User-Centred Energy Systems Academy

Webinar #54, 15 January 2025

Shaping the Energy Transition: Advances in Demand-Side Flexibility and Community Engagement

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Overview

1. Context: **Challenges** brought by the energy transition
2. Demand-side flexibility in the **residential sector**
3. Electricity **dynamic pricing design** considering DR
4. Demand-side flexibility in practice: **real case studies** ①, ② and ③
5. Demand-side flexibility in **energy communities**
6. Conclusions and **policy recommendations**

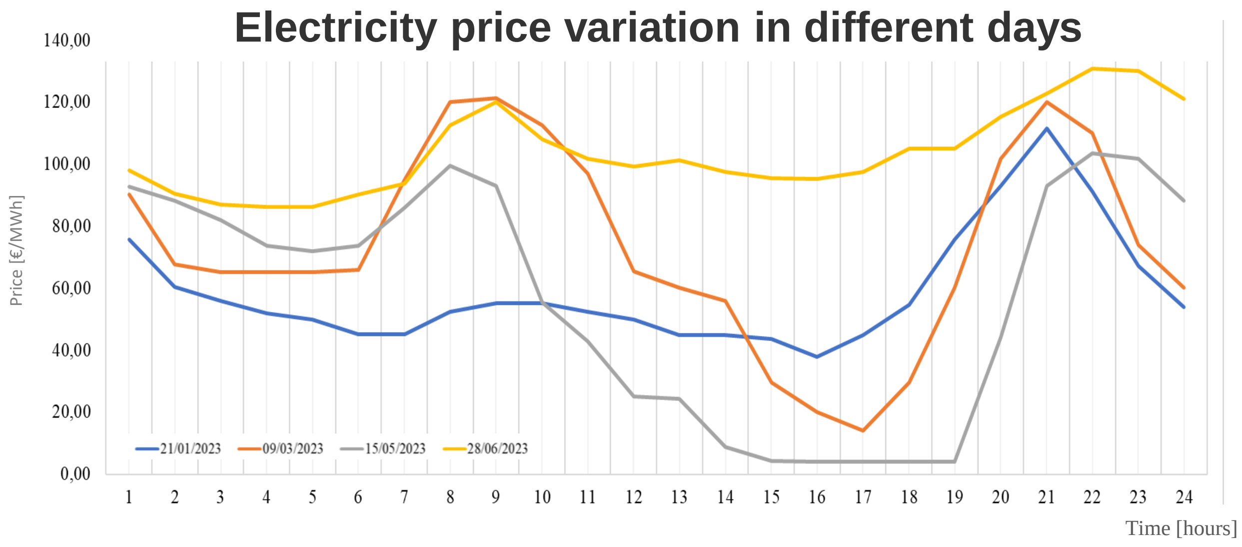
1. Context: Challenges brought by the Energy Transition

Renewables Integration — Growth in wind and solar power generation challenges the power system **stability and reliability**

Adaptable Energy Systems — **Flexibility both on demand and supply sides** is crucial to adapt to fluctuating energy generation

Individual Flexibility — Harvesting flexibility **without compromising comfort or service quality** is essential, yet challenging

End-Users' engagement — **Automating flexibility** at the individual level enables demand response (DR)



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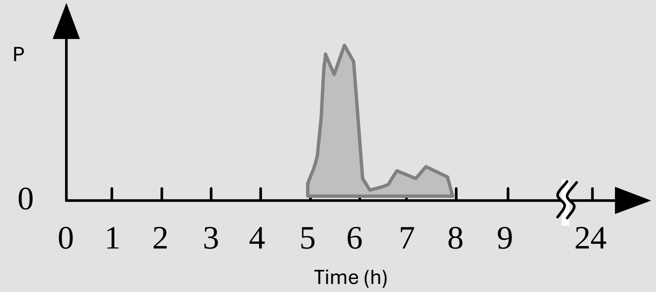
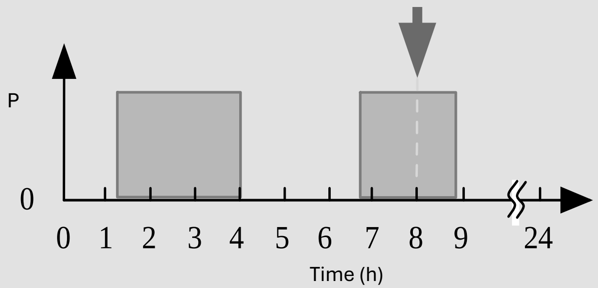
2. Demand-side flexibility in the residential sector

Demand-side flexibility depends on the **household daily activities**, schedules and usage of appliances

	Friday	Saturday	Sunday
00:00	Sleeping	Sleeping	Sleeping
01:00			
02:00			
03:00			
04:00			
05:00			
06:00			
07:00	Family care & meals		
08:00	At (and going to/or coming from) work & school	Family care & meals	Family care & meals
09:00		Home & family care	Home & family care
10:00			
11:00			
12:00		Meals	Leisure outdoors
13:00			
14:00		Home & family care, leisure	
15:00			
16:00		Work at home, leisure	
17:00			
18:00	Home & family care		
19:00	Meals	Meals	Meals
20:00			
21:00	Home & family care, leisure, sleeping	Home & family care, work at home, leisure, sleeping	Home & family care, work at home, leisure, sleeping
22:00			
23:00	Sleeping		Sleeping



Shiftable loads



Thermostatically controlled loads

(anticipate the working cycle / modify set point temperatures)

G2V

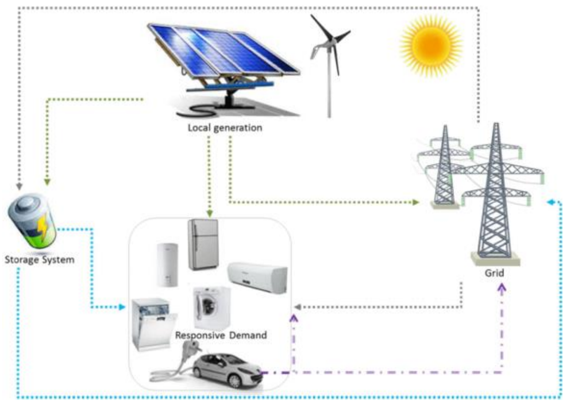
V2G

Electric Vehicle + Storage Systems

A. Soares, Á. Gomes, C. H. Antunes, "Categorization of residential electricity consumption as a basis for the assessment of the impacts of demand response actions", in Renewable and Sustainable Energy Reviews, 30, 490–503. 2014, doi:10.1016/j.rser.2013.10.019

2. Demand-side flexibility in the residential sector

PROBLEM: Optimization of the **integrated usage of multiple residential energy resources**



Resources:

- Local generation
- Shiftable/interruptible loads
- Thermostatically controlled loads
- Storage systems (batteries, EVs)
- Exchanges with the grid

OBJECTIVES:

- ➢ Minimization of the **energy cost**
- ➢ Minimization of **end-user's dissatisfaction** associated with management strategies

ACTIONS:

- **Allocating the working cycles** of the manageable loads according to the most favorable time slots
- **Regulating temperature settings** of cold appliances, water heater pumps and air conditioner systems
- Deciding **when to store, sell, or buy electricity** and how to use **storage** systems

A. Soares, Á. Gomes, C. H. Antunes and C. Oliveira, "A Customized Evolutionary Algorithm for Multiobjective Management of Residential Energy Resources," in IEEE Transactions on Industrial Informatics, vol. 13, no. 2, pp. 492-501, April 2017, doi: 10.1109/TII.2016.2628961

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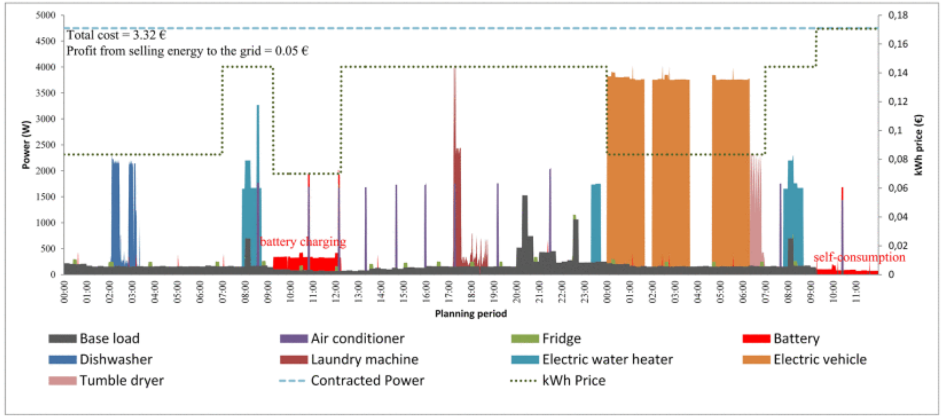
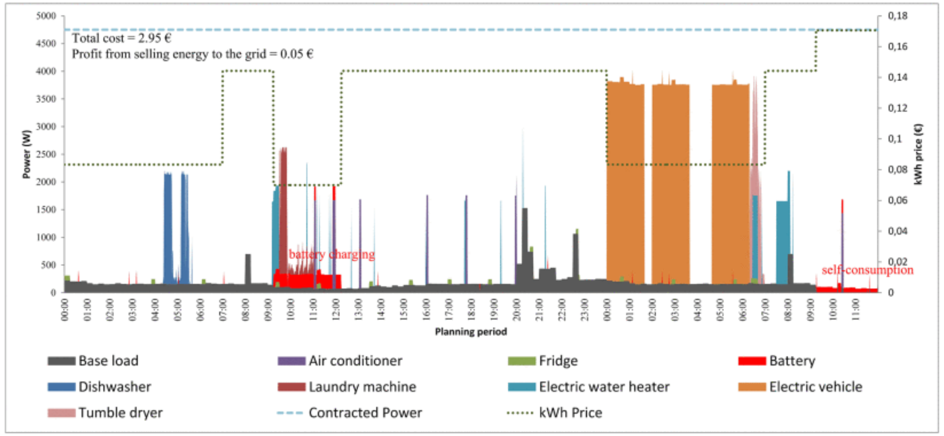
2. Demand-side flexibility in the residential sector

Solution that **optimizes end-user's dissatisfaction**



Solution that **optimizes the electricity bill**



RESULTS

- An **evolutionary algorithm approach** was developed
- It endowed the EMS with a **fast and reliable method to automatically make decisions** concerning the optimal integrated usage of multiple residential energy resources
- Results show **significant savings achieved through DR** actions implemented over **thermostatically** controlled loads
- Savings are dependent on **end-user's preferences and degree of willingness to accept direct load control** (DLC)

A. Soares, Á. Gomes, C. H. Antunes and C. Oliveira, "A Customized Evolutionary Algorithm for Multiobjective Management of Residential Energy Resources," in IEEE Transactions on Industrial Informatics, vol. 13, no. 2, pp. 492-501, April 2017, doi: 10.1109/TII.2016.2628961

2. Demand-side flexibility in the residential sector

PROBLEM: Optimization of the integrated usage of multiple residential energy resources, but now **under variable power charges** according to the peak power requested from the grid

Does it affect the power grid management?

RESULTS

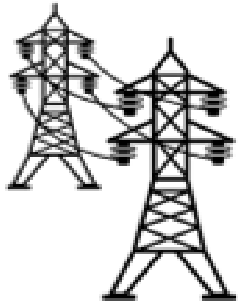
Variable power charges present several advantages compared to contracted power scenarios

End-Users

↓ **power** and energy costs

↑ **flexibility**

No risk of energy supply interruption



Power grid management

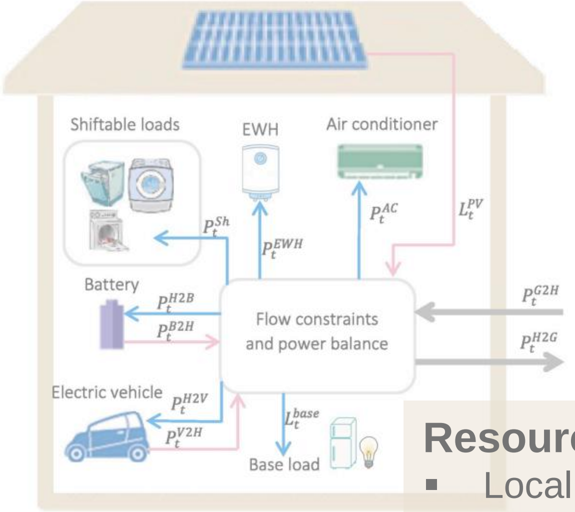
Do not present any particular risk of incurring in very high peaks of power requests

I. Gonçalves, Á. Gomes, C. H. Antunes and C. Oliveira, "Optimizing the management of smart home energy resources under different power cost scenarios," in Applied Energy, 242, pp. 351-363, 2019, doi: 10.1016/j.apenergy.2019.03.108

3. Electricity dynamic pricing design considering DR

The **design of ToU pricing schemes considering DR** is of utmost importance for the **electricity retail** businesses

The usual PROBLEM:
Optimization of the **integrated usage of multiple residential energy resources**



The accurate physical modelling of these resources imposes a high computational burden

Resources:

- Local generation
- Shiftable/interruptible loads
- Thermostatically controlled loads
- Storage systems (batteries, EVs)
- Exchanges with the grid

- **The retailer's GOAL** is to determine the optimal ToU electricity prices to offer to consumers during a planning horizon **to maximize profit**
- End-users' reaction to **minimize cost** affects the retailers' profit

This becomes a hierarchical decision setting for which Bilevel (BL) optimization models are well suited

Retailer: LEADER and **Consumer: FOLLOWER**

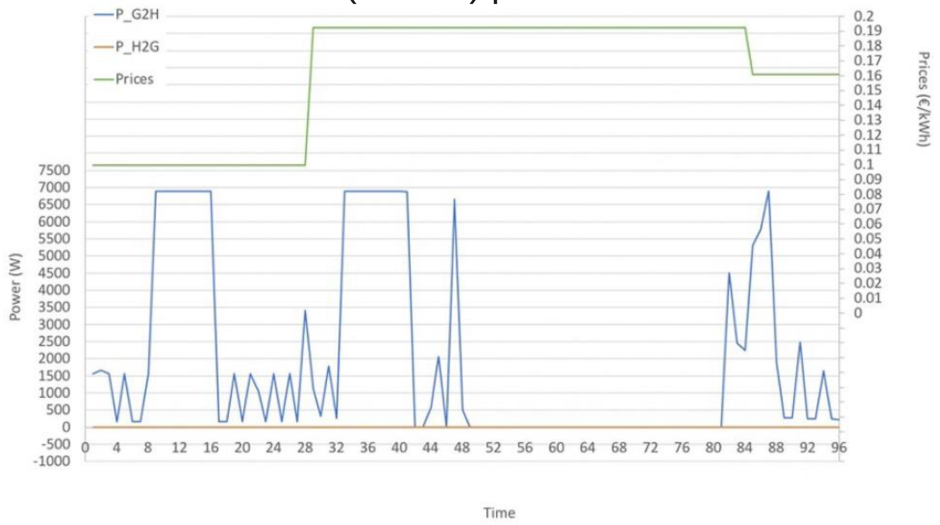
Soares, I., Alves, M. J., & Antunes, C. H. (2023). A deterministic bounding algorithm vs. a hybrid meta-heuristic to deal with a bilevel mixed-integer nonlinear optimization model for electricity dynamic pricing. Computers & Operations Research, 155, 106195. https://doi.org/10.1016/j.cor.2023.106195

3. Electricity dynamic pricing design considering DR

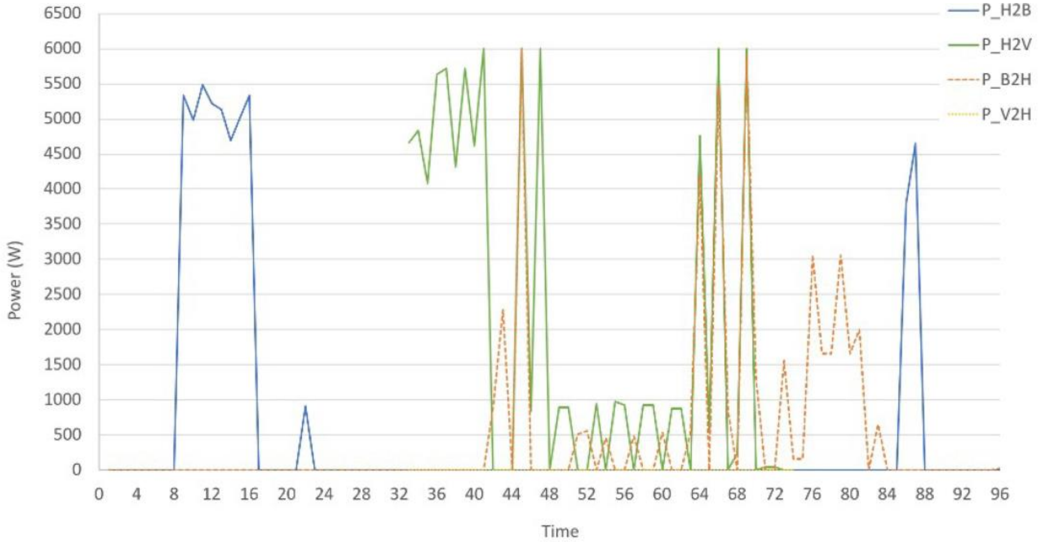
RESULTS

- A deterministic bounding algorithm (DBA) using an optimal-value-function approach for BL optimization offered the best solutions, **being able to assist retailers in making sound decisions**
- The **BL model is flexible**, enabling to **accommodate different regulatory frameworks** for tariff design **and up-to-date data resulting from the volatility in electricity markets**

Grid to home (PtG2H) and **home to grid** (PtH2G) power



Home to battery (PtH2B and PtH2V) **and battery to home** (PtB2H and PtV2H) power



Soares, I., Alves, M. J., & Antunes, C. H. (2023). A deterministic bounding algorithm vs. a hybrid meta-heuristic to deal with a bilevel mixed-integer nonlinear optimization model for electricity dynamic pricing. Computers & Operations Research, 155, 106195. https://doi.org/10.1016/j.cor.2023.106195

4. Demand-side flexibility in practice: Real case study 1

Houses located in the residential districts in the Netherlands: Soesterberg, Heerhugowaard, Woerden and Soest

OBJECTIVE:

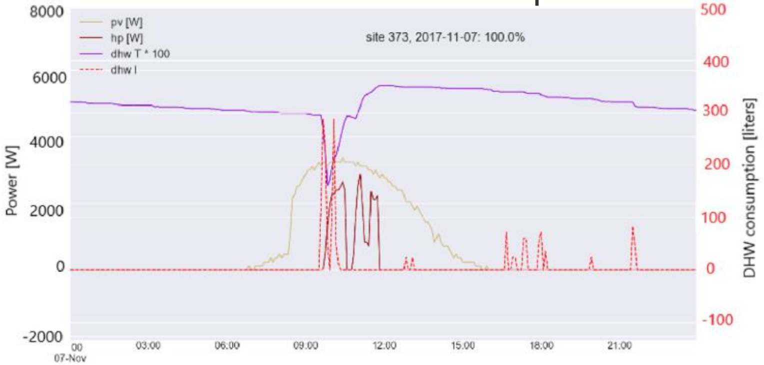
Maximize the instantaneous **self-consumption** of the local PV production

ENERGY RESOURCES:

- Local PV generation
- Heat pumps for DHW
- Stationary residential batteries

Model-based reinforcement learning approach: The proposed algorithm learns the stochastic occupant behavior, uses predictions of local PV production and considers the dynamics of the system

Example with 100% performance of the PV self-consumption



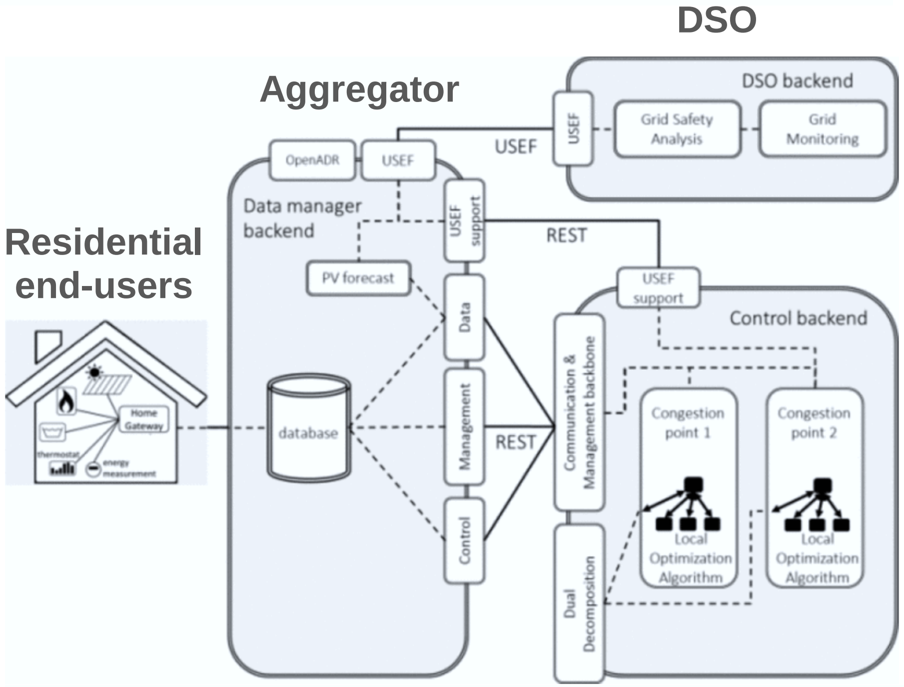
RESULTS

- **Average self-consumption increased on average by 14%**
- The **average energy shifted per day** from the solar production period to the night by batteries was **1.5 kWh**
- It is possible **to improve even further** the integration of local production **using flexible loads**

Soares, A., Geysen, D., Spiessens, F., Ectors, D., De Somer, O., & Vanthournout, K. (2020). Using reinforcement learning for maximizing residential self-consumption – Results from a field test. Energy and Buildings, 207, 109608. doi: 10.1016/j.enbuild.2019.109608

4. Demand-side flexibility in practice: Real case study 2

Small residential sample in Soesterberg
The Netherlands



Two levels of control:

- End-users (local optimization)
- District level (aggregator - grid congestion management)

OBJECTIVE: activate flexibility at the residential level to solve bottlenecks and power surpluses in the grid

Considered ENERGY RESOURCES:

- Local PV generation
- Heat pumps for DHW ← **DR**

A **transactive control process** that activates flexibility is used to cope with predicted grid congestions

Dual decomposition is used to compute virtual prices, enabling the negotiation process of flexibility requests and responses

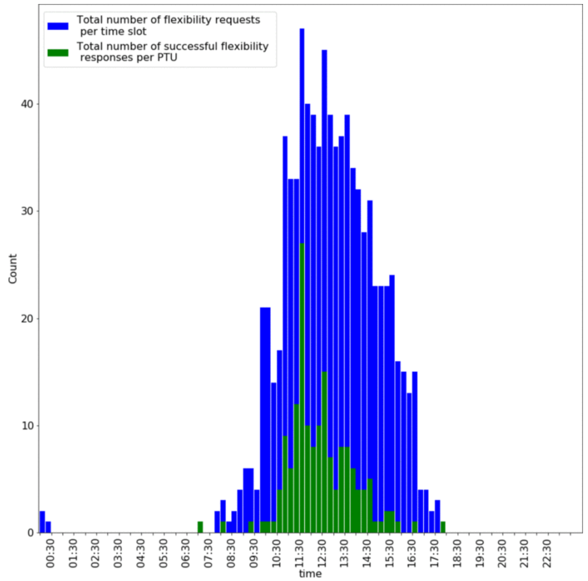
Soares, A., Somer, O. D., Ectors, D., Aben, F., Goyvaerts, J., Broekmans, M., . . . Vanthournout, K. (2019). Distributed Optimization Algorithm for Residential Flexibility Activation—Results From a Field Test. IEEE Transactions on Power Systems, 34(5), 4119-4127. doi:10.1109/TPWRS.2018.2809440

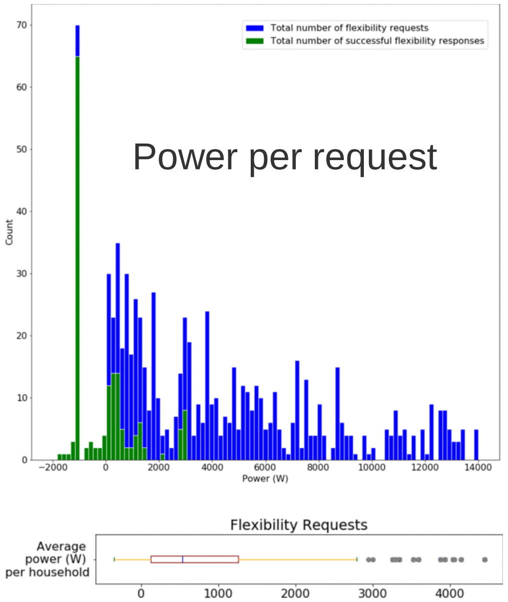
4. Demand-side flexibility in practice: Real case study ②

RESULTS

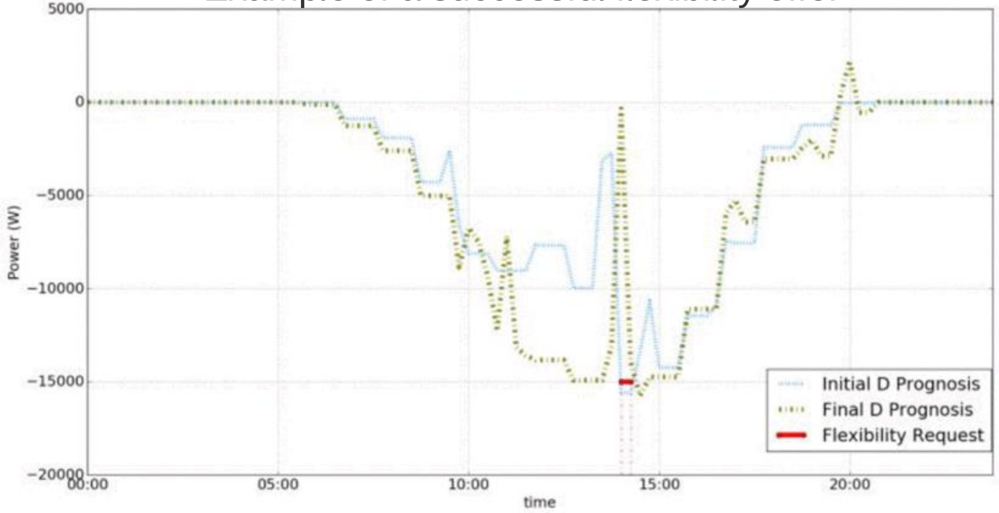
- In most tests, **congestions** in the grid **could be suppressed through flexibility**
- **Flexibility offered** is dependent on the **power** requested, the **period** of the day, and its **duration**
- Under **very high local production** conditions, HPs alone are insufficient → **need for storage**
- Other limitations: **operational constraints** and **end-users' comfort requirements**

Flexibility requested/offered





Example of a successful flexibility offer



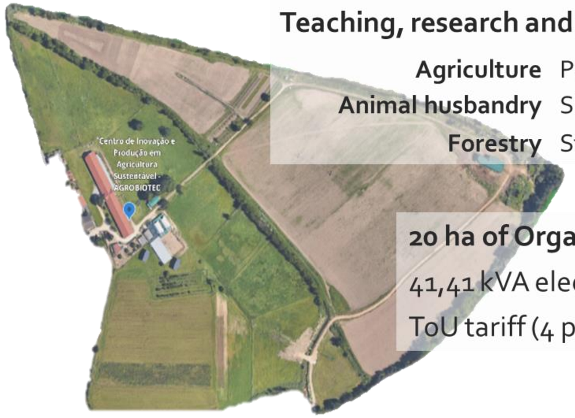
Soares, A., Somer, O. D., Ectors, D., Aben, F., Goyvaerts, J., Broekmans, M., . . . Vanthournout, K. (2019). Distributed Optimization Algorithm for Residential Flexibility Activation—Results From a Field Test. IEEE Transactions on Power Systems, 34(5), 4119-4127. doi:10.1109/TPWRS.2018.2809440

4. Demand-side flexibility in practice: Real case study

3

PROBLEM: integrated management of energy resources and deploying demand-side flexibility in agriculture

Case study: Agriculture School, Coimbra - Portugal



Teaching, research and productive activities:

Agriculture	Pastures, forages, horticulture
Animal husbandry	Sheep, rabbits, chickens, pigs
Forestry	Strawberry trees

20 ha of Organic Farming

41,41 kVA electricity supply

ToU tariff (4 prices)

PRELIMINARY RESULTS:

Flexibility in **agriculture is understudied**

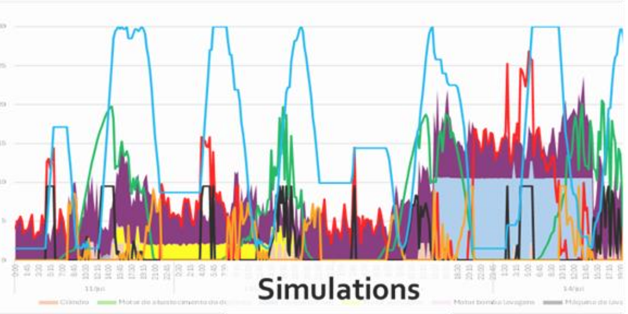
There are **relevant technological, operational, regulatory and social challenges**:

- Farmers are a **hard-to-reach** audience
- **Stakeholders** from agriculture and energy need to be brought together
- **Technology upgrade** is needed
- **Energy literacy** is crucial
- Regulations and **administrative procedures need simplification**

Roof PV 25 kWp

Agrivoltaics 17 kWp

Storage: 22 kWh



Simulations

Sensing devices

Actuators

Lopes, M., Soares, A., Miranda, R., Pena, J., Antunes, C.A. Energy Demand Flexibility in Agriculture. ECEEE Summer Study, France, 10-15 June 2024

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5. Demand-side flexibility in energy communities

Some archetype **business models** focused on flexibility:

PROSUMERISM

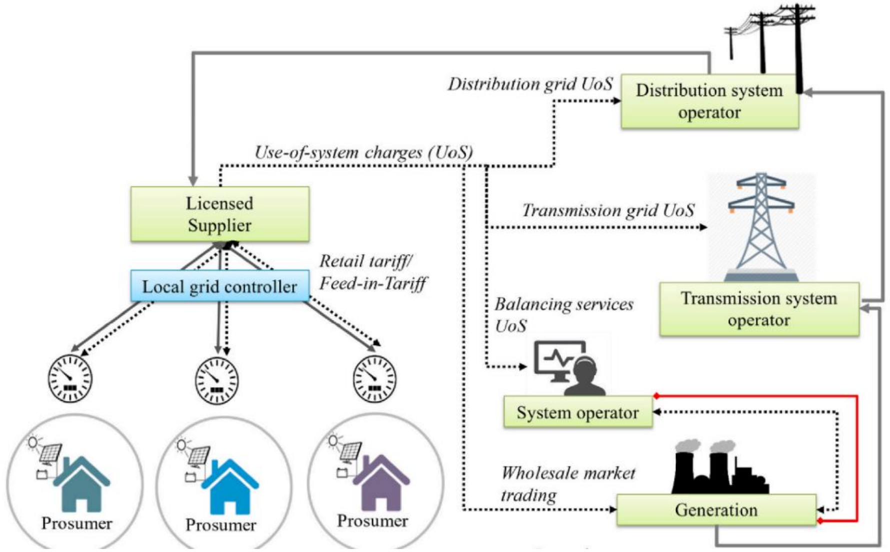
- **Aim to** gain dimension to **acquire assets**, participate in **flexibility markets**, collective **energy efficiency** initiatives or to participate in **LEM**
- Communities of place created by prosumers

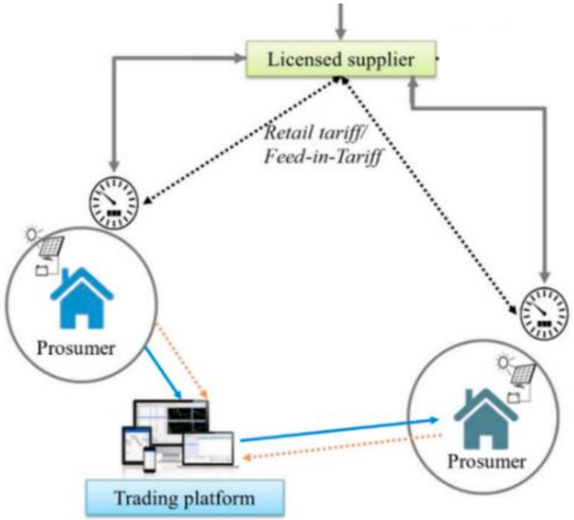
LOCAL ENERGY MARKETS

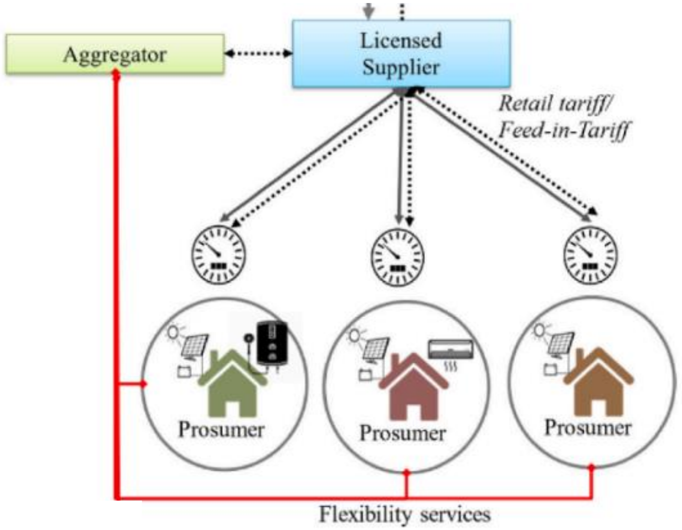
- **Aim to** work collaboratively to **maximize self-sufficiency**
- Developed by prosumerism-driven communities

COMMUNITY FLEXIBILITY AGGREGATION

- **Aim to engage in collective DSM strategies and flexibility markets**
- Communities of interest, started by aggregators or by end-users

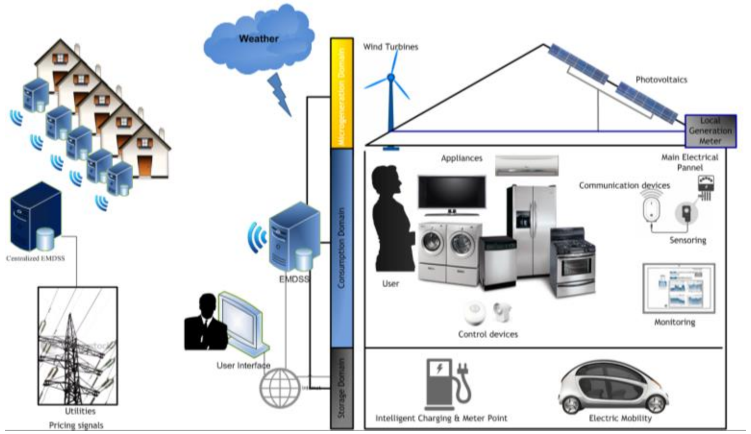






Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. Business models for energy communities: A review of key issues and trends. Renewable and Sustainable Energy Reviews, Vol. 114(7), pp. 111013, 2021. https://doi.org/10.1016/j.rser.2021.111013

5. Demand-side flexibility in energy communities



- Multiobjective models **optimize the integrated usage of multiple energy resources in the communities**
- Exploiting members' flexibility in load operation to modulate demand according to **time-differentiated prices, generation availability and grid conditions → Load follows supply**

Objective Functions

min

Energy bills
Energy bought from the grid
Costs (investment, operation, maintenance)
Dissatisfaction / discomfort
Losses, voltage deviation
Environmental impacts (emissions)
Risks (portfolio investment, supply diversification)

max

Self-sufficiency
Revenues
Satisfaction / Comfort
System reliability / safety
Quality of service
Services to the grid
Social impacts

Constraints

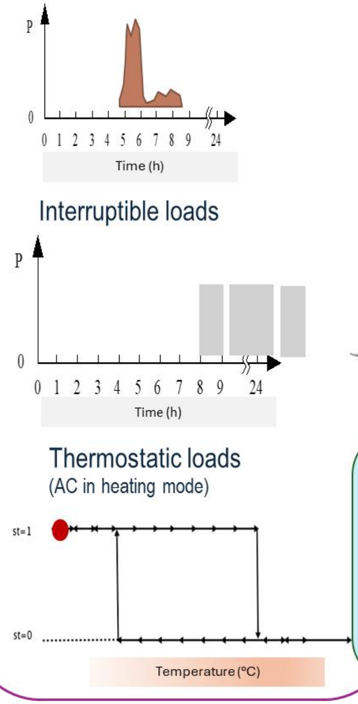
RES generation capacity and availability
Storage limits, charge/discharge rates
Budgetary limitations
Billing mechanisms
Power balance, lines and transformers limitations

C. Henggeler Antunes. "Multiobjective Optimization in the Energy Sector: Selected Problems and Challenges". In: M. Doumpos, J. Figueira, S. Greco, C. Zopounidis (Editors), "New Perspectives in Multicriteria Decision Analysis", 357-370, Springer, 2019.

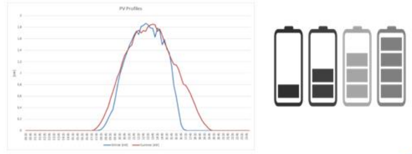
5. Demand-side flexibility in energy communities

PROBLEM: To what extent can demand-side flexibility of **residential, non-residential and cross-sectoral activities** be exploited to achieve **community self-sufficiency?**

Residential agents:



Local resources



User characteristics

- Cost driven
- Comfort driven
- Balanced

User preferences

- Preferred time slots
- Ideal and minimum acceptable final SoC
- Temperature comfort range

SMEs and cross-sectoral agents:

SMEs

Electricity consumption data retrieved from a **public database** on:

Lighting, Equipment, Ventilation, Cooling, Heating

3 Profiles were considered to address the possible flexibility range for each load:

Conservative	Moderate	Stretch
No load reduction	10% load reduction	20% load reduction

Street lighting

- Electricity consumption of public lighting was estimated considering the **required luminance levels**
- **Public lighting flexibility** is exploited through the application of **light-on-demand techniques**

EV charging station

- On average, **25 EVs** are daily charged and most chargings are performed between **9am** and **8pm**
- Different initial SoC are randomly generated and public charging is paid by service users

Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. A multi-agent system approach to exploit demand-side flexibility in an energy community. Utilities Policy, Vol. 67, pp. 101-114, 2020. https://doi.org/10.1016/j.jup.2020.101114

5. Demand-side flexibility in energy communities

RESULTS

Community self-sufficiency

	With SME demand optimization		Without SME demand optimization	
	Winter	Summer	Winter	Summer
Scenario A	20%	23%	19%	21%
Scenario B	24%	53%	23%	52%
Scenario C	28%	89%	27%	86%

Residential agents - A: 0% prosumers, B: 50% prosumers, C: 100% prosumers

Community aggregated weekly costs(-) and revenues(+)

	Scenario A [€]		Scenario B [€]		Scenario C [€]	
	Summer	Winter	Summer	Winter	Summer	Winter
With SME demand optimization	-5121	-4718	-1771	-4261	1434	-3623
Without SME demand optimization	**-5377**	**-4954**	**-1850**	**-4474**	**1362**	**-3807**

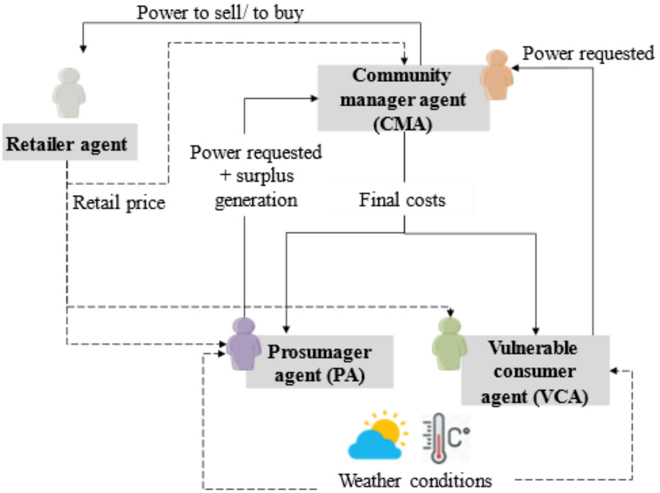
- **Prosumers** contribute significantly to community self-sufficiency
- **SMEs** demand flexibility contribute to the community self-sufficiency and to reduce energy costs

How to **distribute costs and profits** in a diversified community in a **fair and equitable** manner?

Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. A multi-agent system approach to exploit demand-side flexibility in an energy community. Utilities Policy, Vol. 67, pp. 101-114, 2020. https://doi.org/10.1016/j.jup.2020.101114

5. Demand-side flexibility in energy communities

PROBLEM: What can be the **role of vulnerable consumers** in energy communities?



- **Collective goal: self-sufficiency**
- Individual goals: **MIN electricity costs and discomfort** associated with changes in load use patterns
- Constraints: physical characteristics (loads, grid, storage)
- Algorithmic approach: Non-Dominated Sorting Genetic Algorithm (NSGA-II)

Vulnerable consumers are economically benefited in all scenarios

Although differences may appear to be of little significance (due to **little demand and flexibility**), they contribute to **mitigate energy poverty**

Average daily costs (-) and benefits (+)

			Summer				Winter			
			A	B1	B2	B3	A	B1	B2	B3
Average daily costs before sharing [EUR/day]	VCA		–	-2.36	-2.39	-2.24	–	-2.31	-2.43	-2.36
	PA	Cost-oriented	4.09	6.18	3.33	4.24	-1.72	-0.50	0.20	-1.77
		Balanced	3.30	2.72	1.77	3.70	-2.70	-1.53	-1.42	-2.69
		Comfort-oriented	1.46	-1.05	1.21	0.67	-5.30	-4.41	-3.84	-5.24
Average daily costs after sharing [EUR/day]	VCA		–	-2.21	-2.29	-2.11	–	-2.21	-2.34	-2.24
	PA	Cost-oriented	4.27	6.51	3.62	4.44	-1.46	-0.24	0.56	-1.50
		Balanced	3.50	3.03	2.06	3.95	-2.35	-1.27	-1.13	-2.36
		Comfort-oriented	1.87	-0.49	1.51	1.00	-4.70	-3.88	-3.45	-4.64

Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. Towards inclusive community-based energy exchanges: A multiagent framework. Applied Energy, Vol. 307, pp. 118115, 2022. https://doi.org/10.1016/j.apenergy.2021.118115

5. Demand-side flexibility in energy communities

RESULTS

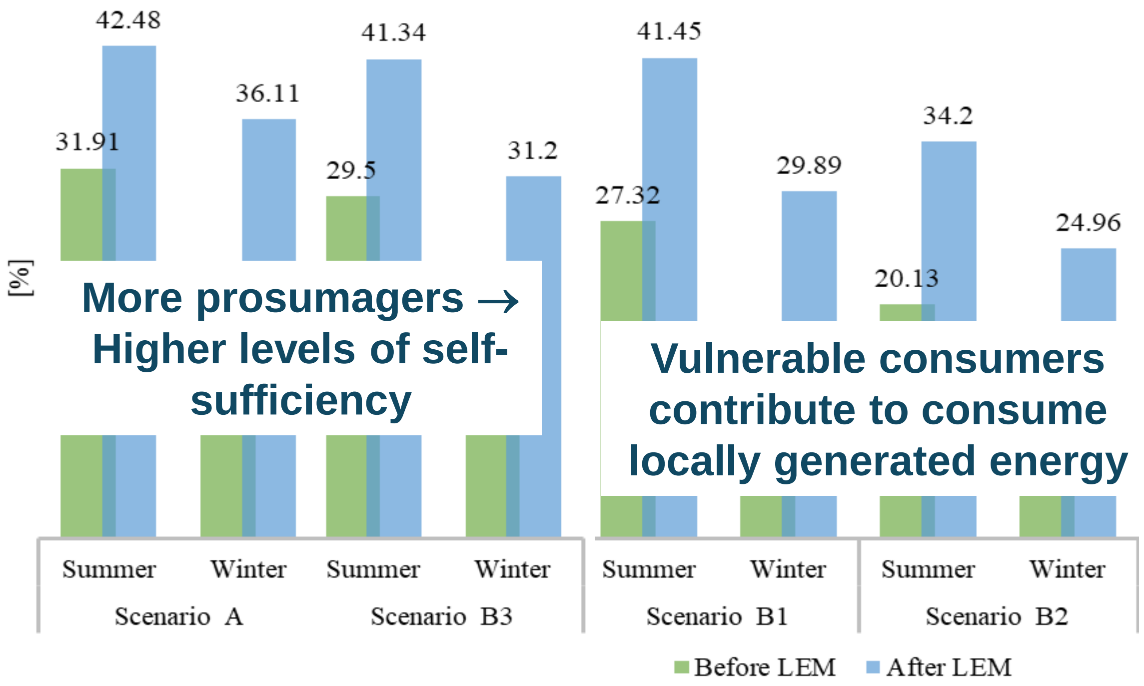
Prosumagers:

- Benefit differently depending on their sensitivity to cost and comfort
- Overall, **benefit** from when there is **more demand as they seek to maximize sales**

Vulnerable consumers:

- Contribute to **consume self-generated energy** and benefit from prosumagers

SELF-SUFFICIENCY



EC diversity (including different activities, energy poor) **is beneficial to self-sufficiency and energy balance**

Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. Towards inclusive community-based energy exchanges: A multiagent framework. Applied Energy, Vol. 307, pp. 118115, 2022. https://doi.org/10.1016/j.apenergy.2021.118115

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6. Conclusions and policy recommendations

- **Barriers** to demand-side flexibility comprise **regulatory, technical, economic, organisational, operational, behavioural** dimensions (for a review see doi: 10.1016/j.rser.2017.01.043)
- Optimization-based models are **useful tools to incorporate complexity - including behavioural/social and regulatory dimensions** - **facilitating the implementation of technical solutions and policies**
- Combining modelling with real cases confirms that:
  - **End-users play a key role in providing flexibility**
  - **↑ decentralised generation** ⇨ **↑ storage capacity** to be able to ensure the required DS flexibility
  - Technology and interoperability are essential, but not sufficient: **operational/processual, behavioural/organisational and literacy** issues are also relevant

- **Policy** has a key role in deploying DS flexibility by **removing barriers**, providing the **right regulatory context** and **supporting innovative multidisciplinary research** in real-world settings

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All our colleagues at INESC Coimbra
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Polytechnic University of Coimbra - Agriculture College
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