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Cât de verde poate fi un oraș și cât poate contribui la tranziția energetică?

Florin Capitanescu

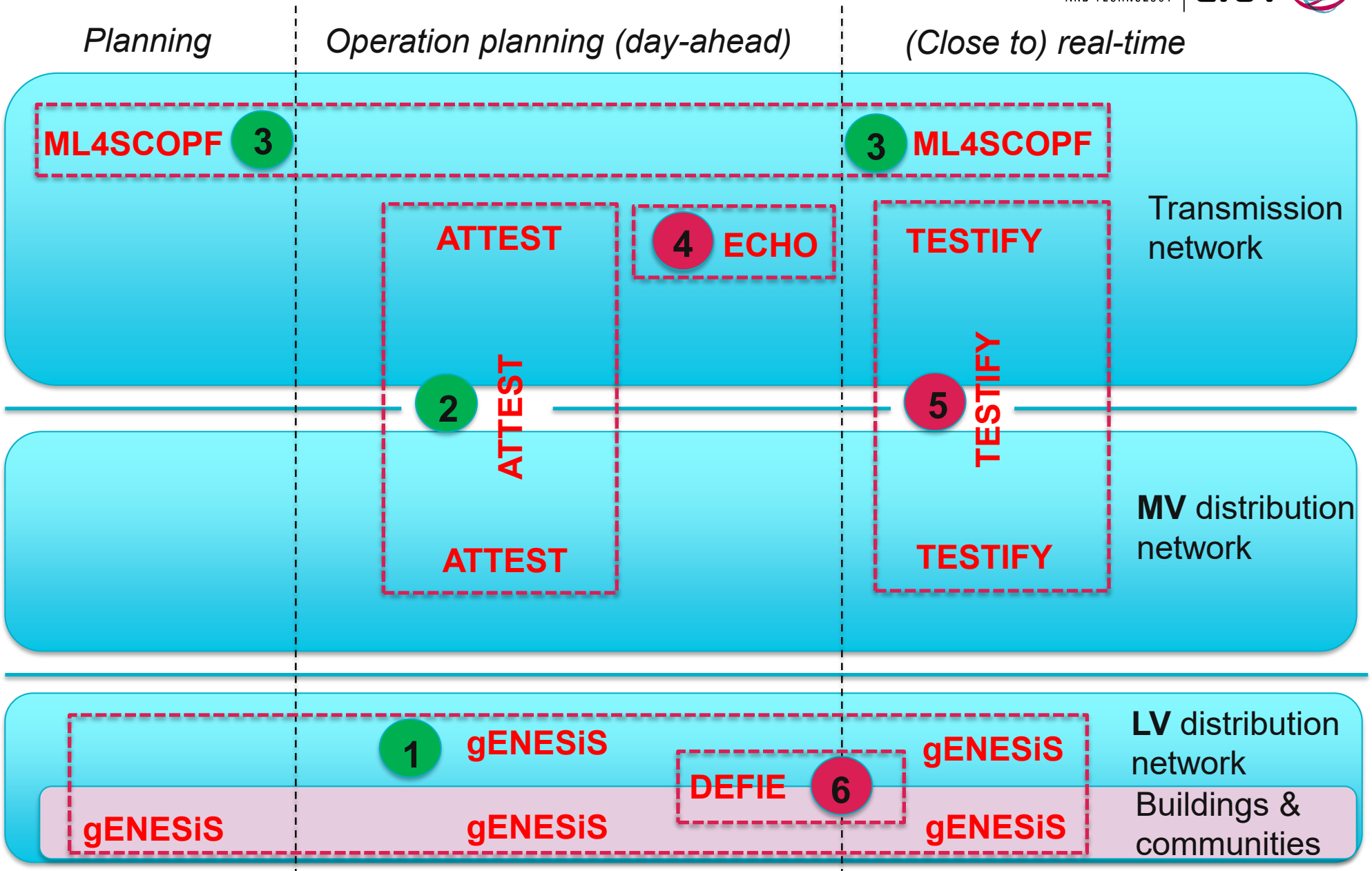
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Conferinta Smart Diaspora 2025, Cluj-Napoca, November 5-th, 2025



PROJECTS HIGH LEVEL POSITIONING **PER NETWORK LEVEL AND TIMEFRAME**

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OVERALL TOP-DOWN MAPPING OF PROJECTS **PER TOPICS**

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optimization, optimization, optimization!

…

except if highlighted in yellow

1) New contributions to the envisioned **power system security optimization** in **IBR renewable**-rich grids to:

- **Uncertainties** in day-ahead operation
  - **Chance-constrained** optimization approach (**ECHO**)
- **Uncertainties** and **temporal coupling** aspects of energy assets (e.g. storage) in day-ahead operation
  - **Stochastic multi-period** security-constrained optimal power flow (**SCOPF**) approach (**ATTEST**)
- **Temporal coupling** of energy assets and **risk**-based security close to real-time
  - **Multi-period risk**-based SCOPF approach (**TESTIFY**)
- Computation **speed-up** close to real-time
  - **Machine learning** techniques to speed up AC SCOPF calculations (**ML4SCOPF**)
- **Uncertainties** and **reactive power issues** during the **energy transition** in planning
  - Evaluation of **reactive power scarcity** and re-thinking **VAr planning** (**ML4SCOPF**)
- **TSO-DSO coordination** to meet security by sharing the energy flexibility of active distribution systems
  - In day-ahead operation planning (**ATTEST**) and close to real-time (**TESTIFY**)
  - Range and **cost of active/reactive power aggregated flexibility** from active distribution systems (**TESTIFY**)
- Enhanced **cascading outages simulation** and **risk quantification** in support to resilience (**TESTIFY**)
  - New AC power flow models including steady-state models of IBRs (GFM and GFL) (**TESTIFY**)

2) New contributions to **optimal operation of active distribution systems (MV and LV layers)** addressing:

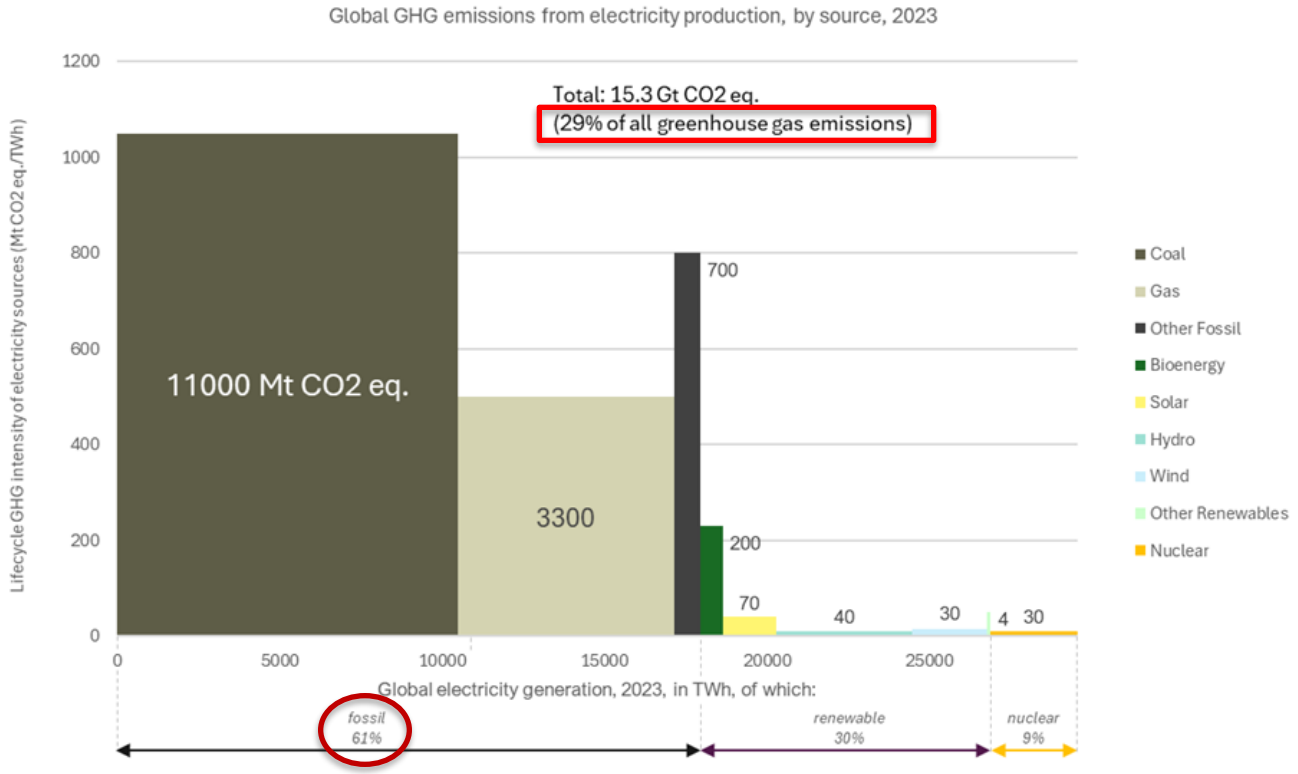
- **Uncertainties** and **temporal coupling** aspects of energy assets (e.g. storage) in day-ahead operation
  - **Stochastic multi-period** optimal power flow approach at MV level (**ATTEST**) and at LV level (**gENESiS**)
  - **Flexibility range and cost** of active distribution systems at the interface with the TSO (**TESTIFY & ATTEST**)
- **Dynamic operation envelopes** of distributed energy resources (**DEFIE**)

3) New contributions to **optimizing smart sustainable buildings (SSBs)** and **energy communities** addressing:

- Optimal sizing of energy devices in SSBs, **energy management system** for optimal operation of SSBs (**gENESiS**)
- Optimal use the flexibility provided by a cluster of SSBs in the operation of active distribution grid (**gENESiS**)
- Optimal share of energy storage battery in an energy community (**gENESiS**)

ENERGY TRANSITION TO (100%?) RENEWABLE SUPPLY

- A global (world-wide) issue
  - Is the world really or efficiently combating climate change?



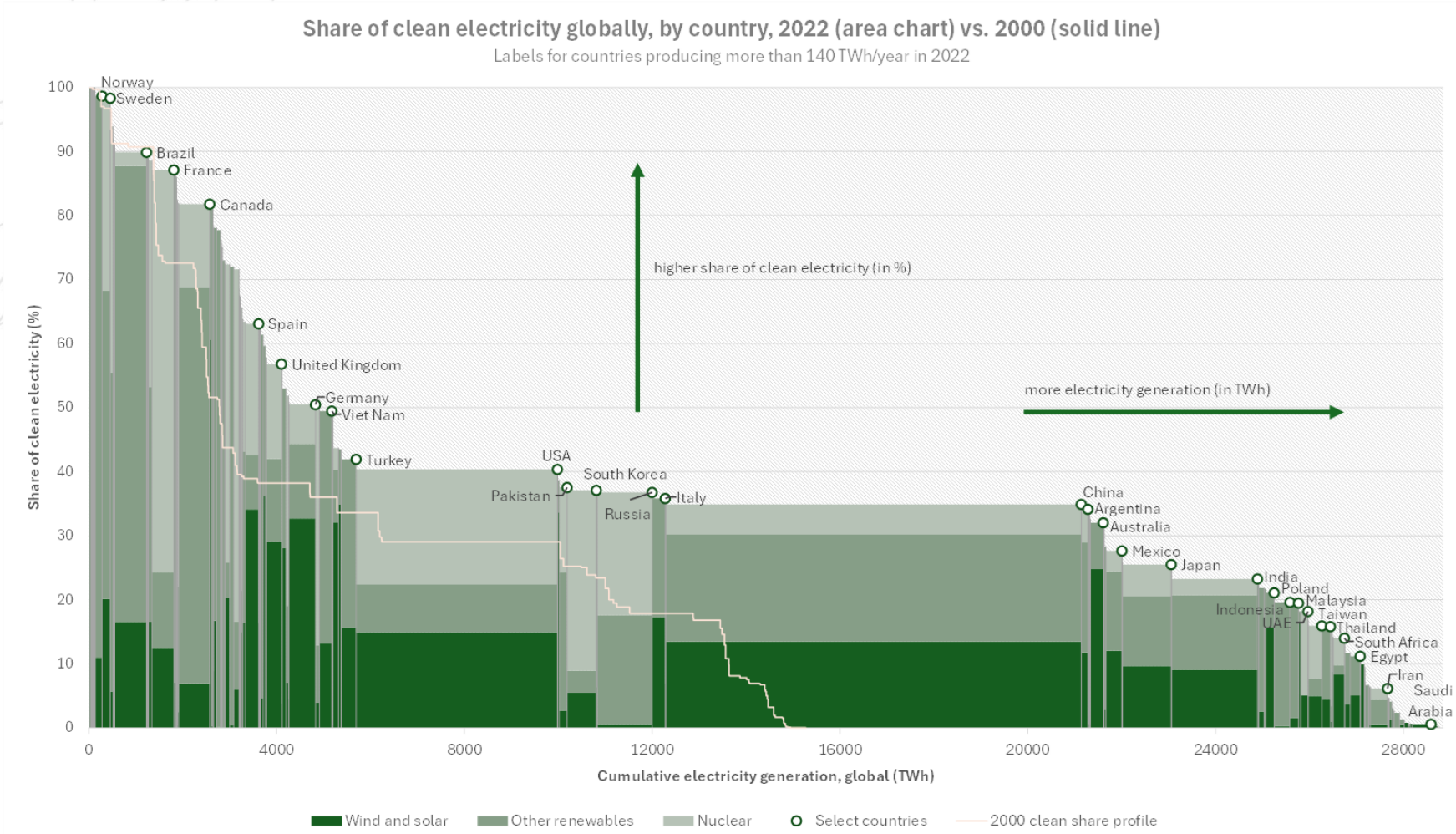
- Are we prepared against blackouts during the energy transition?

F. Capitanescu, T. Gibon, The Energy Transition's Hidden Iceberg: Practical Barriers and Proposed Solutions Toward Sustainable Electricity Systems, IEEE Energy Sustainability Magazine 1 (1), 66-76, 2025.

F. Capitanescu, Are we prepared against blackouts during the energy transition?: Probabilistic risk-based decision making encompassing jointly security and resilience, IEEE Power and Energy Magazine 21 (3), 77-86, 2023.

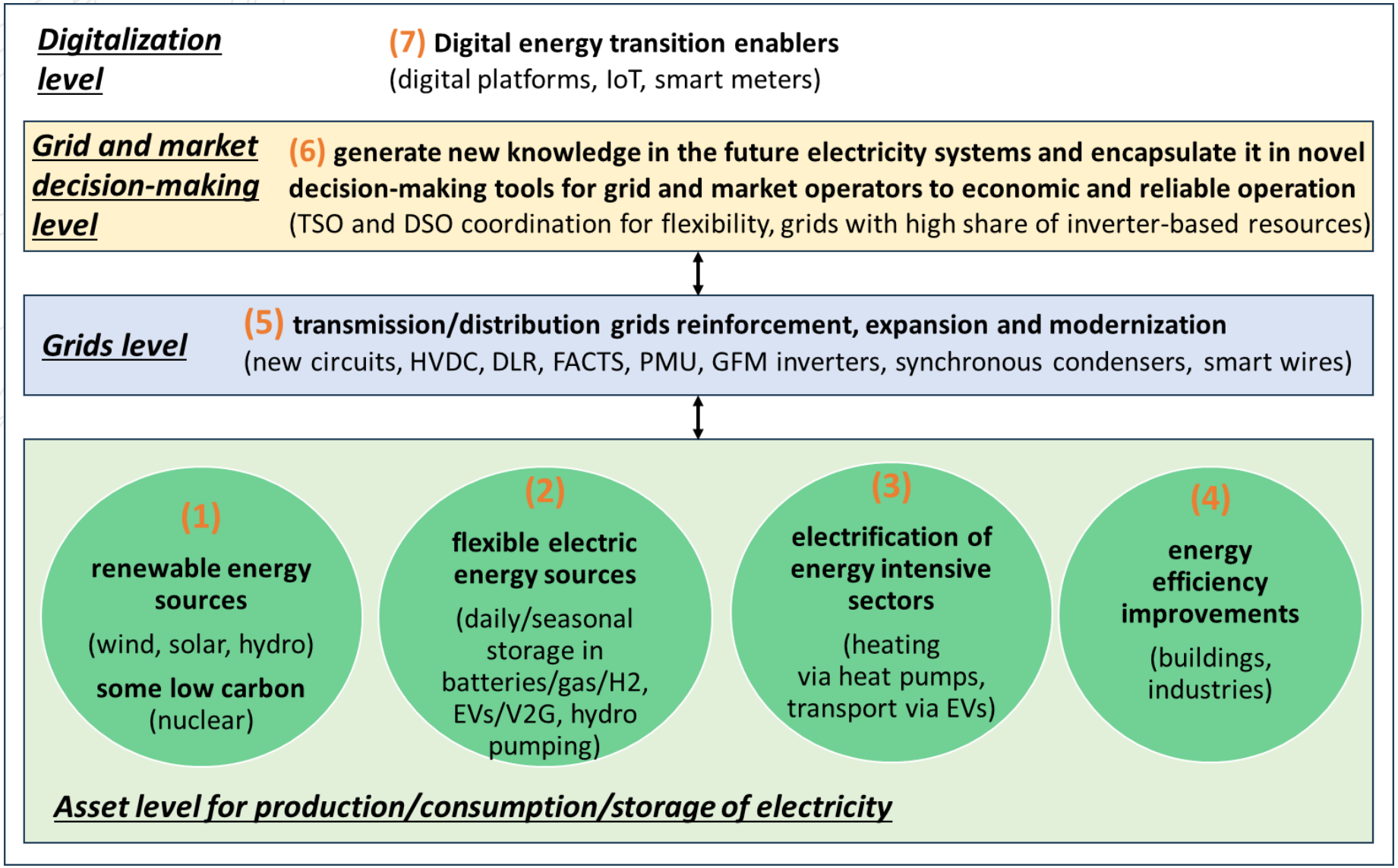
ENERGY TRANSITION TO (100%?) RENEWABLE SUPPLY

- Some countries have the luxury of abundant renewable energy resources
- Fairness of reducing CO_2 emissions: some countries under development should develop their infrastructure



F. Capitanescu, T. Gibon, The Energy Transition's Hidden Iceberg: Practical Barriers and Proposed Solutions Toward Sustainable Electricity Systems, IEEE Energy Sustainability Magazine 1 (1), 66-76, 2025.

SEVEN STEPS OF THE ENERGY TRANSITION TO RENEWABLE SUPPLY



F. Capitanescu, T. Gibon, The Energy Transition's Hidden Iceberg: Practical Barriers and Proposed Solutions Toward Sustainable Electricity Systems, IEEE Energy Sustainability Magazine 1 (1), 66-76, 2025.

HOW GREEN COULD A BIG CITY BE?





- Characteristics of big cities
  - Large energy/electricity consumption; it keeps increasing!
  - Energy efficiency improvements are possible
    - Urbanism limitations: many (historical) buildings, which are energy inefficient, cannot be retrofitted
  - Renewable electricity production is limited (e.g. possibility to deploy PV panels on some roofs)
    - But, even when it is sunny, this does not cover peak consumption
    - Would you install a nuclear reactor in the city center? ☺
  - May provide some flexibility (EV charging, V2G, shiftable demand like HVAC, demand response to dynamic prices) at local or global grid level

HOW MUCH COULD A “GREEN CITY” CONTRIBUTE TO THE ENERGY TRANSITION?

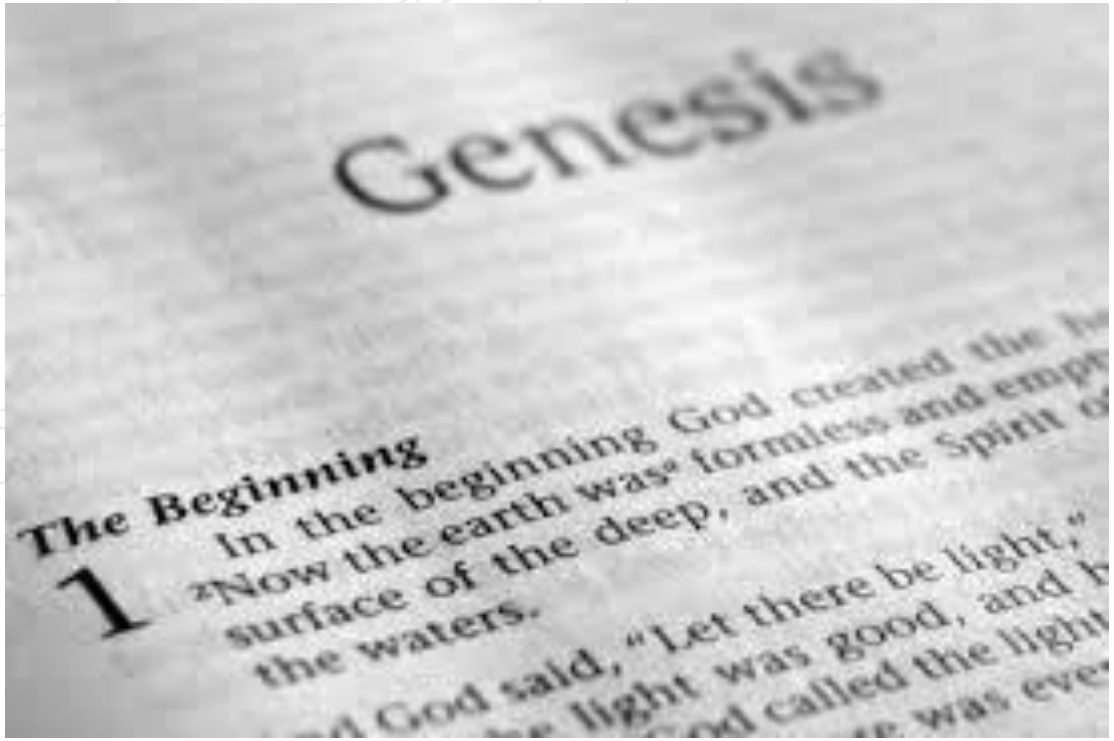
- Incentivize/empower consumer centric initiatives by investing in renewables, storage, or forming energy communities
  - These measures give people a sense of involvement in and financial profit from the transition
  - Their efficiency is questionable because, without them, the transition will anyway occur with investment in larger scale
  - The excess of PV panels in weak low voltage grids leads to spillage of solar energy

- Pushing forward the **net-zero energy** requirement (updated to **zero emission** buildings) for new buildings
  - We want smart & “green” buildings, but they aren’t self-sustaining
  - They are NOT net zero in higher time resolution (e.g. minute, hour, day) i.e. when really needed at system level!
    - => matching instantaneously generation and demand will still need to be satisfied from additional sources!
  - While it can mitigate to some extent the climate change, a system composed only of such buildings is not a solution as **it cannot operate autonomously in self-sufficiency**
    - “An endless number of green buildings doesn’t make a sustainable city”, Jan Gehl

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THE GENESIS PROJECT

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Initial Motivation

Buildings
- 40% Energy consumption
- 36% CO2 emissions



EU Energy Performance of Buildings Directive 2010 → Zero Energy Buildings (ZEBs)

- ZEB = generates yearly roughly as much energy from renewable sources as it consumes
- ZEB may host: PV panels, electric energy storage … but also solar thermal collector, heat storage as well as opportunities for consumption modulation (HVAC, heat pumps, etc.)

ENERGY MANAGEMENT SYSTEM FOR SMART SUSTAINABLE BUILDINGS: PLANNING, OPERATION AND OPTIMAL INTEGRATION IN THE SMART GRID

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- gENESiS -

- **gENESiS** project was funded by **FNR Luxembourg** (CORE call 2018): duration: **01/09/2019-31/08/2022**

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  - Works at the intersection between smart sustainable buildings (**SSB**s) and smart grids
  - Motivations: trend to net zero energy buildings, grow of distributed energy resources in buildings, SSB flexibility opportunities for the smart grid, challenges to optimally operate smart grids with growing amounts of distributed energy resources
  - Sustainable building:
    - Net/nearly zero energy building (**nZEB**)
    - Stock material (and technologies adopted) has a low environmental impact according to life cycle assessment (**LCA**) approach
  - Smart building:
    - Possesses a smart algorithm integrated in the energy management system (**EMS**) to optimally steer renewable energy production, consumption and storage
  - some language abuse on what we call a “building” -> smart residential home (but methods developed are rather generic)
  - building “scope”: electric and thermal energy flows
  - **key feature is inter-disciplinarity**: buildings, smart grids, sustainability (LCA), mathematical optimisation, automatic control

GENESIS PROJECT
CONSORTIUM AND TEAM

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uni.lu UNIVERSITÉ DU LUXEMBOURG

KATHOLIEKE UNIVERSITEIT LEUVEN

AALBORG UNIVERSITET

The core team

Dr. Iason-Iraklis Avramidis 

Dr. Himanshu Nagpal 

Dr. Florin Capitanescu (PI) 

Dr. Patrick Kobou Ngani 

Dr. Mahdi Mehrtash 

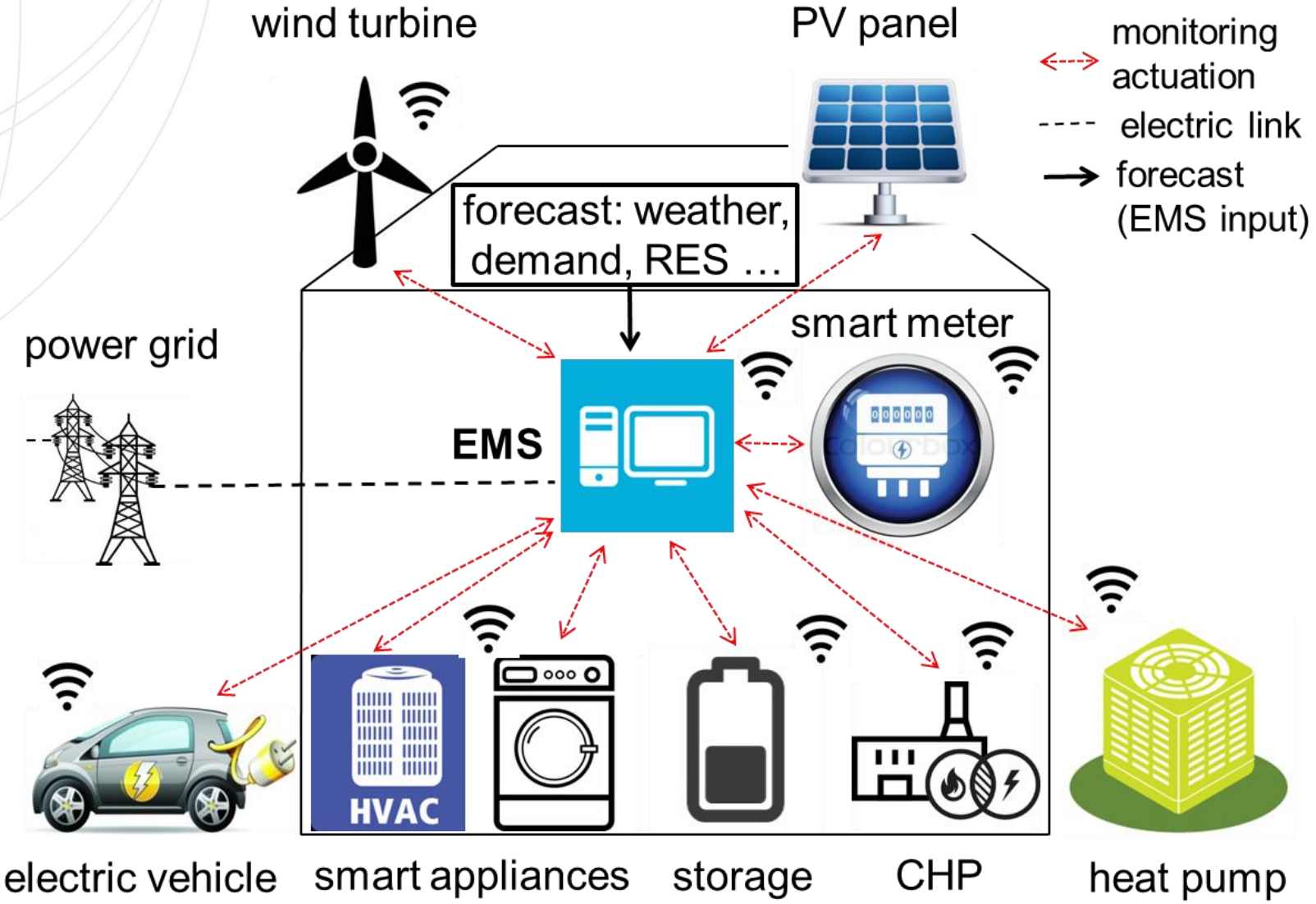
Prof. Geert Deconinck 

Prof. Per Kvols Heiselberg 

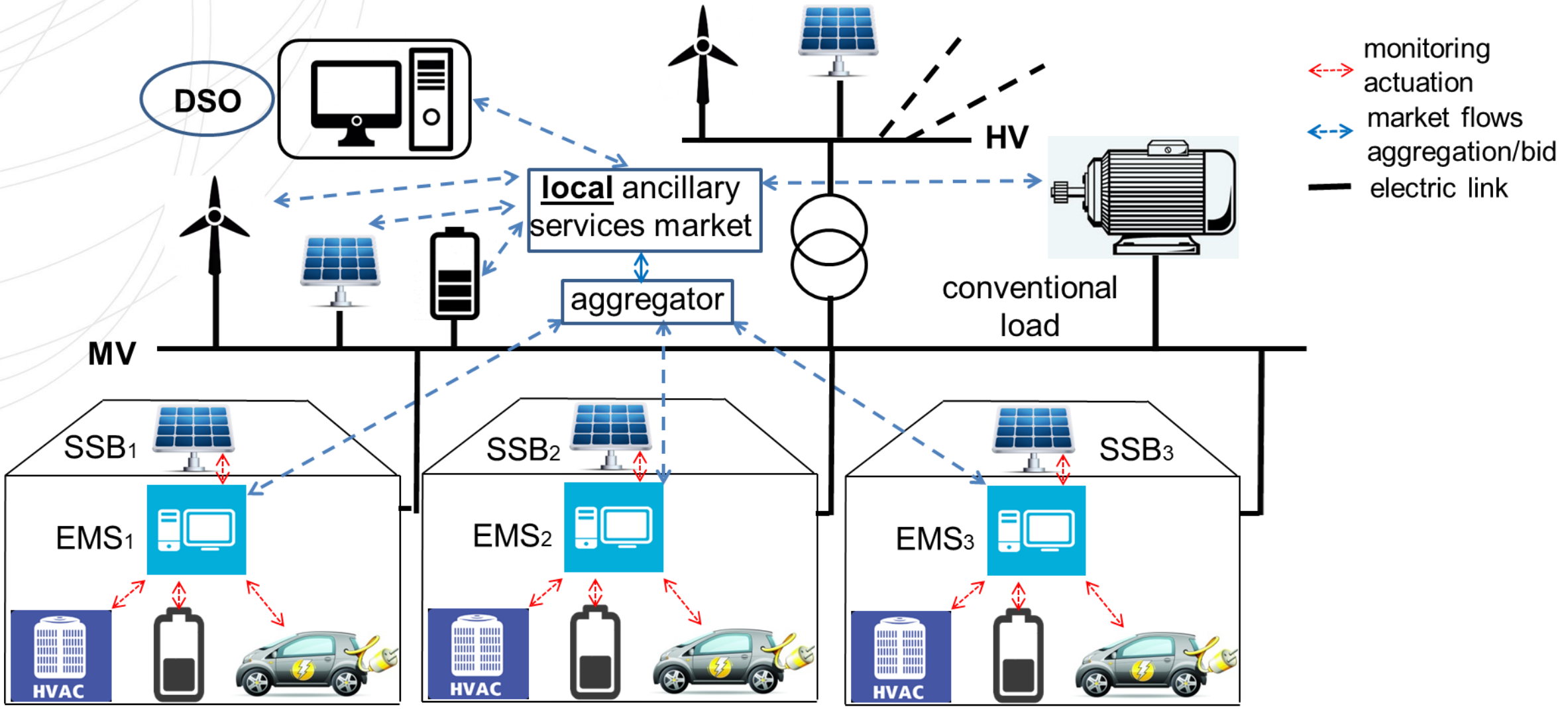
Prof. Jean-Régis Hadji-Minaglou 

Dr. Thomas Gibon 

SMART SUSTAINABLE BUILDING AS A SINGLE ENTITY



CLUSTER OF BUILDINGS INTEGRATED IN A SMART ENERGY SYSTEM



ENERGY MANAGEMENT SYSTEM FOR SMART SUSTAINABLE BUILDINGS: PLANNING, OPERATION AND OPTIMAL INTEGRATION IN THE SMART GRID (GENESIS)

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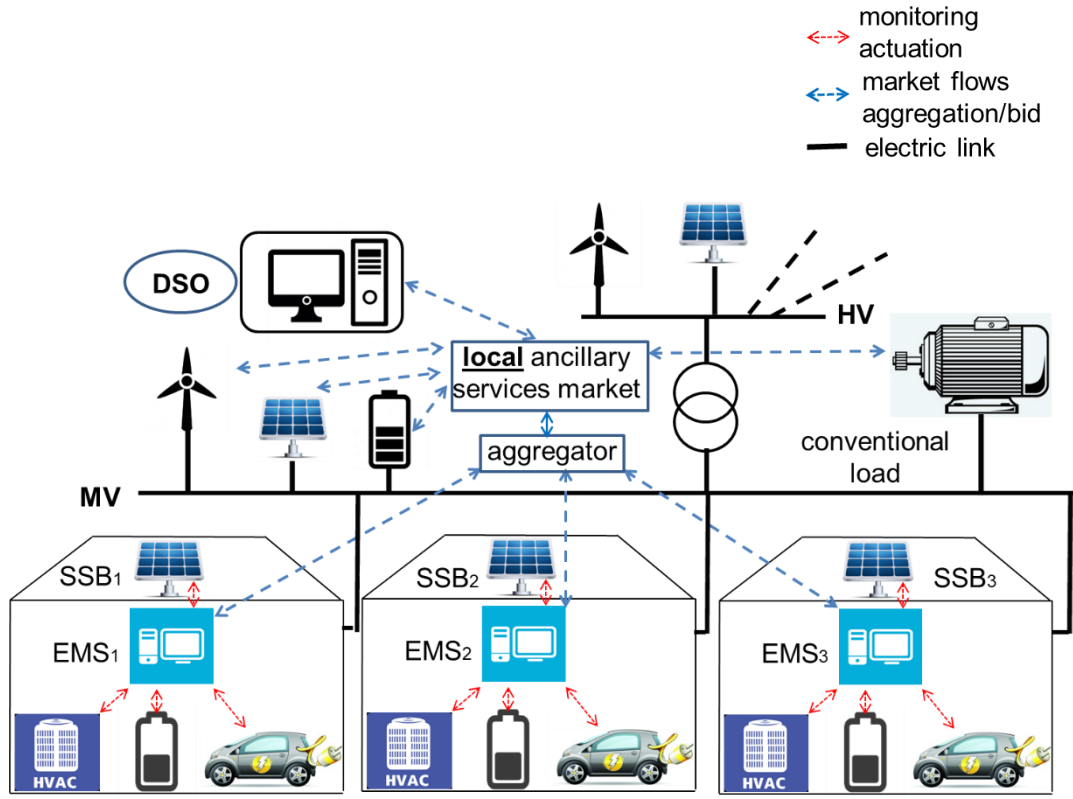
- 3-year project FNR-CORE
- Duration: **01/09/2019-31/08/2022**

Partners: LIST, UniLux, KUL, AAU

FNR funding: 770 k€

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- **Outcome 1** (building scale, *planning*):
  - MILP-based method and tool to optimally size renewable energy sources and energy storage devices to satisfy the net zero energy criterion of a smart sustainable building (SSB)
    - goal: ensure **building stakeholders optimal investment** in renewables/storage
- **Outcome 2** (building scale, *operation*):
  - MILP-based method for an energy management system tool supporting daily optimal SSB operation
    - goal: cost-optimally steer daily the renewable resources, storage, shiftable demand (heat pumps, electric vehicles, smart apps)
- **Outcome 3** (interaction of SSBs cluster and smart grid):
  OPF method and tool allowing DSO to use the flexibility provided by a cluster of SSBs for optimal grid operation
    - goal: cost-optimal operation of smart grid (day-ahead & real-time) including also SSBs flexibility



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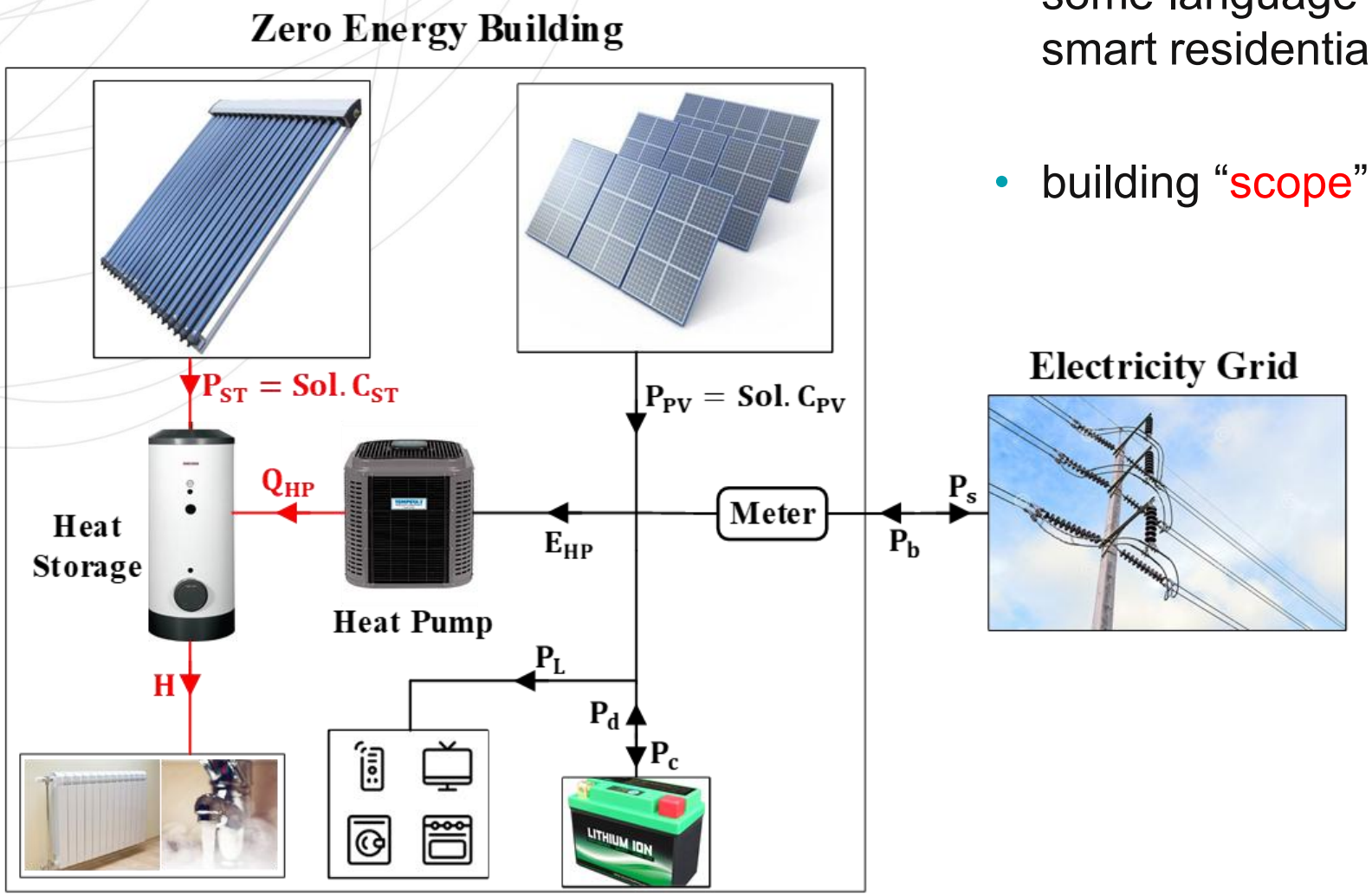
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Optimal sizing of energy production/storage devices in smart sustainable buildings

M. Mehrtash, F. Capitanescu, P.K. Heiselberg, T. Gibon, A. Bertrand, An Enhanced Optimal PV and Battery Sizing Model for Zero Energy Buildings Considering Environmental Impacts, IEEE . Transactions on Industry Applications 56 (6), 6846-6856, 2020.

M. Mehrtash, F. Capitanescu, P.K. Heiselberg, T. Gibon, , A New Bi-objective Approach for Optimal Sizing of Electrical and Thermal Devices in Zero Energy Buildings Considering Environmental Impacts, IEEE Transactions on Sustainable Energy 12 (2), 886 – 896, 2021.

Building “meaning” and setting



- some language abuse on what we call a “building” -> smart residential home (generic methods developed)
- building “scope”: electric and thermal energy flows

The optimal energy devices sizing problem

Bi-objective optimization problem seeking the optimal trade-off between:

- Maximizing building owner profit including:
  - investment in PV panels, electric energy storage, solar thermal collector, heat storage
  - building operation cost (generation/demand mismatch, electricity price and feed-in-tariff)

- Minimizing (LCA-based) environmental impact of the building

such that:

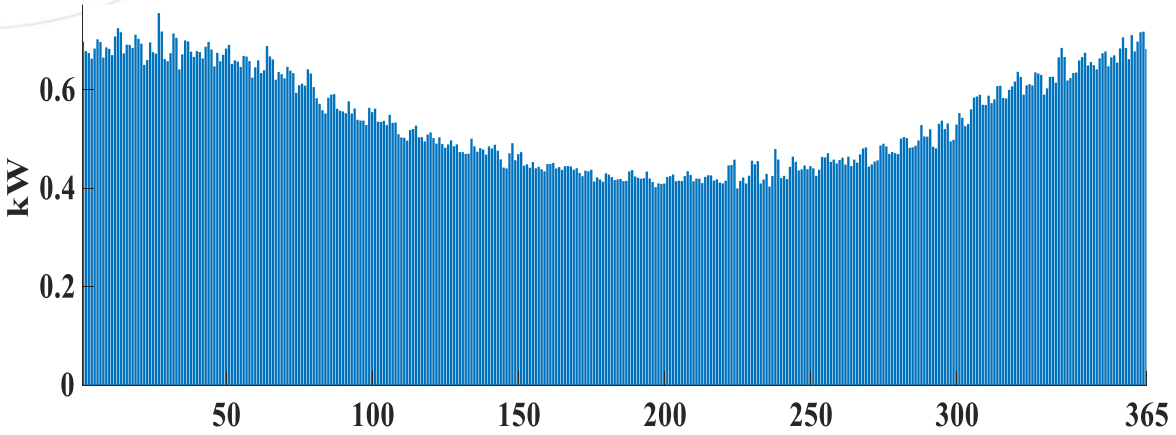
- nZEB criterion is met
- building operation (particularly storage) and energy flow exchange with the grid are modelled

One needs to estimate and model yearly operation!

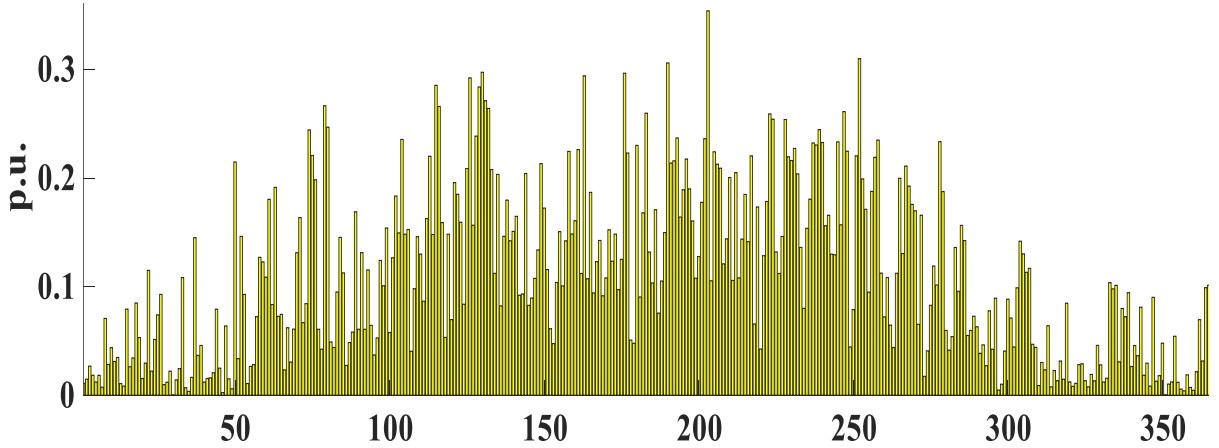
The optimal energy devices sizing problem

Challenges

- Electricity price > than FIT → Prioritise storing the excess power in the battery instead of selling it to the grid → introduce binary variables → creates bilinear terms → large scale MINLP problem!
- Large problem size (model 1 year) → large scale MINLP problem!



Demand

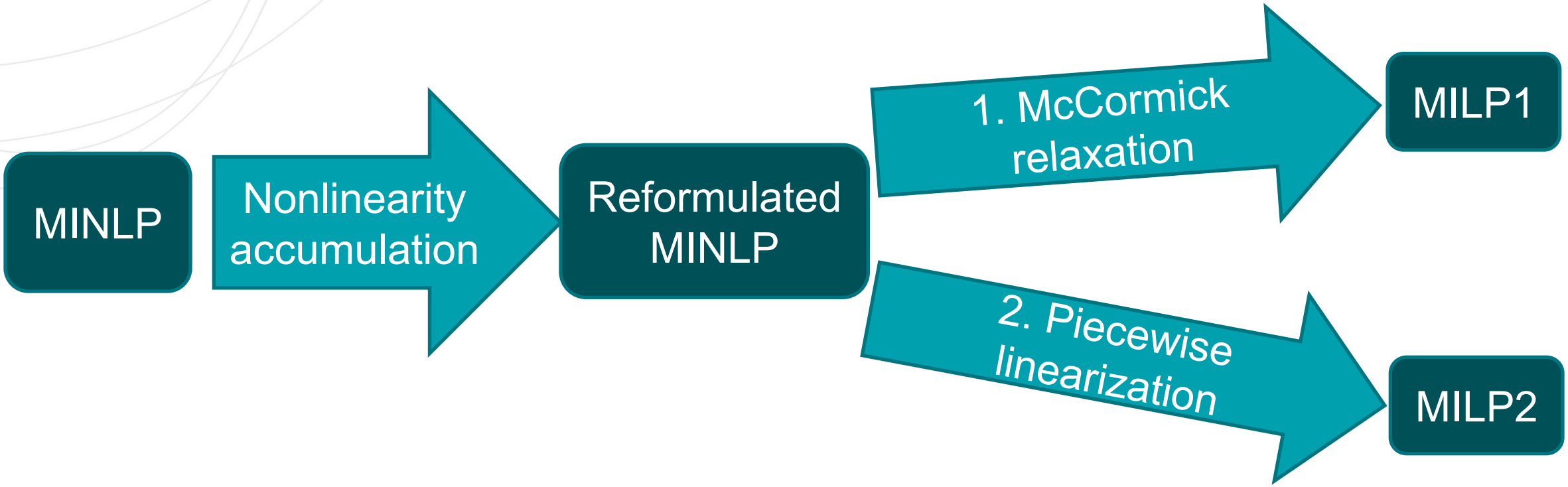


Solar irradiation

Proposed Model

A novel mathematical model

✓ Priority of having the excess power stored in the battery rather than sold to the grid



Proposed Model

McCormick Relaxation:

$$\omega(t) = C_B.SOC(t);\ \forall t$$

bilinear constraint



$$\omega(t) \geq C_B.SOC_{min};\ \forall t$$

over-estimators

$$\omega(t) \geq C_B^{max}.SOC(t) + C_B.SOC_{max} - C_B^{max}SOC_{max};\forall t$$

$$\omega(t) \leq C_B^{max}.SOC(t) + C_B.SOC_{min} - C_B^{max}.SOC_{min};\forall t$$

under-estimators

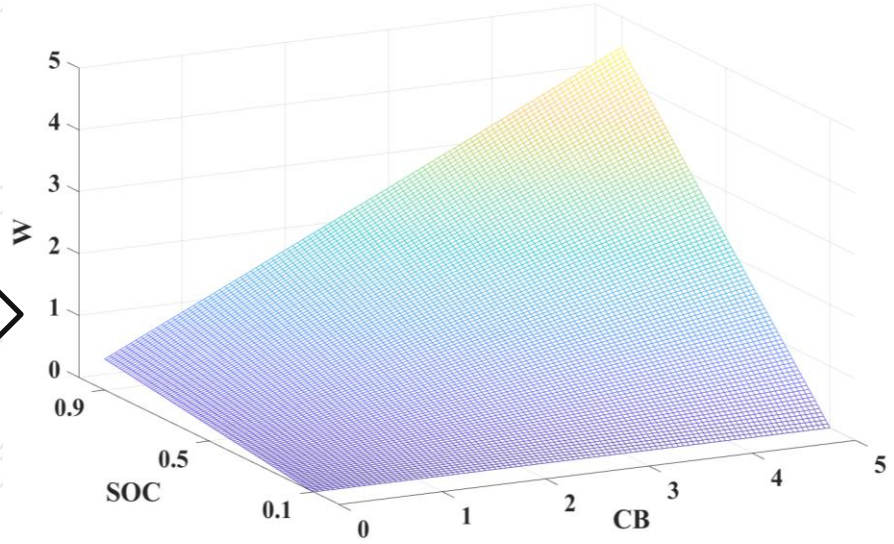
$$\omega(t) \leq C_B.SOC_{max};\ \forall t$$

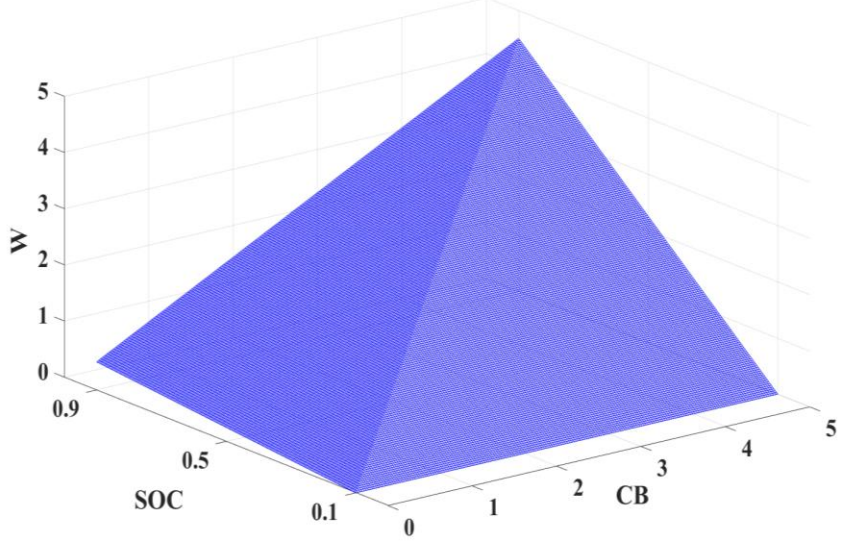
Proposed Model

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Our empirical observation: McCormick relaxation is tight!

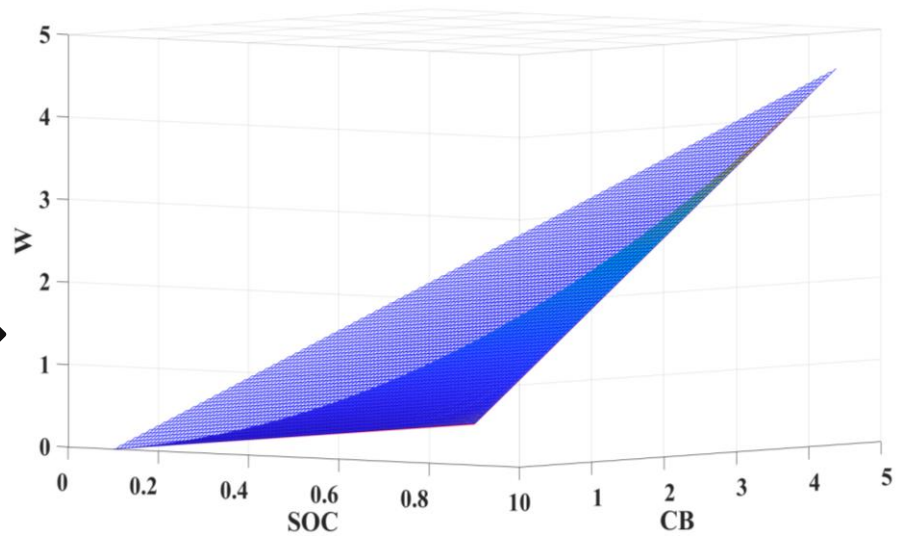
Bilinear constraint

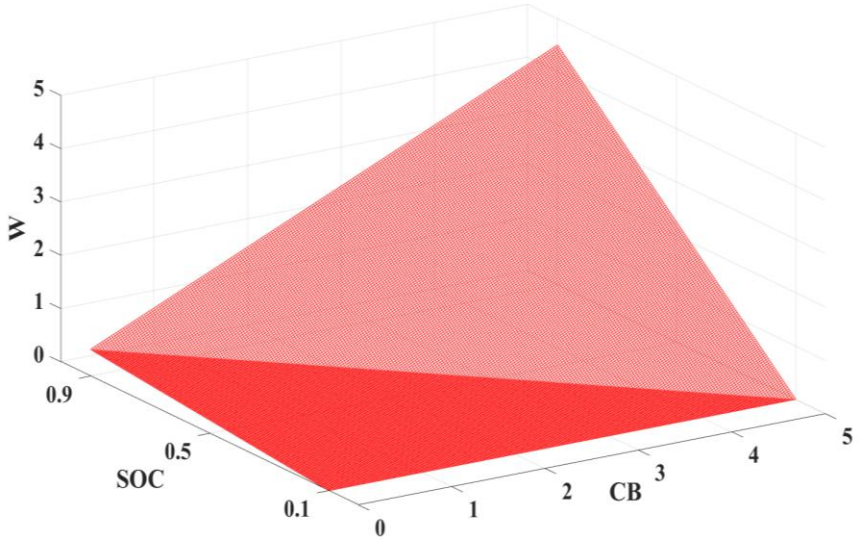




Over-estimator

Side view





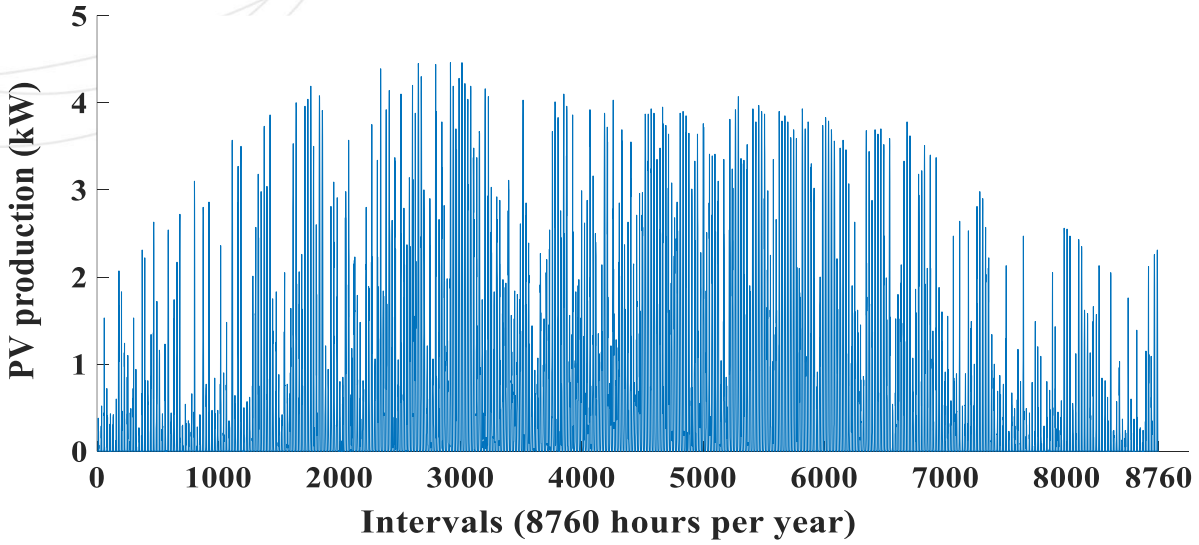
Under-estimator

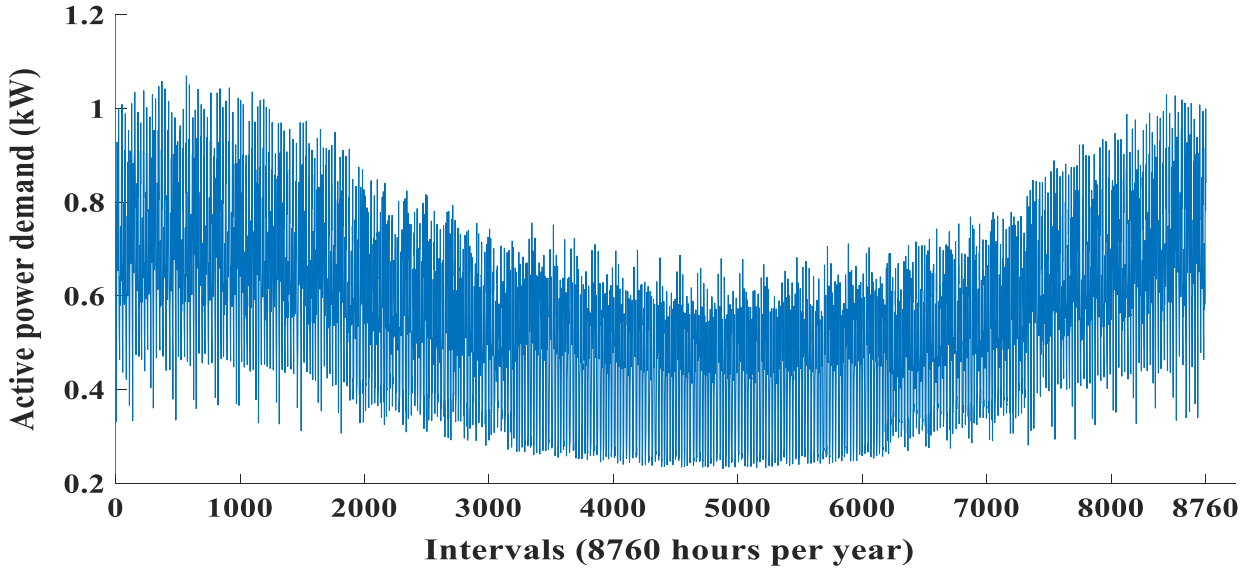
Simulation Results

A typical residential building located in Luxembourg (with a 5 kWp PV panel)

4880.57 kWh

4800 kWh



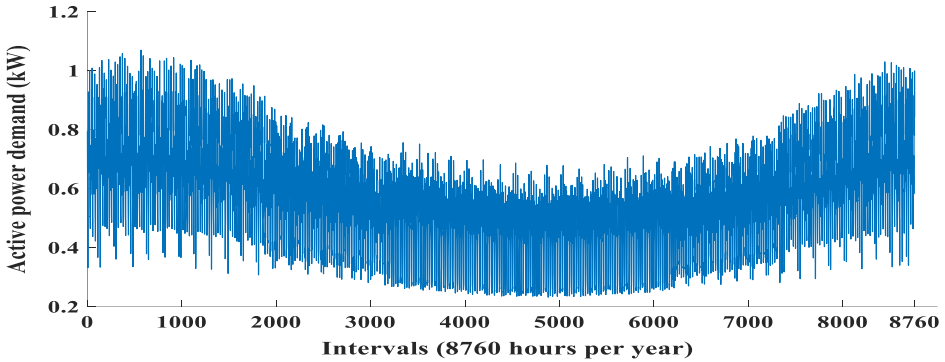


Simulation Results

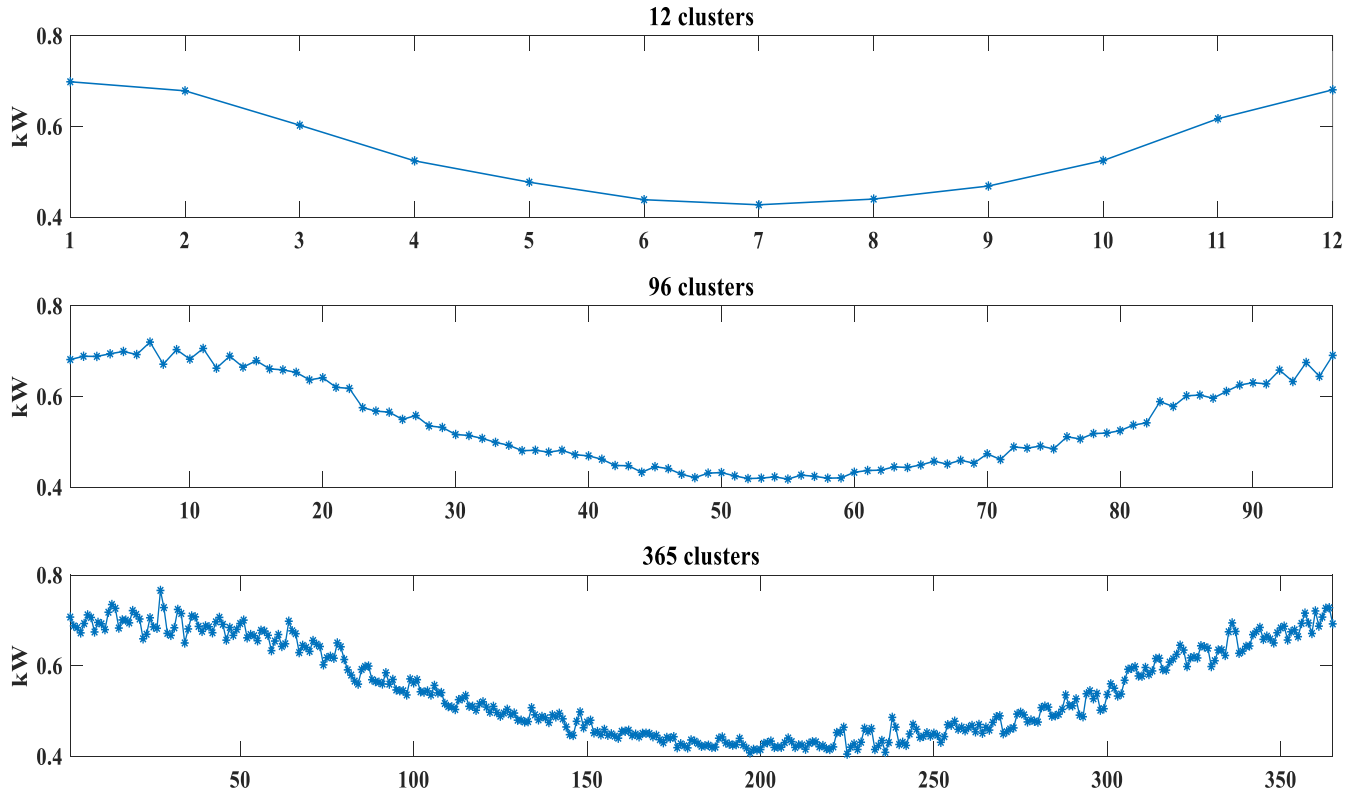
Checking the scalability

K-means++

Data clustering

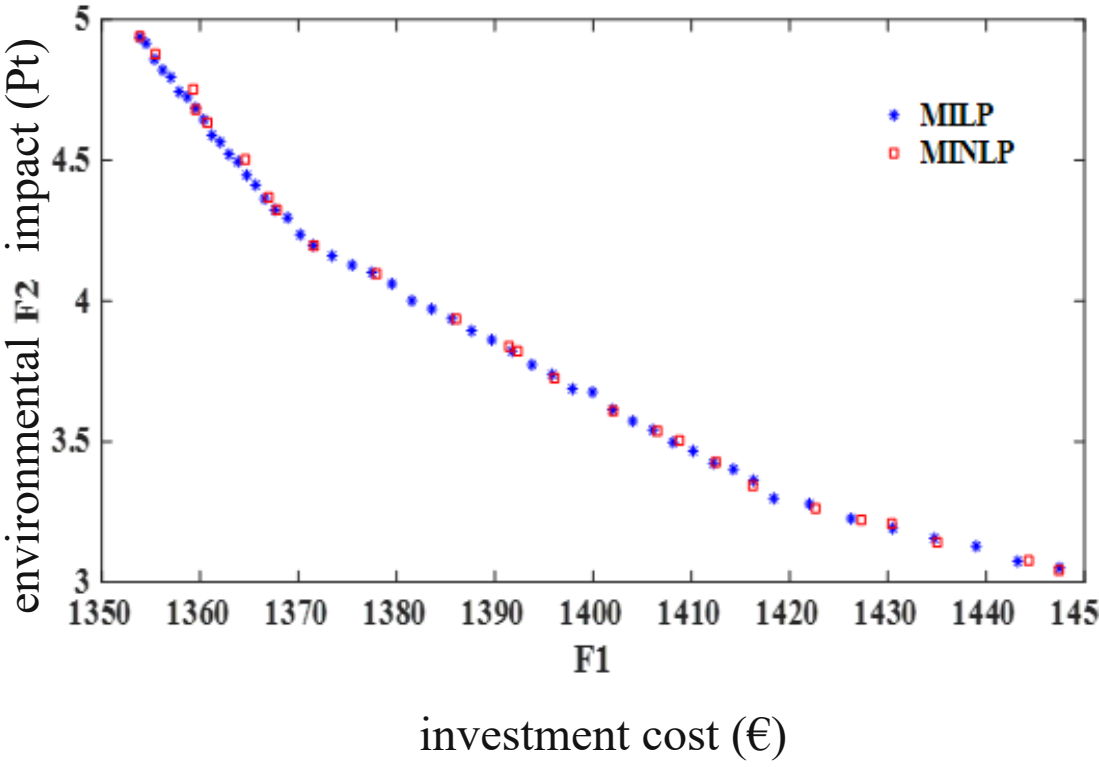


Electricity demand



Environmenal impacts and Pareto optima

(mPt/kWh)	CEI_b	CEI_B	CEI_{PV}	CEI_{ST}	CEI_{Hs}	CEI_{HP}
Climate change	15.401	0.00105	0.05434	0.29434	0.06604	0.17473
Ozone depletion	0.098	0.00001	0.00055	0.00221	0.00042	0.00255
Ionising radiation, HH	2.281	0.00004	0.00233	0.02578	0.00268	0.02268
Photochemical ozone formation	0.866	0.00026	0.00955	0.04054	0.01258	0.00904
Respiratory inorganics	2.853	0.00044	0.01714	0.09395	0.02901	0.02910
Non-cancer human health effects	1.680	0.00171	0.02824	0.20415	0.05461	0.01965
Cancer human health effects	2.973	0.00078	0.02561	0.54766	0.40580	0.03233
Acidification terrestrial and freshwater	3.932	0.00090	0.01737	0.12722	0.01584	0.04044
Eutrophication freshwater	7.476	0.00148	0.02254	0.20008	0.01965	0.07664
Eutrophication marine	0.473	0.00008	0.00266	0.01405	0.00288	0.00482
Eutrophication terrestrial	2.685	0.00015	0.00535	0.04387	0.00690	0.02688
Ecotoxicity freshwater	0.220	0.00019	0.00391	0.03086	0.01456	0.00249
Land use	0.210	0.00002	0.00080	0.00701	0.00389	0.00211
Water scarcity	0.688	0.00012	0.01549	0.02123	0.00597	0.00701
Resource use, energy carriers	12.331	0.00067	0.03218	0.19562	0.03659	1.02338
Resource use, mineral and metals	0.800	0.00367	0.10676	0.38264	0.04276	0.01406
Total	54.967	0.01157	0.34482	2.23122	0.720186	0.58790



Simulation results (sizing all devices)

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	Number of intervals	MINLP (reformulated)	MILP (McCormick)
Economic Objective F1 [€/year]	12	**1,060.14**	**1,060.14**
	365	**1,353.97**	**1,353.97**
	8760	-	1,431.74
Optimal BES size [kWh]	12	1.269	**1.269**
	365	0.812	**0.812**
	8760	-	**0.8011**
Optimal PV size [kWp]	12	5.052	**5.052**
	365	6.227	**6.227**
	8760	-	**6.235**
Optimal solar thermal collector size [kWp]	12	0.529	**0.529**
	365	0	**0**
	8760	-	**0**
Optimal heat storage tank size [kWh]	12	2.465	**2.465**
	365	0	**0**
	8760	-	**0**
Optimal heat pump size [kWh]	12	0.958	**0.958**
	365	1.365	**1.365**
	8760	-	**1.681**
Cost of buying electricity [€/year]	12	104.81	104.81
	365	366.87	366.87
	8760	-	366.77
Revenue for selling electricity [€/year]	12	74.603	74.603
	365	261.12	261.12
	8760	-	261.96
Total CPU time [Seconds]	12	**32.9**	**3.12**
	365	**5,695**	**1,058**
	8760	**-**	**29,612**

Conclusions

- We developed a new method for optimally sizing energy devices in an SSB
- Decision on the optimal size of energy devices **depends on the size of the dataset!**

  Intuitively, the larger the dataset is, the more accurate the decision will be
- Piecewise linearized model did not provide promising solutions
- McCormick-based model provided **high accuracy** results in **reasonable runtime**

  Therefore, **relaxation is tight** as illustrated by numerical results and 3D visualization
- We did not consider uncertainties but performed sensitivity analysis ☺

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Model predictive control-based energy management system in smart sustainable buildings

H. Nagpal, I. Avramidis, F. Capitanescu, P. Heiselberg, Optimal energy management in smart sustainable buildings–A chance-constrained model predictive control approach, Energy and Buildings 248, 111163, 2021.

WHY IS ENERGY MANAGEMENT NEEDED IN BUILDINGS?

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From Occupant's perspective

- Minimize the electricity bill
- Maintain the desired comfort level
- Finish the daily required tasks in a timely manner







From grid operator's perspective

- Use buildings as energy systems entities to manage power flow in the grid
- Reduce and shift power load consumption for congestion free operation of power grid



From a common perspective

- Improve energy efficiency of global energy sector
- Reduce the CO2 emission related to the building sector



MODEL PREDICTIVE CONTROL (MPC)

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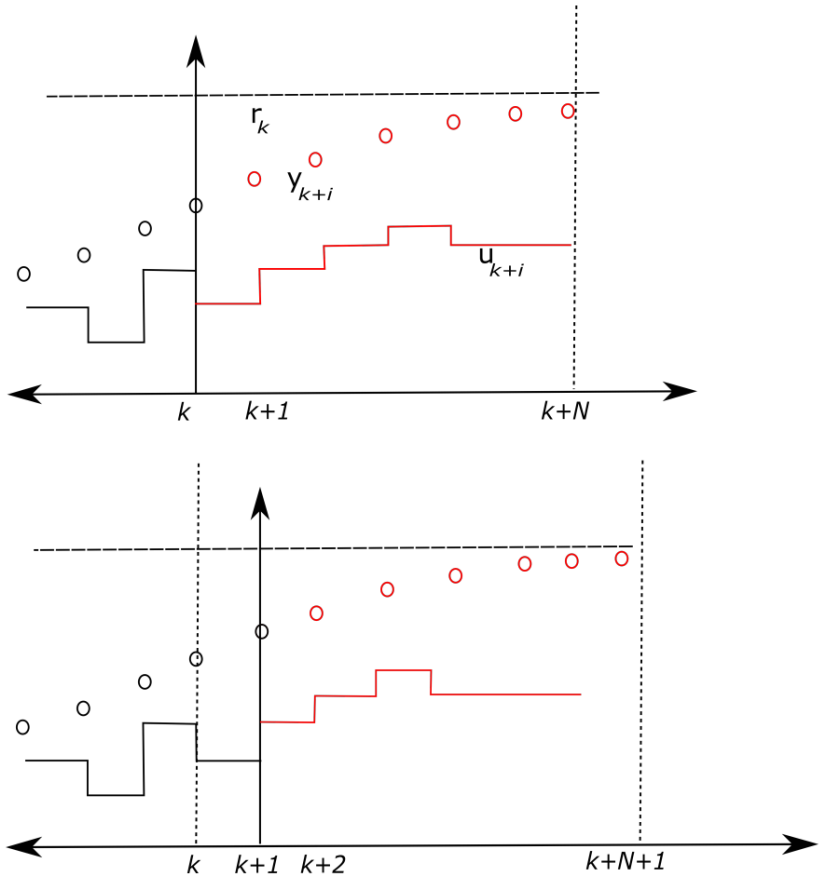
- Use the model of the process to predict the future evolution of the system and optimize the control signal

- At each time step k, solve an open-loop optimal control problem over a finite horizon N

$$\min_{u_i} J(x_{k+i}, u_{k+i})$$
$$g(x_{k+i}, u_{k+i}) \geq 0$$
$$x_{k+i+1} = h(x_{k+i}, u_{k+i}),\ i = 0,1,\dots N-1$$
$$y_{k+i} = f(x_{k+i}, u_{k+i})$$

- Apply the first control input u_0^* from the optimal control sequence to the system and discard the rest

- At time step $k+1$, repeat the procedure with updated values of the system states



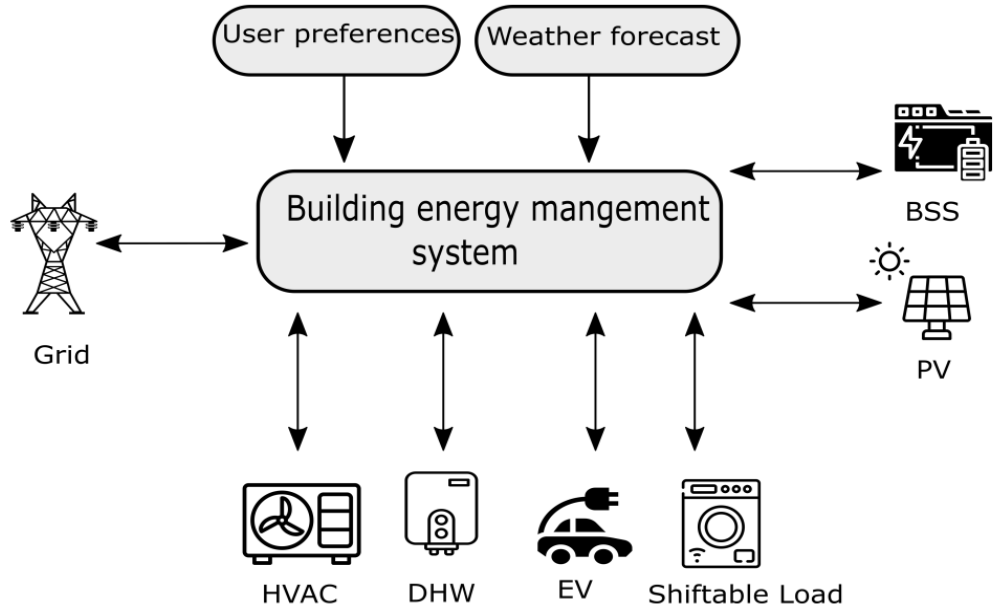
MPC strategy

NUMERICAL CASE STUDY

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Modelled Energy Devices

- Building model from literature
- Domestic hot water system
- Battery storage system
- Electric vehicle with V2G capabilities
- Shiftable appliances – washing machine, clothes dryer and dishwasher with different phases of operation
- Photovoltaic panel

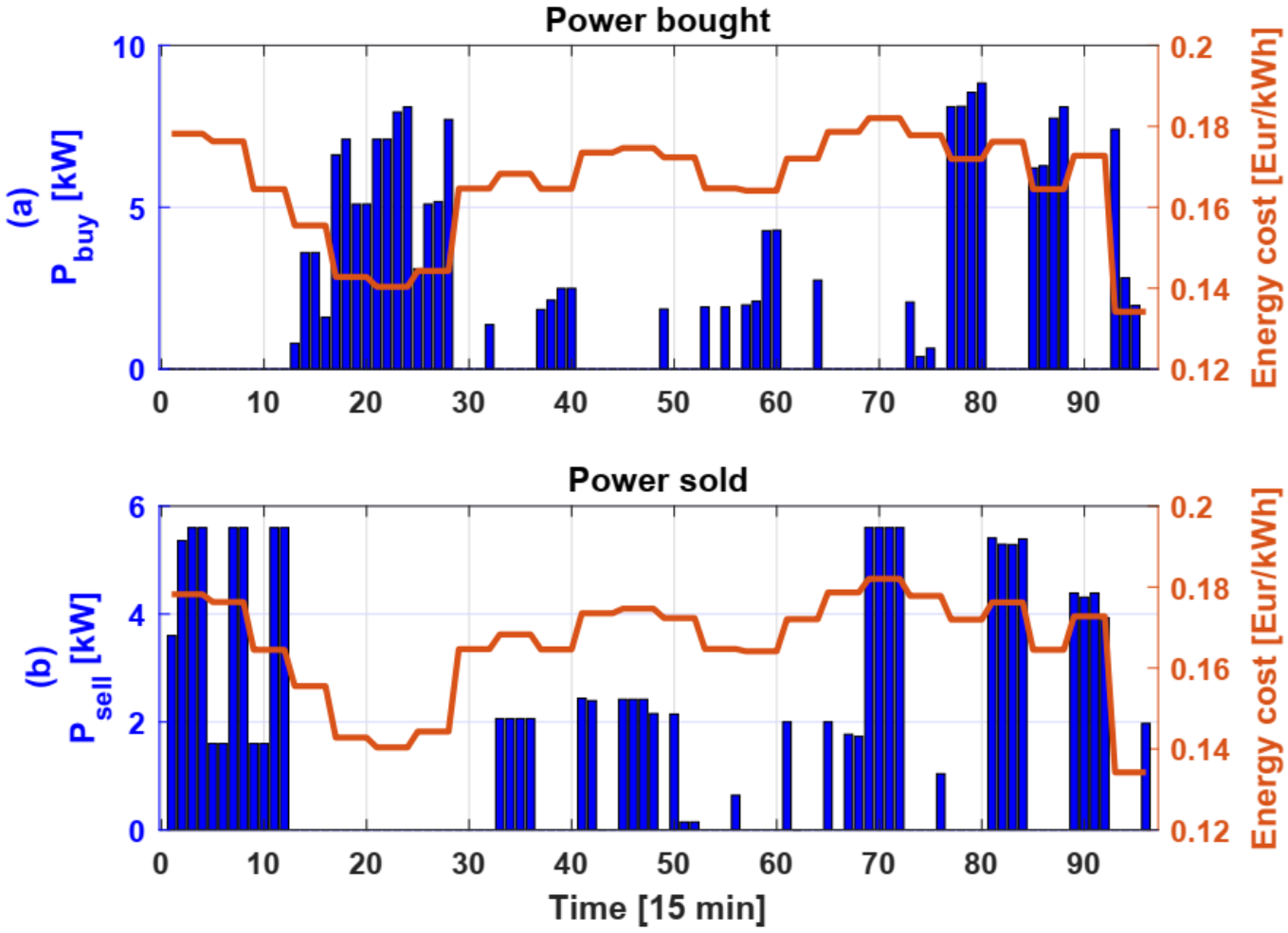


System architecture for energy management framework

- Simulations in Matlab with Gurobi optimizer with 15 min time step over 24 hours period with Luxembourg weather conditions

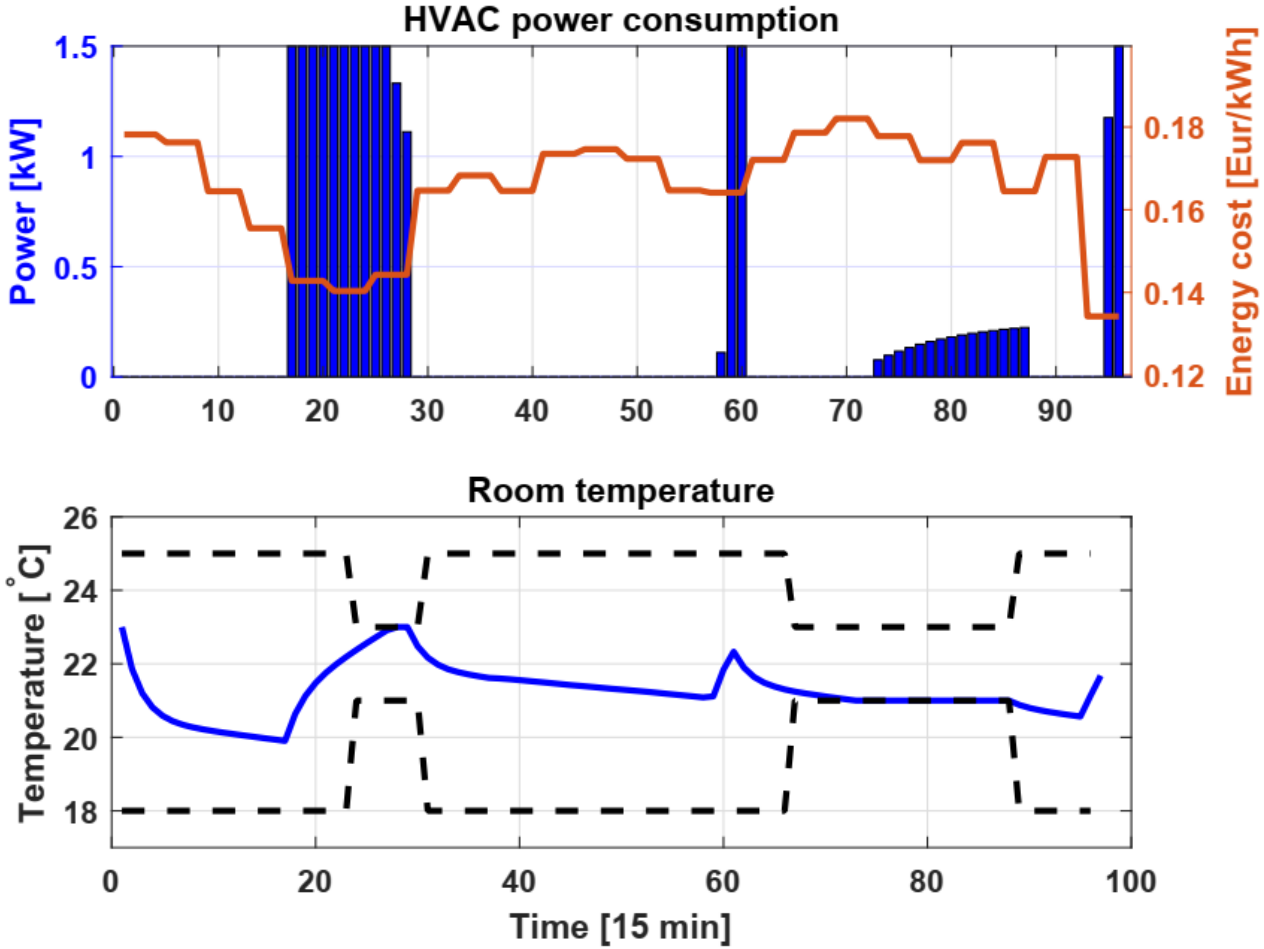
SIMULATION RESULTS

- ***Power exchange of the building with power grid***



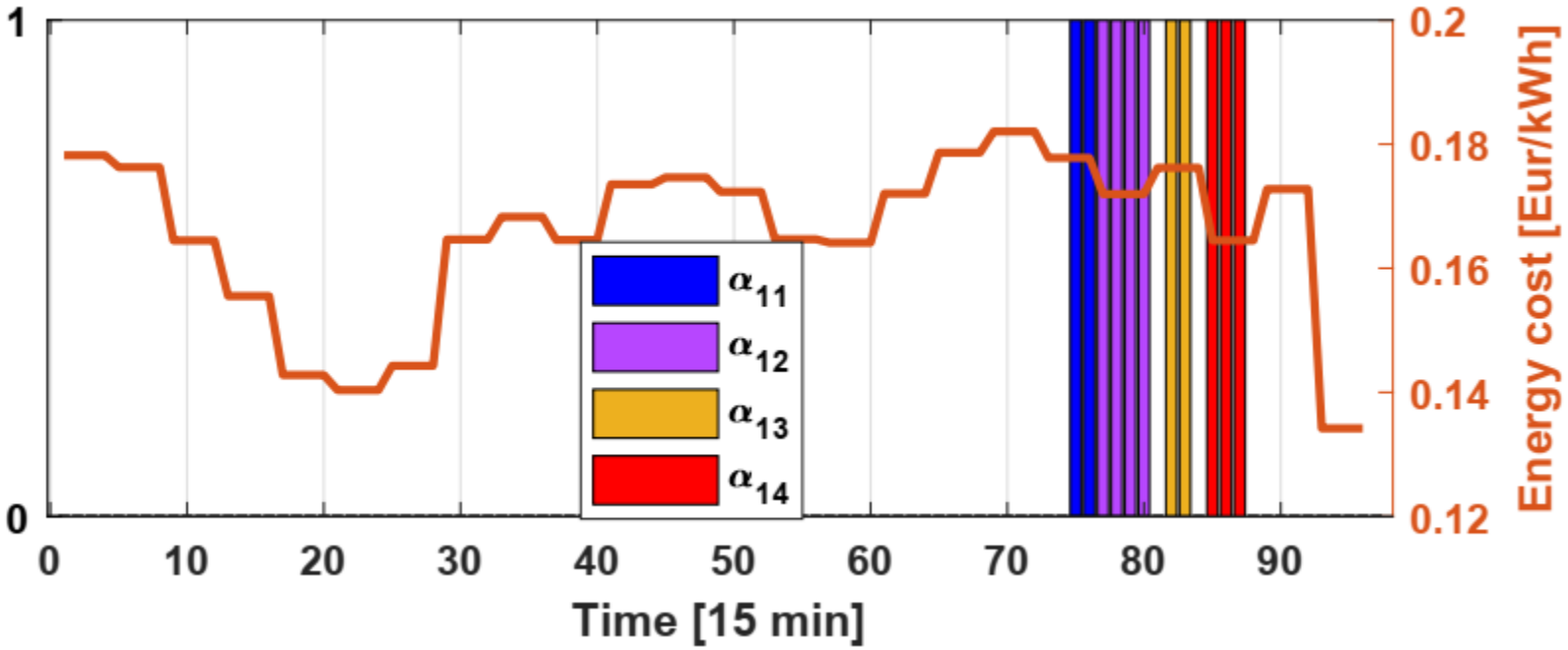
SIMULATION RESULTS

- *Thermal dynamics of the building*



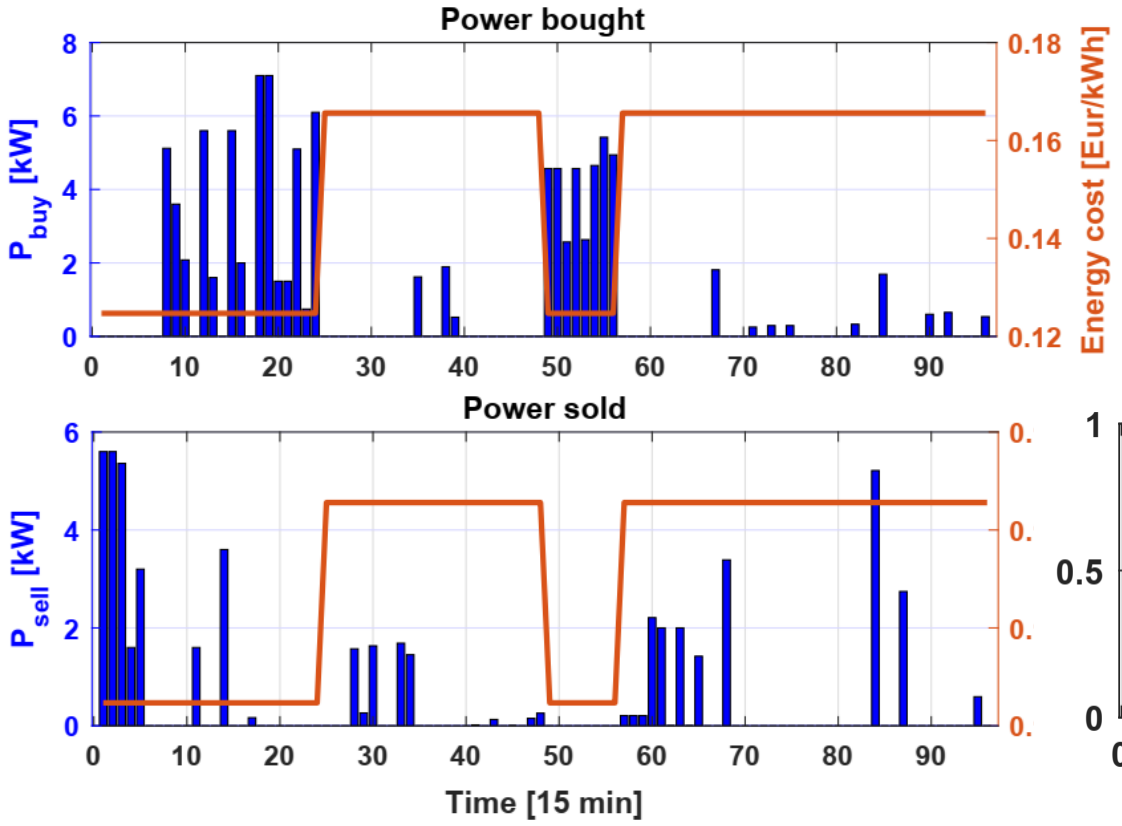
SIMULATION RESULTS

- ***Operation of different phases of washing machine***

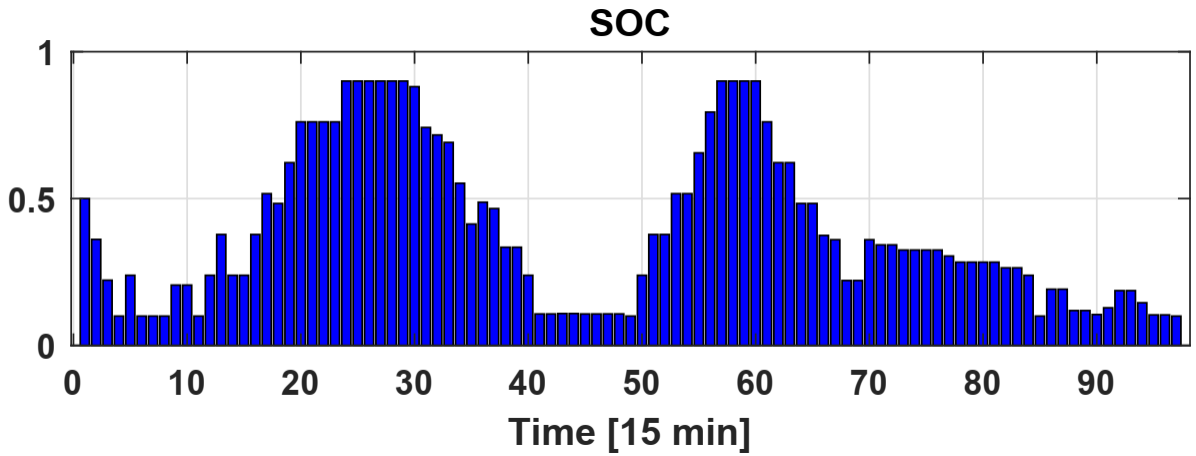


SIMULATION RESULTS

- ***Power exchange of the building with power grid with Time-of-Use pricing structure***



Time hours	Cost [€/kWh]
00:00-06:00 and 12:00-14:00	0.1247
Rest of the day	0.1656



CHALLENGES AND ONGOING WORK

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Challenges

- Require infrastructure to allow real-time bi-directional communication with power grid
- Modeling of energy devices and thermal dynamics of building is specific to the building
- Intrinsic uncertainties in the disturbance forecast can jeopardize the comfort of the occupants

Ongoing work

- Implement chance-constraint MPC to account for the uncertainties in disturbance forecast
- Take the sustainability of the building into consideration in optimization problem

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Shared energy storage in local energy communities: a hierarchical approach

H. Nagpal, I. Avramidis, F. Capitanescu, A. Madureira, Local energy communities in service of sustainability and grid flexibility provision: Hierarchical management of shared energy storage, IEEE Transactions on Sustainable Energy, 13(3), pp.1523-1535, 2022.

PROPOSED LEC LAYOUT

- BEMS in individual buildings
- On-site RES in individual buildings
- Shared community energy storage (CES)
- CEMS for the entire community

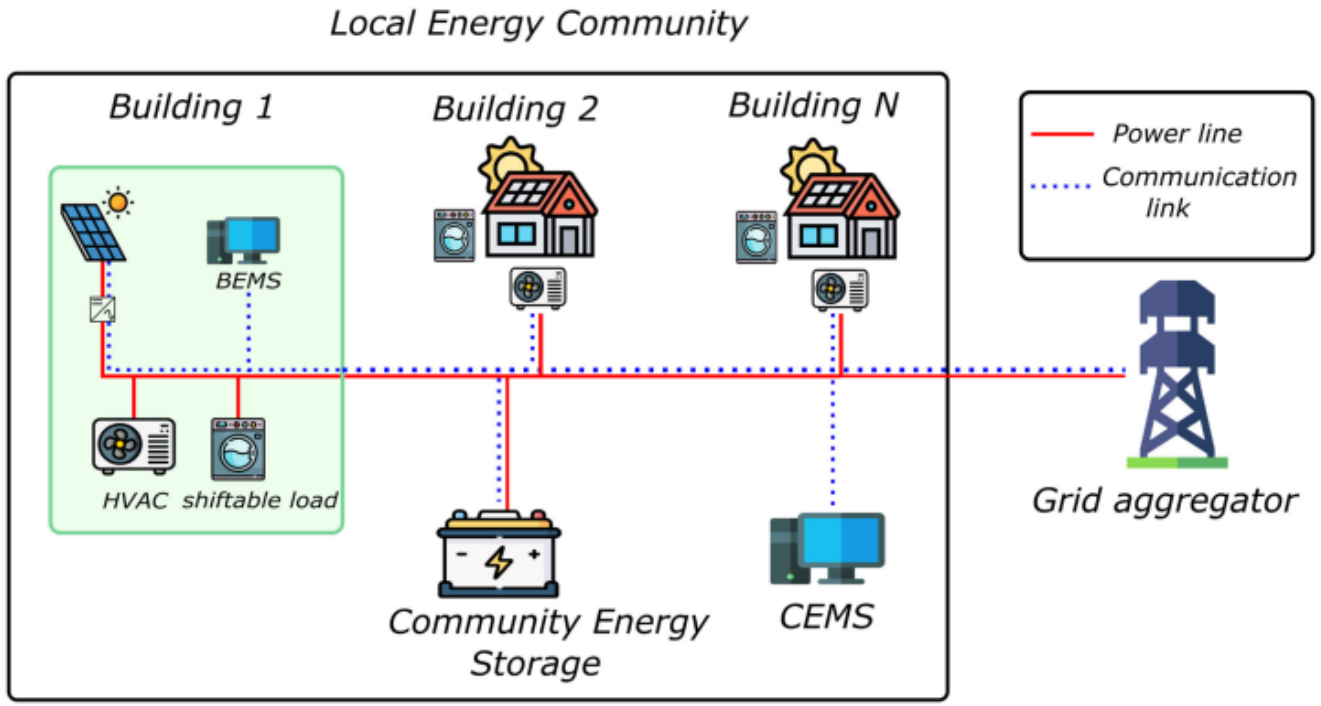


Fig: Schematic layout of the local energy community

H. Nagpal, I. Avramidis, F. Capitanescu, A. Madureira, Local energy communities in service of sustainability and grid flexibility provision: Hierarchical management of shared energy storage, IEEE Transactions on Sustainable Energy, 13(3), pp.1523-1535, 2022.

TWO-STAGE HIERARCHICAL MPC APPROACH

- **Individual building optimization**
  - Cost minimization
  - Dispatch optimized power profile
- **Community optimization**
  - SS + SC maximization assisted by CES
  - Ensure individual optimized cost is not jeopardized.

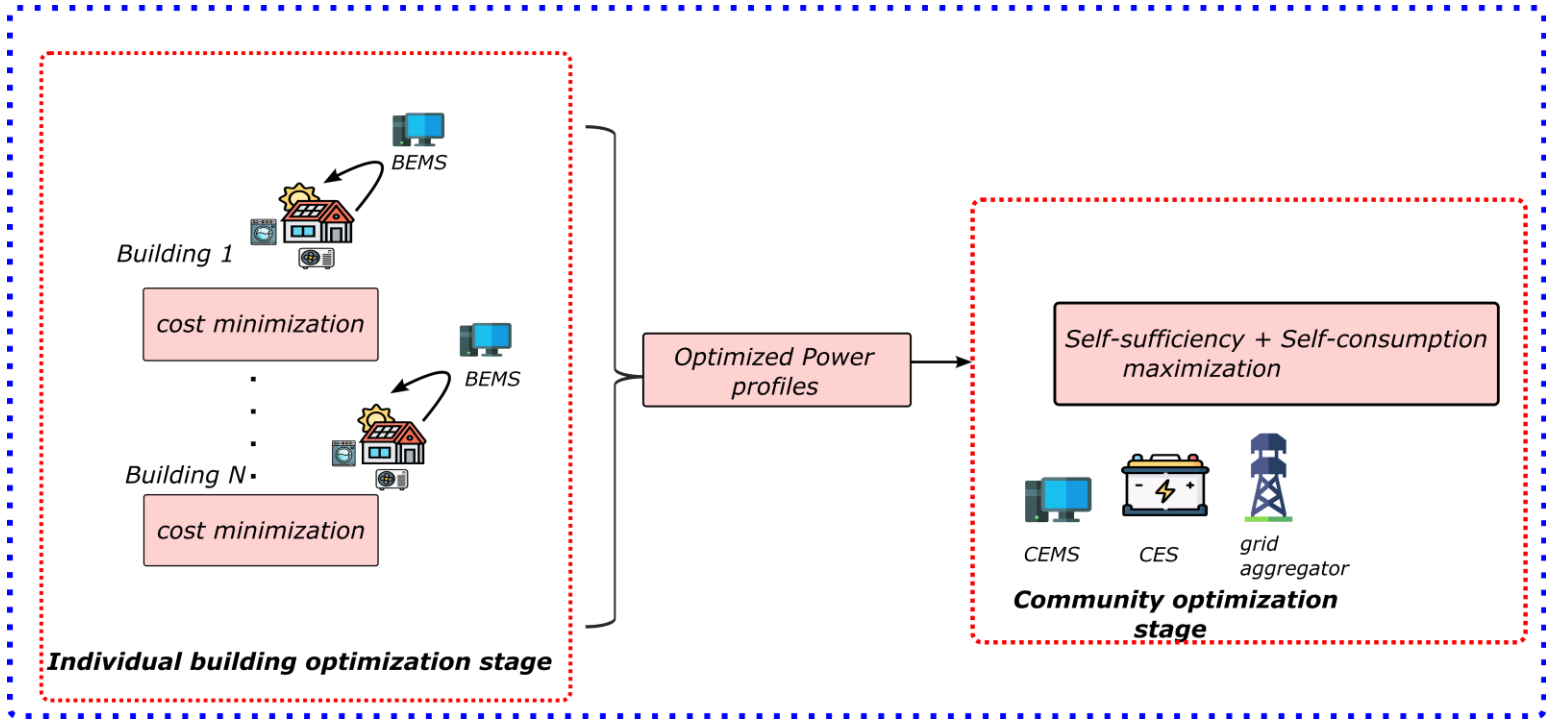


Fig: Schematic representation of Two-stage Hierarchical MPC approach

SERVICE 2: SHARING CES WITH THE GRID

- CES capacity can be shared with the grid for temporary usage.
- The community users can be fairly renumerated based on the shared capacity.

$$C_{\mathrm{f}}(E_{\mathrm{CES}}) = \psi_0 + \psi_1 \times (E_{\mathrm{CES}}) \quad \psi_0, \psi_1 > 0$$

Total service cost

Increased cost due to renting CES

Mutually agreed cost per kWh of CES capacity

Rented CES capacity

NUMERICAL SIMULATION AND RESULTS

- Three building archetypes: Office building, Health care facility, and residential building

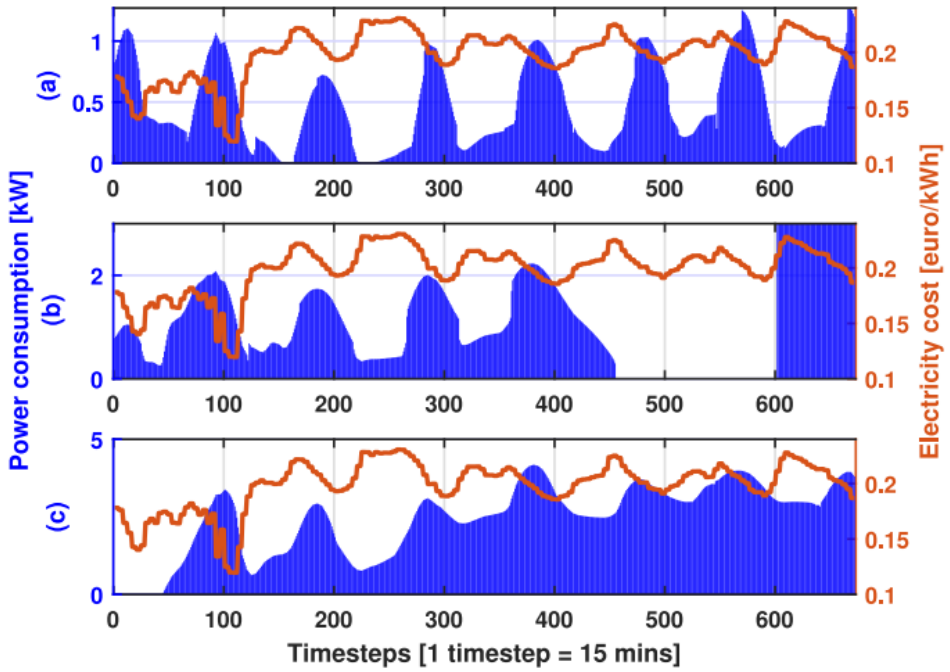


Fig: Stage 1 – HVAC system power consumption for (a) residential building (b) office building (c) health-care facility

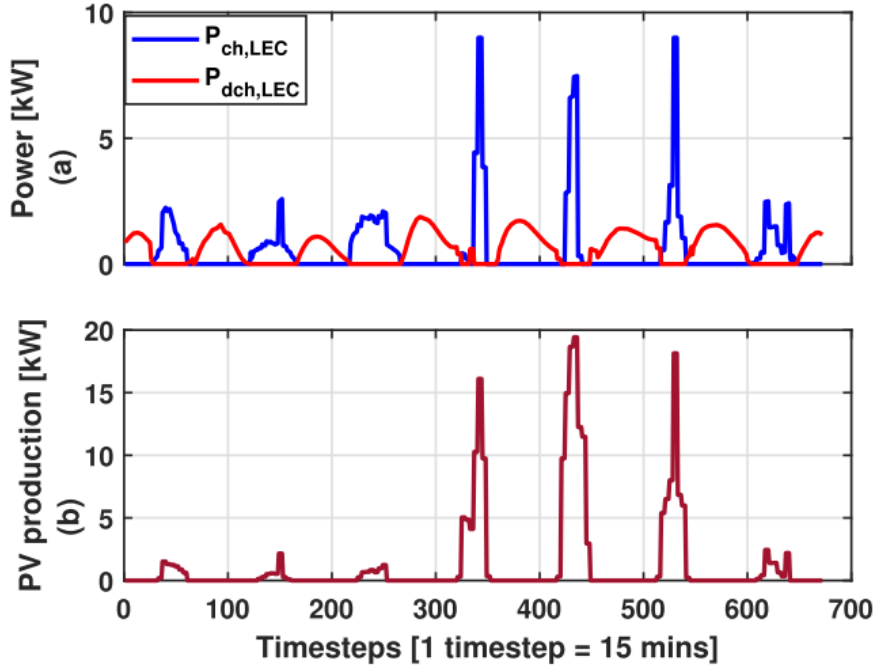


Fig: Stage 2 – (a) Power dynamics of CES (b) Community PV production

NUMERICAL SIMULATION AND RESULTS

- **Service 2: Sharing CES capacity**

Table: Total cost for LEC operation + Total cost to the grid operator for renting CES capacity

Procured capacity	LEC operation cost	Aggregator	
		Base cost (ψ_0)	Total cost (C_f)
0%	453.78	0	0
25%	483.98	30.2	31.71
50%	490.7	36.92	39.94
75%	594.13	140.35	144.89
100%	776.58	322.8	328.85

NUMERICAL SIMULATION AND RESULTS

- Centralized vs Decentralized approach

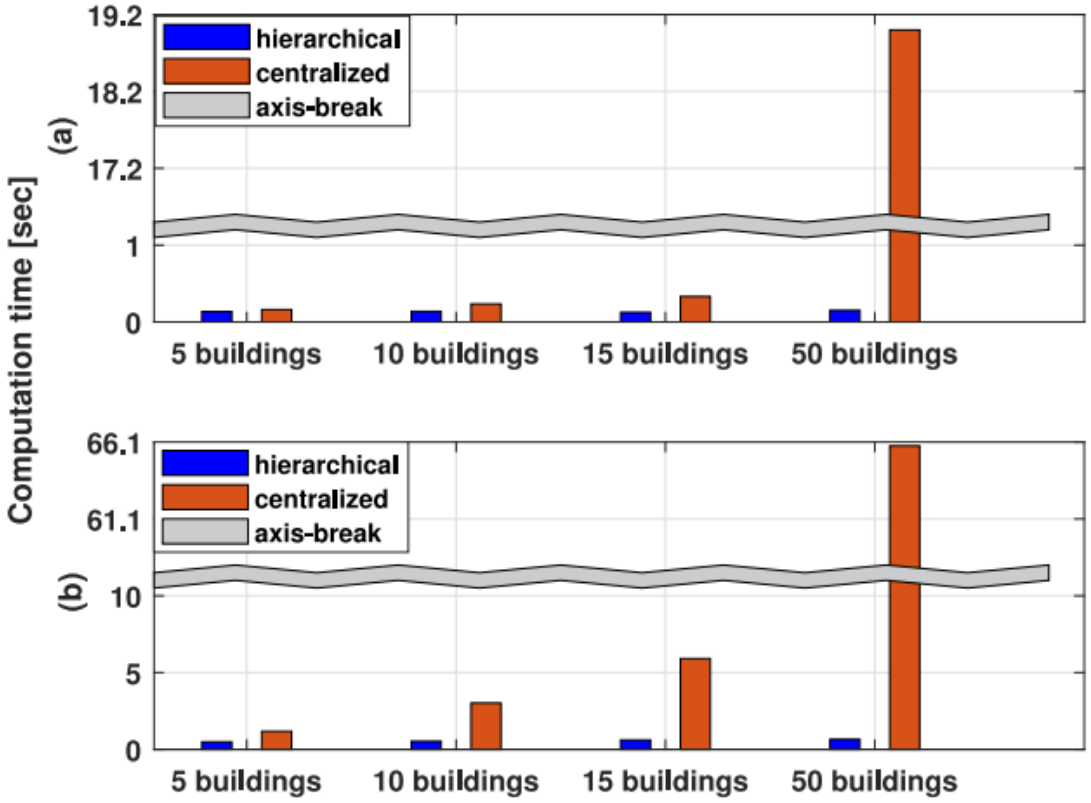


Fig: Computational time comparison for centralized vs decentralized approach

CONCLUSIONS

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- LECs initiatives promotes the transition towards a low-carbon energy system.
- LECs offers economic, environmental, and social benefits to its members, and additionally, support grid operation via flexibility services.
- The decentralized energy management approach computationally outperforms centralized approach for slight increase in energy cost.
- The proposed decentralized approach inherently preserves the end-users privacy since they only share their aggregated load profile.

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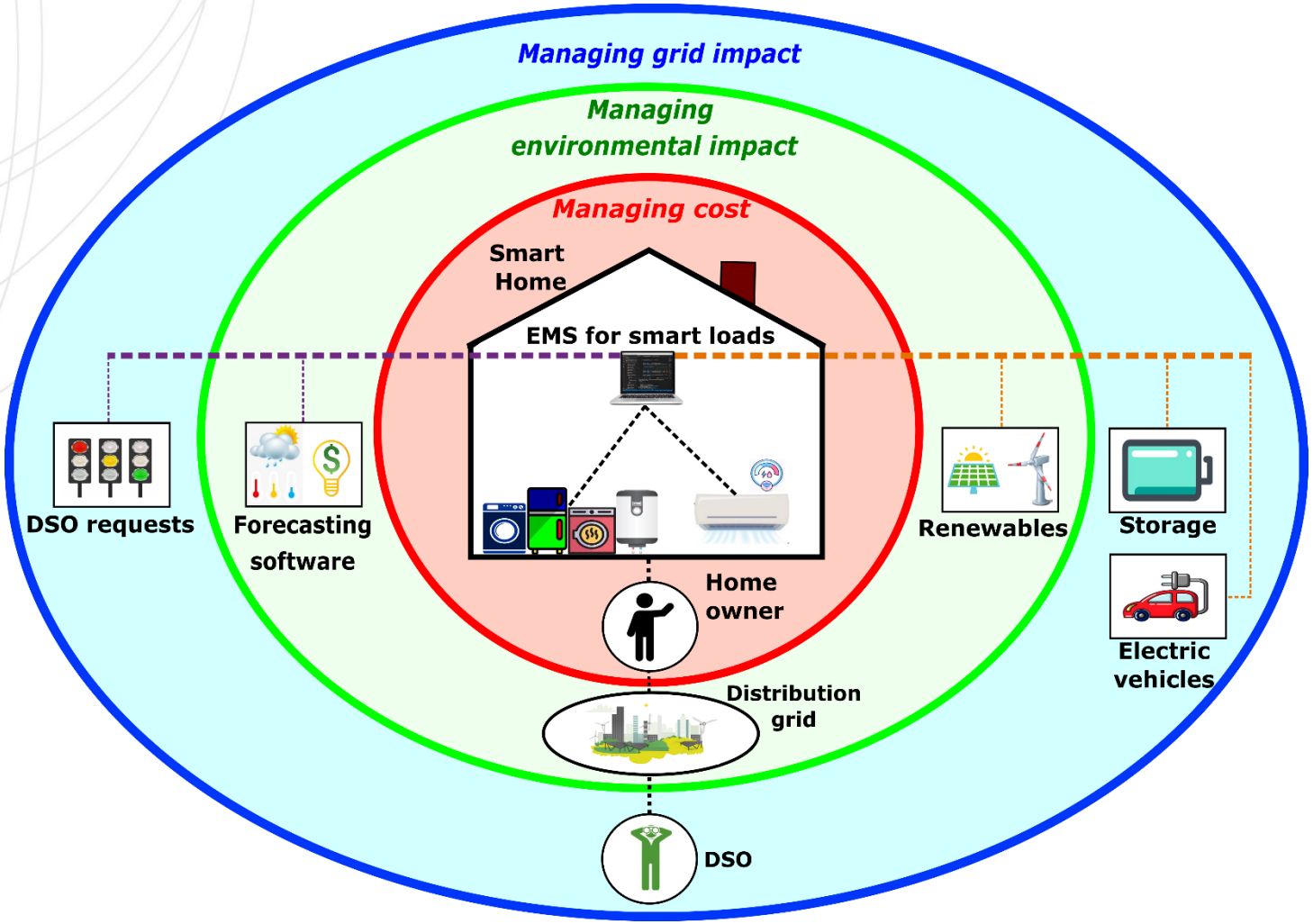
Bottom-up and Top-down Approaches for Integrating Smart Sustainable Buildings into Low Voltage Networks

I. Avramidis, F. Capitanescu, G. Deconinck, From Smart to Sustainable to Grid-Friendly: A Generic Planning Framework for Enabling the Transition between Smart Home Archetypes, IEEE Transactions on Sustainable Energy, 12(3), pp. 1684-1694, 2021.

I. Avramidis, F. Capitanescu, G. Deconinck, A Comprehensive Multi-Period Optimal Power Flow Framework for Smart LV Networks, IEEE Transactions on Power Systems, 36(4), pp.3029-3041, 2021.

I. Avramidis, F. Capitanescu, V. Evangelopoulos, P. Georgilakis, G. Deconinck, In pursuit of new real-time ancillary services providers: Hidden opportunities in low voltage networks and sustainable buildings, IEEE Transactions on Smart Grid, 13 (1), pp. 429-442, 2022.

THE BOTTOM-UP APPROACH



THE NEED FOR DISTINCT BUILDING ARCHETYPES

Smart building (SB)

$$\max F_1 = \sum_{t \in \mathcal{T}} (P^{\mathrm{E}}_{\mathrm{d,t}} \cdot p^{\mathrm{fit}}_{\mathrm{d,t}} - P^{\mathrm{I}}_{\mathrm{d,t}} \cdot p^{\mathrm{el}}_{\mathrm{d,t}})$$

Objective: Maximize profit

Smart sustainable building (SSB)

$$\sum_{z=1}^{d-1} E_{\mathrm{z}} + E_{\mathrm{d}} + E_{[(\mathrm{d+1}) \text{ to } 365]} \leq E^{\mathrm{nZE}}$$

Adjustable energy constraint

Grid-friendly SSB (GF-SSB)

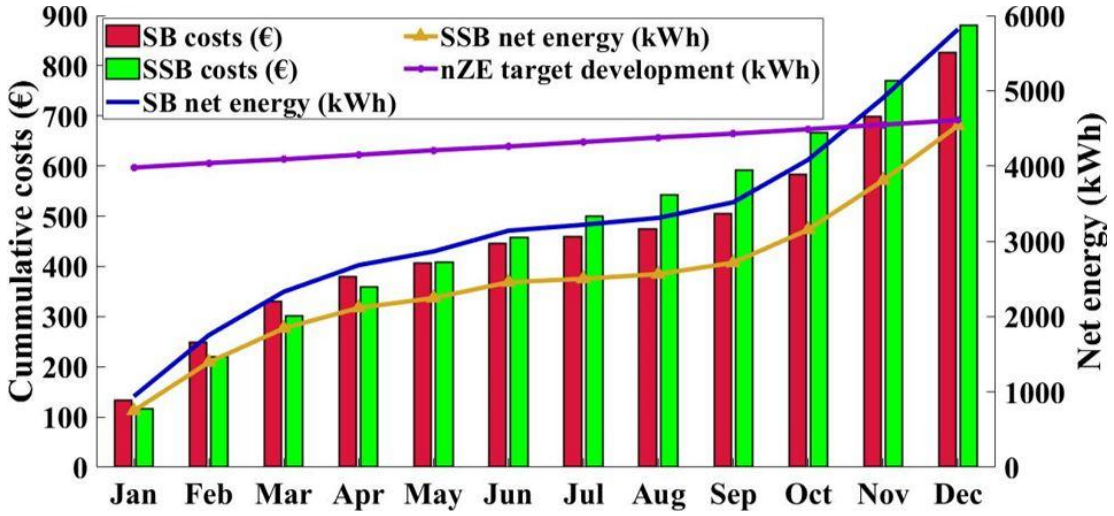
$$E_{\mathrm{d}}^{\text{re-adjusted}} \leq E_{\mathrm{d}}^{\text{original}}$$

$$F_1 \leq F_1^{\text{optimal}} \cdot [1 + \mathrm{sign}(F_1^{\text{optimal}}) \cdot \epsilon)]$$

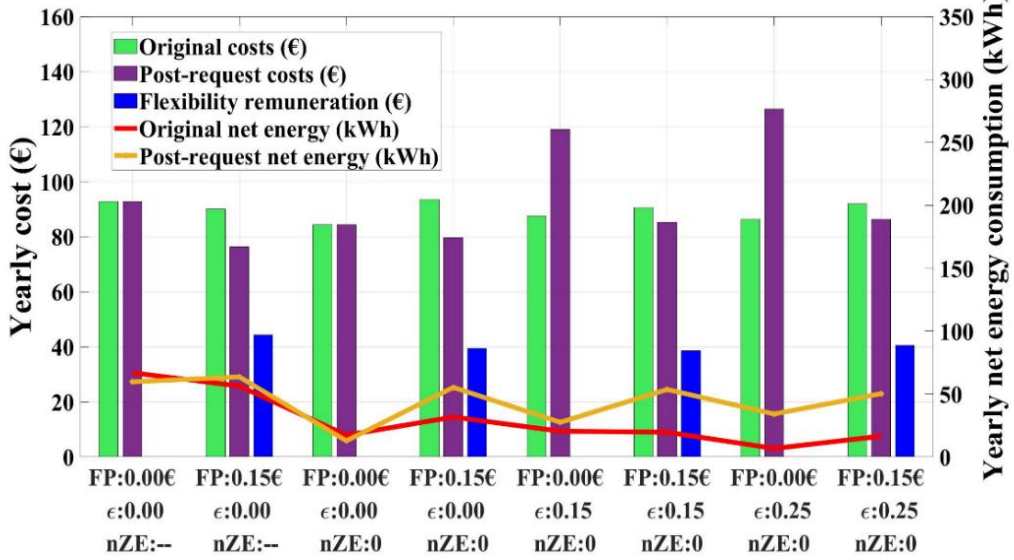
Energy-neutral re-adjustment

Financially-constrained re-adjustment

THE NEED FOR DISTINCT BUILDING ARCHETYPES



Smartness and sustainability are conflicting



Sustainability and grid-friendliness are conflicting

BOTTOM-UP VS TOP-DOWN INTEGRATION

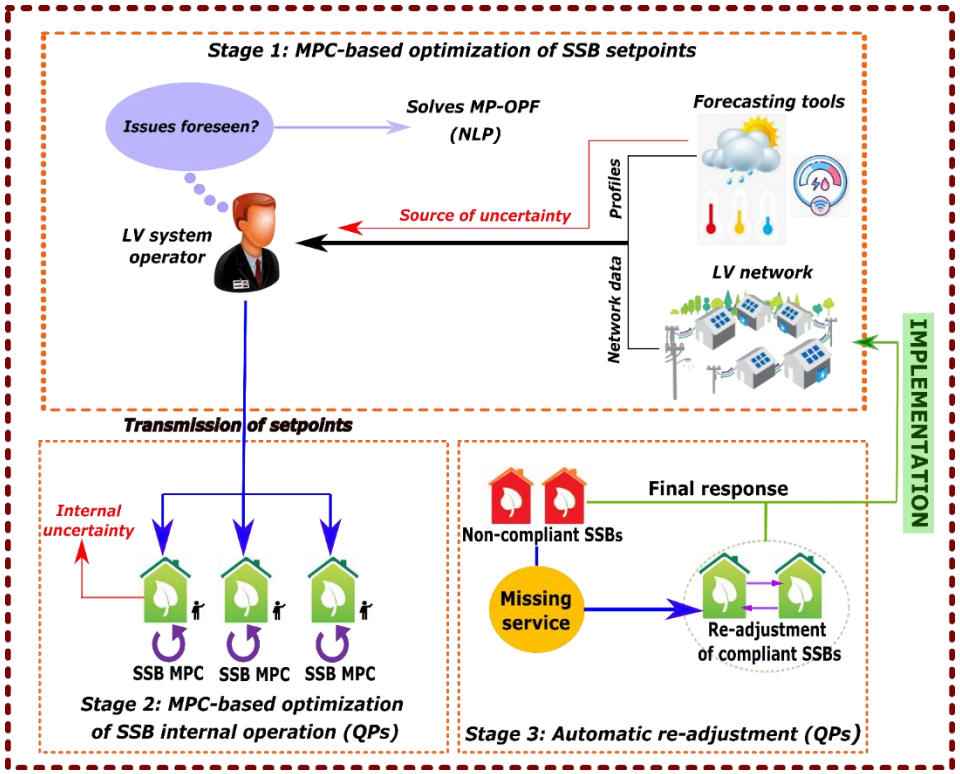
Bottom-up	Top-down
Non-intrusive/restrictive	High degrees of optimality
Flexible/easily customizable	Grid-compliant
User-friendly	Superior overview & control
Fully end-user-dependent	Too much operator authority
Unreliable for the grid	Highly intrusive/restrictive
Model-sensitive	Technical requirements

BOTTOM-UP VS TOP-DOWN INTEGRATION

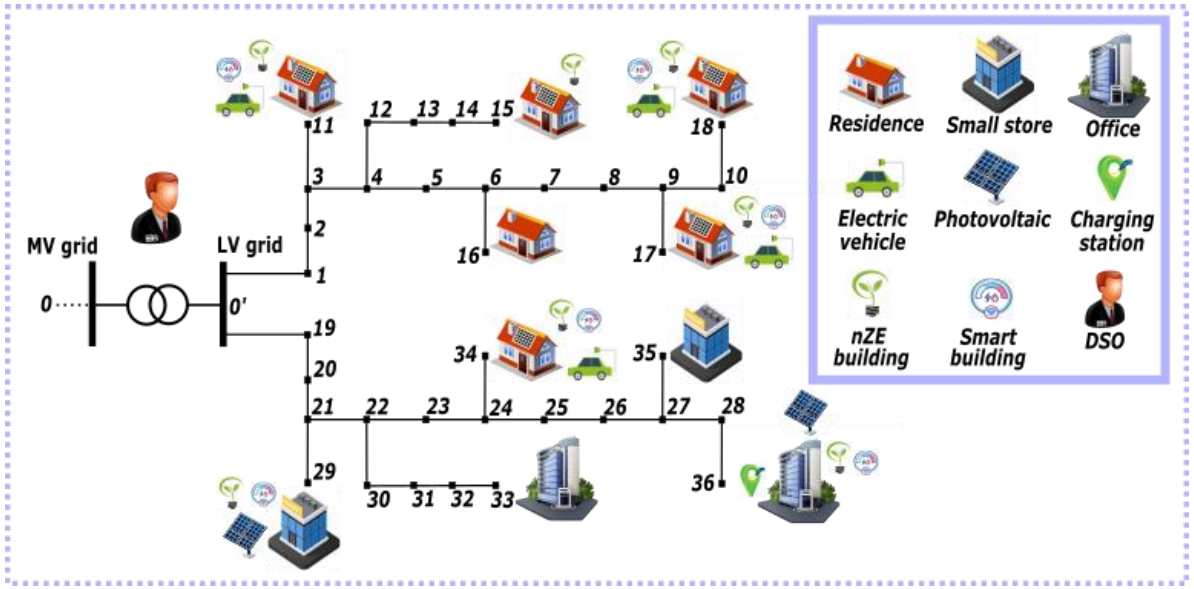
Bottom-up	Top-down
Non-intrusive/restrictive	High degrees of optimality
Flexible/easily customizable	Grid-compliant
Unreliable for the grid	Highly intrusive/restrictive
Model-sensitive	Technical requirements

Idea: Hybrid approach that balances pros and cons.

THE (ACADEMIC) CONCEPT OF HYBRID INTEGRATION



CASE STUDY: REAL-TIME MANAGEMENT



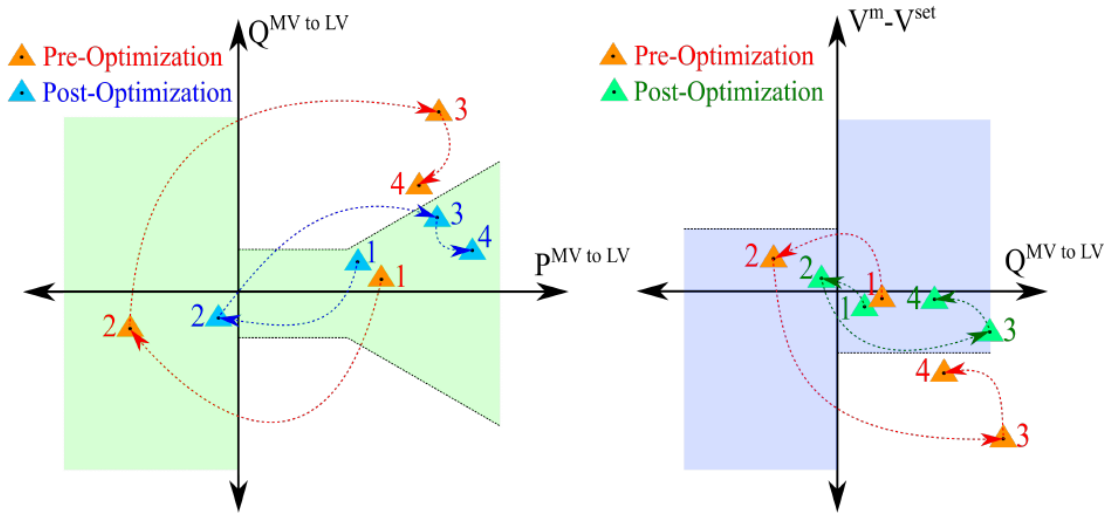


Fig. 6: Performance of ancillary schemes in characteristic hours (left-passive, right-active)

CASE STUDY: REAL-TIME MANAGEMENT

TABLE III: Daily network costs (24 hours, 6-hour horizon)

	MINLP		MILP		Original
	w/o Stage 3	w. Stage 3	w/o Stage 3	w. Stage 3	
Violation costs (€)	17.2	0.7	17.1	0.7	175
Passive penalties (€)	12.4	0	12.5	0	47.2
Active penalties (€)	-18.3	-56.1	-17.6	-55.06	32.6
Request costs (€)	82.5	39.3	83.9	39.7	–
Total solution time* **(s)**	20,102.6	20,318.9	984.2	1,193.7	–

*Refers to (stage 1 + stage 2 + stage 3) summed over all 96 iterations

TABLE VIII: Performance for various request failure probabilities (MILP formulation, 24 hours, 6-hour horizon)

Probability of request failure (%)	**Total failures recorded (-)**	**Cost increase-passive scheme (%)**	**Cost increase-active scheme (%)**
0	0	0 (benchmark)	0 (benchmark)
1	3	0.00	0.01
2	10	0.05	0.03
5	23	0.19	0.26
10	54	0.68	0.87