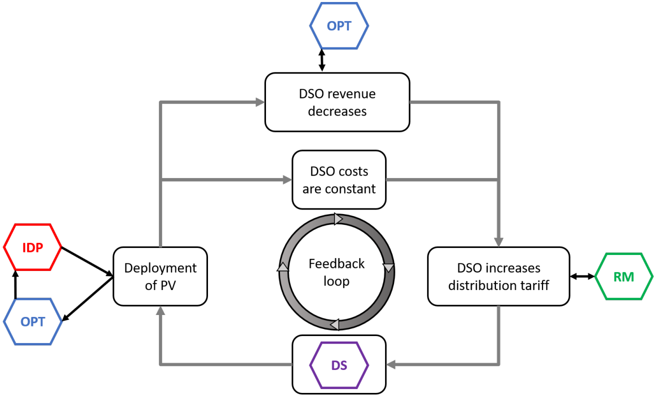
Assess their impact on the DSO

Tarif simulator

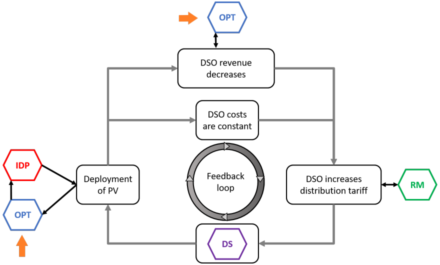


Gradually deploy PV installations

Assess their impact on the DSO

Repeat for different combinations of metering technology & tariff design

Tariff simulator



Tariff simulator

- Optimally size DER (PV) installations with PV and/or batteries;
- Instantiated as an MILP[4] minimising the LVOE[5].

[4] **MILP:** Mixed Integer Linear Program

[5] **LVOE:** Levelised value of electricity – discounted costs minus revenue divided by discounted demand

Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

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$P \subseteq \mathbb{R}_+^4 \Rightarrow$ **Technology Prices (PV and battery)**

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$\mathbf{U} = \subseteq \left(\mathbb{R}_+^2\right)^T \Rightarrow$ **Time-series** where $\mathcal{T} = \{0, \ldots, T\}$

Tariff simulator

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4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

$\min \sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

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$X_t \Rightarrow$ **Matrix variable related to energy balance**

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Tariff simulator

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Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}^4_+ \times \mathbb{R}^5_+ \times \mathbb{R}^5_+ \times \left(\mathbb{R}^2_+\right)^T$

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$\zeta^-_y \Rightarrow$ **electricity imports (consumption)**

Tariff simulator

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$\zeta_y^- \Rightarrow$ **electricity imports (consumption)**
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$\gamma \Rightarrow$ **peak consumption**

Tariff simulator

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Constraints of the problem:

Tariff simulator

Inputs:

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Constraints of the problem:

$\Theta_t\left(G, A, X_t, B_t^2\right) \geq 0, \ \ \forall t \in \mathcal{T} \Rightarrow$ **Energy balance & PV and battery control**

Tariff simulator

Compactly, the MILP can be written as:

$$\begin{aligned} \min \quad & \text{LVOE} \\ s.t. \quad & \text{Energy balance} \\ & \text{PV \& Battery control} \end{aligned}$$

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Affected by the metering technology

Tariff simulator

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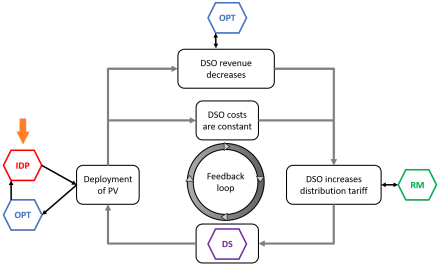
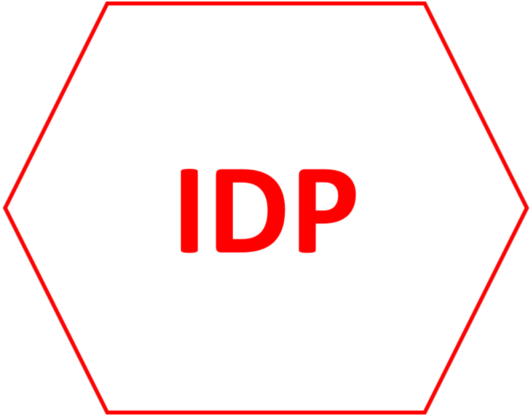
Affected by the metering technology

Affected by the tariff design

Tariff simulator





Tariff simulator

Decision to deploy or not the optimised DER installation through a cost comparison:

- LVOE;
- Retail price.

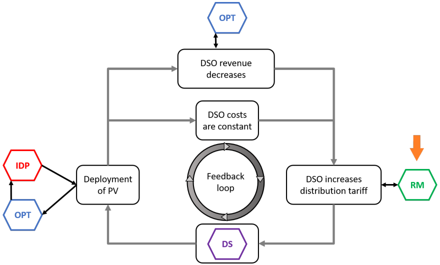
The cost comparison leads to a price gap (Γ), used in a binary distribution:

$$\beta \sim (1, \alpha \cdot \Gamma)$$

α: bias to adjust the model with empirical data

- if $\beta = 1 \Rightarrow$ DER IS deployed
- if $\beta = 0 \Rightarrow$ DER IS NOT deployed

Tariff simulator



Tariff simulator

This mechanism allows the DSO to:

- collect revenue;
- compare revenue with costs;
- adjust distribution fee.

Tariff simulator

Tariff simulator

1. $\text{Revenue} = \text{EnergyConsumed} \cdot \Pi^{(vol)} + \text{PeakPower} \cdot \Pi^{(cap)} + \#\text{Users} \cdot \Pi^{(fix)}$

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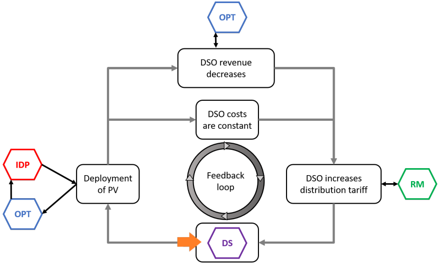
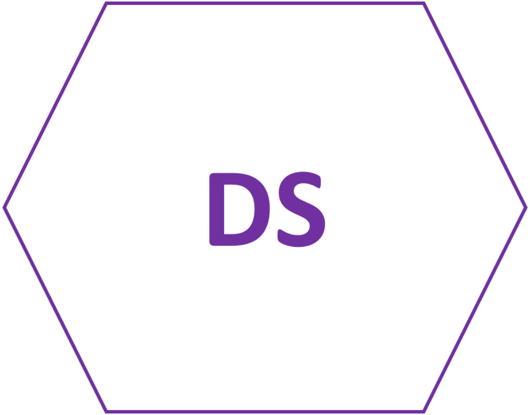
$$\Pi^{(vol)}_{\text{next}} = \left[\frac{\text{Costs} + \Delta}{\text{EnergyConsumed}}\right] \cdot \mu_1, \qquad \text{where } \mu_1 = \text{Share of volumetric fee}$$

$$\Pi^{(cap)}_{\text{next}} = \left[\frac{\text{Costs} + \Delta}{\text{PeakPower}}\right] \cdot \mu_2, \qquad \text{where } \mu_2 = \text{Share of capacity fee}$$

$$\Pi^{(fix)}_{\text{next}} = \left[\frac{\text{Costs} + \Delta}{\#\text{Users}}\right] \cdot \mu_3, \qquad \text{where } \mu_3 = \text{Share of fixed fee}$$

Tariff simulator





Tariff simulator

To account for the consumers decisions over time we introduce:

- discrete-time dynamical system $\mathcal{N} = \{0, \ldots, N\}$,
- a regulatory period is represented with $n \in \mathcal{N}$.

At each time-step n:

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1. potential prosumers perform cost optimisations via OPT;
2. potential prosumers invest via IDP;
3. DSO performs cost-revenue analysis via RM;
4. transition $n \to n + 1$ and repeat.

Results & Policy recommendations

Results & Policy recommendations

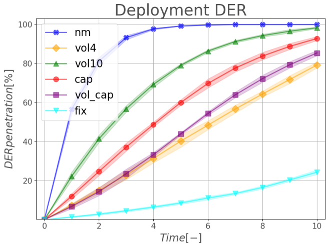
Table 1: Scenarios used in test case.

Scenario	Metering technology	Tariff design	Selling price
nm	net-metering	100% volumetric	[4]overall retail tariff
vol4	net-purchasing	100% volumetric	0.04€
cap	net-purchasing	100% capacity	0.04€
vol_cap	net-purchasing	50% volumetric + 50% capacity	0.04€
fix	net-purchasing	100% fixed	0.04€

volumetric: charges in €/kWh
capacity: charges in €/kWp
fixed: charges in € per consumer

[4]With net-metering the exports of electricity are removed from the imports and thereby the selling price is the retail tariff.

Results & Policy recommendations



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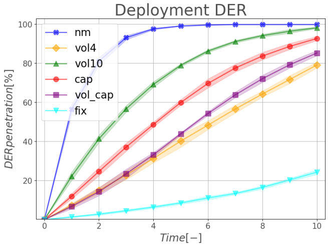

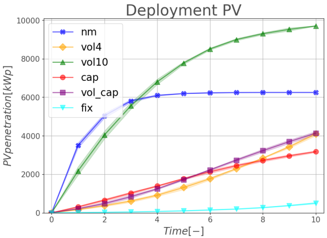

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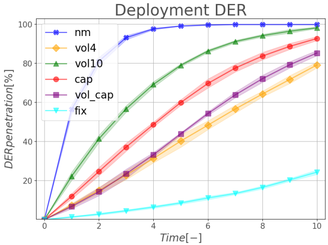
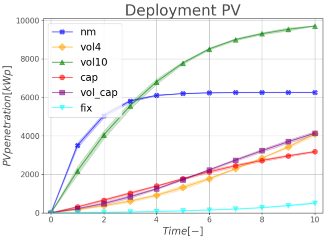
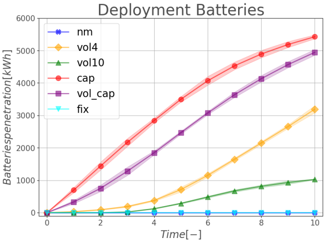
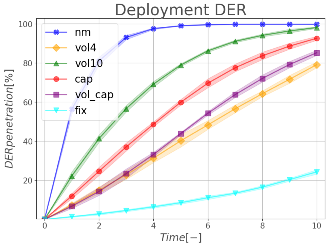
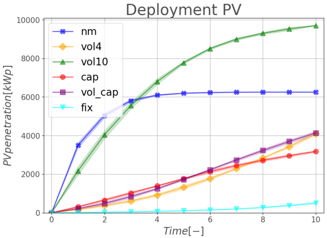


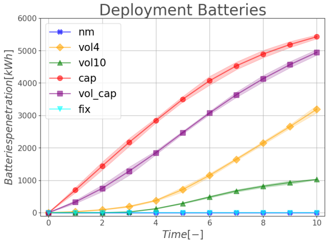


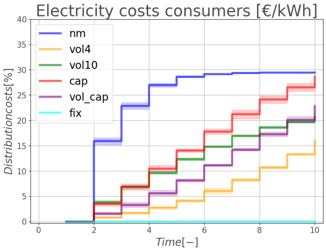


Results & Policy recommendations









Results & Policy recommendations

- The choice of metering technology is critical, with larger implications than the choice of tariff design:
  - net-metering favours PV deployment but not battery;
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- In terms of costs for consumers:
  - net-metering leads to significant increased costs;
  - net-purchasing with capacity fees result in significant increased costs;
  - net-purchasing with volumetric fees result in more contained costs.

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  - net-purchasing with volumetric fees result in more contained costs.

Any combination may result in inequalities and induce death-spiral behaviours (save 100% fixed fees)

New decentralised electricity markets

New decentralised electricity markets

Local electricity markets as an alternative to traditional retailing, consumers can:

- directly participate in the electricity markets;
- better cooperate and coordinate themselves;
- procure services traditionally associated to large market players:
  - supply of electricity;
  - demand response programmes for flexibility procurement;
  - balance responsibilities (BRP[5] services).

[5] **BRP:** balance responsible party.

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These services may be centralised through an aggregator/retailer/manager

[5] **BRP:** balance responsible party.

New decentralised electricity markets

Focus on RECs[6] as described by European directive[7]:

- consumers,
- prosumers, or
- generation and/or storage devices.

RECs are managed by a central entity: the ECM[8].

[6] **REC:** renewable energy community.
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RECs are managed by a central entity: the ECM[8].

Why are RECs interesting? – Matching of supply and demand locally

- stimulate of DER adoption, favouring their integration;
- potential to decrease DSO costs (reduction of peaks);
- reduce the exposure to traditional markets, using local generation instead.

[6]**REC:** renewable energy community.

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[8]**ECM:** energy community manager

Flexibility services

Flexibility services

Interaction model based on multi-agent paradigm:

- Each consumer/prosumer is an individual agent that:
  - consumes and produces (if prosumer) electricity;
  - exchanges electricity with the ECM;
- The ECM is another agent that:
  - aggregates the demand and production of the REC members;
  - exchanges electricity with the retailer or wholesale markets;

Flexibility services

Interaction model based on multi-agent paradigm:

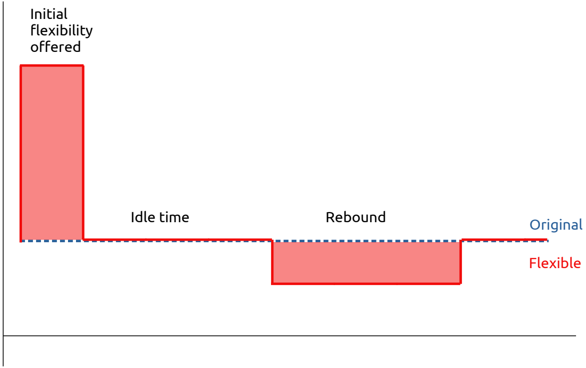
- Each consumer/prosumer is an individual agent that:
  - consumes and produces (if prosumer) electricity;
  - exchanges electricity with the ECM;
  - offers flexibility to the ECM.
- The ECM is another agent that:
  - aggregates the demand and production of the REC members;
  - exchanges electricity with the retailer or wholesale markets;
  - accepts/rejects the flexibility offered by REC members.

Flexibility services

Use of flexibility bids – least amount of information shared among agents.

Flexibility bids

1. Flexibility offered;
2. Idle time;
3. Rebound.



Flexibility services

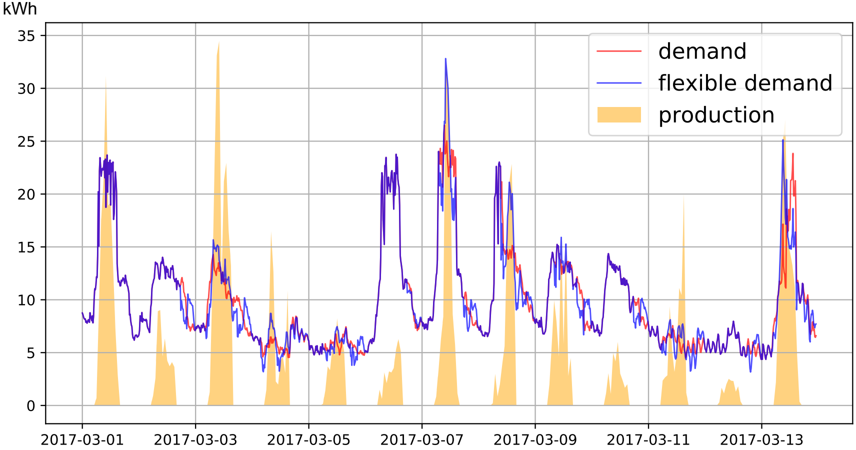
Simulation environment created where the ECM:

- uses day-ahead market to purchase electricity needed;
- activates bids minimising the costs of the REC;
- uses 24h forecasts of consumption, production, and prices.

Cost minimisation accounting for flexibility bids instantiated as a linear program:

- **objective function**: minimisation of sum of electricity bills accounting for the flexibility bids;
- **subject to:** energy balance accounting for the flexibility bids.

Flexibility services



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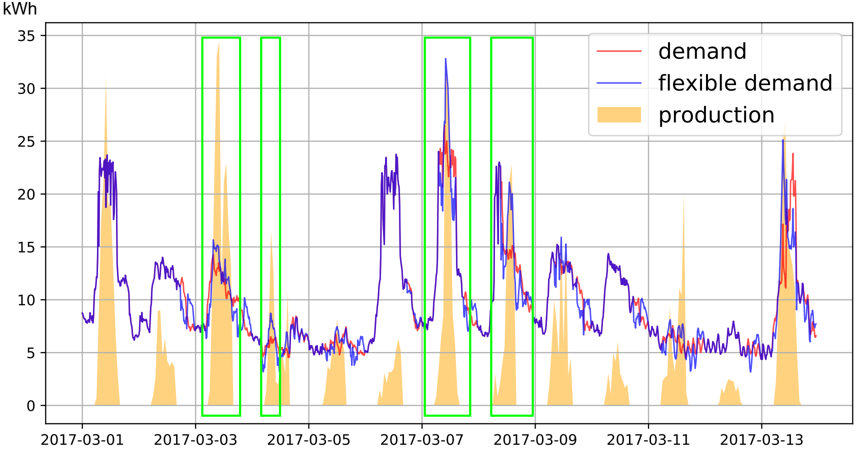

Flexibility services

Table 2: Costs of the system without REC (column 1), with REC (column 2), and with REC and flexibility (column 3).

Case	NO REC (%)	REC NO FLEX (%)	REC FLEX (%)
1 day	262 k€ (-)	260.6 k€ (-0.006)	260.6 k€ (-0.006)
1 week	1,785 k€(-)	1,730 k€ (-3.1)	1,726 k€ (-3.3)
1 month	7,054 k€ (-)	6,863 k€ (-2.7)	6,850 k€ (-2.9)
1 year	65,455 k€ (-)	61,303 k€ (-6.3)	61,019 k€ (-6.8)

Market design based on repartition keys

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Focus on allocation of local production among the REC members:

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Repartition keys

- represent the percentage of total local production allocated to each REC member;
- computed by the ECM and sent to the DSO.

Market design based on repartition keys

When?

- after electricity delivery and with real measurements;
- total demand and local production are known.

How?

- optimal allocation of the repartition keys;
- distribute the local production among the REC members.

Why?

- the new allocation is used to adjust the meter readings;
- electricity exchanges do not change.

Market design based on repartition keys

When? *ex-post*

- after electricity delivery and with real measurements;
- total demand and local production are known.

How? *optimisation framework*

- optimal allocation of the repartition keys;
- distribute the local production among the REC members.

Why? *financial optimisation*

- the new allocation is used to adjust the meter readings;
- electricity exchanges do not change.

Market design based on repartition keys

An optimisation problem is formulated to compute the repartition keys.

Objective function:

Minimises the sum of the electricity bills of all final customers, composed of four elements: (i) retailing costs, (ii) retailing profits, (iii) REC costs, and (iv) REC profits.

Subject to:

- repartition keys constraints;
- energy balance constraints;
- *extra* – self-sufficiency rate constraints;
- *extra* – initial contractual repartition keys constraints.

Market design based on repartition keys

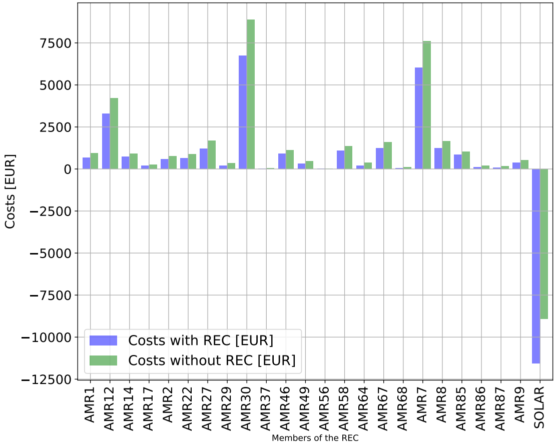


Figure 5: Costs of the REC members.

Market design based on repartition keys

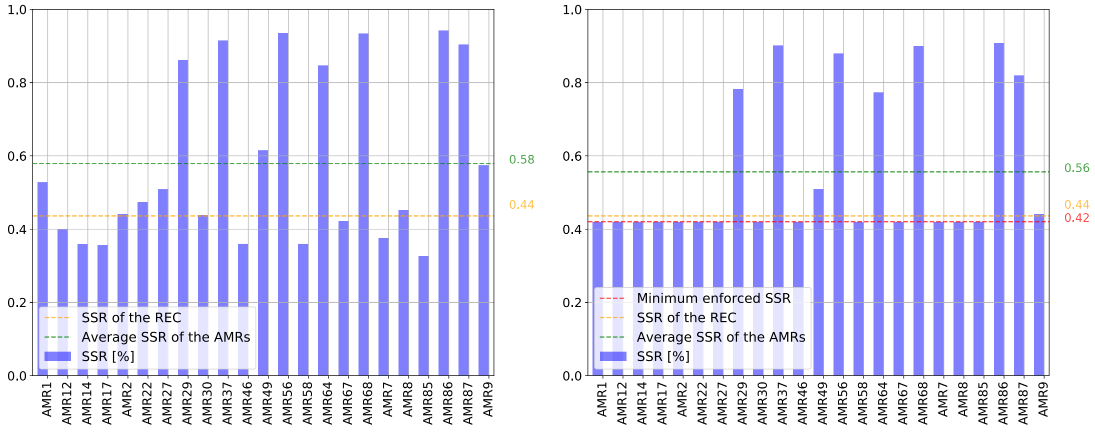
Self-sufficienty rate (SSR) constraints:

$$\text{SSR} = \frac{\text{Allocated Production}}{\text{Total Demand}}$$

- enables *artificially* increasing the SSR of some REC members;
- at the expense of the overall average SSR;
- sub-optimalities due to fixed (finite) amount of local production.

Some REC members may accept the REC more easily if a minimum SSR can be ensured

Market design based on repartition keys



(a) Without minimum SSR bound.

(b) With an enforced minimum SSR of 42%

Figure 6: Example enforcing an SSR of 42%.

Market design based on repartition keys

Initial contractual repartition keys constraints:

- initial keys may be signed upon by ECM and REC members;
- maximum deviations from these keys may be imposed.

Examples:

- uniform – evenly distributed key among REC members.
- proportional static – each REC member receives one key proportional to their average demand.
- proportional dynamic – each REC member receives one key per time-step proportional to their instantaneous demand.

Market design based on repartition keys

Table 3: Total consumption, production, and allocated production for the different keys.

Total local production	11.35 MWh
Allocated production with uniform keys	44% of total
Allocated production with proportional static keys	60% of total
Allocated production with proportional dynamic keys	78% of total

Insights on new decentralised electricity markets

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New local consumer-centric electricity markets:

- enable market participation to prosumers;
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Repartition keys:

- practical and ready to use formulation compliant with current European regulation;
- extra constraints (SSR, contractual initial keys) can help enhance the acceptability of these markets.

Conclusion & Outlook

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Integrating renewable electricity generation technologies in a decentralised manner:

- Current regulatory framework with no market structure:
  - any combination of metering technology and tariff design may lead to increased distribution rates;
  - striking a balance between promotion of DER and contained increases in distribution rates is not trivial;
  - acceptability problems for these types of technology;
  - the design of new regulations is key to a seamless energy transition.
- New consumer-centric market structures may help integrate distributed renewable generation technologies:
  - increased welfare for market participants may be achieved;
  - these market structures may enable the engagement in additional services (flexibility, or balancing);
  - gaining partial independence from more volatile wholesale markets may be desirable;
  - the design of new regulation is crucial.

Conclusion & Outlook

Concerning the models developed in this work:

- quantifying the extent to which collective benefits are obtained through private investments from prosumers;
- explicitly modelling the costs of the DSO;
- exploring other options for the procurement of flexibility (ranges instead of bids);
- introducing the idea of repartition keys into the control problem of a decentralised market.

Concerning new research avenues:

- measuring the DSO loss of revenue in decentralised markets;
- modelling physical constraints in decentralised markets to assess the economic gains of the DSO that may counteract their losses;
- creating sound regulatory frameworks for the integration of these new entrants in the electricity markets.

Acknowledgements to the team

    

Smart Regulation for Distribution Networks: Modelling New Local Electricity Markets and Regulatory Frameworks for the Integration of Distributed Electricity Generation Resources

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Advisor: Prof. Damien Ernst

Smart Grids Laboratory, Department of Electrical Engineering and Computer Science,
Montefiore Institute, Faculty of Applied Sciences, University of Liège

APPENDIX

A1 – Decentralisation of the power sector and challenges

The electricity delivery process:

1. production in conventional power plants;
2. transmission network (high voltage);
3. consumption by end users in distribution networks;

Distribution network role:

- carries electricity from the high voltage transmission grid to industrial, commercial and domestic users;

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4. **production by end users in distribution networks.**

Distribution network role:

- carries electricity from the high voltage transmission grid to industrial, commercial and domestic users;
- **distributes the electricity produced by within the distribution network.**

A2 – Distribution tariff design

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- sustainable design providing enough revenue to break-even;

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- simple enough, transparent, stable, and consistent so that final customers can undesrtand and predict their costs;
- non-distortive design – sending the right signal to final customers to incentivise certain behaviours.

A2 – Distribution tariff design

DSO charges are typically created following one of these two models:

- pay-per-energy or **volume fees**: the most widely adopted – final customers pay in currency/unit of energy (e.g. EUR/kWh), used in Belgium, France, Germany, or United Kingdom.
- pay-per-power or **capacity fees**: less used – final customers pay in currency/unit of peak power (e.g. EUR/kWp), used in Netherlands and partially in Portugal, Spain, or Italy.

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Other types of charges may be used:

- pay-per-connection or **fixed fees**: final customers pay in currency/connection point (e.g. EUR/connection).
- pay-per-time or **time-of-use fees**: final customers pay depending on the time of consumption, they can be applied to both volume or capacity.

A3 – Tariff simulator

MILP structure – **Sizing variables**

$$\mathcal{A} = \left\{ (p, b) \,|\, p \in [0, \overline{p}] \,;\, b \in [0, \overline{b}] \right\}, \quad \text{with:}$$

p: PV size in kWp (upper bound $\overline{p}$);
b: battery size in kWh (upper bound $\overline{b}$).

MILP structure – **Constraints**

- Investment costs; $\chi\,(G, A) \geq 0$
- costs of operation; $\Phi_y\,(\zeta_y, \gamma, G, A) \geq 0, \quad \forall y \in \mathcal{Y}$
- PV and battery related; $\Theta_t\,(X_t, G, A) \geq 0, \quad \forall t \in \mathcal{T}$
- energy balance. $\Psi_t\,(X_t, G, A) = 0, \quad \forall t \in \mathcal{T}$

A3 – Tariff simulator

MILP structure – **Objective function**

Minimisation of the levelised value of electricity (LVOE), depending on (i) inputs gathered in 4-tuple G and (ii) the optimal given combination of sizing variables $A \in \mathcal{A}$.

The LVOE is computed as:

$$\widehat{LVOE} = \min_{\substack{A \in \mathcal{A} \\ \text{s.t.} \quad \chi(G, A) \geq 0 \\ \Phi_y(\zeta_y, \gamma, G, A) \geq 0, \forall y \in \mathcal{Y} \\ \Theta_t(X_t, G, A) \geq 0, \forall t \in \mathcal{T} \\ \Psi_t(X_t, G, A) = 0, \forall t \in \mathcal{T}}} LVOE(G, A)$$

The optimal sizing configuration is:

$$A^* \in \operatorname*{arg\,min}_{\substack{A \in \mathcal{A} \\ \text{s.t.} \quad \chi(G, A) \geq 0 \\ \Phi_y(\zeta_y, \gamma, G, A) \geq 0, \forall y \in \mathcal{Y} \\ \Theta_t(X_t, G, A) \geq 0, \forall t \in \mathcal{T} \\ \Psi_t(X_t, G, A) = 0, \forall t \in \mathcal{T}}} LVOE(G, A)$$

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$$\text{Net-metering:} \quad \zeta_y = \max\left\{0, \sum_{reg.period} (imports - exports)\right\}$$

A3 – Tariff simulator

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$$\text{Net-metering:} \quad \zeta_y = \max \left\{ 0, \sum_{reg.period} (imports - exports) \right\}$$

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Metering technology, a crucial choice:

$$\text{Net-metering:} \quad \zeta_y = \max\left\{0, \sum_{reg.period} (imports - exports)\right\}$$

$$\text{Net-purchasing:} \quad \zeta_y = \sum_{reg.period} imports$$

Peak consumption:

$$\gamma = \max\{imports | reg.period\}$$

A3 – Tariff simulator

A3 – Tariff simulator

Optimally size DER installations with PV[9] and/or batteries

Instantiated as an MILP[10] minimising the LVOE[11]

[9] PV: photovoltaic

[10] MILP: Mixed Integer Linear Program

[11] LVOE: Levelised value of electricity – discounted costs minus revenue divided by discounted demand

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

$P = \left(Q^{(pv)}, Q^{(bat)}, P^{(pv)}, P^{(bat)}\right) \subseteq \mathbb{R}_+^4 \Rightarrow$ **Technology Prices (PV and battery)**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}^4_+ \times \mathbb{R}^5_+ \times \mathbb{R}^5_+ \times \left(\mathbb{R}^2_+\right)^T$

$P = \left(Q^{(pv)}, Q^{(bat)}, P^{(pv)}, P^{(bat)}\right) \subseteq \mathbb{R}^4_+ \Rightarrow$ **Technology Prices (PV and battery)**

$\Pi = \left(\Pi^{(ot)}, \Pi^{(sp)}, \Pi^{(vol)}, \Pi^{(cap)}, \Pi^{(fix)}\right) \subseteq \mathbb{R}^5_+ \Rightarrow$ **Electricity prices**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

$P = \left(Q^{(pv)}, Q^{(bat)}, P^{(pv)}, P^{(bat)}\right) \subseteq \mathbb{R}_+^4 \Rightarrow$ **Technology Prices (PV and battery)**
$\Pi = \left(\Pi^{(ot)}, \Pi^{(sp)}, \Pi^{(vol)}, \Pi^{(cap)}, \Pi^{(fix)}\right) \subseteq \mathbb{R}_+^5 \Rightarrow$ **Electricity prices**
$H = \left(\eta^{(-)}, \eta^{(+)}, F^{(-)}, F^{(+)}, B\right) \subseteq \mathbb{R}_+^5 \Rightarrow$ **Battery parameters**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

$P = \left(Q^{(pv)}, Q^{(bat)}, P^{(pv)}, P^{(bat)}\right) \subseteq \mathbb{R}_+^4 \Rightarrow$ **Technology Prices (PV and battery)**

$\Pi = \left(\Pi^{(ot)}, \Pi^{(sp)}, \Pi^{(vol)}, \Pi^{(cap)}, \Pi^{(fix)}\right) \subseteq \mathbb{R}_+^5 \Rightarrow$ **Electricity prices**

$H = \left(\eta^{(-)}, \eta^{(+)}, F^{(-)}, F^{(+)}, B\right) \subseteq \mathbb{R}_+^5 \Rightarrow$ **Battery parameters**

$\mathbf{U} = \left\{\left(U_t^{(c)}, U_t^{(p)}\right)\right\}_{t=0}^{T-1} \subseteq \left(\mathbb{R}_+^2\right)^T \Rightarrow$ **Time-series** where $\mathcal{T} = \{0, \ldots, T\}$

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

$\min \sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

$\min \sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

$X_t \Rightarrow$ **Matrix variable related to energy balance**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

$$\min \sum_{t\in\mathcal{T}} \sum_{y\in\mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$$

$X_t \Rightarrow$ **Matrix variable related to energy balance**

$B^1 \Rightarrow$ **Binary variables controlling the initial investment**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

$$\min \sum_{t\in\mathcal{T}} \sum_{y\in\mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$$

$X_t \Rightarrow$ **Matrix variable related to energy balance**

$B^1 \Rightarrow$ **Binary variables controlling the initial investment**

$B_t^2 \Rightarrow$ **Binary variables controlling battery charge and discharge**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

$\min \sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq$
$\left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

$X_t \Rightarrow$ **Matrix variable related to energy balance**
$B^1 \Rightarrow$ **Binary variables controlling the initial investment**
$B_t^2 \Rightarrow$ **Binary variables controlling battery charge and discharge**
$A \Rightarrow$ **Sizing variables**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

min $\sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

$X_t \Rightarrow$ **Matrix variable related to energy balance**

$B^1 \Rightarrow$ **Binary variables controlling the initial investment**

$B_t^2 \Rightarrow$ **Binary variables controlling battery charge and discharge**

$A \Rightarrow$ **Sizing variables**

$\zeta_y \Rightarrow$ **Variable showing yearly electricity consumption**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

$\min \sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

$X_t \Rightarrow$ **Matrix variable related to energy balance**
$B^1 \Rightarrow$ **Binary variables controlling the initial investment**
$B_t^2 \Rightarrow$ **Binary variables controlling battery charge and discharge**
$A \Rightarrow$ **Sizing variables**
$\zeta_y \Rightarrow$ **Variable showing yearly electricity consumption**
$\gamma \Rightarrow$ **Variable representing peak consumption**

A3 – Tariff simulator

Inputs:
4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:
$\min \sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

Constraints of the problem:

A3 – Tariff simulator

Inputs:
4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:
$\min \sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

Constraints of the problem:
$\chi\left(G, A, B^1\right) \geq 0 \Rightarrow$ **Investment costs**

A3 – Tariff simulator

Inputs:

4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

Objective function and decision variables:

$\min \sum_{t \in \mathcal{T}} \sum_{y \in \mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

Constraints of the problem:

$\chi\left(G, A, B^1\right) \geq 0 \Rightarrow$ **Investment costs**

$\Phi_y\left(G, A, \zeta_y, \gamma\right) \geq 0, \ \forall y \in \mathcal{Y} \Rightarrow$ **Electricity costs (and operation)**

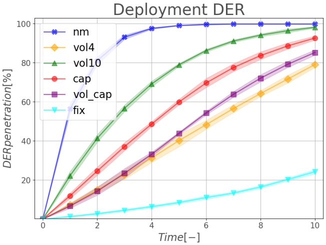
A3 – Tariff simulator

Inputs:
4-tuple $G = (P, \Pi, H, \mathbf{U}) \subseteq \mathbb{R}_+^4 \times \mathbb{R}_+^5 \times \mathbb{R}_+^5 \times \left(\mathbb{R}_+^2\right)^T$

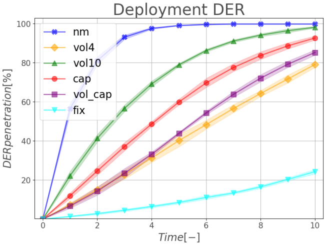
Objective function and decision variables:
$\min \sum_{t\in\mathcal{T}} \sum_{y\in\mathcal{Y}} LVOE\left(G, X_t, B^1, B_t^2, A, \zeta_y, \gamma\right) \subseteq \left(\mathbb{R}_+^6\right)^T \times \{0,1\}^2 \times \{0,1\}^T \times \mathbb{R}_+^2 \times \mathbb{R}_+^Y \times \mathbb{R}_+$

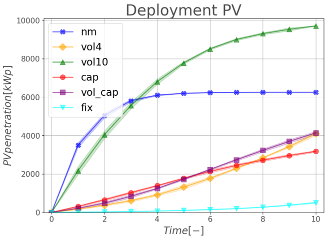
Constraints of the problem:
$\chi\left(G, A, B^1\right) \geq 0 \Rightarrow$ **Investment costs**
$\Phi_y\left(G, A, \zeta_y, \gamma\right) \geq 0, \ \ \forall y \in \mathcal{Y} \Rightarrow$ **Electricity costs (and operation)**
$\Theta_t\left(G, A, X_t, B_t^2\right) \geq 0, \ \ \forall t \in \mathcal{T} \Rightarrow$ **Energy balance (PV and battery control too)**

A4 – Results & Policy recommendations

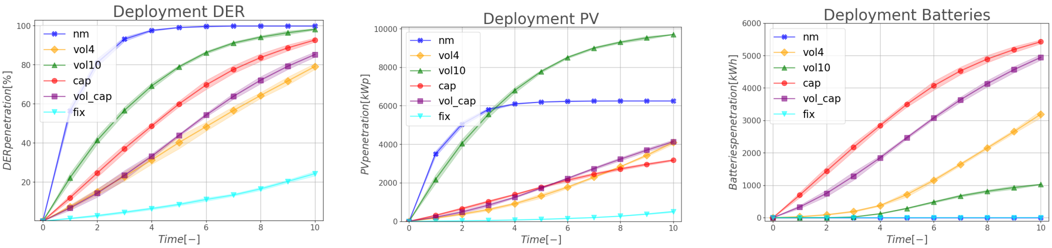


A4 – Results & Policy recommendations

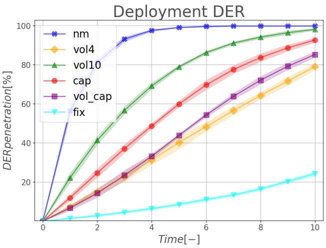


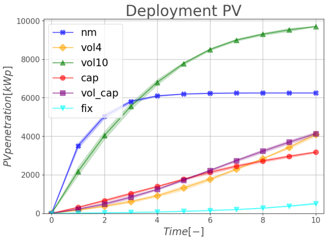


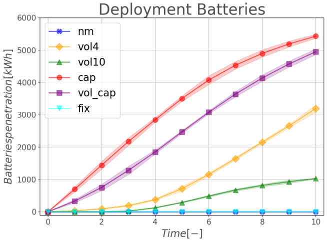
A4 – Results & Policy recommendations

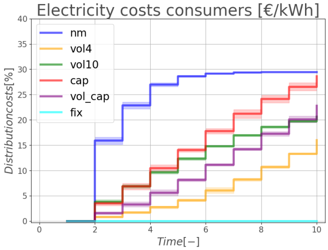


A4 – Results & Policy recommendations

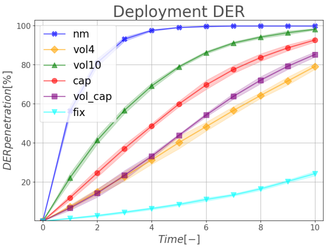


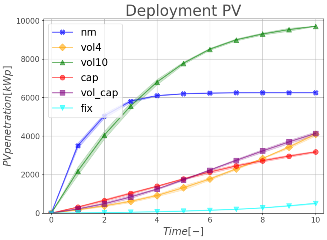


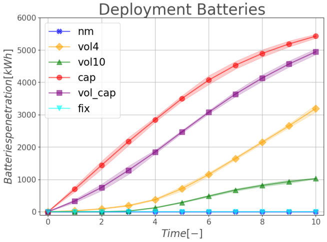


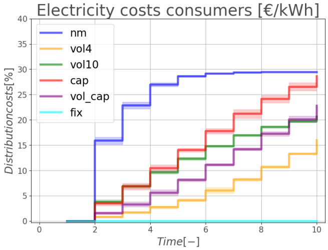


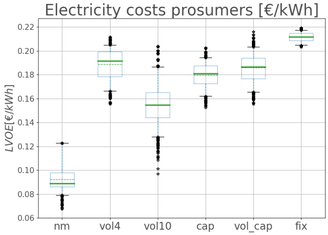
A4 – Results & Policy recommendations











A4 – Results & Policy recommendations

Considering the principles of tariff design, and the goals of the energy policies worldwide:

- net-metering technologies fail to meet most of these principles, only serving the purpose of quickly increase the adoption of solar PV at the expense of the rest of the consumers;
- net-purchasing checks more of this principles, particularly in combination with a tariff designs not purely volumetric;
- the full roll-out of smart-meters will enable these new tariffs.

A5 – Market design based on repartition keys

Repartition keys can be computed by an optimisation problem with the following inputs:

- demand profiles of the REC's members;
- netted production profiles of the members with production devices;
- a set of initial repartition keys (starting point of the optimization);
- a set of price signals, including retail tariff for imports, retail price for exports, local tariff for imports, and local tariff for exports.

With these inputs, we want to determine:

- a set of optimal keys that minimises a given objective;
- the allocation of production according to these keys;
- the self-sufficiency rate of each final customer as well as the self-sufficiency rate of the REC.

A5 – Market design based on repartition keys

Four examples are provided:

1. basic functioning: 4 users (2 consumers, 1 producer, 1 prosumer), 2 time-steps;
2. cost analysis: 24 users (23 consumers, 1 producer), 1 year;
3. self-sufficiency rate: 24 users (23 consumers, 1 producer), 1 year;
4. impact of different initial conditions: 6 users (5 consumers, 1 producer), 1 year;
5. complexity analysis: computational times.

Resolution 15 minutes for all cases, price signals:

Table 4: Price signals in €/MWh.

Retail price (grid)	Selling price (grid)	Local imports (REC)	Selling price (REC)
220	60	100	98

A5 – Market design based on repartition keys

Table 5: Consumption, initial repartition keys, and initial allocated production.

Metering period	User1	User2	User3	User4
Consumption				
2017-03-01 00:00	0.17	0.21	-0.50	0.08
2017-03-01 00:15	0.21	0.23	-0.30	-0.02
Initial repartition keys				
2017-03-01 00:00	0.42	0.49	0.00	0.089
2017-03-01 00:15	0.42	0.49	0.00	0.089
Initial allocated production				
2017-03-01 00:00	0.21	0.24	0.00	0.04
2017-03-01 00:15	0.13	0.16	0.00	0.03

Table 6: Optimised repartition keys, verified allocated production, local sales, and global sales.

Metering period	User1	User2	User3	User4
Optimised repartition keys				
2017-03-01 00:00	0.39	0.45	0.00	0.16
2017-03-01 00:15	0.47	0.53	0.00	0.00
Optimised verified allocated production				
2017-03-01 00:00	0.17	0.21	0.00	0.08
2017-03-01 00:15	0.15	0.17	0.00	0.00
Production sold locally to the REC				
2017-03-01 00:00	0.00	0.00	0.46	0.00
2017-03-01 00:15	0.00	0.00	0.30	0.02
Production sold to the main network				
2017-03-01 00:00	0.00	0.00	0.04	0.00
2017-03-01 00:15	0.00	0.00	0.00	0.00

Market design based on repartition keys

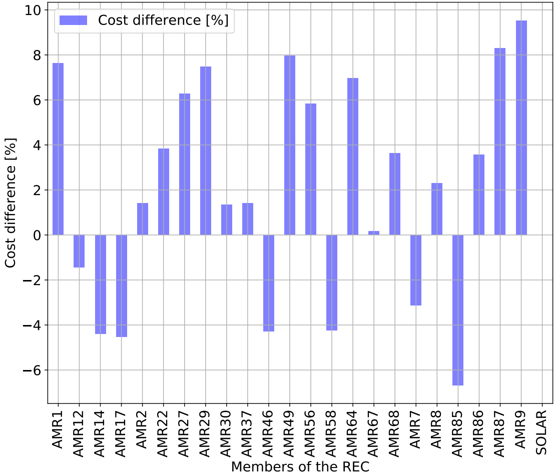


Figure 7: Cost difference before and after SSR is enforced.

A3 – Market design based on repartition keys

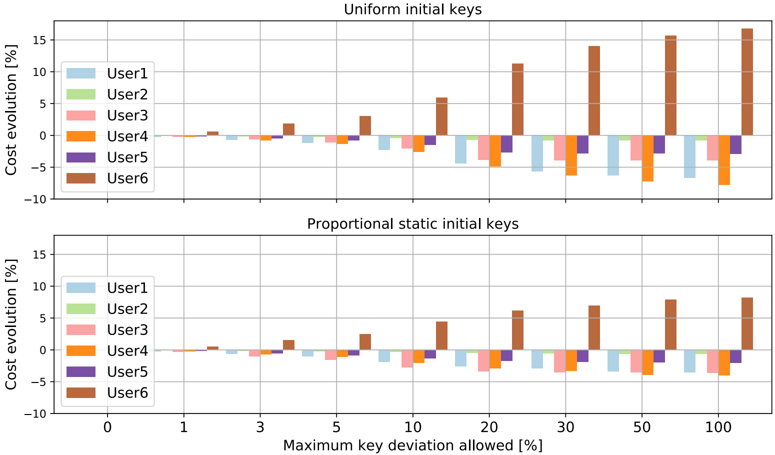


Figure 8: Costs of the REC members for a range of maximum key deviations ($X_{t,i}$) relative to the costs when $X_{t,i} = 0$.

A3 – Market design based on repartition keys

$$N_{cons} = 9|\mathcal{T}||\mathcal{U}| + |\mathcal{T}| + |\mathcal{U}|$$

$$N_{var} = 17|\mathcal{T}||\mathcal{U}| + 2|\mathcal{T}| + |\mathcal{U}|$$

Table 7: Running times of the proposed algorithm.

$\lvert\mathcal{T}\rvert$	$\lvert\mathcal{U}\rvert$	N_{cons}	N_{var}	Build time [s]	Solve time [s]
1,440	10	131,050	247,690	5.01	5.96
2,880	10	262,090	495,370	9.71	12.23
1,440	50	649,490	1,226,930	20.36	27.72
2,880	50	1,298,930	2,453,810	43.55	56.55
1,440	100	1,297,540	2,450,980	39.67	58.93
2,880	100	2,594,980	4,901,860	85.92	133.93