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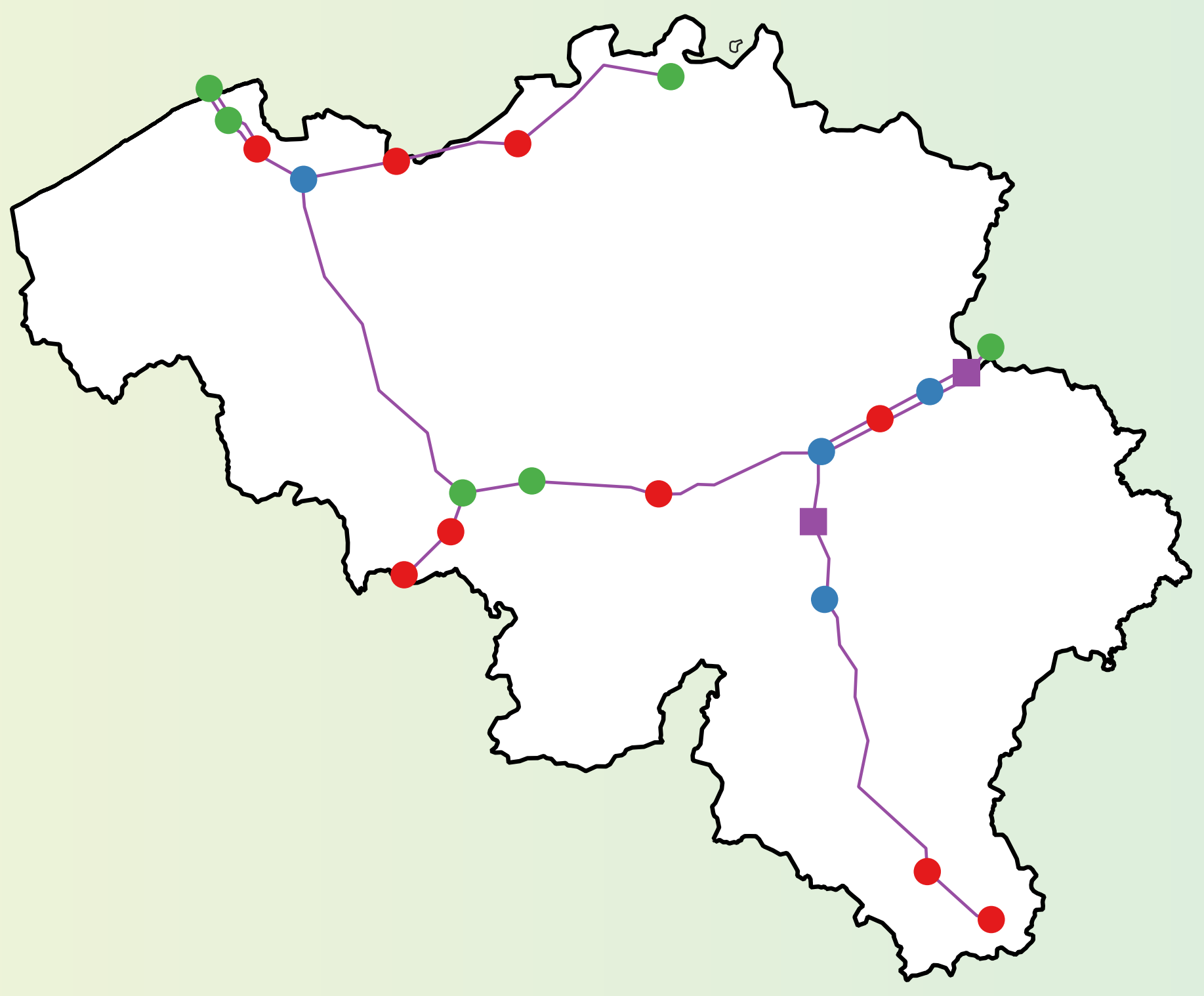
Optimizing energy networks with dynamic gas flow models: An efficient solution procedure



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1 Introduction

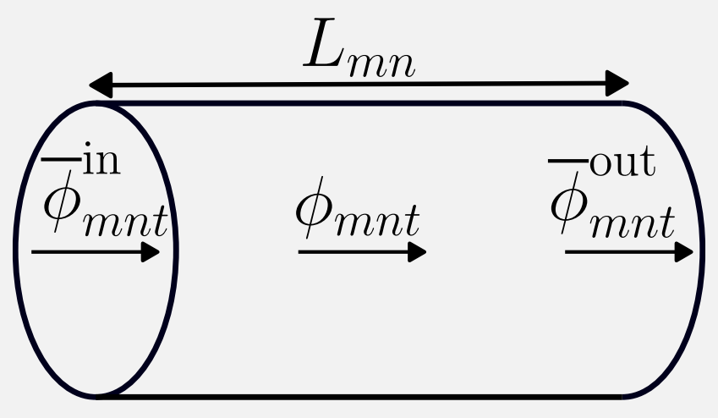
Gas flow modeling is key to gas network optimizations, e.g., economic dispatch of hydrogen (Zheng *et al.*, *CSEE J Power Energy Syst*, 2022) and expansion planning of natural gas networks (Borraz-Sánchez *et al.*, *INFORMS J Comput*, 2016). However, the equations governing gas flow dynamics are **computationally challenging** for optimization on an annual horizon. Hence, we propose a procedure that combines **gas flow models** according to **pipe properties** and **accuracy requirement** for efficiently solving optimizations with gas flow dynamics.

2 Gas Flow Models

Gas network optimization takes the general form

$$\min_{x} f(x) \quad \text{s.t. } g(x) \leq 0, \tag{1}$$

where $g(x)$ includes gas flow constraints, detailed below for pipe mn (Correa-Posada *et al.*, *IEEE Trans Power Syst*, 2015).



Momentum equation (Weymouth equation):

$$\phi^2_{mnt} = K^{\phi}_{mn}(p^2_{mt} - p^2_{nt}) \tag{2}$$

Continuity equation (Linepack relation):

$$\begin{aligned} l_{mnt} - l_{mn(t-1)} &= \Delta t\left(\phi^{\text{in}}_{mnt} - \phi^{\text{out}}_{mnt}\right) \\ l_{mnt} &= K^{l}_{mn}(p_{mt} + p_{nt}) \\ \phi_{mnt} &= \frac{1}{2}\left(\phi^{\text{in}}_{mnt} + \phi^{\text{out}}_{mnt}\right) \end{aligned} \tag{3}$$

Technical limits on mass flow and pressure:

$$\phi^{\text{in}}_{mnt} \leq \overline{\phi}^{\text{cs}}_{mn}, \phi^{\text{out}}_{mnt} \leq \overline{\phi}^{\text{cs}}_{mn} \tag{4}$$

$$\underline{p}_{mn} \leq p_{mt} \leq \overline{p}_{mn}, \ \underline{p}_{mn} \leq p_{nt} \leq \overline{p}_{mn} \tag{5}$$

SOC dynamic (second-order cone relaxation):

The nonconvex Eq. (2) is relaxed to second-order cone (SOC) and linear constraints:

$$\left\| \begin{matrix} \phi_{mnt} \\ \sqrt{K^{\phi}_{mn}} p_{nt} \end{matrix} \right\|_2 \leq \sqrt{K^{\phi}_{mn}} p_{mt}, \tag{6}$$

$$Linearize\left[p^2_{mt} - p^2_{nt} - \phi^2_{mnt}/K^{\phi}_{mn}\right] \leq \gamma_{mnt}.$$

To tighten the relaxation, we augment the objective function with penalty terms as $f(x) + \sum \tau \, \gamma_{mnt}$.

SOC static (static approximation):

For pipes with small volume, i.e., small K^{l}_{mn}, Eq. (3) simplifies to

$$\phi_{mnt} = \phi^{\text{in}}_{mnt} = \phi^{\text{out}}_{mnt}. \tag{7}$$

Linear static (linear approximation):

For short pipes, i.e., large K^{ϕ}_{mn}, Eq. (2) simplifies to

$$\begin{aligned} p_{mt} &= p_{nt}, \\ \phi_{mnt} &\leq K^{\phi}_{mn}\left(\overline{p}^2_{mn} - \underline{p}^2_{mn}\right). \end{aligned} \tag{8}$$

Summary of gas flow models and their complexity factors

Model	Constraints	Time-linking	Nonlinear	Mixed-integer*
SOC dynamic	(3,4,5,6)	×	×	×†
SOC static	(4,5,6,7)		×	×
Linear static	(4,5,7,8)			

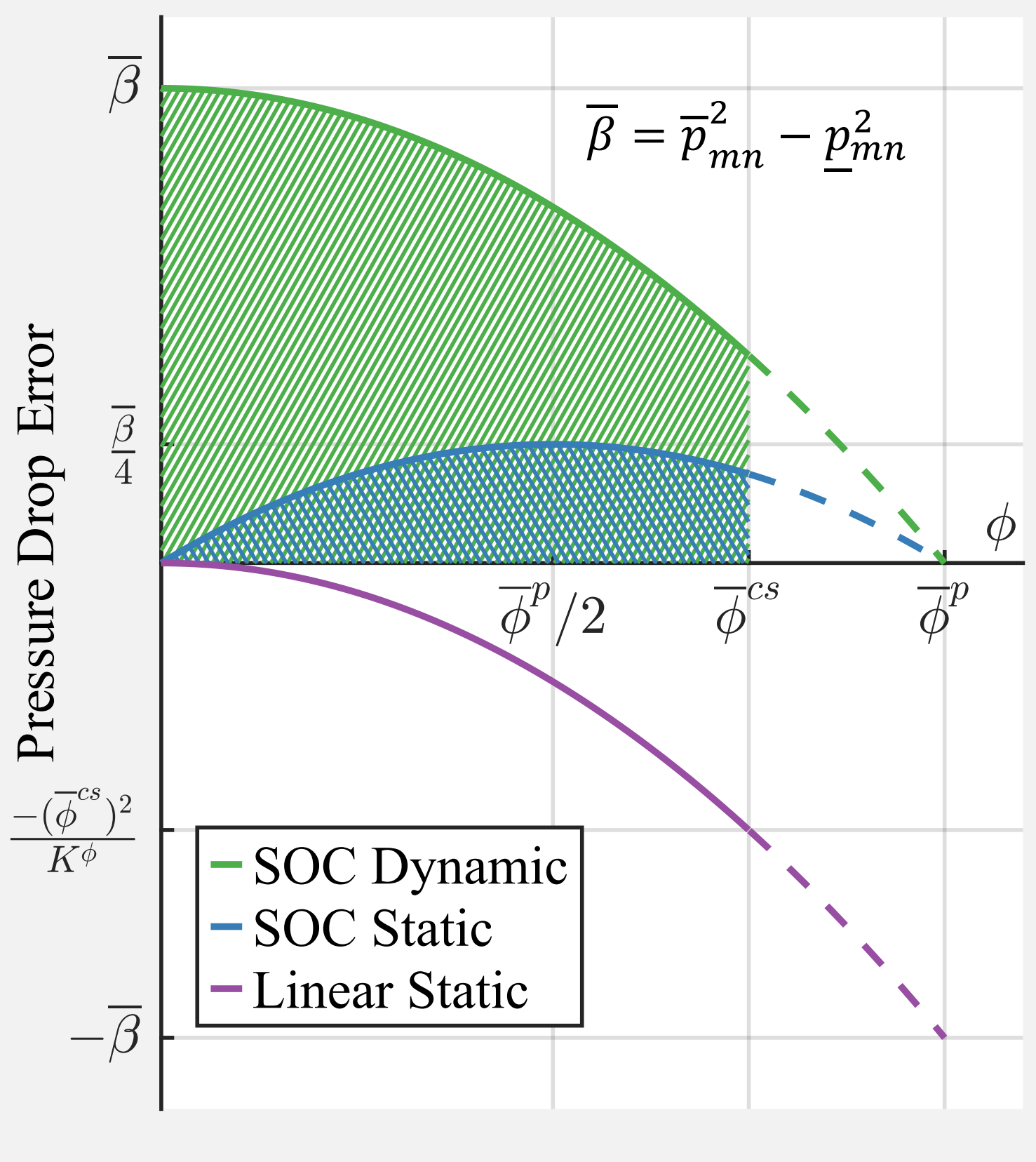
*Integer variables model flow directions in bidirectional pipes.
†Integer variables are fixed in the proposed solution procedure.

3 Accuracy Metrics

Pressure drop error, $p^2_{mt} - p^2_{nt} - \phi^2_{mnt}/K^{\phi}_{mn}$, measures the deviation from Eq. (2). The error of the SOC models lies in the hatched areas and is typically close to zero due to the penalty terms. But the error of the linear static model grows with mass flow, up to $\left(\overline{\phi}^{\text{cs}}_{mn}\right)^2/K^{\phi}_{mn}$.

Gas supply cost can be optimized by leveraging the linepack flexibility of pipes, which acts as network storage. Static models do not capture linepack flexibility in Eq. (3), and, therefore, may yield suboptimal solutions.

Accuracy metric	Dimension	Object of assessment
Pressure drop error	Static accuracy	SOC relaxation of (2) to (6) Linear approximation of (2) to (8)
Gas supply cost	Dynamic accuracy	Static approximation of (3) to (7)



4 Solution Procedure

1. Aggregate parallel and series pipes, while preserving total linepack and flow relations

2. Classify network pipes based on a prespecified tolerance for pressure drop error

3. Solve the optimization, Eq. (1), using the linear static and SOC static models

4. Using the static solution, fix the flow directions and set the linearization point in Eq. (6) and the penalty coefficient τ

5. Solve the optimization, Eq. (1), using the linear static and SOC dynamic models

4 Results

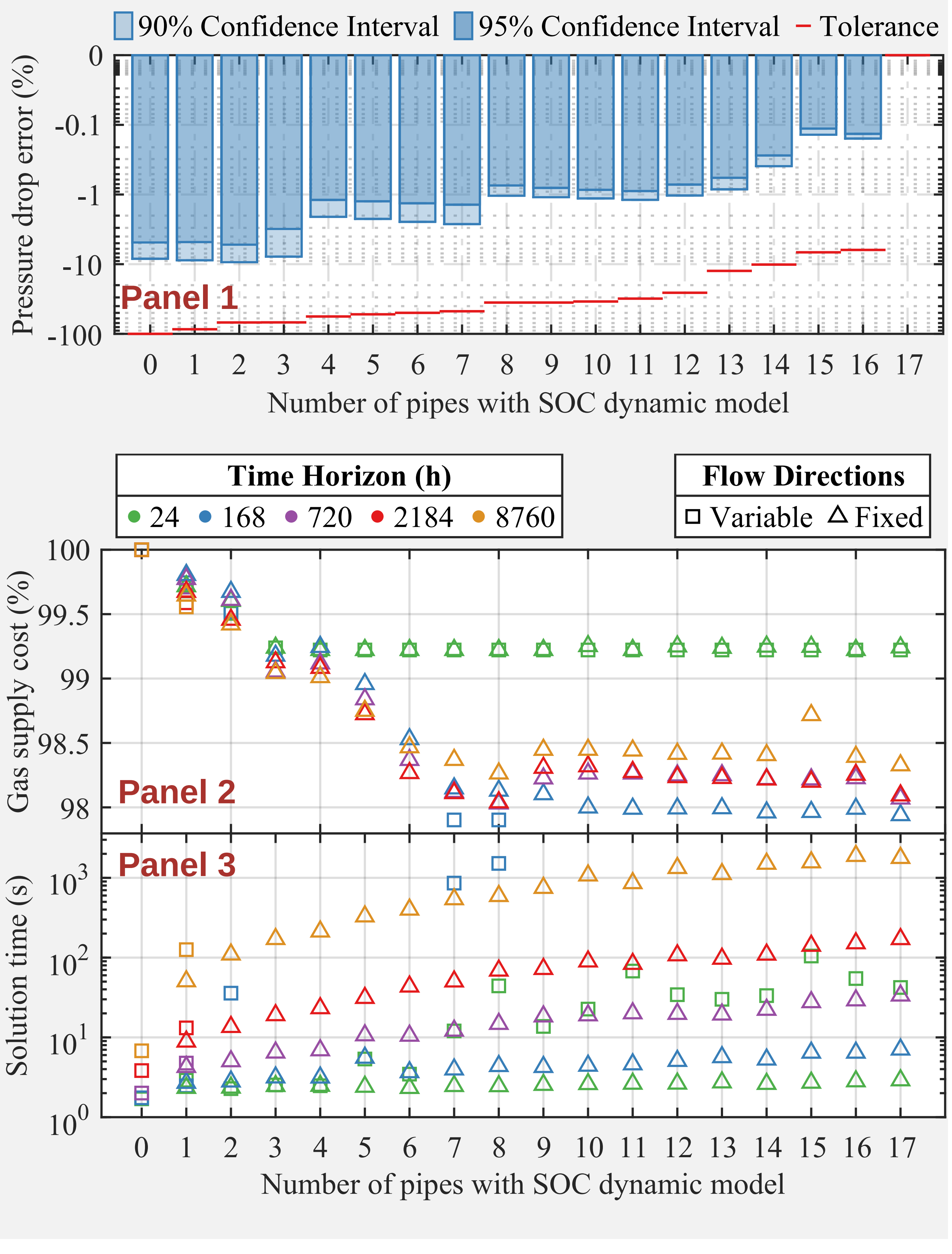
We apply the solution procedure for minimizing gas supply cost. Pipe aggregation reduces the 24-pipe Belgian gas network to 17 pipes.

Panel 1: Capturing more pipes with the SOC dynamic model reduces the pressure drop error. As pipes are rarely operated close to their cross-section capacities, the 95th percentile of the error is below 14% of the tolerance.

Panel 2: Static models neglect linepack flexibility and overestimate gas supply costs up to 2.0%. This should be weighed against other cost-driving uncertainties such as the gas price forecast to guide model selection.

Panel 3: The solution time increases superlinearly with the horizon length and the number of pipes with the SOC dynamic model. Thus, we boost computational efficiency through pipe aggregation and selectively using the SOC dynamic model.

Step 4 in the solution procedure boosts the computational performance and tightens the 95th percentile of the relaxation gaps to 0.03%, while containing the suboptimality to 0.3% in 95% of the instances.



Flexibility assessment of power-hydrogen-power (P2H2P) system in multi-energy districts

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[1] Empa Urban energy system Lab

1 BACKGROUND AND OBJECTIVES

- Decarbonization of the built-environment is increasingly becoming important.
- P2H2P systems are emerging in urban energy landscape.
- This work studies the flexibility of P2H2P in a multi-energy buildings/districts.

2 CONTRIBUTION

- A hydrogen-based multi-energy system is modelled with a mixed-integer linear programming based Ehub optimization tool.
- Quantitative assessment of the performance of P2H2P system including short and long-term flexibility.

3 METHODOLOGY

- Multi-family house Brütten: A fully autarkic P2H2P system in operation since 2016 in Switzerland with a energy reference area of 1328 m^2, consists of 9 apartments.

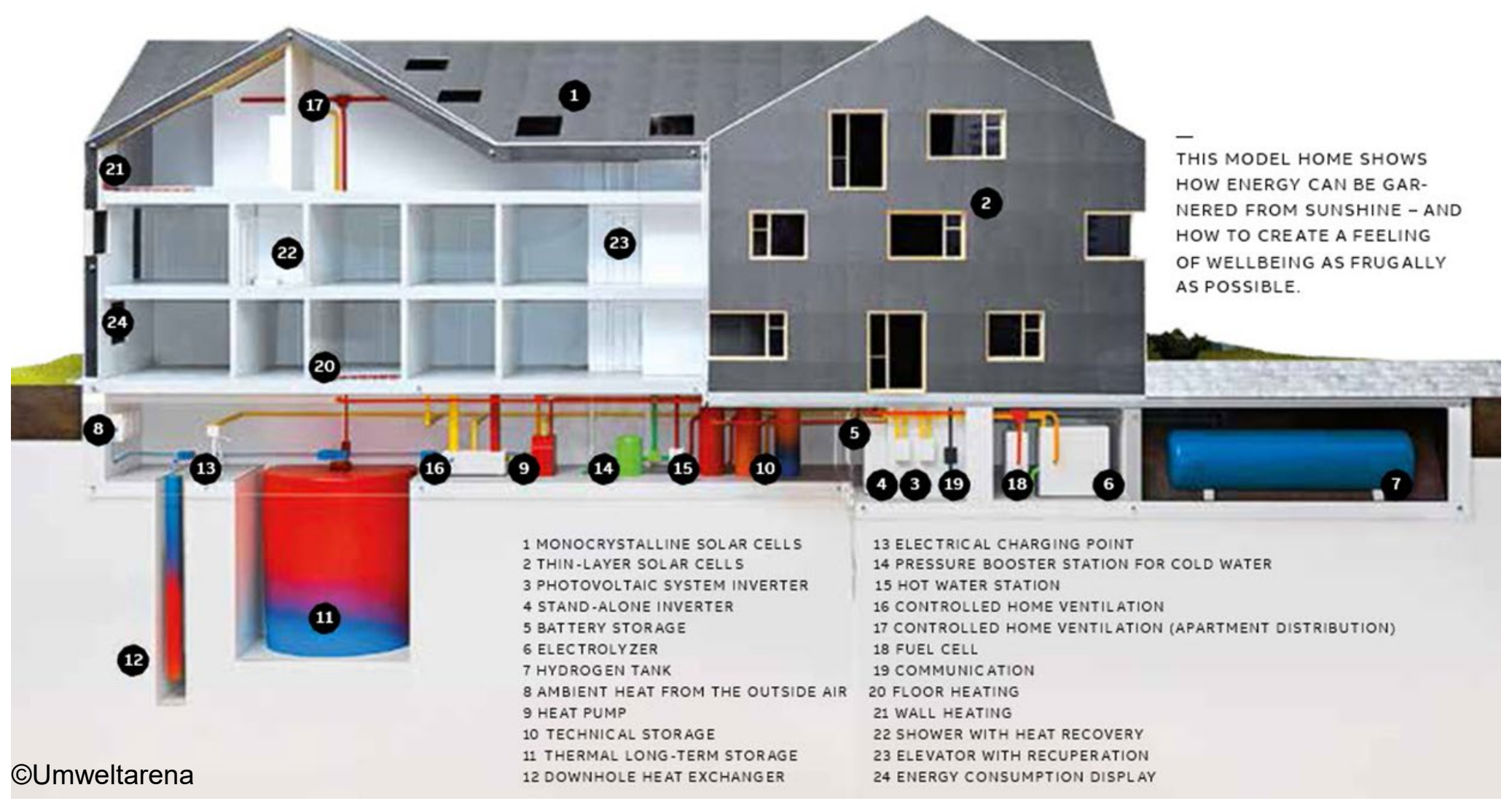

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Figure 1: Schematic of P2H2P system in MFH Brütten

- It consists of 79 kWp roof-top PV and 47 kWp façade PV, 14.5 kW electrolyser, 6.2 kW fuel cell, 28 kW$_{th}$ heat pump, 129 kWh battery, 8700 kWh thermal storage and 10000 kWh hydrogen storage.

- E-hub Tool of Empa is used to perform the design and operation optimization of P2H2P system in multi-family house (MFH) at Brütten, Switzerland.

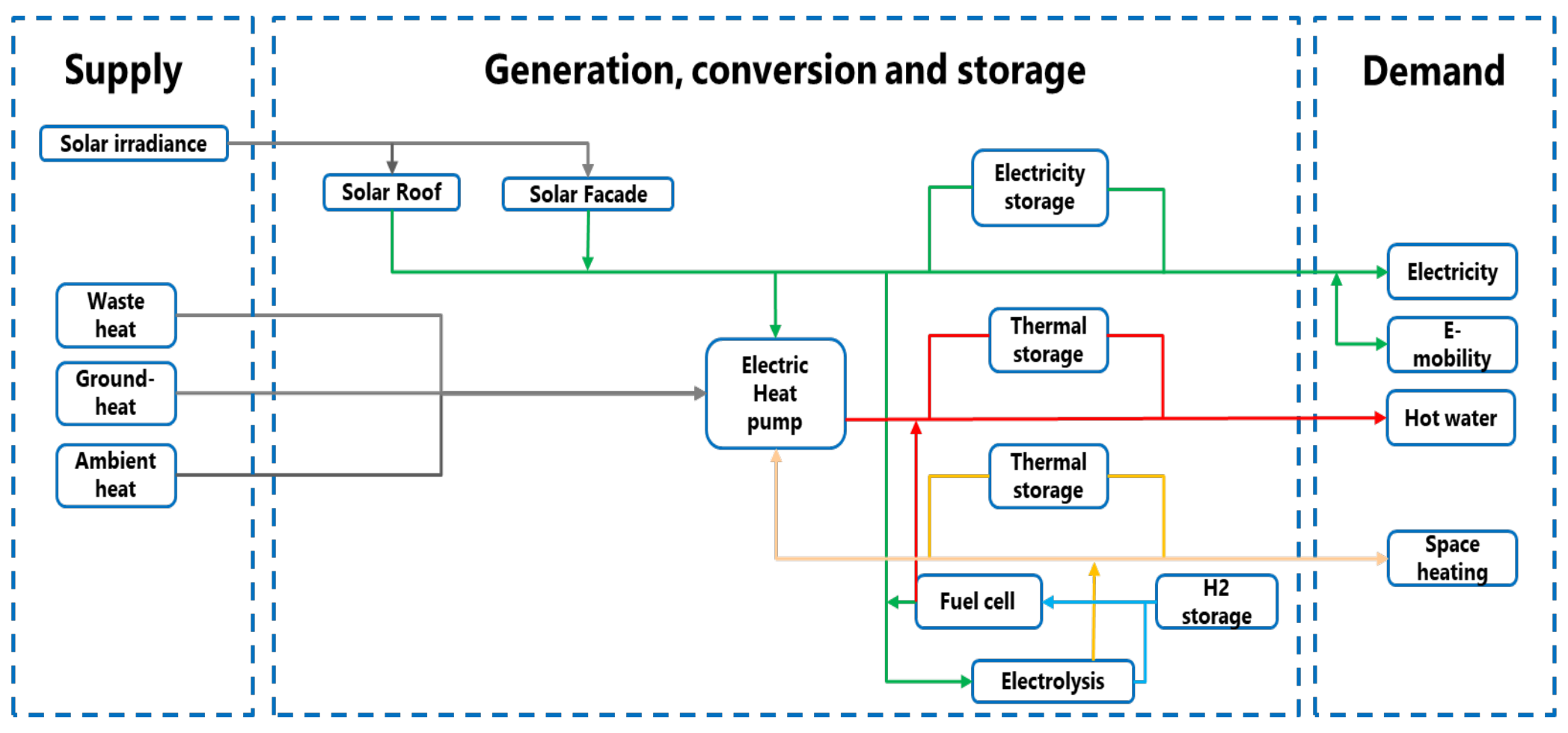

Figure 2: Representation of P2H2P MFH Brütten in Ehub tool

- The P2H2P system is optimized to minimize total energy costs under autarkic constraints.

- The energy demand for MFH Brütten is obtained using measured data. Annual electricity, space heating and hot water demand are 22, 28 and 10 MWh, resp.

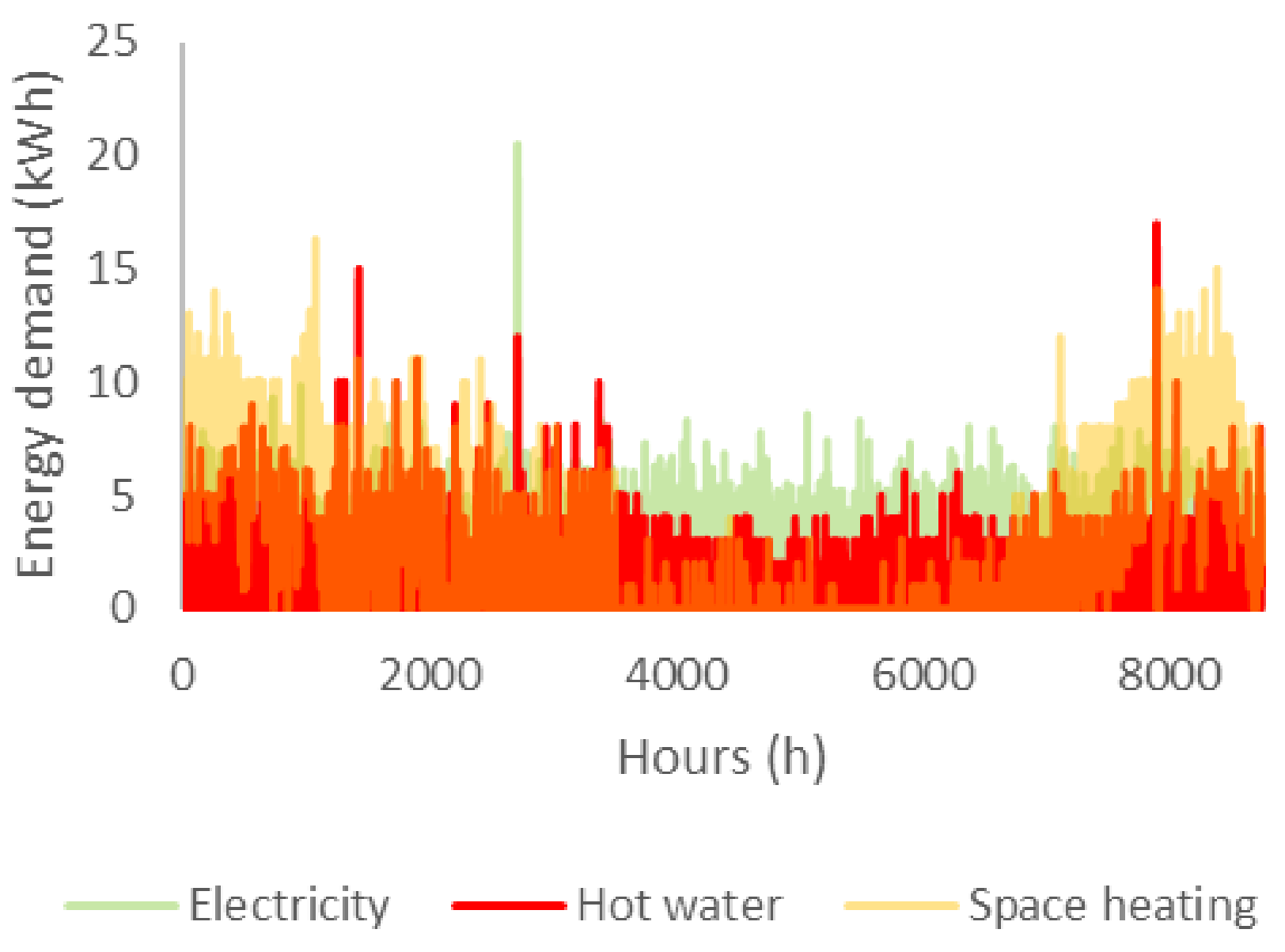

Figure 3: Measured electricity, hot water and space heating demand profiles

4 RESULTS AND CONCULUSIONS

- P2H2P can provide short-term and long-term flexibility in the multi-energy system, see Fig. 4 - 5.
- Under the given boundary conditions, an autarkic P2H2P system is technically feasible.
- Sector coupling enabled through P2H2P system including seasonal storage can partially mitigate seasonal imbalance in energy supply and demand.
- Hydrogen is expected to have good potential at the national and regional scale, more in-depth studies are needed to analyse boundary conditions under which it is also a viable solution for the district scale.

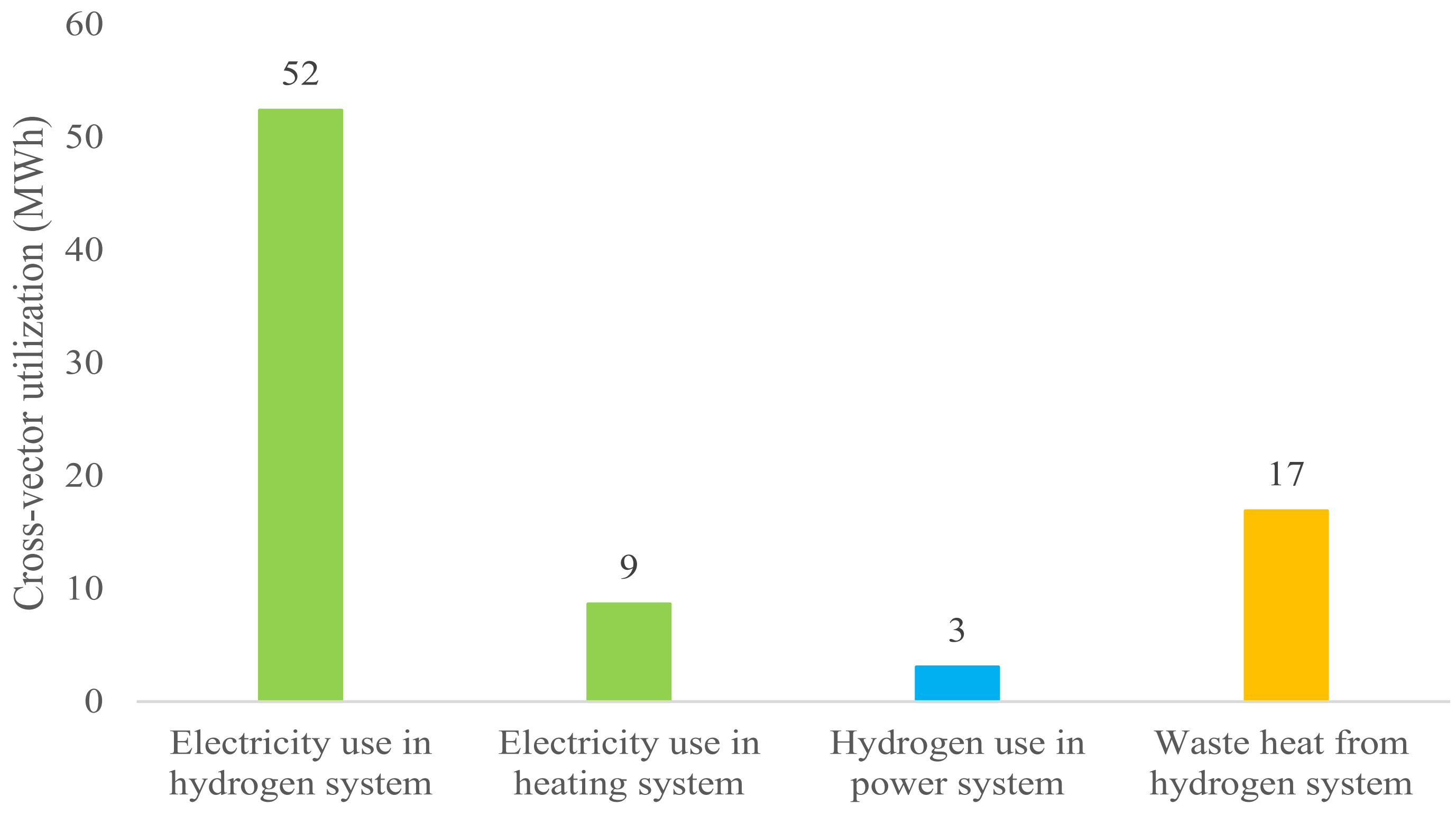

Figure 4: *Cross-sector utilization and flexibility of hydrogen, electricity and heat energy carrriers*

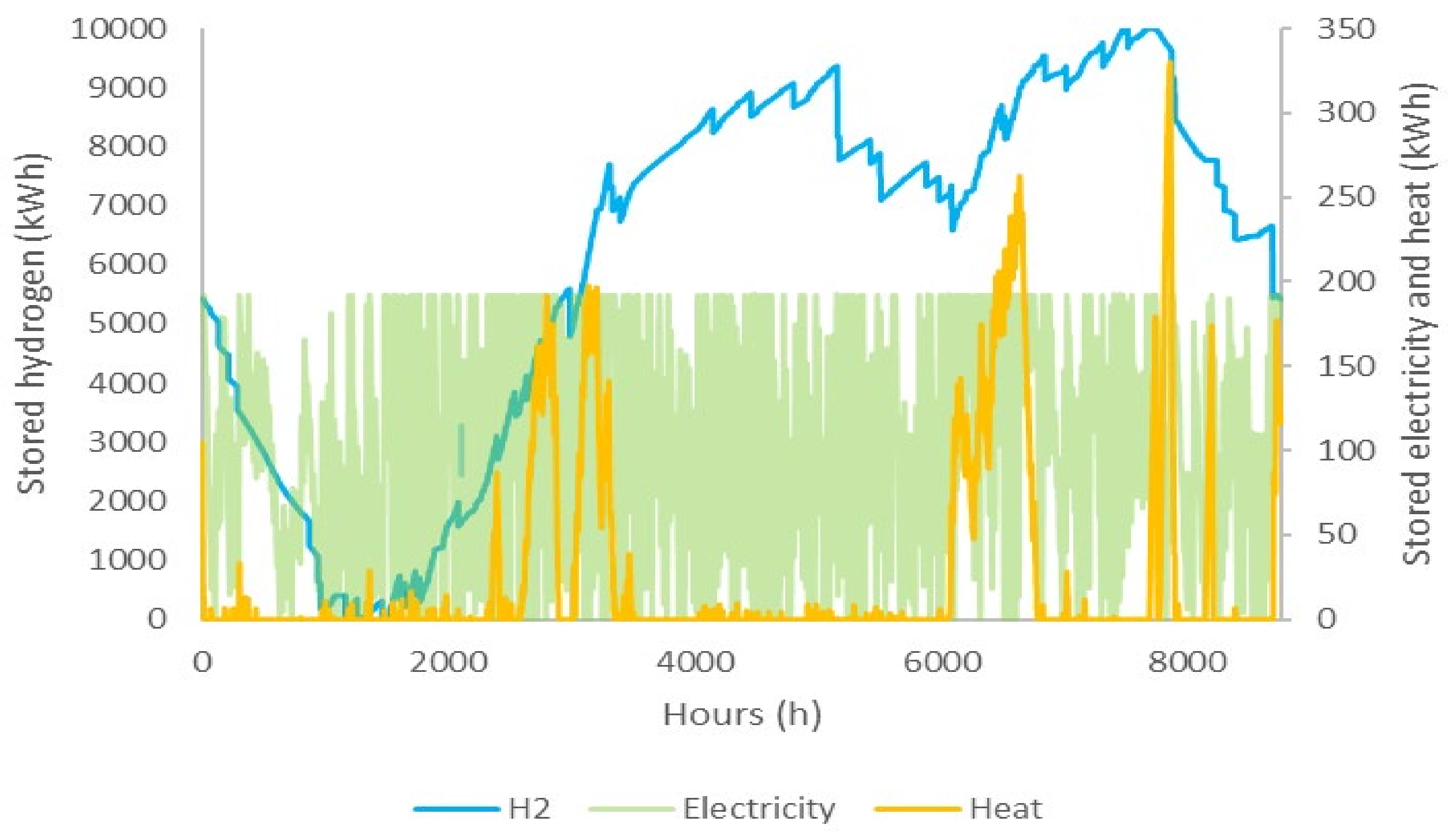

Figure 5: Hourly energy storage levels of different energy carriers

REFERENCES

1 B. Koirala, Mutschler, A. Bartolini, A. Bollinger, and K. Orehouning, “Flexibility assessment of e-mobility in multi-energy districts ,” CIRED e-mobility workshop, 2-3 June 2022, Porto, doi: 10.1049/icp.2022.0827

2 L. A. Bollinger and V. Dorer, “The Ehub Modeling Tool: A flexible software package for district energy system optimization,” *Energy Procedia*, vol. 122, pp. 541–546, Sep. 2017, doi: 10.1016/j.egypro.2017.07.402.

3 Umwelt Arena Schweiz 2016 Architektur, Bauprojekte, Leuchtturmprojekte | Umwelt Arena Schweiz, https://www.umweltarena.ch/besuchen/fuehrungen/energieautarkes-mfh-modell/. accessed: 20.08.2023

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Flexibility provision from thermal inertia of buildings

Work package 2

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[1]Hochschule Luzern, Competence Centre Thermal Energy Storage

1 OBJECTIVES

With an increasing number of heat pumps in Switzerland, space heating and domestic hot water loads will soon represent a significant share of the electricity demand. For the electrical grid, it is advantageous if large loads may be operated flexibly. Buildings can provide such flexibility through utilization of their thermal inertia. By storing energy within the building itself, heat pump loads may be shifted away from peak periods, or towards periods with excess production.

This work aims to quantify the load-shifting potential from buildings. To this end, dynamic building models were developed based on information from publicly available databases ([1][2]). These models are simulated at a community level to investigate the effect of grid-level interventions (e.g. heat pump curtailment) and local heat pump control strategies.

2 CONTRIBUTION TO PATHFDNR

A major goal of WP2 is to provide recommendations regarding operational strategies for local energy networks. The flexibility available from end user loads is a critical piece of knowledge to conduct such analysis.

This work contributes to this goal by assessing the shifting potential of heat pumps serving building heating loads. Such flexibility recommendations serve as an input to simulation frameworks at the district multi-energy system level constructed by our partners in WP2.

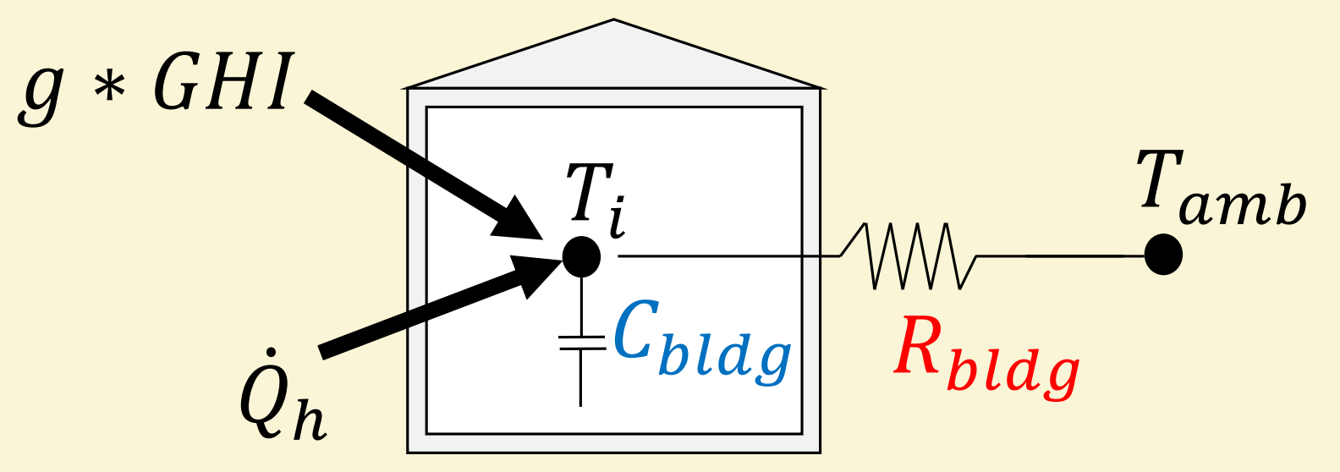
2 METHODOLOGY

Data from public databases:

e.g. for one single family home

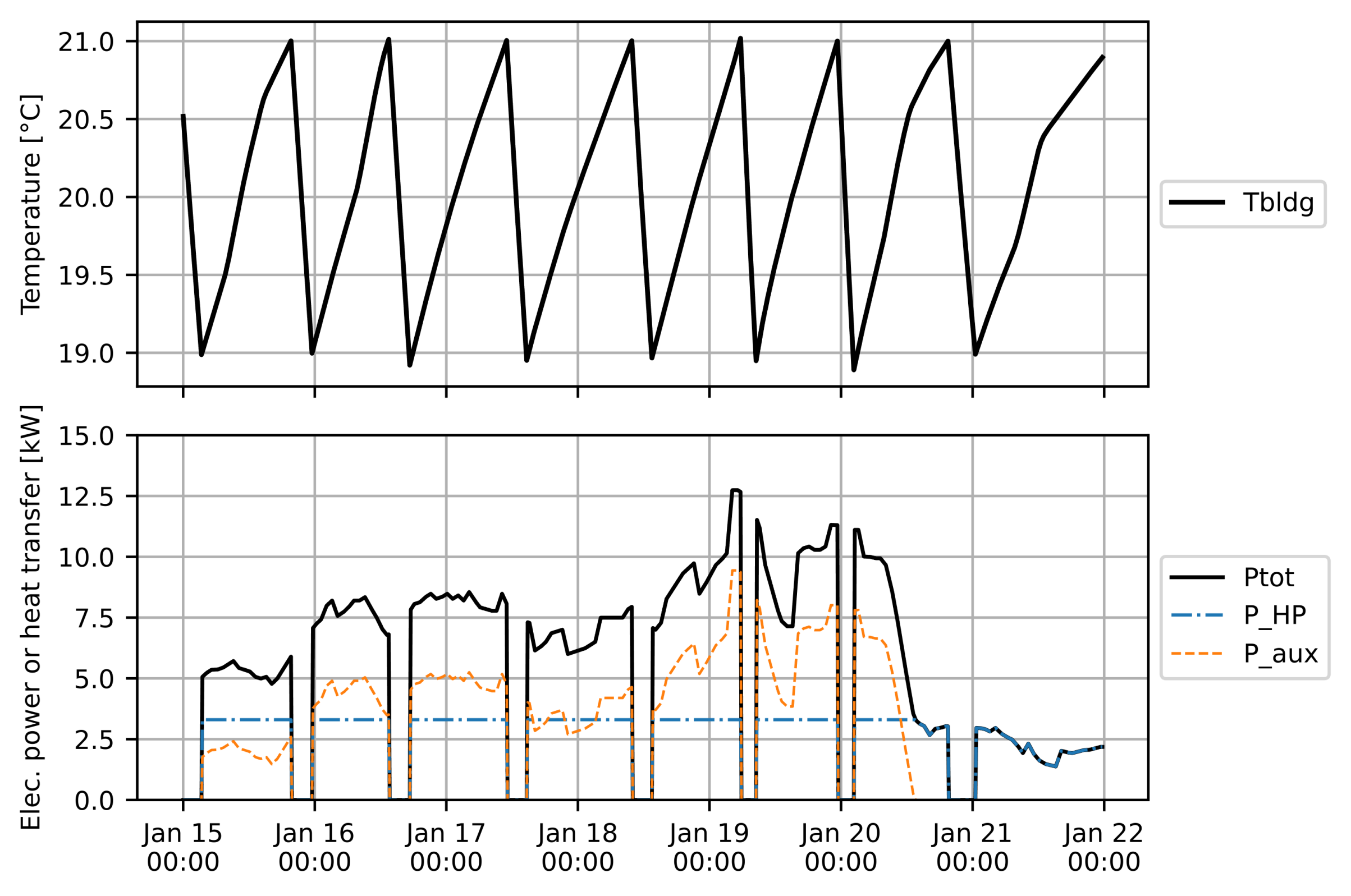
Property	Value
Year	1908
Area	128 m^2
Construction	Heavy
Annual heating	325 kWh/m^2
Heat pump power	3.3 kW
Time const, $\tau = C_{bldg} R_{bldg}$	37 hrs

Dynamic building models



$$C_{bldg}\frac{\partial T_i}{\partial t} = \frac{1}{R_{bldg}}(T_i - T_{amb}) + g * GHI + \dot{Q}_h$$

Simulation of individual building dynamics

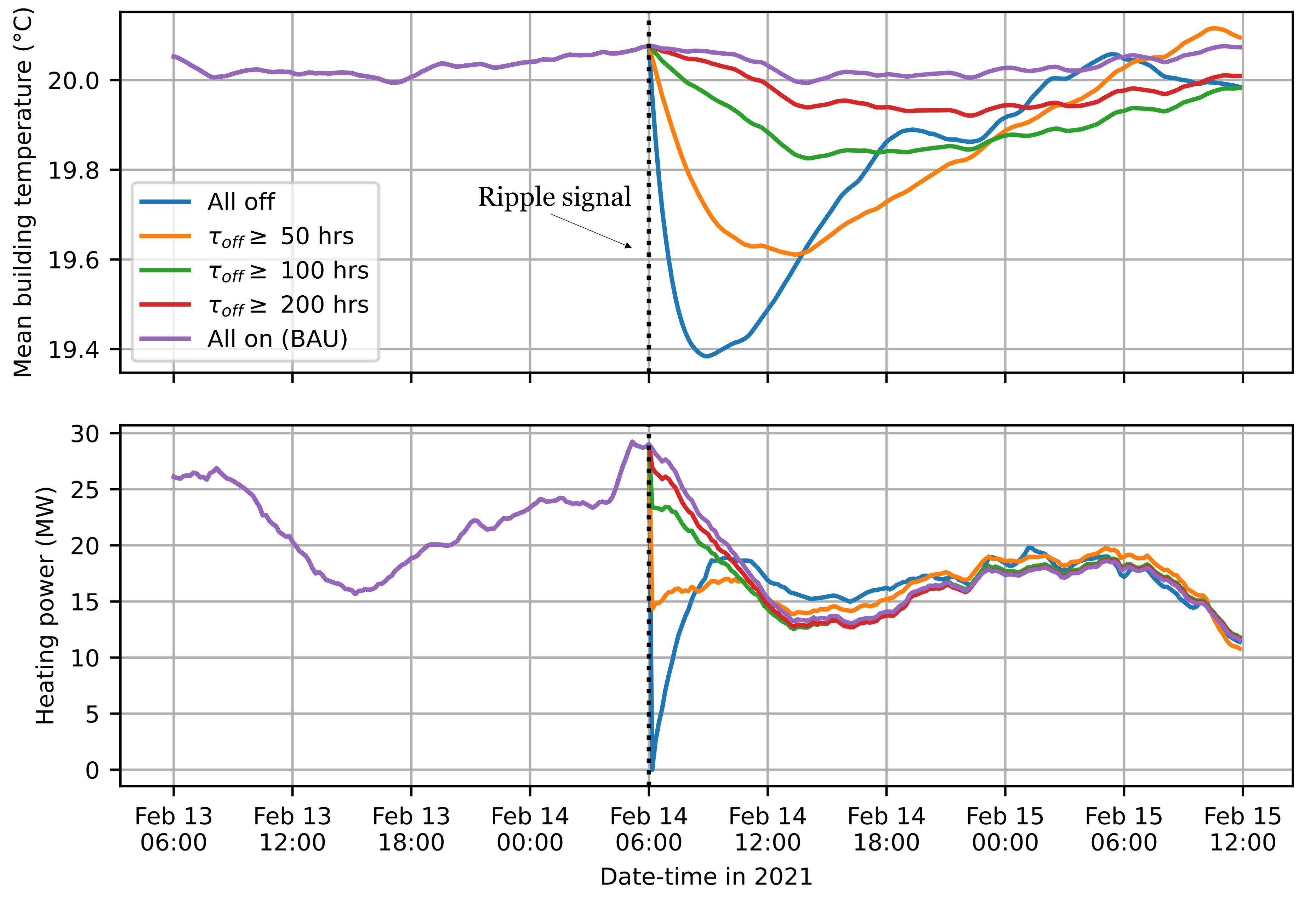


3 Simulation of grid-level heat pump curtailment events

- Dynamic building models are simulated in parallel. The grid operator signals heat pumps to be curtailed at 06:00.
- Simulated heat pumps are not forced to remain off. Rather, the building thermostat enters the 'free cooling' phase, such that the building is allowed to cool only until it reaches the minimum temperature of 19°C, upon which the heat pump re-activates.
- Power reduction of 42.5% over 2 hours by resetting buildings with τ > 50 hrs.

Parameters	
Community:	Liestal, BL
Number of buildings:	2411
Maximum heating power:	38 MW

Simulation of a community of 2411 buildings



REFERENCES

1 "GWR | Eidg. Gebäude- und Wohnungsregister." https://www.housing-stat.ch/de/madd/index.html (accessed May 16, 2023).
2 "GEAK." https://www.geak.ch/ (accessed May 11, 2023).

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Low-fidelity modelling and techno-economic analysis of small-scale energy systems

Work package 3

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1 OBJECTIVES

Seldom is thermal energy stored or used to **bridge the seasonal energy gap** in Switzerland, despite the residential sector alone using nearly one third of total energy consumption; with 50 % from oil and gas burning[1]. To reduce CO_2 emissions significantly**, flexible integrated energy systems utilizing renewable, sustainable generation and energy storage technologies that enables sector coupling** are required. These systems are crucial to reach the net zero goal by 2050 of the Swiss climate strategy[2].

To analyse integrated systems of various designs and compositions of generation and storage technologies, it is necessary to have validated models that accurately describe the system and its operational characteristics.

2 CONTRIBUTION TO PATHFNDR

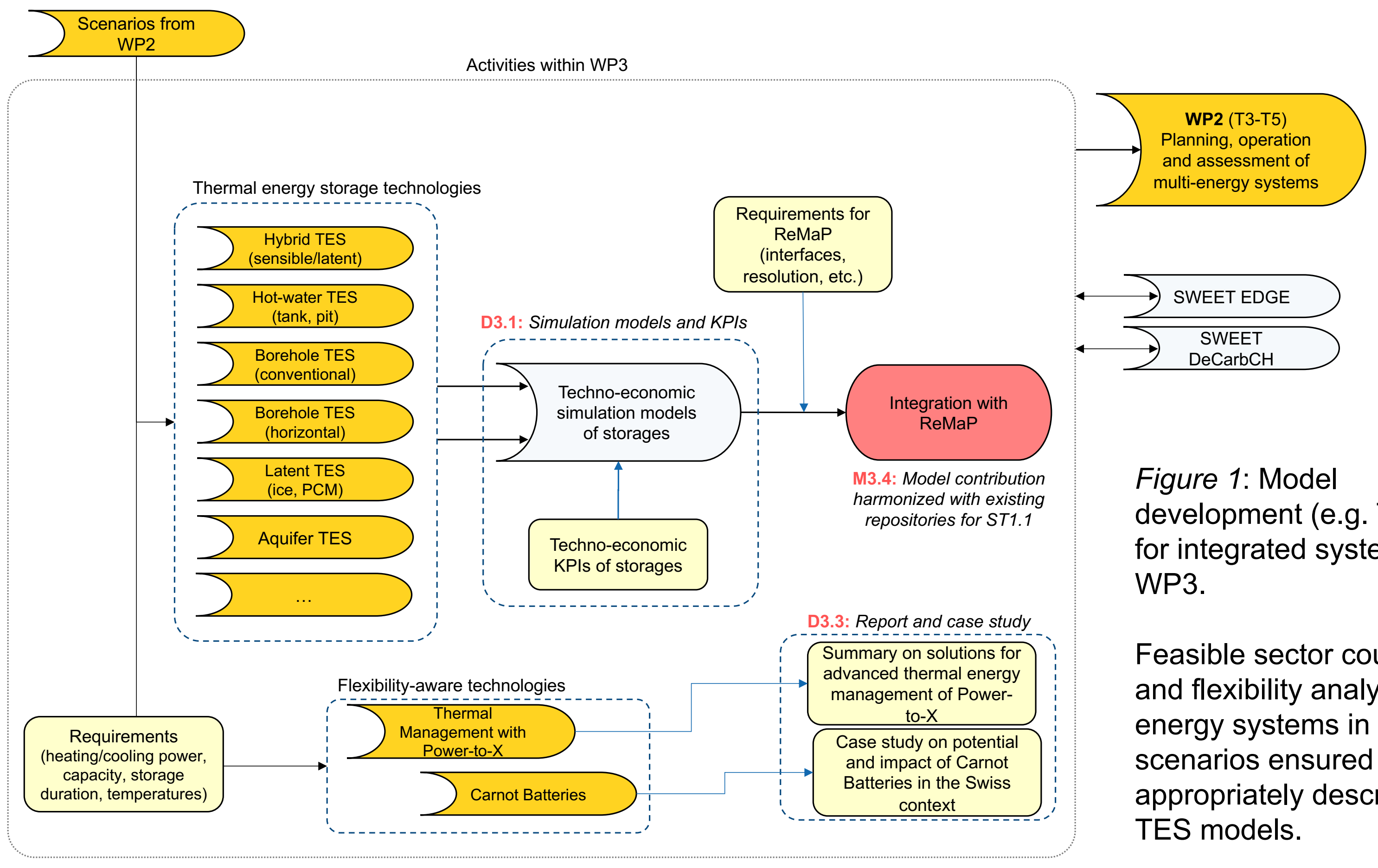
Specifically, the contributions are to **provide validated component models of a range of generation and storage technologies**, at various levels of complexity and dynamic detail. In this poster, an application of modelling an integrated system using water-based seasonal energy storage is shown.

To identify viable renewables integration pathways and the potential for energy systems flexibility, this portfolio of validated models is necessary to facilitate conceptual system design, feasibility analysis, as well as eventually operational and techno-economic optimization of such systems. **These models will be used to inform scenario analysis in Work Package 2**.

2 METHODOLOGY

In assembling a suite of models based on an identified set of modelling requirements from WP2, energy generation technologies and storage technologies have both been considered. **Models at various levels of complexity and time-resolution exist and are being developed** – the goal being that analysis is conducted in the most efficient manner; utilizing models at the appropriate level of detail for the degree of insights required (e.g. only using more complex models when dynamic system behaviour is of interest).

It is crucial that models, especially when simplified, nonetheless retain the critical pieces of information necessary to arrive at correct outcomes and insights. An example of this is Thermal Energy Storage (TES) systems that must include operational temperatures within models rather than simply gross energetic content – leading potentially to infeasible flexibility outcomes. **Key performance indicators (KPIs) for each of the technologies are identified**, and agreed upon by experts, allowing subsets of these KPIs to be used as a general method of comparison between conceptualised, existing, and optimized systems[3]. Figure 1 shows the adopted methodology and how these activities relate.



Scenarios from WP2

Activities within WP3

Thermal energy storage technologies

Hybrid TES (sensible/latent)

Hot-water TES (tank, pit)

Borehole TES (conventional)

Borehole TES (horizontal)

Latent TES (ice, PCM)

Aquifer TES

…

D3.1: *Simulation models and KPIs*

Techno-economic simulation models of storages

Techno-economic KPIs of storages

Requirements for ReMaP (interfaces, resolution, etc.)

Integration with ReMaP

M3.4: *Model contribution harmonized with existing repositories for ST1.1*

WP2 (T3-T5) Planning, operation and assessment of multi-energy systems

SWEET EDGE

SWEET DeCarbCH

Requirements (heating/cooling power, capacity, storage duration, temperatures)

Flexibility-aware technologies

Thermal Management with Power-to-X

Carnot Batteries

D3.3: *Report and case study*

Summary on solutions for advanced thermal energy management of Power-to-X

Case study on potential and impact of Carnot Batteries in the Swiss context

Figure 1: Model development (e.g. TES) for integrated systems in WP3.

Feasible sector coupling and flexibility analysis of energy systems in WP2 scenarios ensured via appropriately described TES models.

3 RESULTS AND NEXT STEPS

Application of simplified energy balance modelling to a planned seasonal thermal energy storage system (Figures *2* and 3), envisioned as a **sustainable and relatively inexpensive solution to bridging the seasonal energy gap** for small to medium sized residences[4], is readily achieved. Relatively simple steady-state (with the exception of the storage itself) component models are used to **rapidly estimate the suitability and/or feasibility** of implementing such a system under various scenario conditions.

Here, one can explore practical insights in how the system would respond to changes to the physical and economic environmental variables. We see how the temperature levels would plausibly develop and oscillate within the envisioned seasonal storage during the first and subsequent two years of operation. Such modelling allows engineers to extract insights, say, **the amount of heat available from the storage at a particular temperature throughout the year**, as a way of estimating the relative utility of installing such a storage to meet a particular heating demand seen in a test scenario. A relatively easy question could be: would such a system operate in a manner that allows residents to have reliable access to domestic hot water throughout the year? A more complex inquiry could be: **How can such TES systems contribute to the flexibility characteristics of the overall energy system?**

Next steps are to complete validation of the seasonal TES model using existing validated transient models and field data.

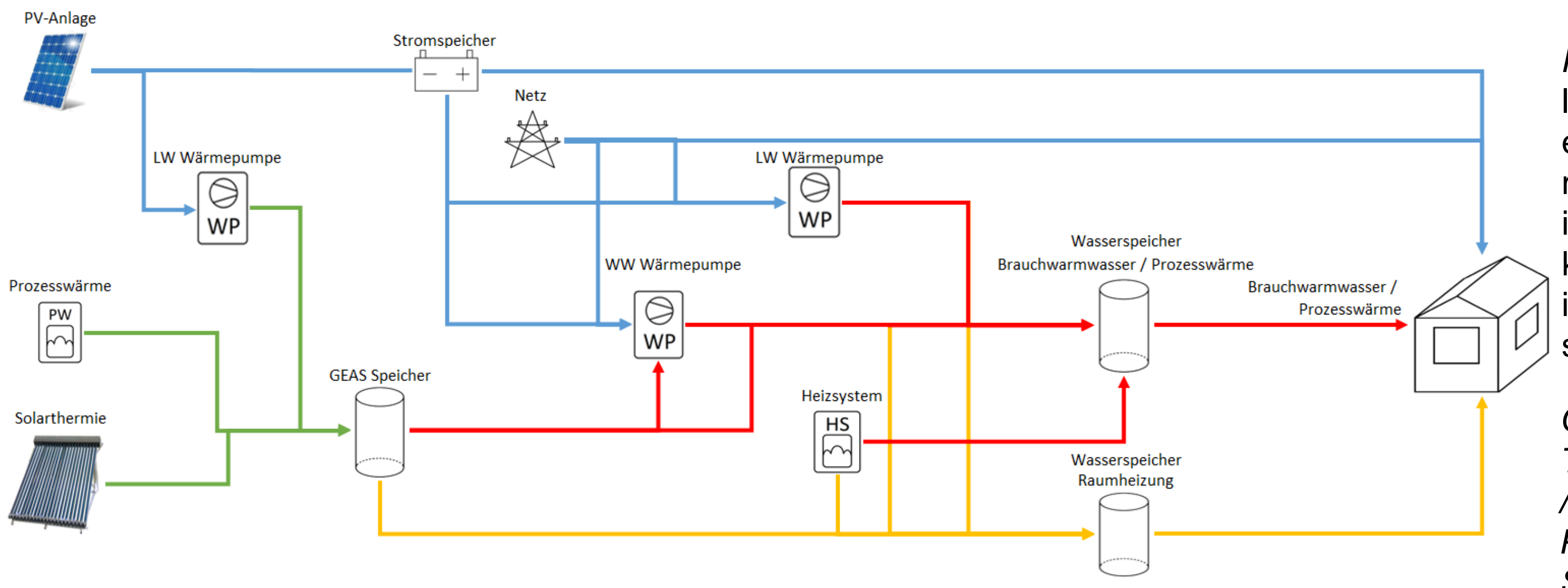


Figure 2: A conceptual layout for an integrated energy system for a residential application, including some example key performance indicators of the chosen storage technology.

Generation: Solar Thermal / Photovoltaic / Boiler System / Heat Pump
Storage: Water-based sensible storage with possibility of discharge through heat pump.

Example KPIs (Seasonal Thermal Energy Storage): CAPEX per unit of installed capacity (kCHF/Mwh), Maximum loading and unloading power (kW), Volumetric energy density (kJ/m³)

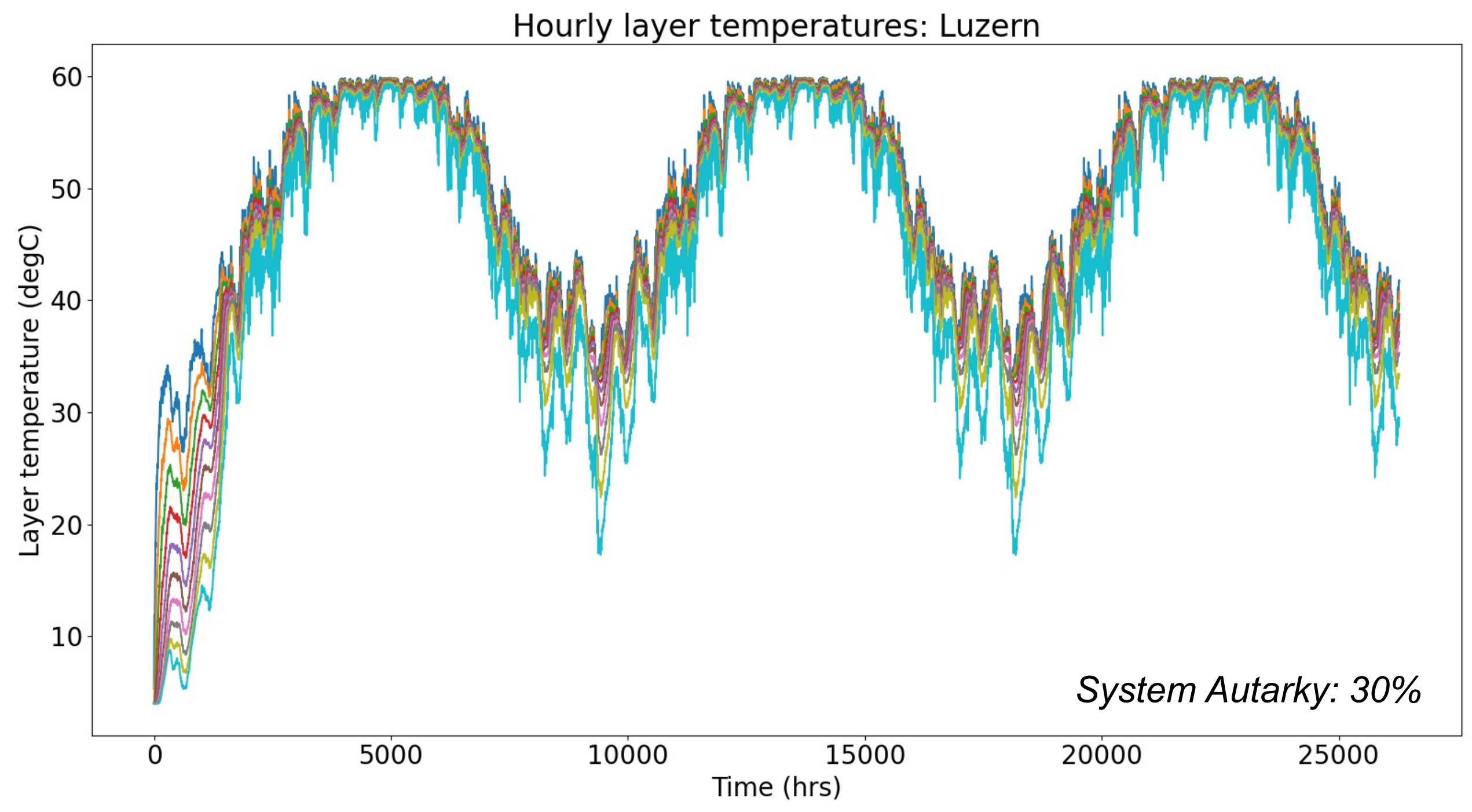


Figure 3: Simulated temperature profile of the water-based seasonal thermal energy storage showing how tank temperatures develop and change throughout the year in accordance with seasonal charging and discharging behaviour. The modelled location used weather data from the city of Luzern.

REFERENCES

1 Overall energy statistics, Federal Office of Energy.
2 Long-term climate strategy to 2050, Federal Office for the Environment.
3 Evaluation of energy density as performance indicator for thermal energy storage at material and system levels, Joaquim Romaní et al. 2019 Applied Energy 235, 954-962
4 GEAS Project, Luzern University of Applied Sciences

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Hybrid Storage for Week-ahead Flexibility

Work package 3

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1: Distributed Electrical Systems Laboratory, EFPL

1 OBJECTIVES

- ☐ Investigate benefits of coupling electricity network to hydrogen storage systems
- ☐ Control interaction between different types of energy storage (battery energy storage and hydrogen energy storage)
  → Need to consider longer time horizons → larger problem
- ☐ Show feasibility of a combined scheduling of the network energy exchange and the hydrogen storage system.
- ☐ Develop Simple Linearized Control Models for PEM FC/EL

2 CONTRIBUTION TO PATHFDNR

- ☐ Develop and Validate Linearized Models for Fuel Cell / Electrolyzer Systems
- ☐ Provide a framework for scheduling and balancing on weekly timescales
- ☐ Couple Electricity Network with a Hydrogen Storage System

2.1 METHODOLOGY: Scheduling

Scheduling Stage

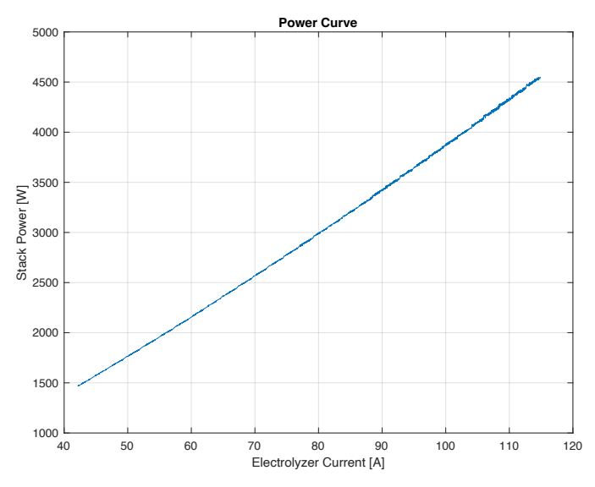
- ☐ Scenario-based MILP
- ☐ Linearized AC-OPF and linearized resource models[1]
- ☐ Week-ahead Scheduling → Active Power Trajectory at the GCP + Unit Commitment
- ☐ Solution through (rolling) reduced MILP and iterative LP solution

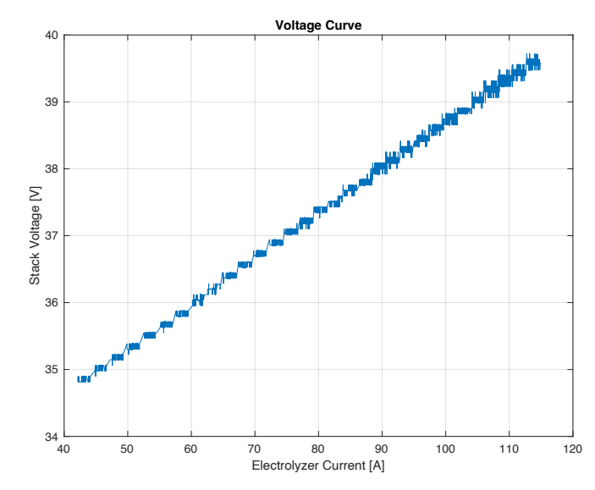
Tracking Stage

- ☐ Real-time two-layer MPC[2] using expected power profiles and unit commitment schedule
- ☐ Upper layer: determine storage target using full horizon
- ☐ Lower layer: Minimize tracking error in current period

2.2 METHODOLOGY: Modelling

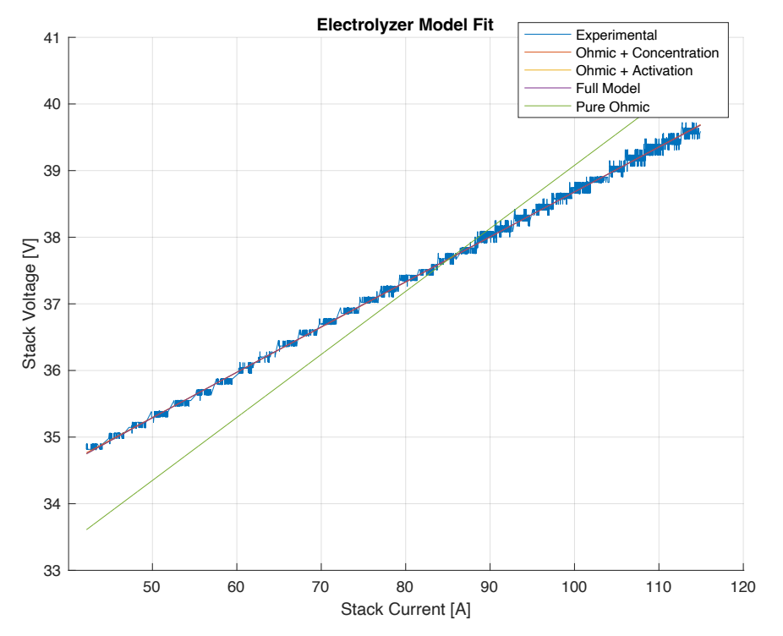
- ☐ PEM Electrolyzer Modelling[3]
- ☐ Static Model[4] (Fast dynamics, slow control, constant temperature)
- ☐ Calibrate voltage efficiency model to static response

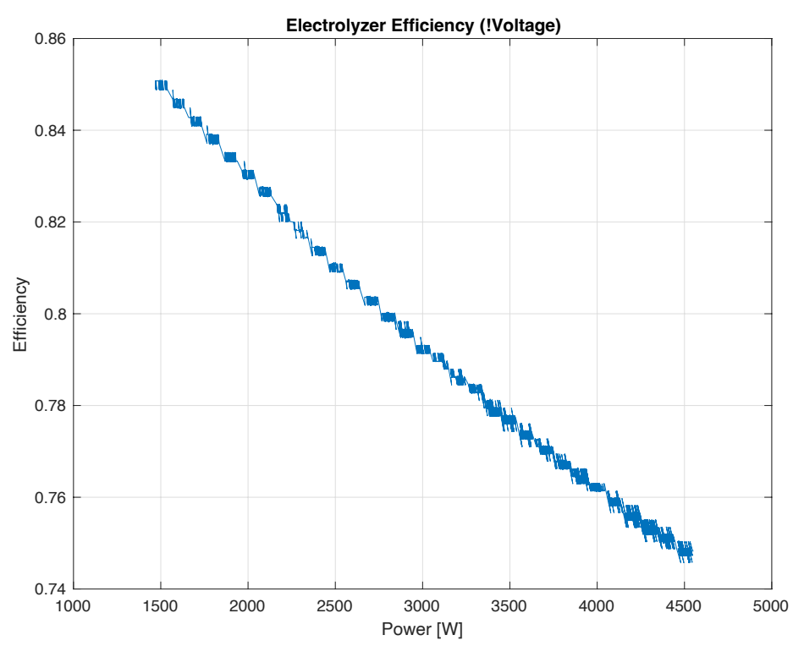




DESL Electrolyzer
5 kW, 20 cells in series

Efficiency Range: 75-85 %
(!Only Voltage Efficiency)

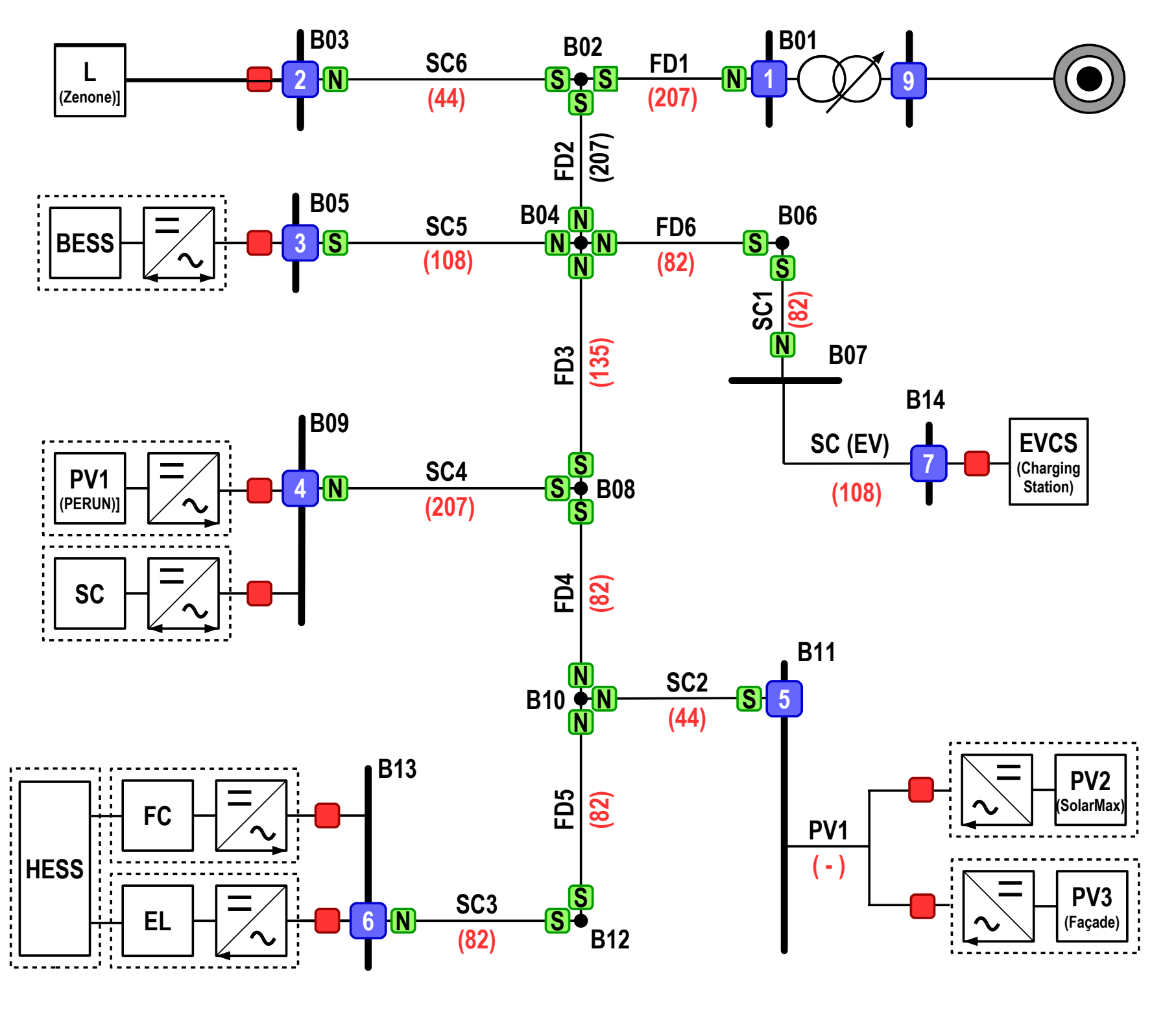




3 RESULTS

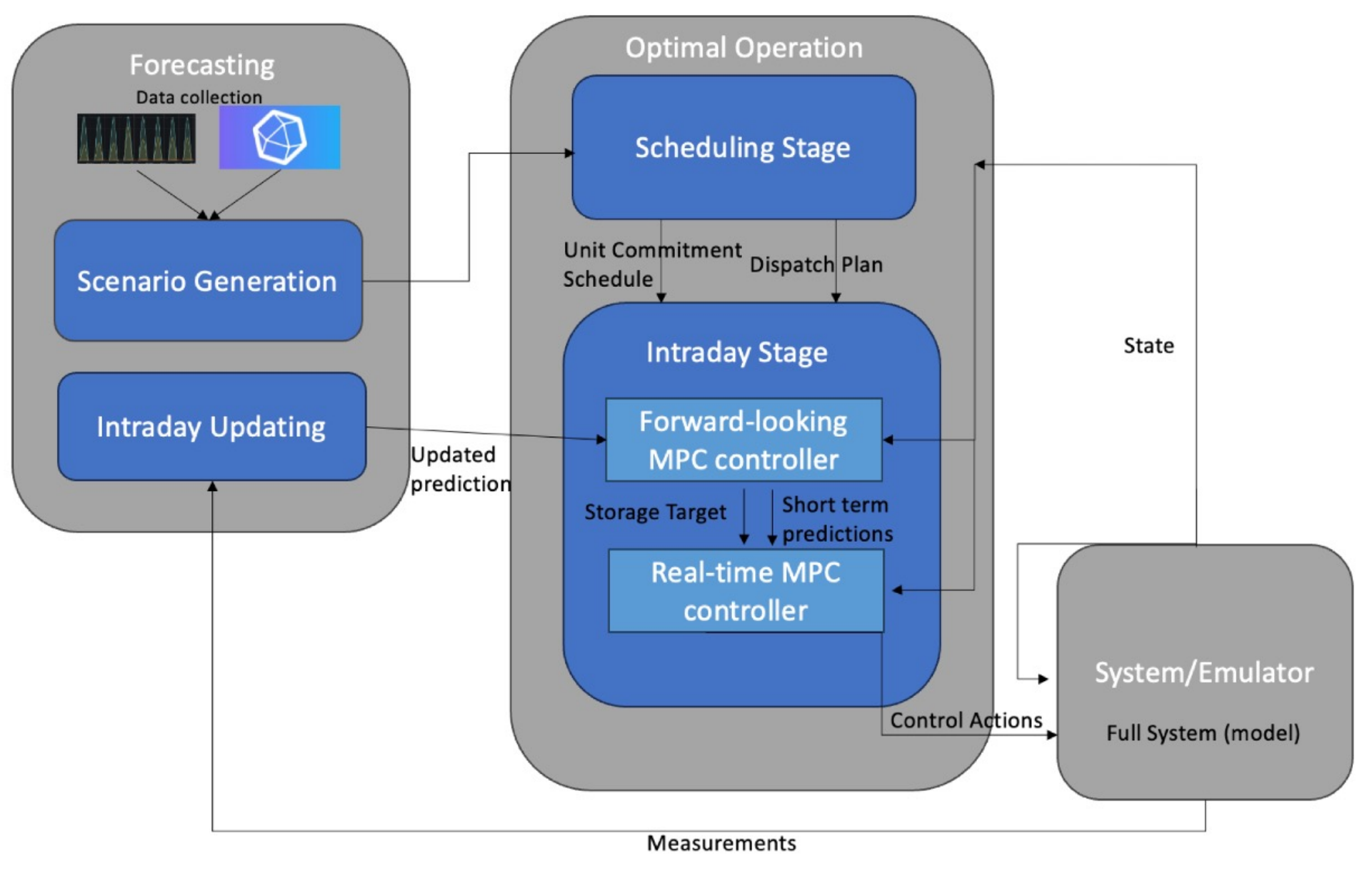
Microgrid Infrastructure and Key Figures

🟦	PMU Locations	**L**	Loads	**SC**	Supercapacitors
🟥	AGENTS Locations	**BESS**	Battery Energy Storage	**FC**	Fuel Cell
N	Breaker Locations	**PV**	Photovoltaic Plant	**EL**	Electrolyser
(207)	Lines' Ampacities (A)	**EVCS**	EV Charging Station	**HESS**	Hydrogen Energy Storage

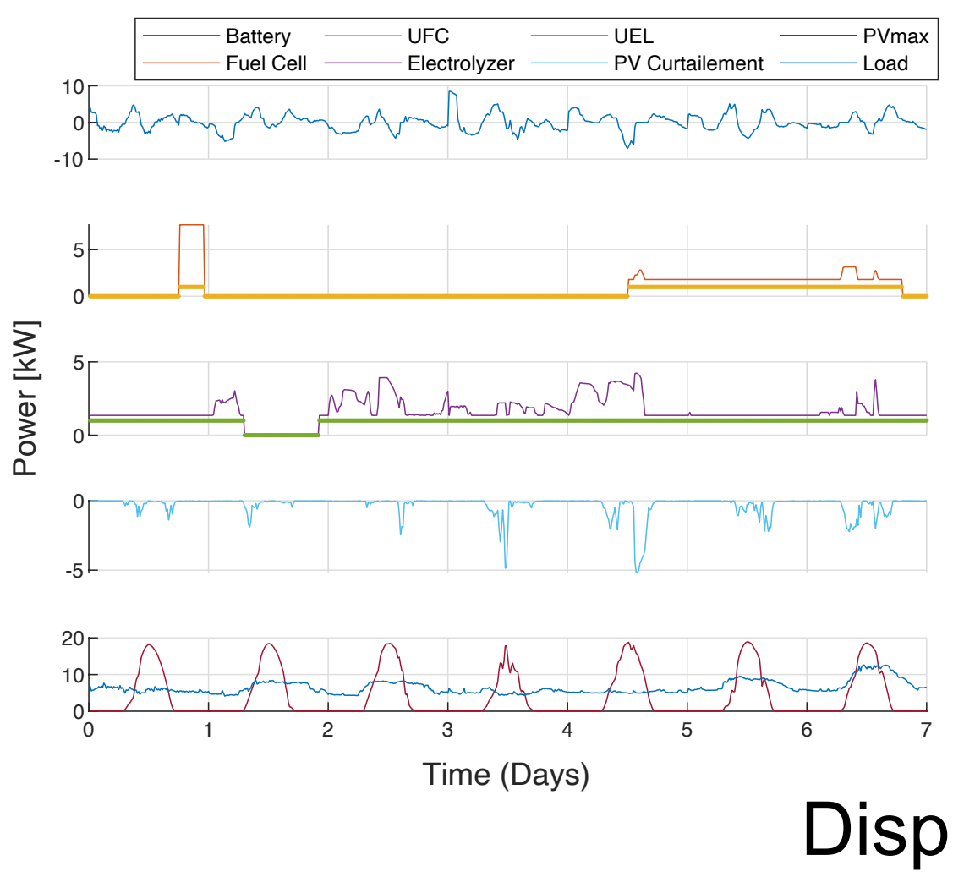


Resource	Battery (Power)	Battery (Energy)	Fuel Cell	Electrolyzer	Hydrogen Storage	PV Peak Total	Peak Load Total
Capacity	25 kW	25 kWh	18 kW	5 kW	132 kWh	29 kW	26 kW

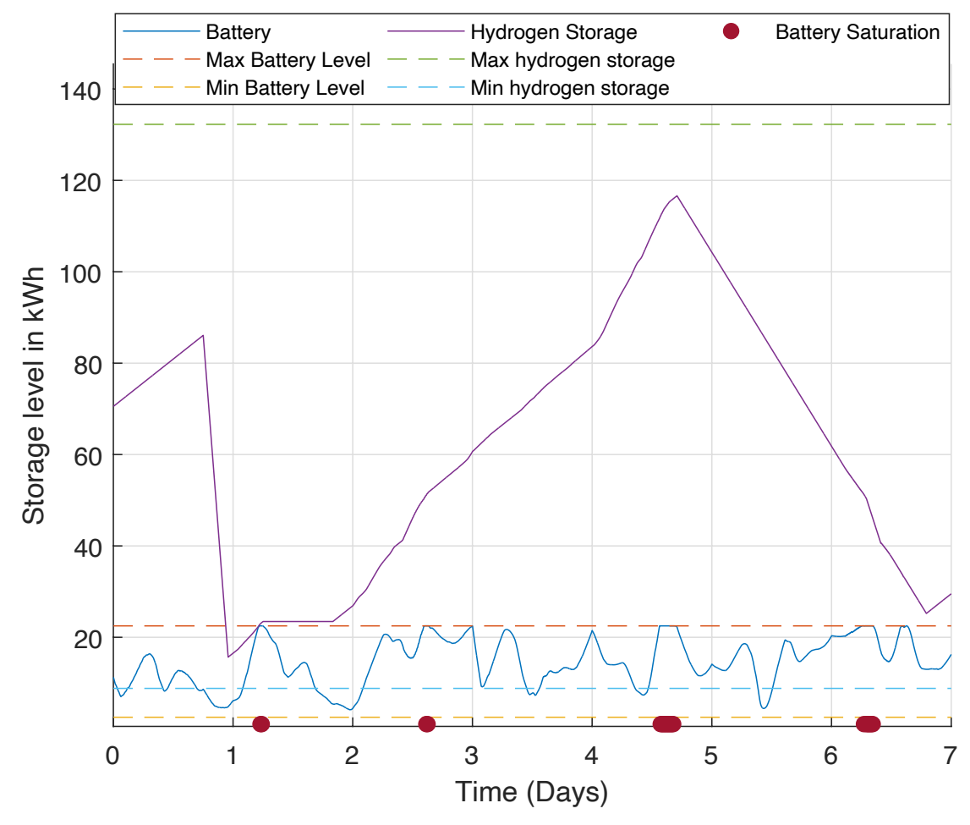
Numerical Experiment



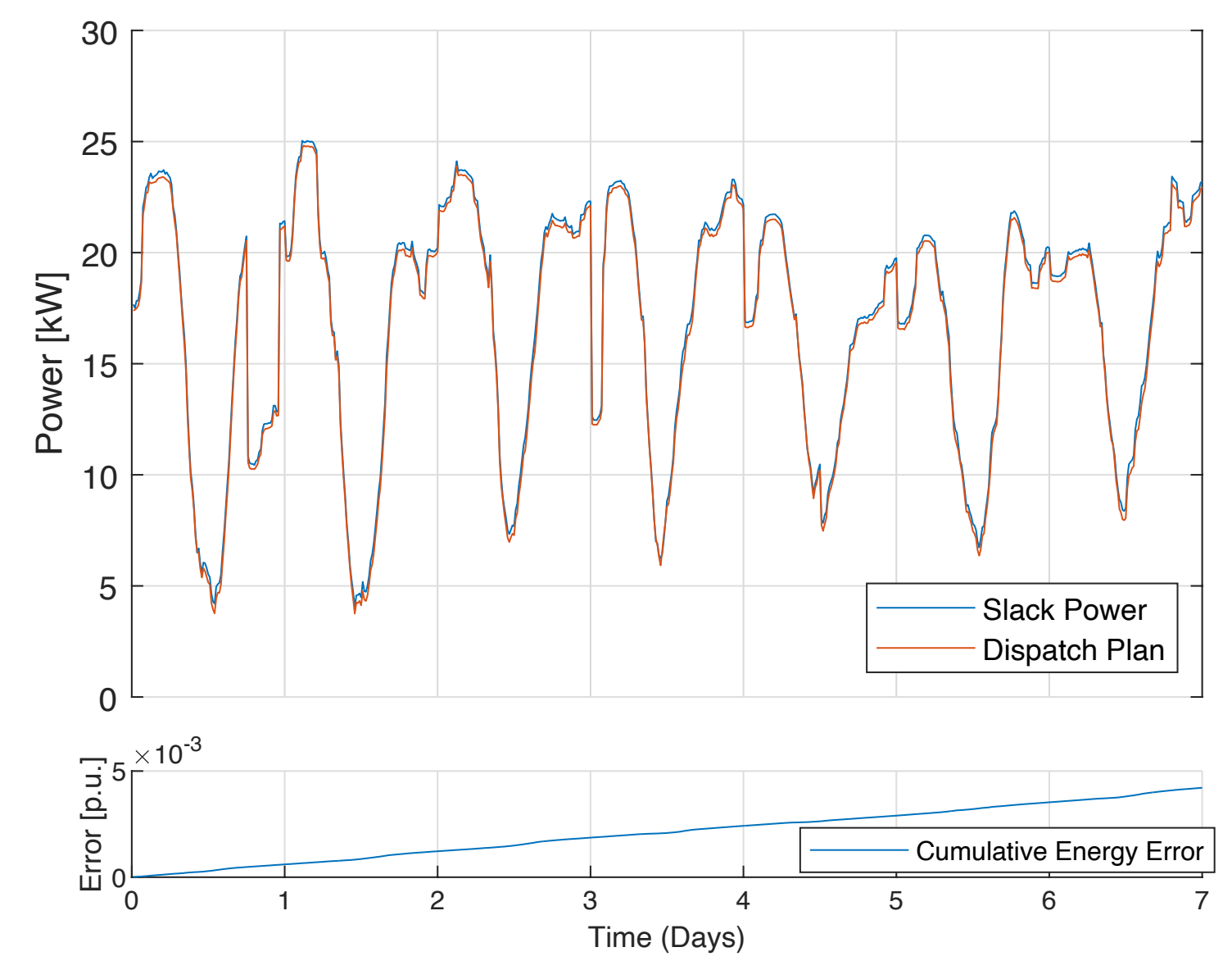
Controllable Power Injections



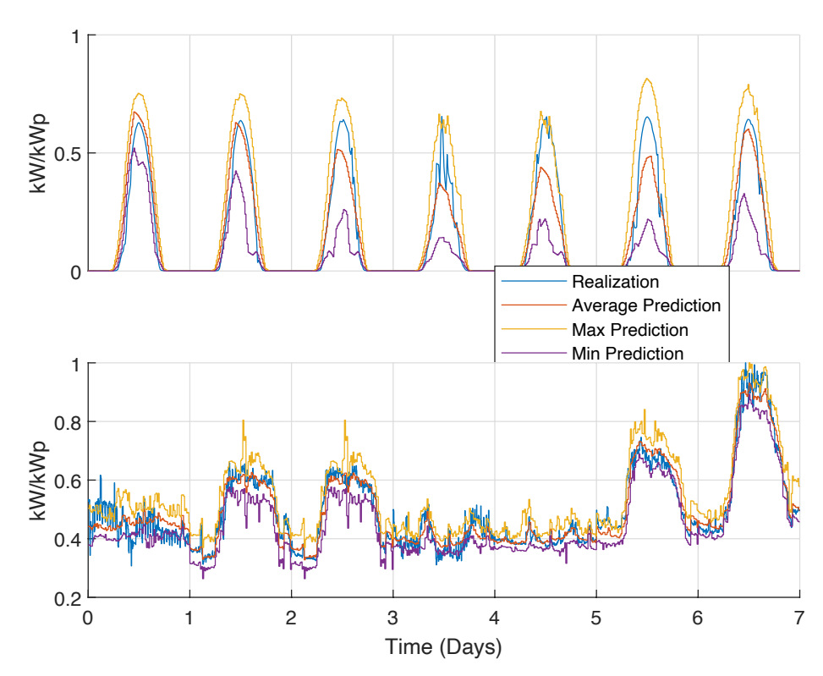
Energy Storage Levels



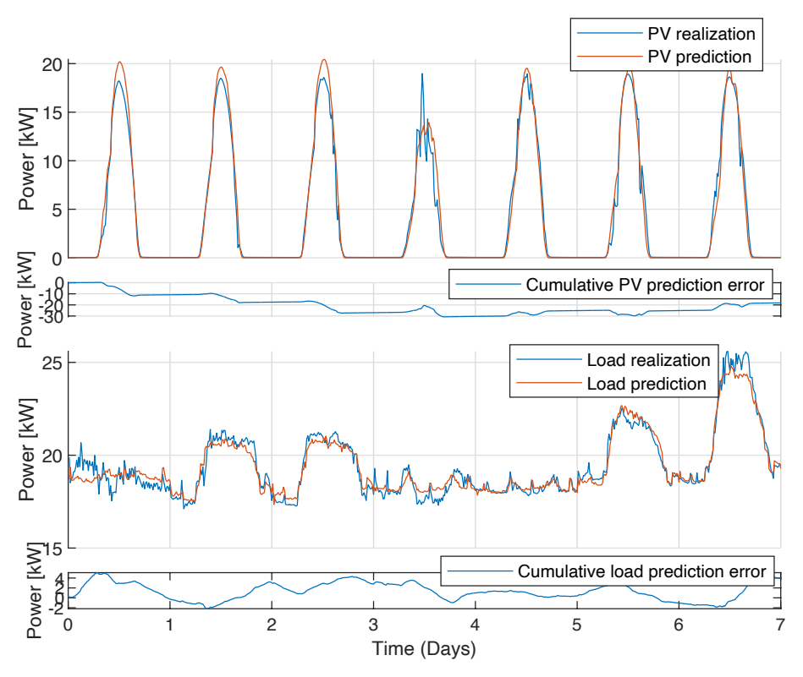
Dispatch Tracking



Week-ahead Predictions



Intra-day Predictions



Description	Intraday Load Prediction	Intraday PV Prediction	Day-ahead Load Prediction	Day-ahead PV Prediction	Dispatch	Relative Dispatch
Error	4.0 kWh	-18.2 kWh	6.3 kWh	16.6 kWh	11.7 kWh	0.11%

REFERENCES

1 Methods for Grid-aware Operation and Planning of Active Distribution Networks, PhD Thesis EPFL, Rahul Gupta, 2023

2 Reliable Dispatch of Active Distribution Networks via a Two-Layer Grid-Aware Model Predictive Control: Theory and Experimental Validation, Rahul Gupta, 2022

3 Modelling of PEM Fuel Cell Performance: Steady-State and Dynamic Experimental Validation, Idoia San Martín, Alfredo Ursúa, and Pablo Sanchis, 2014

4 A model predictive control strategy for the space heating of a smart building including cogeneration of a fuel cell-electrolyzer system, Fabrizio Sossan et al, 2014

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Powertrain of Trucks: Which Road to Take?

Work package 6

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1 OBJECTIVES

- Asses the four most promising powertrain technologies for the future (diesel, natural gas, fuel cell, battery-electric), their related ecosystem, and its members.
- Evaluate innovation diffusion aspects like availability, cost, demand, and policy for the technology transition.
- Analyze decision making process under uncertainty to improve strategic foresight[1].
- RQ: *How does technology substitution towards sustainable innovations occur in ecosystem?*

2 CONTRIBUTION TO PATHFDNR

- Sustainable drive technologies are the key to decarbonizing the Swiss mobility sector.
- The dominant drive technology for the long-term future is battery electric. However, it remains unclear whether and for how long bridging technologies such as hydrogen or natural gas will be used.
- Customers can currently choose between old and new technologies. To accelerate the transition of propulsion technologies, it is important to understand the critical factors that influence the readiness to adopt more sustainable technologies.

2 METHODOLOGY

Investigating by an qualitative case study approach as this method is in particular suitable for understanding the 'how' and 'why'.

By focus on the case of domestic road freight transport in Switzerland, we contribute to PATHFNDR aims and goals of decarbonization of Switzerland. The case setting can clearly be observed in isolation due to the heavy vehicle charge tax (LSVA).

In analyzing the adoption of new trucks, we asses the impact of the diffusion aspects for new technology by a heterogenous group of ecosystem members, i.e. truck buyers.

Currently, we are interviewing additional truck owners for understanding their investment decision towards a specific technology. We plan a common workshop with informants (expert and informant interviewees) to present our findings to strengthen our construct validity.

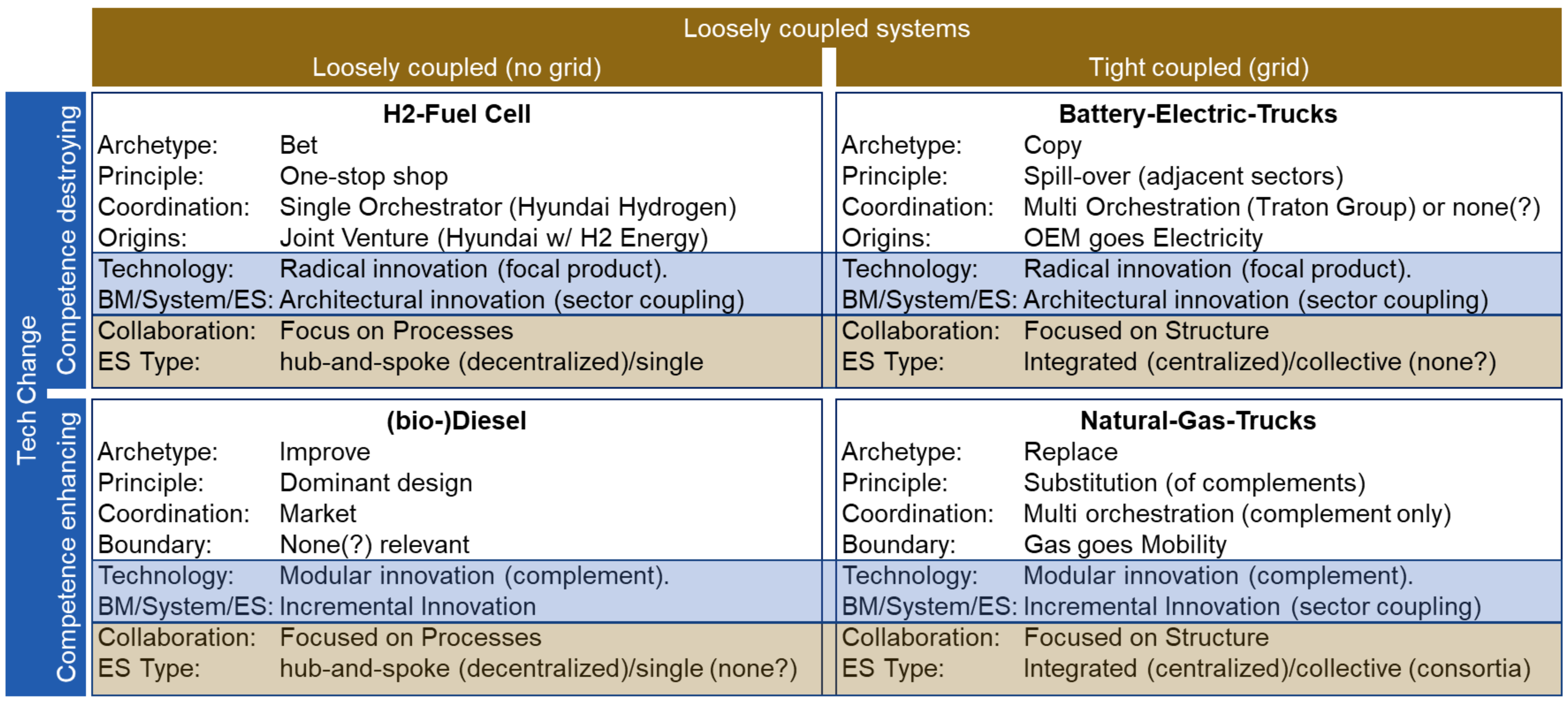
Data collection in two phases

1. Expert interviews to get an overview about the field (Delphi study)
2. Informant interviews to explore the purchase process of truck owners
   ➔ Started with phase 2

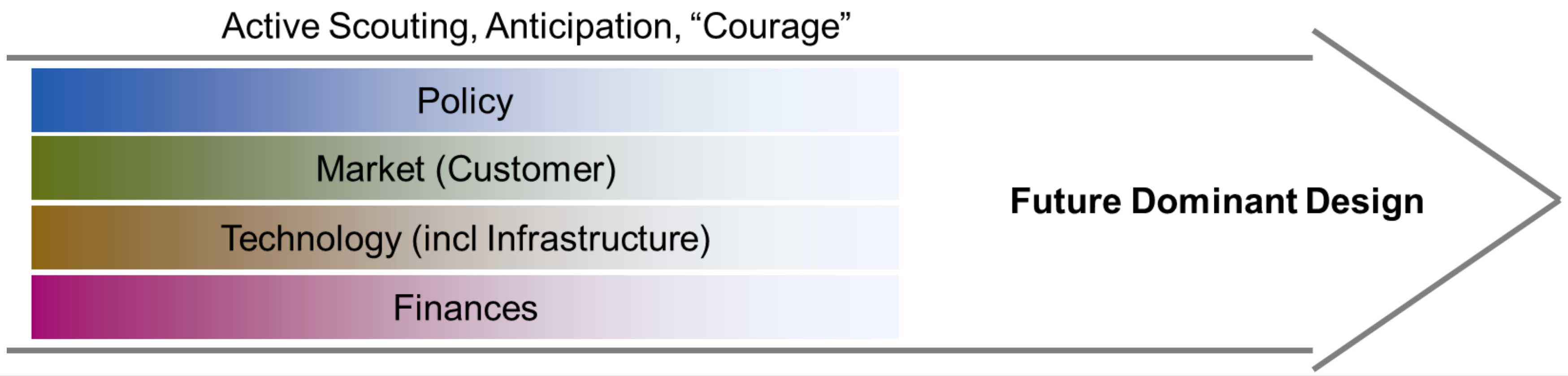
Actor Type	Counter
Authority	1
Association	2
Gas Stations	0 yet – do you have contacts?
OEM	5
Research Institutions	1
Suppliers	1
User	5
Total	**15**

3 Preliminary Results

- The ecosystem for road freight transportation relies on different coupling[2]. The coupling between actors derive from the complementors providing the energy for the powertrain (i.e., fuel, H2, [bio]gas, or electricity).
- The powertrain technologies require OEM to focus on technological change[3]. Focus on existing technologies for improvement (efficiency) or explore new technologies (effectiveness)
- Changes of the powertrain technology trigger changes in the ecosystem – new entries begin to compete with incumbents (new truck manufacturers vs. traditional truck OEM, utility firms vs. oil & gas firms)
- Active scouting by truck transport firm increases the openness towards new technologies.
- Proximity to the final customer, public procurement, and exemption from heavy vehicle charge tax (LSVA) are essential criteria that promote the adaptation of new technologies.



Tech Change	Loosely coupled systems Loosely coupled (no grid)	Loosely coupled systems Tight coupled (grid)
Competence destroying	**H2-Fuel Cell** Archetype: Bet Principle: One-stop shop Coordination: Single Orchestrator (Hyundai Hydrogen) Origins: Joint Venture (Hyundai w/ H2 Energy) Technology: Radical innovation (focal product). BM/System/ES: Architectural innovation (sector coupling) Collaboration: Focus on Processes ES Type: hub-and-spoke (decentralized)/single	**Battery-Electric-Trucks** Archetype: Copy Principle: Spill-over (adjacent sectors) Coordination: Multi Orchestration (Traton Group) or none(?) Origins: OEM goes Electricity Technology: Radical innovation (focal product). BM/System/ES: Architectural innovation (sector coupling) Collaboration: Focused on Structure ES Type: Integrated (centralized)/collective (none?)
Competence enhancing	**(bio-)Diesel** Archetype: Improve Principle: Dominant design Coordination: Market Boundary: None(?) relevant Technology: Modular innovation (complement). BM/System/ES: Incremental Innovation Collaboration: Focused on Processes ES Type: hub-and-spoke (decentralized)/single (none?)	**Natural-Gas-Trucks** Archetype: Replace Principle: Substitution (of complements) Coordination: Multi orchestration (complement only) Boundary: Gas goes Mobility Technology: Modular innovation (complement). BM/System/ES: Incremental Innovation (sector coupling) Collaboration: Focused on Structure ES Type: Integrated (centralized)/collective (consortia)



REFERENCES

1 cf. Murmann, J. P., & Schuler, B. A. (2023). Exploring the structure of internal combustion engine and battery electric vehicles: implications for the architecture of the automotive industry. *Industrial and Corporate Change*, *32*(1), 129-154.
2 Orton, J. D. & Weick, K. E. (1990). Loosely coupled systems: A reconceptualization. *Academy of Management Review*, *15*(2), 203-223.
3 Tushman, M. L. & Anderson, P. (1986). Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly, 311*, 439-465.

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Leveraging electrolyzer modularity to reduce renewable hydrogen production costs

Work package 6

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OBJECTIVES

- Assess quantitatively the contribution of three cost-reduction mechanism (economies of scale, learning by doing, technology performance improvements) to the evolution of renewable hydrogen costs
- Evaluate alternative scaling-up pathways and plant-design strategies for water electrolysis based on distributed and centralized renewable hydrogen production
- Analyze the impact of low and high hydrogen demand levels and the sensitivity of cost evolution pathways to parametric uncertainty

CONTRIBUTION TO PATHFDNR

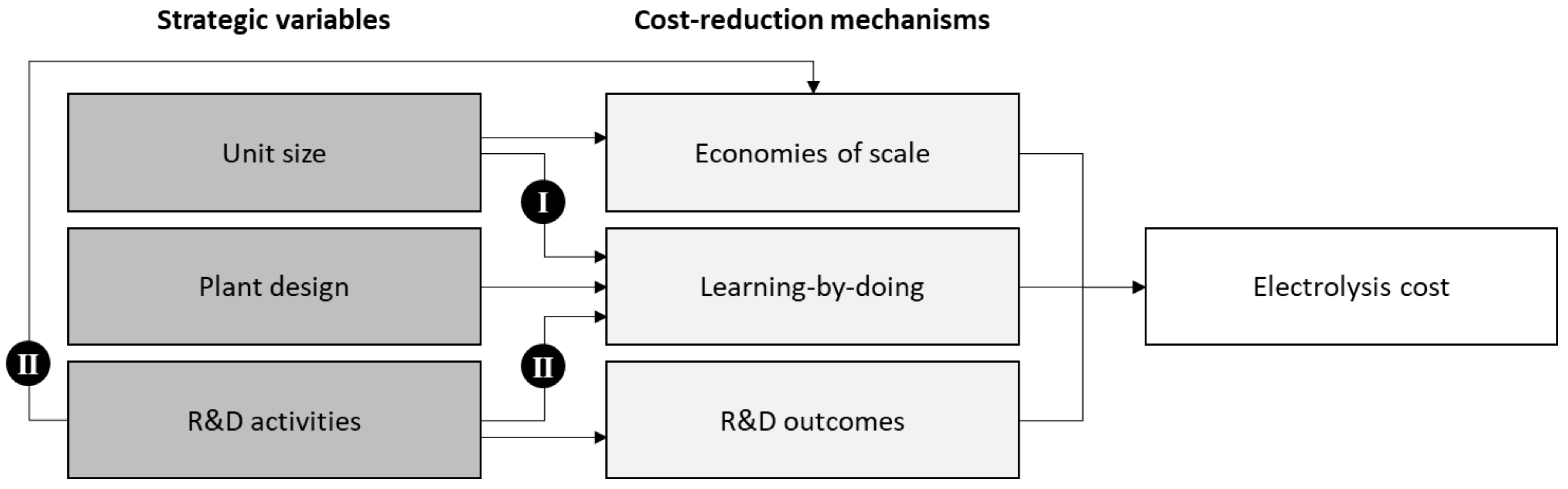
- Renewable hydrogen is a potential solution for the decarbonization of hard-to-abate sectors and could contribute to Switzerland's energy security[1] and economy[2]
- However, hydrogen from water electrolysis powered with renewable electricity remains costly and scarce in Switzerland and abroad[3]
- Policymakers and practitioners can choose to prioritize different cost-reduction mechanisms and scaling-up strategies, each with specific opportunities, risks, and trade-offs

METHODOLOGY

The evolution of renewable hydrogen production costs is simulated using a **techno-economic model** than considers economies of scale, learning by doing, and technology improvements at the water electrolysis plant system and component level.

Water electrolysis plants have four main components: electrolyzers, power supply, gas conditioning, and balance of plant.

Each component has an associated scaling factor and experience curve. Technology performance improvements from innovation efforts are aggregated in the overall system efficiency and stack lifetime.



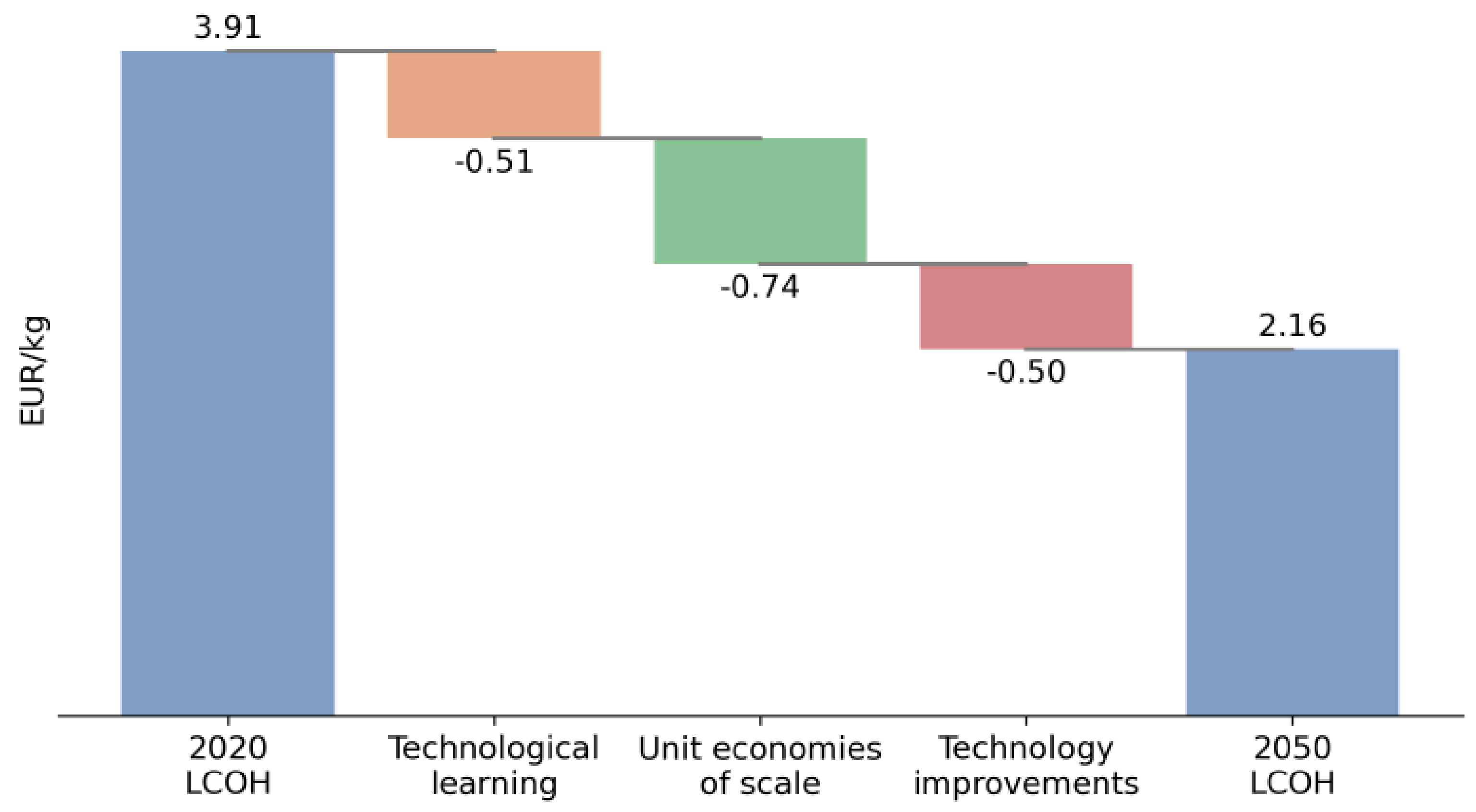
Conceptual representation of the techno-economic model and the three strategic variables considered.

PRELIMINARY RESULTS

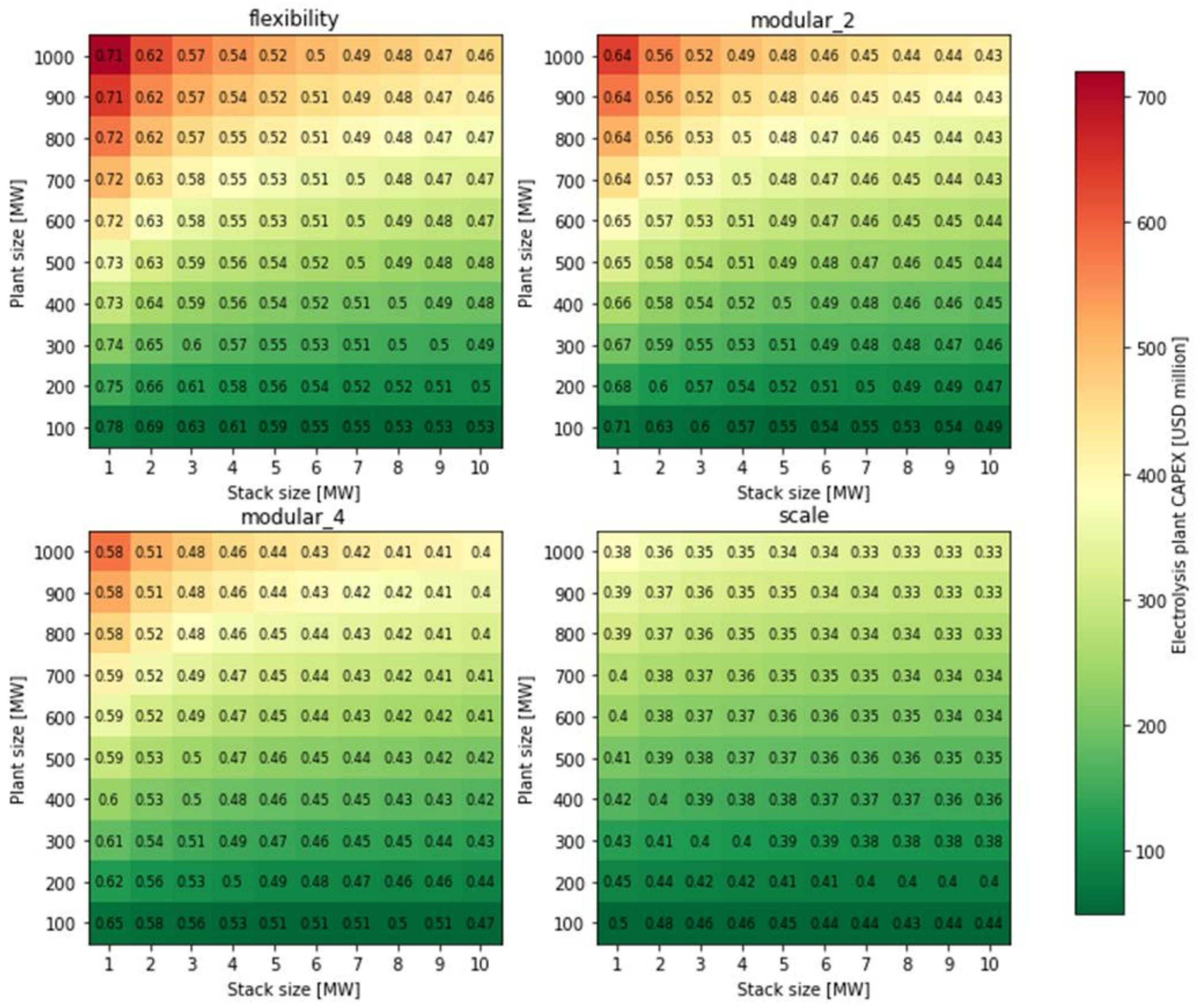
Reference case: 1 GW electrolysis plant, 10 MW electrolyzers

Alternative plant-design strategies strategies:

- Flexibility (1 electrolyzer : 1 power supply block)
- Modular 2 (2:1)
- Modular 4 (4:1)
- Scale (N:1)



Contribution of cost-reduction mechanisms in the reference case (preliminary)



flexibility

Plant size [MW]	1	2	3	4	5	6	7	8	9	10
1000	0.71	0.62	0.57	0.54	0.52	0.5	0.49	0.48	0.47	0.46
900	0.71	0.62	0.57	0.54	0.52	0.51	0.49	0.48	0.47	0.46
800	0.72	0.62	0.57	0.55	0.52	0.51	0.49	0.48	0.47	0.47
700	0.72	0.63	0.58	0.55	0.53	0.51	0.5	0.48	0.47	0.47
600	0.72	0.63	0.58	0.55	0.53	0.51	0.5	0.49	0.48	0.47
500	0.73	0.63	0.59	0.56	0.54	0.52	0.5	0.49	0.48	0.48
400	0.73	0.64	0.59	0.56	0.54	0.52	0.51	0.5	0.49	0.48
300	0.74	0.65	0.6	0.57	0.55	0.53	0.51	0.5	0.5	0.49
200	0.75	0.66	0.61	0.58	0.56	0.54	0.52	0.52	0.51	0.5
100	0.78	0.69	0.63	0.61	0.59	0.55	0.55	0.53	0.53	0.53

modular_2

Plant size [MW]	1	2	3	4	5	6	7	8	9	10
1000	0.64	0.56	0.52	0.49	0.48	0.46	0.45	0.44	0.44	0.43
900	0.64	0.56	0.52	0.5	0.48	0.46	0.45	0.45	0.44	0.43
800	0.64	0.56	0.53	0.5	0.48	0.47	0.46	0.45	0.44	0.43
700	0.64	0.57	0.53	0.5	0.48	0.47	0.46	0.45	0.44	0.43
600	0.65	0.57	0.53	0.51	0.49	0.47	0.46	0.45	0.45	0.44
500	0.65	0.58	0.54	0.51	0.49	0.48	0.47	0.46	0.45	0.44
400	0.66	0.58	0.54	0.52	0.5	0.49	0.48	0.46	0.46	0.45
300	0.67	0.59	0.55	0.53	0.51	0.49	0.48	0.48	0.47	0.46
200	0.68	0.6	0.57	0.54	0.52	0.51	0.5	0.49	0.49	0.47
100	0.71	0.63	0.6	0.57	0.55	0.54	0.55	0.53	0.54	0.49

modular_4

Plant size [MW]	1	2	3	4	5	6	7	8	9	10
1000	0.58	0.51	0.48	0.46	0.44	0.43	0.42	0.41	0.41	0.4
900	0.58	0.51	0.48	0.46	0.44	0.43	0.42	0.42	0.41	0.4
800	0.58	0.52	0.48	0.46	0.45	0.44	0.43	0.42	0.41	0.4
700	0.59	0.52	0.49	0.47	0.45	0.44	0.43	0.42	0.41	0.41
600	0.59	0.52	0.49	0.47	0.45	0.44	0.43	0.42	0.42	0.41
500	0.59	0.53	0.5	0.47	0.46	0.45	0.44	0.43	0.42	0.42
400	0.6	0.53	0.5	0.48	0.46	0.45	0.45	0.43	0.43	0.42
300	0.61	0.54	0.51	0.49	0.47	0.46	0.45	0.45	0.44	0.43
200	0.62	0.56	0.53	0.5	0.49	0.48	0.47	0.46	0.46	0.44
100	0.65	0.58	0.56	0.53	0.51	0.51	0.51	0.5	0.51	0.47

scale

Plant size [MW]	1	2	3	4	5	6	7	8	9	10
1000	0.38	0.36	0.35	0.35	0.34	0.34	0.33	0.33	0.33	0.33
900	0.39	0.37	0.36	0.35	0.35	0.34	0.34	0.33	0.33	0.33
800	0.39	0.37	0.36	0.35	0.35	0.34	0.34	0.34	0.33	0.33
700	0.4	0.38	0.37	0.36	0.35	0.35	0.35	0.34	0.34	0.34
600	0.4	0.38	0.37	0.37	0.36	0.36	0.35	0.35	0.34	0.34
500	0.41	0.39	0.38	0.37	0.37	0.36	0.36	0.36	0.35	0.35
400	0.42	0.4	0.39	0.38	0.38	0.37	0.37	0.37	0.36	0.36
300	0.43	0.41	0.4	0.4	0.39	0.39	0.38	0.38	0.38	0.38
200	0.45	0.44	0.42	0.42	0.41	0.41	0.4	0.4	0.4	0.4
100	0.5	0.48	0.46	0.46	0.45	0.44	0.44	0.43	0.44	0.44

Cost-comparison across plant-design and scale-up strategies (preliminary)

REFERENCES

1 Energy Science Center ETH Zurich, 2023. Energy security in a net zero emissions future for Switzerland. *White Paper.* https://esc.ethz.ch/expert-groups/security-of-supply.html
2 Gupta, R., Guibentif, T.M., Friedl, M., Parra, D. and Patel, M.K., 2023. Macroeconomic analysis of a new green hydrogen industry using Input-Output analysis: The case of Switzerland. Energy Policy, 183, p.113768. https://doi.org/10.1016/j.enpol.2023.113768
3. Lux, B. and Pfluger, B., 2020. A supply curve of electricity-based hydrogen in a decarbonized European energy system in 2050. Applied Energy, 269, p.115011. https://doi.org/10.1016/j.apenergy.2020.115011

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PATHFNDR

Co-designing optimal policy mixes and energy systems for decarbonization

Work package 7

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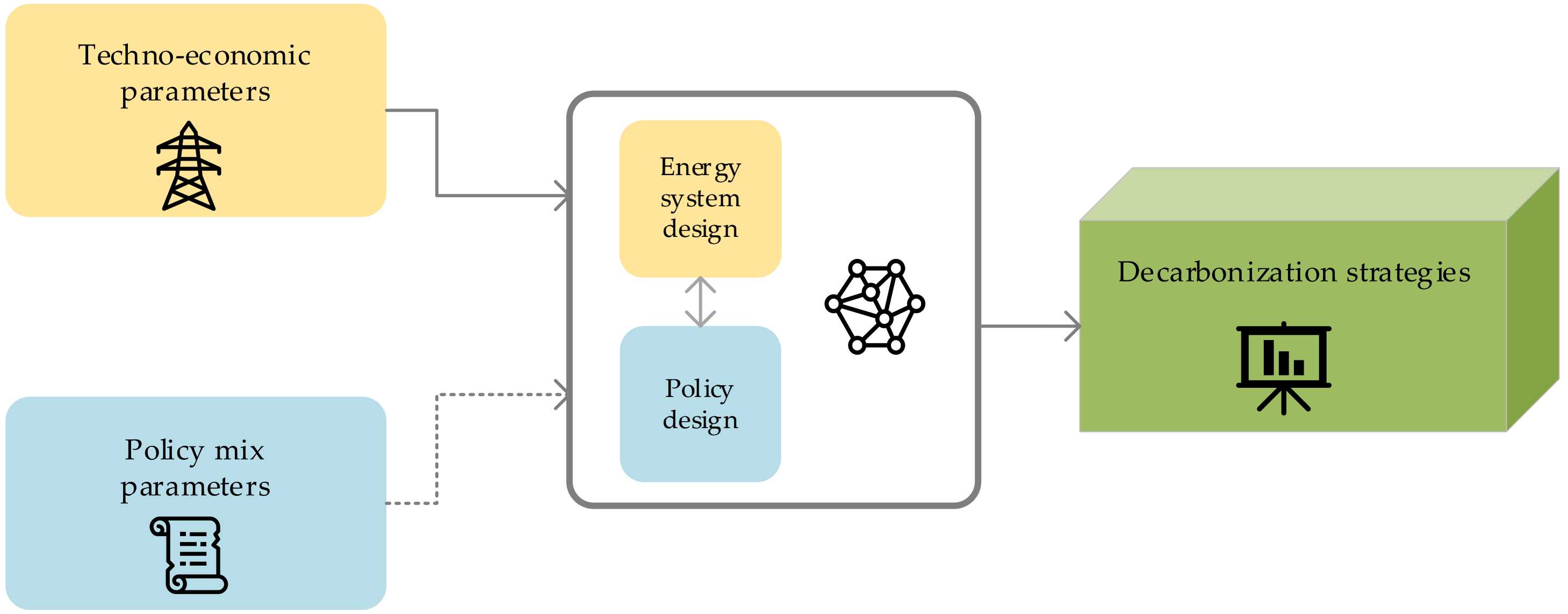
1 Motivation

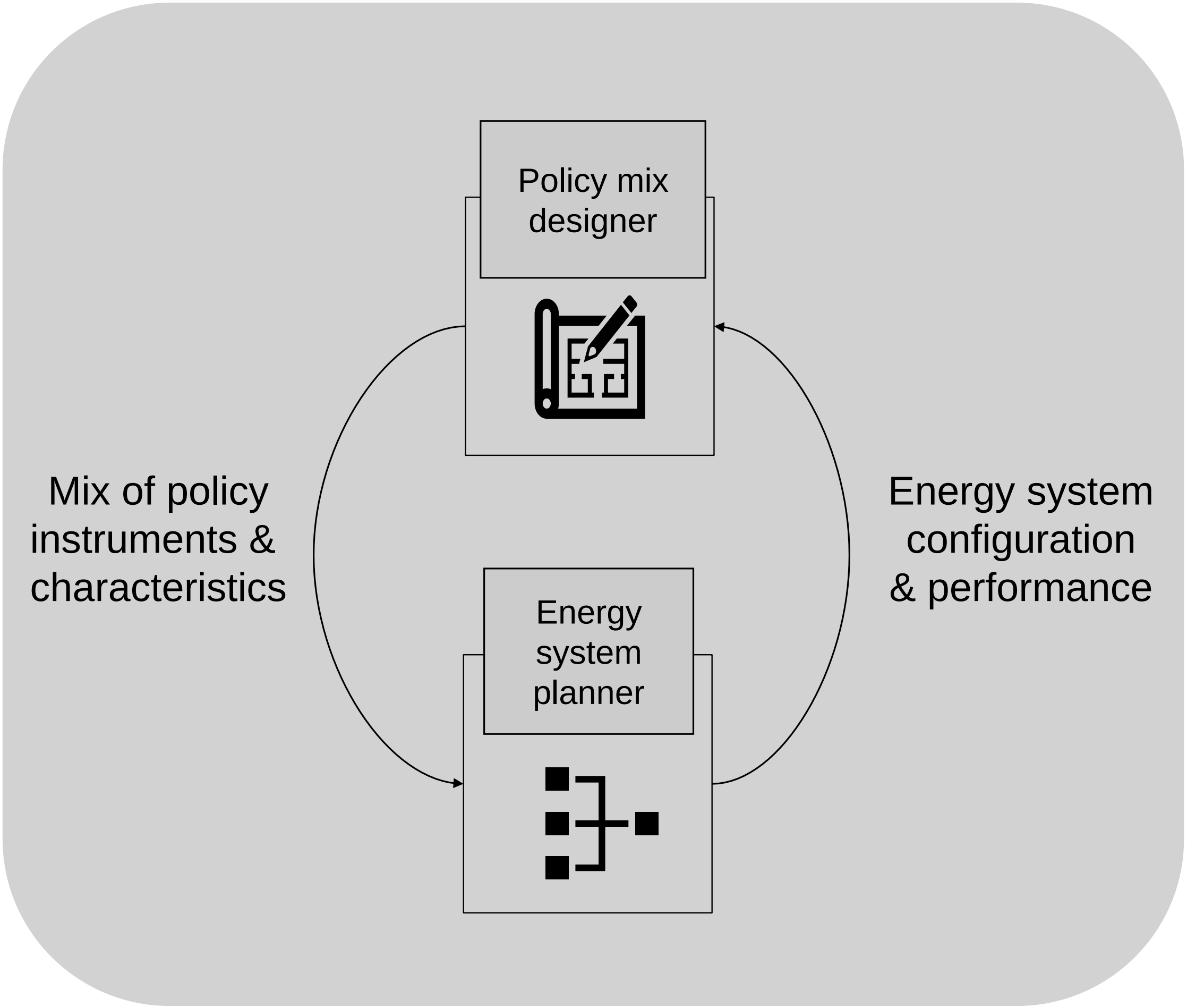
- Decarbonizing our energy systems requires **policy mixes** that address both supply and demand in various sectors, which a single policy instrument cannot achieve.
- To design effective policy mixes, it is crucial to have appropriate tools, particularly to account for the interaction between the **policies** and the **socio-technical system**[2].
- **Energy System Models** (ESMs) are extensively used quantitative tools that can provide ex-ante analysis, enabling policymakers to evaluate the impact of policies on various metrics



How can policy mixes and energy system transformations be co-designed using ESMs, to ensure a successful and cost-efficient decarbonization of energy systems?

2 Methodology - MANGOpol

- Our study presents a new methodology to optimally **co-design policy mixes and energy systems**: **MANGOpol**.
- MANGOpol goes beyond a single decision-maker perspective and incorporates **policy decisions endogenously** to an ESM, not only accounting for which policies to implement, but also when to do so.
- Two modules constitute MANGOpol: the **Energy System Planner** (ESP), which represents the **techno-economic** energy system and is built using the MANGO[3] model; and the **Policy Mix Designer** (PMD), which represents the **policy mix configurations.**
- The goal of the **ESP** is to **minimize system cost**, whereas, for the **PMD,** its multi-objective is both minimize CO_2 and ensure that policies are cost-efficient, i.e. minimizing the total societal cost.
- The two modules operate using **bi-level optimization**, with a metaheuristic algorithm in the PMD (which acts as the leader) and mixed-integer linear program (MILP) in the ESP.



Policy mix designer

Mix of policy instruments & characteristics

Energy system configuration & performance

Energy system planner

3 Results: testing phase on fictitious case

- Currently working with a **fictitious case study** based on Swiss data to showcase the model's potential, including heating and electricity systems with potential sector-coupling technologies such as heat pumps
- Policies includes a CO_2 tax and subsidies for RES, storage, district heating expansion and heat pumps., technology installment and operation bans, work capacity expansion, and demand reduction through energy efficiency measures.
- Initial results for the fictitious case study show confirm that a policy mix approach is more cost-efficient than a single policy such as a carbon price.
- MANGOpol is able to identify **when** and **how stringent** should the **policy** decisions be, to decarbonize the energy system **at a minimum cost** throughout all the Pareto front of solutions.
- Additionally, other goals can be included in the model, such as minimizing government expenditure or aiming for a balanced policy mix.
- Further analysis will use MANGOpol to identify suitable policy mixes for effective decarbonization of the Swiss electricity system and the Swiss building sector.

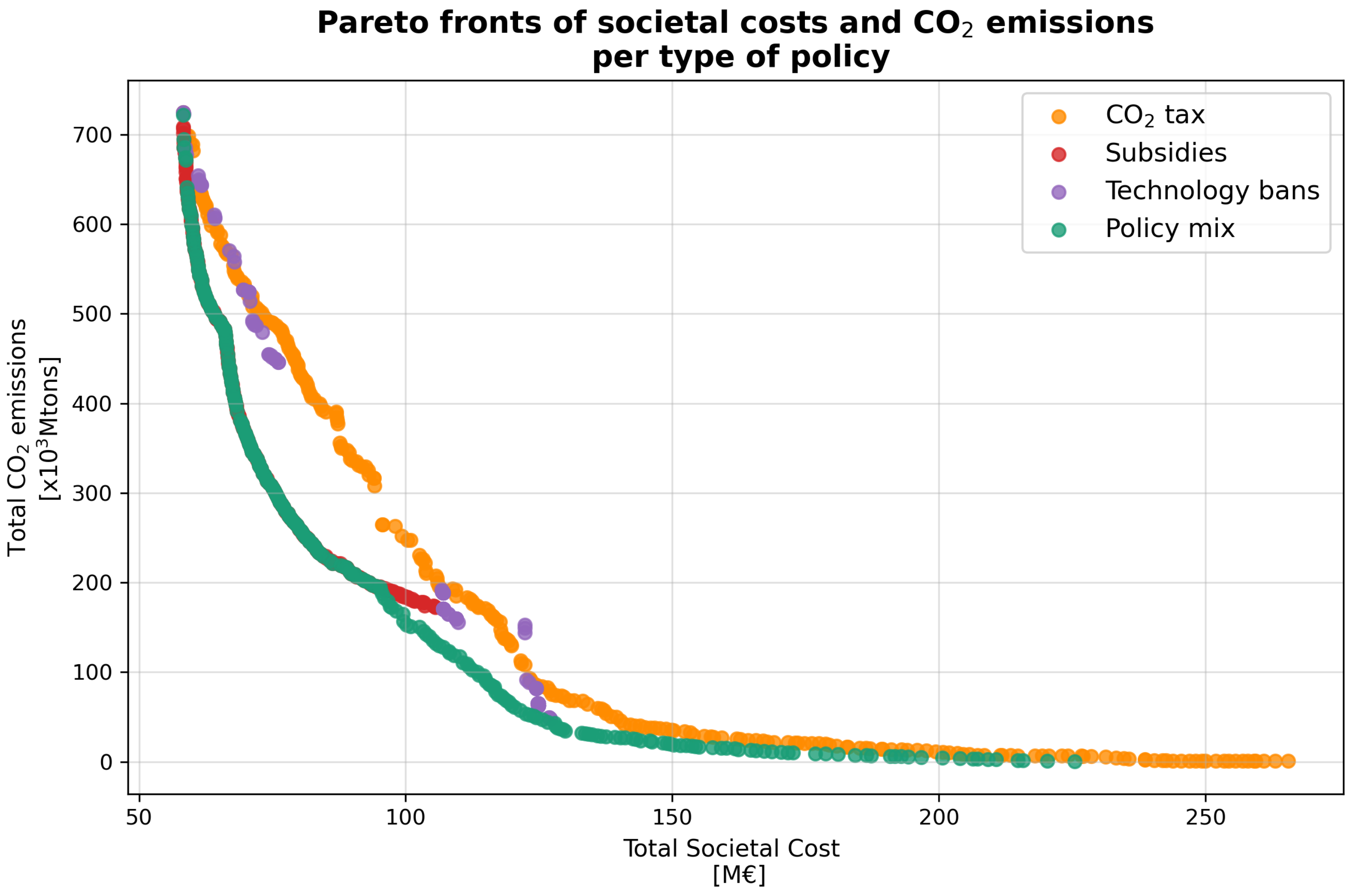


Figure 1: Pareto fronts of minimum societal cost and minimum CO_2 emissions when using only a CO2 tax, subsidies, technology bans or a Policy mix. Note that each of the points of the pareto front represents a different policy mix and energy system configuration. Own elaboration.

REFERENCES

1 Rosenbloom, D., Markard, J., Geels, F. & Fuenfschilling, L. (2020). Why carbon pricing is not sufficient to mitigate climate change—and how "sustainability transition policy" can help. Proceedings of the National Academy of Sciences, 117.

2 Edmondson DL, Kern F, Rogge KS. (2019) The co-evolution of policy mixes and socio-technical systems: Towards a conceptual framework of policy mix feedback in sustainability transitions. Research Policy, 48.

3 Mavromatidis G, Petkov I. (2021). MANGO: A novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems. Applied Energy, 288.

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PATHFNDR

SWEET P+D nanoverbund

Work package 5

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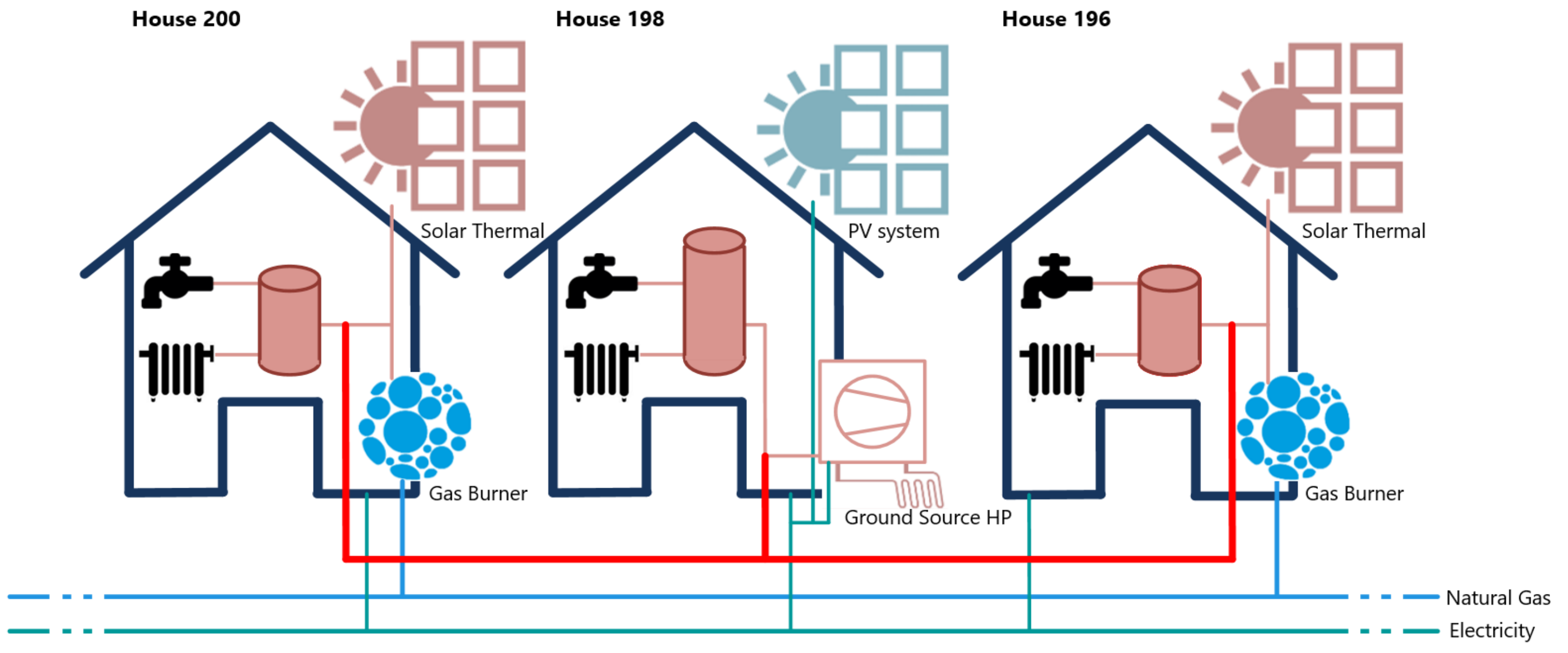
Project motivation

The conceptual idea behind a nanoverbund is to **thermally connect close-by buildings**. This thermal connection allows for an energy exchange between the participating buildings, similarly to "prosumer communities" (ger. ZEV – Zusammenschluss zum Eigenverbrauch) which are exchanging electrical energy behind a common metering point. Especially in cases where the connected buildings **possess different** heating **systems** and/or renewable energy sources and storages, or differing energy demand profiles, interconnecting individual systems leads to synergies between the buildings, and may benefit the distribution grid operators supplying them.

Pilot Set up



Project description

Heating systems in buildings are designed to provide sufficient heating for the coldest expected days of the year. So, for most parts they are **underutilized**. A retrofitted nanoverbund can also provide **more flexibility potential** to upper layer distribution grid operators or energy providers.

Especially in the presence of heterogeneous building energy systems, energy storage and conversion technology can be utilized for the benefit of all parties/stakeholders. A pilot site installation of three buildings in the City of Basel shall be operated by a flexibility aware control scheme in order to demonstrate the potential of the nanoverbund concept.

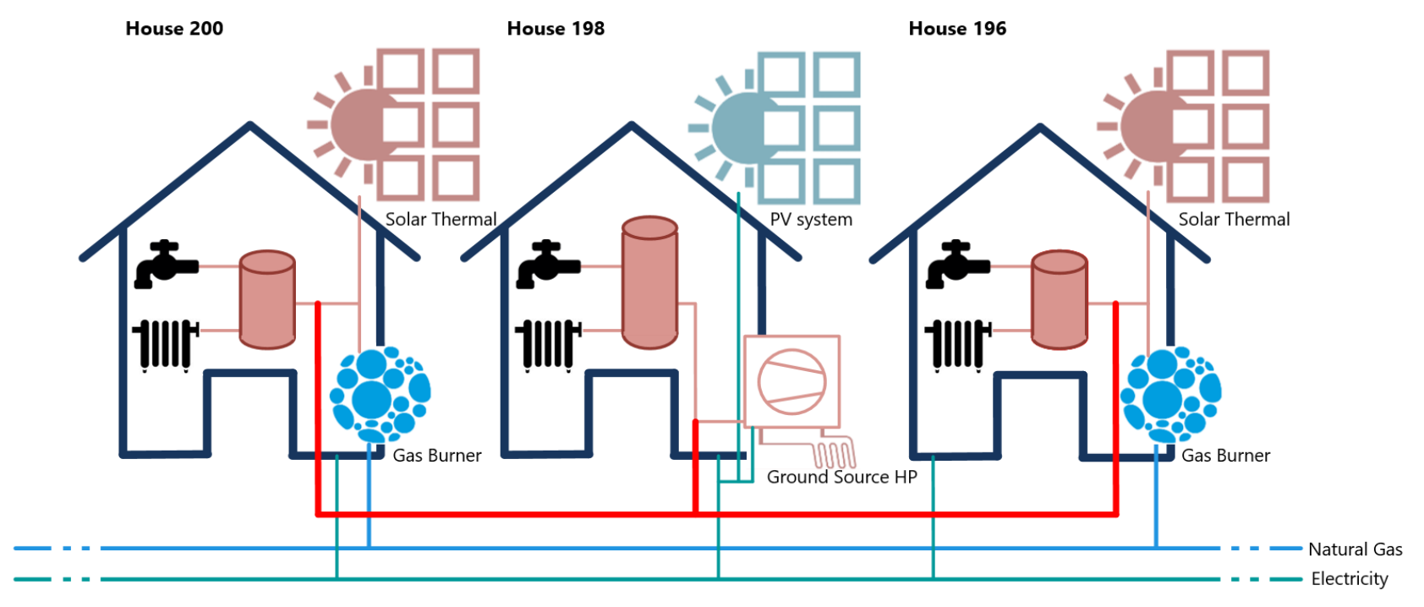
Additionally to that, a **stakeholder ecosystem** study is conducted to understand the key aspect of each involved party.

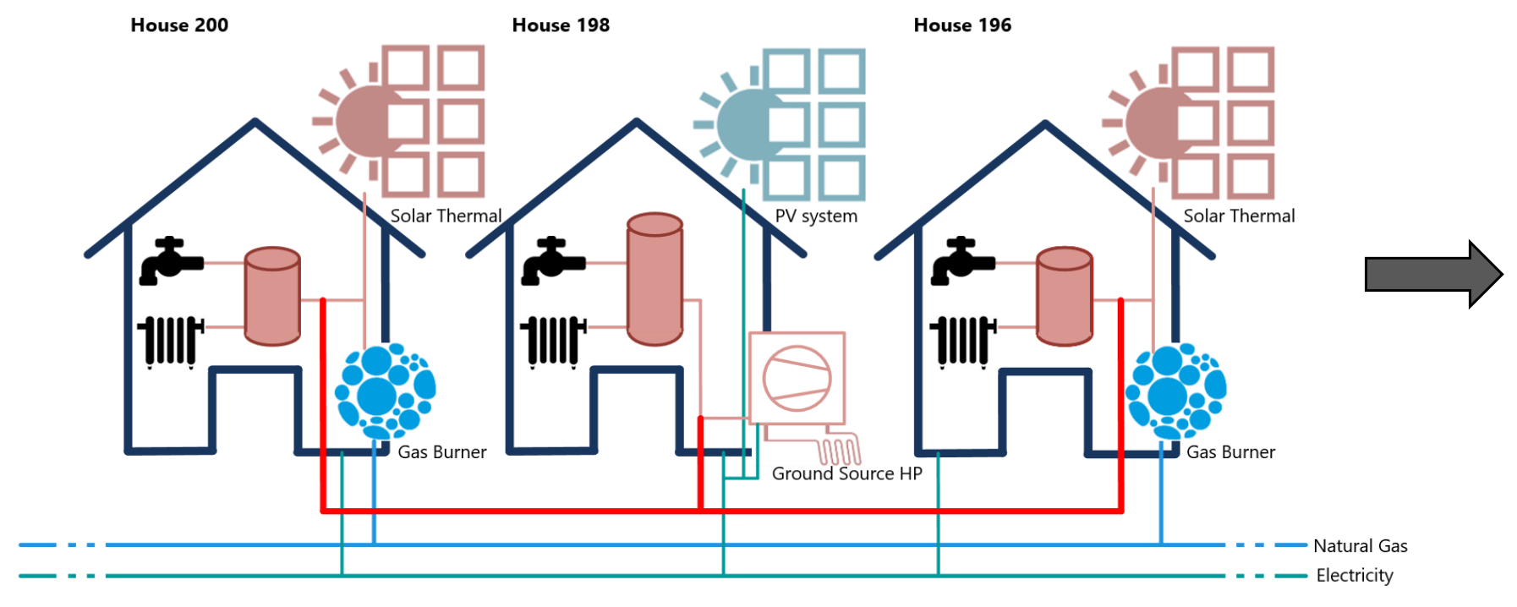
In this project, the benefits of thermally connecting close-by buildings shall be investigated, quantified and **demonstrated**. Additionally, the necessary requirements for an overall economical case are analyzed.

Q1: What technology mix and technology setting lead to an economical and ecological nanoverbund?
Q2: Who has to engage with whom and when?
Q3: How to enable fairness between participants?
Q4: How does the gained flexibility aggregate on DSO level/can it reliably be utilized with benefits for all parties involved

Tie in to PATHFNDR and other projects

PATHFNDR	WP1	Scenario constraints; Scenario settings
	WP2	Demand profiles
	WP3	Techno. model
	WP6	Background/Business Models for Ecosystem study
	WP7	Constraints due to policy shifts
Edge		Building demand data, renewables potential
DeCarbCH		Thermal network inputs
NCCR Automation		Coordination of decentral multi energy hubs
S-DSM		Flexibility aware control framework





Adapted flexibility estimates	WP1	PATHFNDR
Demand validation data	WP2	
Model validation data	WP3	
Ecosystem considerations	WP6	
Success stories	WP9 (KTT)	
Adapted flexibility estimates	Edge	
Thermal validation data	DeCarbCH	
Benchmarking data on Decentral control	NCCR Automation	
Data-workflow for automated data extraction billing	Sympheny	
Pilot Validation, roadmap for rollout, potential analysis	IWB	

nanoverbund KPIs

CHF
flexpot
CO2_eq
flexDSO

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PATHFNDR

High-fidelity modeling for sector coupling and flexibility assessment in planning and operation: a case study of hydrogen generation site

Work package 3

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[1]Urban Energy Systems Laboratory, Empa, Dübendorf, Switzerland

1 INTRODUCTION AND OBJECTIVES

This work deals with cost-effective generation of hydrogen and flexibility provision from hydrogen generation sites. The following research questions were addressed:

Q1 – does the adoption of high-fidelity models affect the identified optimal design?

Q2 – how much can waste heat recovery reduce the levelised cost of hydrogen?

Q3 – how much flexibility can an hydrogen generation site provide?

2 CONTRIBUTIONS TO PATHFDNR

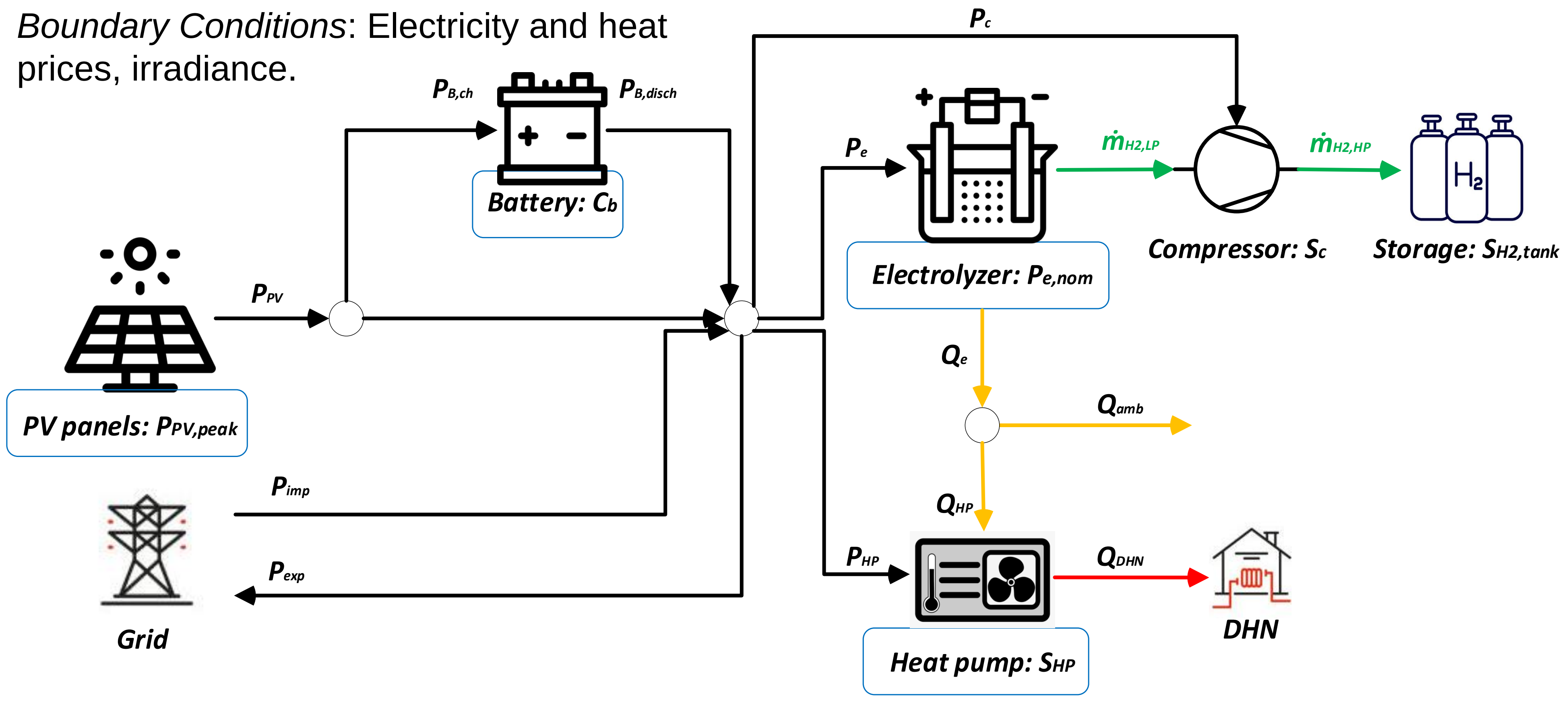
C1 – planning phase: under the hypothesis of perfect predictions, development of a numerical tool for the optimal sizing and operation of hydrogen generation sites and study of the impact of modelling level of fidelity;

C2 – planning phase: assessment of the economical benefits from sector coupling between hydrogen generation sites and district heating networks;

C3 – operational phase: quantification of flexibility provision from the operation of an hydrogen generation site and development of flexible control strategies;

3 METHODOLOGY – ENERGY SYSTEM AND NUMERICAL TOOLS

Boundary Conditions: Electricity and heat prices, irradiance.



Planning phase: perfect forecasts.

Mixed integer linear programming (**MILP**) for the minimization of the levelised cost of hydrogen with the key components sizes and operational variables as design variables;
A desired hydrogen production of 100 kg/day is targeted;
Use of high-fidelity models from manufactures and literature [1];

Analysis of the operation of a representative case study

Operational phase: case study of MOVE [2].

MOVE is a refuelling station for hydrogen vehciles with a PEM electrolyser of 186 kW.
MILP for operational cost minimization with PWA functions calibrated over historical data;
Quantification of flexibility through flexibility envelope [3].

4 PLANNING PHASE – OPTIMAL DESIGN

4.1 Use of high-fidelity models

The optimal sizes are compared for different modelling level of fidelity for the electrolyzer efficiency, η_e,with the symbol *n* indicating the number of breakpoints for the PWA approximation.

The optimal configuration converges for *n*≥2, indicating that n=2 ensures results that are not affected by the to the modelling level of fidelity.

Optimal components’ sizes and capacities

η_e [-]	$P_{PV, peak}$ [kW]	S_{HP} [kW]	C_b [kWh]	$P_{e,nom}$ [kW]
Fixed (nominal)	2480	90	200	360
Linear	2480	94	200	370
n=1	2480	96	200	380
n=2	2480	95	200	380
n=5	2480	95	200	380
n=10	2480	95	200	380

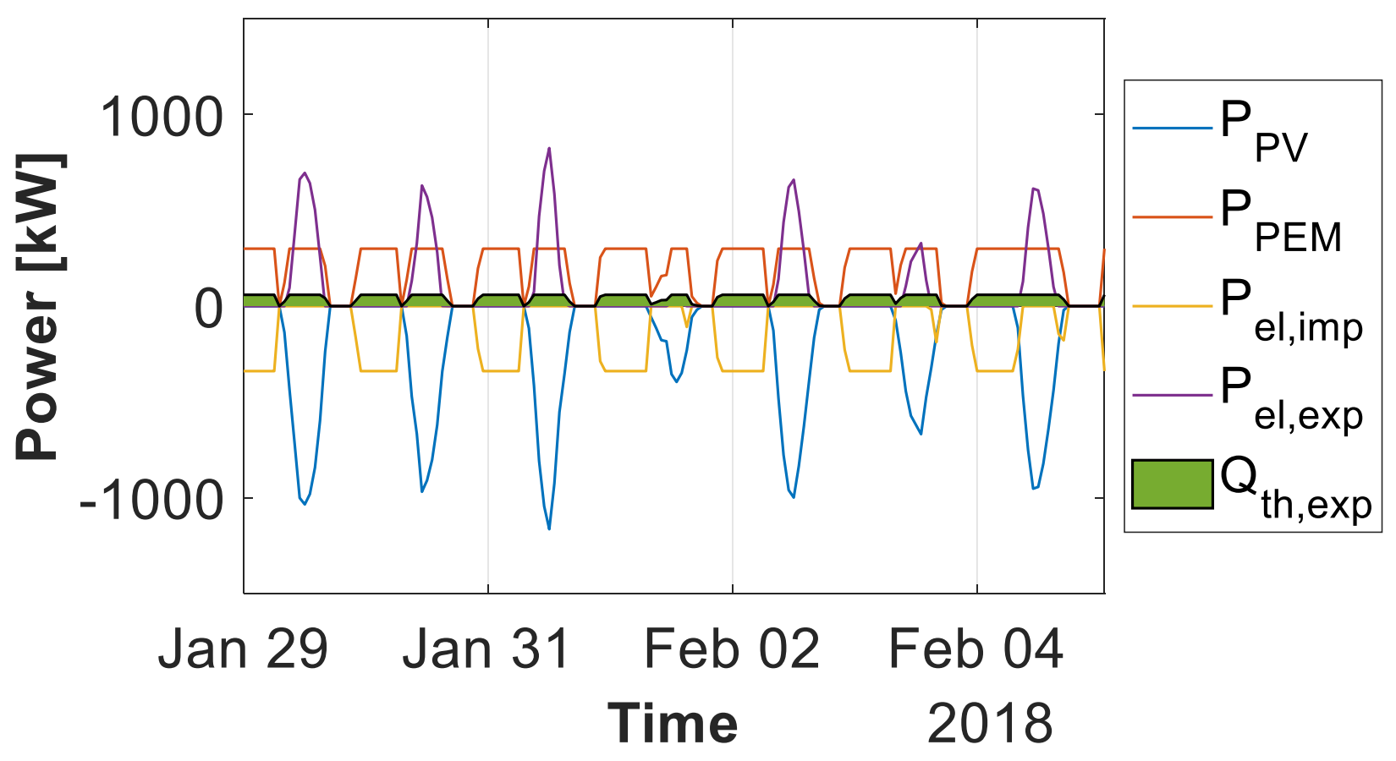
4.2 Benefits from sector coupling

A final LCOH=6.49 CHF/kg is predicted;

The waste heat recovery (WHR) ensure 12.19 kCHF/year of revenues which reduces the LCOH by -2.8% compared to solutions without WHR.

During winter season, heat is always injected in the district heating network when the electrolyzer is operating (figure on the right);

313 MWh$_{th}$/year injected into the DHN.

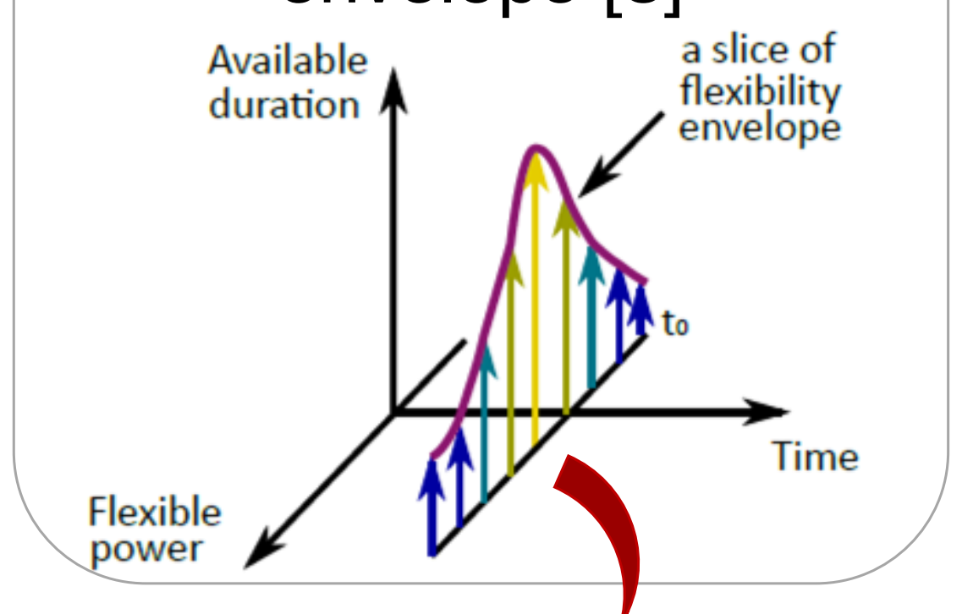


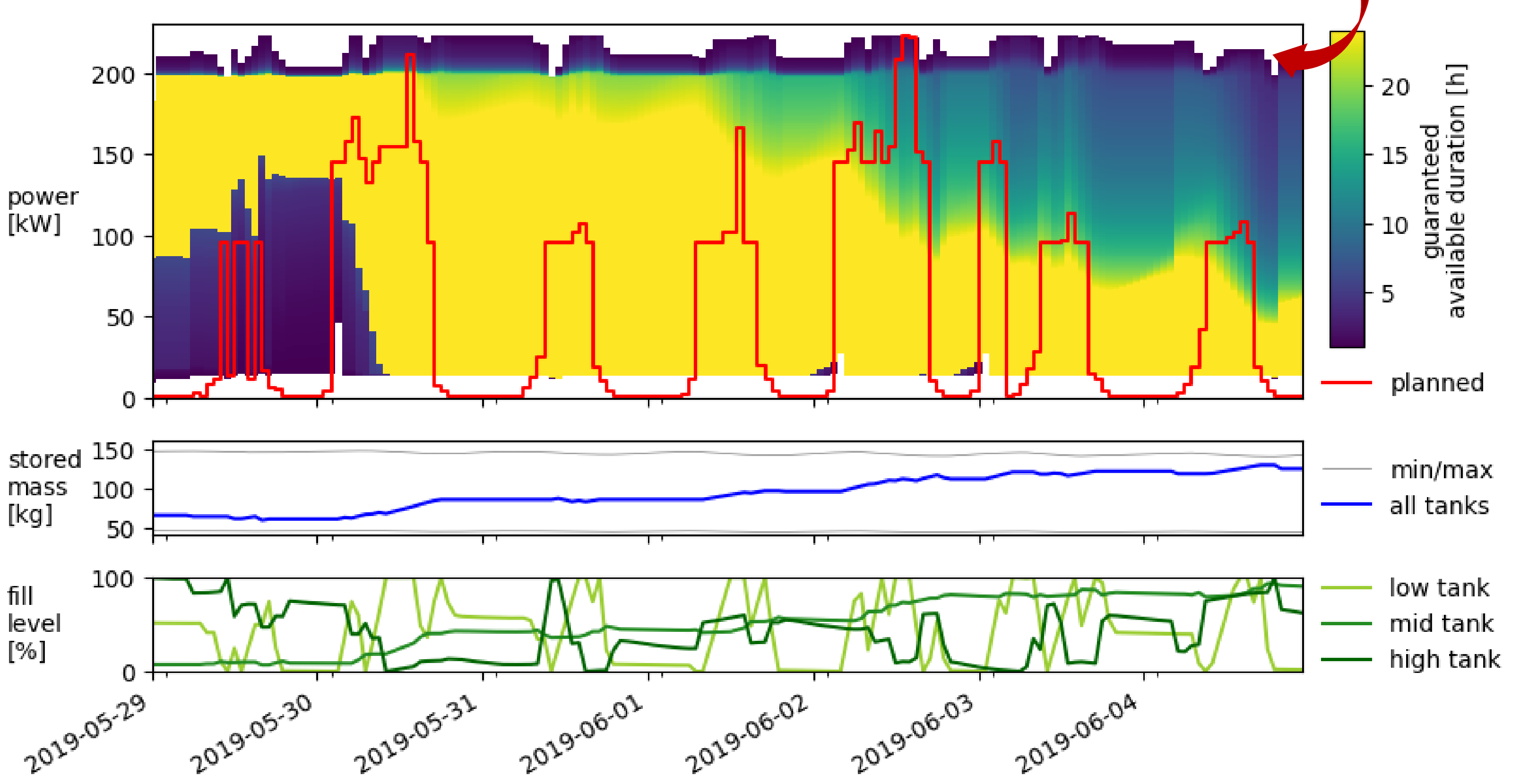
5 OPERATIONAL PHASE – FLEXIBILITY PROVISION

When high fill level are measured in the storage tanks, the **maximum power can be provided for short times**;

The lower power bound has very **sharp drops** in guaranteed duration when going from one power level to the next. This is due to the non-convex energy bounds;

The concept of flexibility envelope [3]





REFERENCES

1 Gabrielli et al., Electrochemical conversion technologies for optimal design of decentralized multi-energy systems: Modeling framework and technology assessment, 2018
2 MOVE – mobility of the future, https://www.empa.ch/web/move
3 Gasser et al., Predictive energy management of residential buildings while self-reporting flexibility envelope, 2021

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PATHFNDR

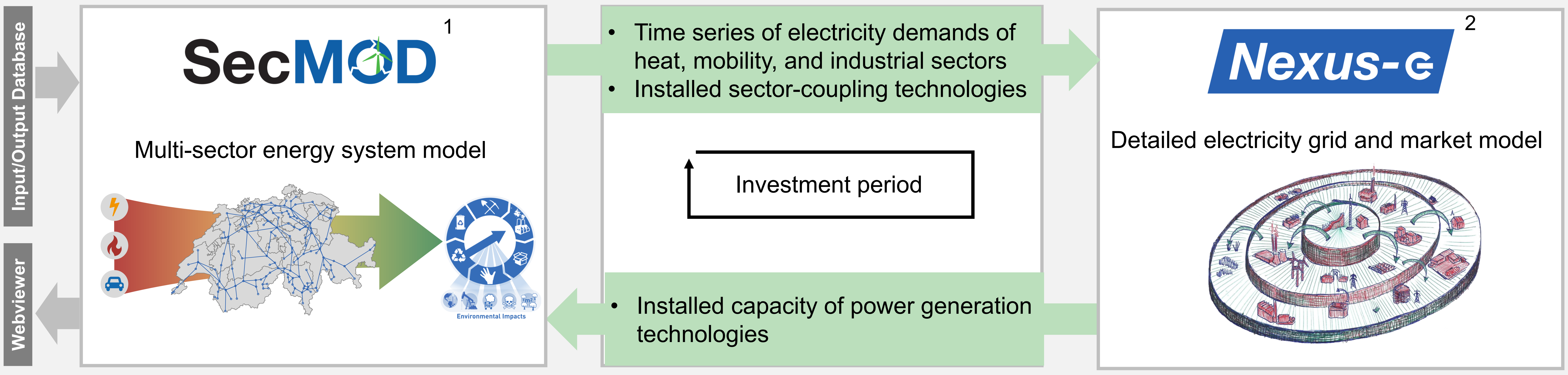
Integrating Detailed Electricity Grid and Sector-Coupled Energy System Models:
An Update on the Nexus-e + SecMOD Integration

Work package 1: Pathways on a national and international scale

Patricia Mayer[1], Florian Joseph Baader[1], Jared Garrison[2], Johan Nöthinger[1], André Bardow[1]

[1]Energy and Process Systems Engineering, Department of Mechanical and Process Engineering, ETH Zurich
[2]Research Center for Energy Networks, ETH Zurich

Concept for the integration: Soft-linking of Nexus-e and SecMOD for transition pathway development



Multi-sector energy system model

- Time series of electricity demands of heat, mobility, and industrial sectors
- Installed sector-coupling technologies

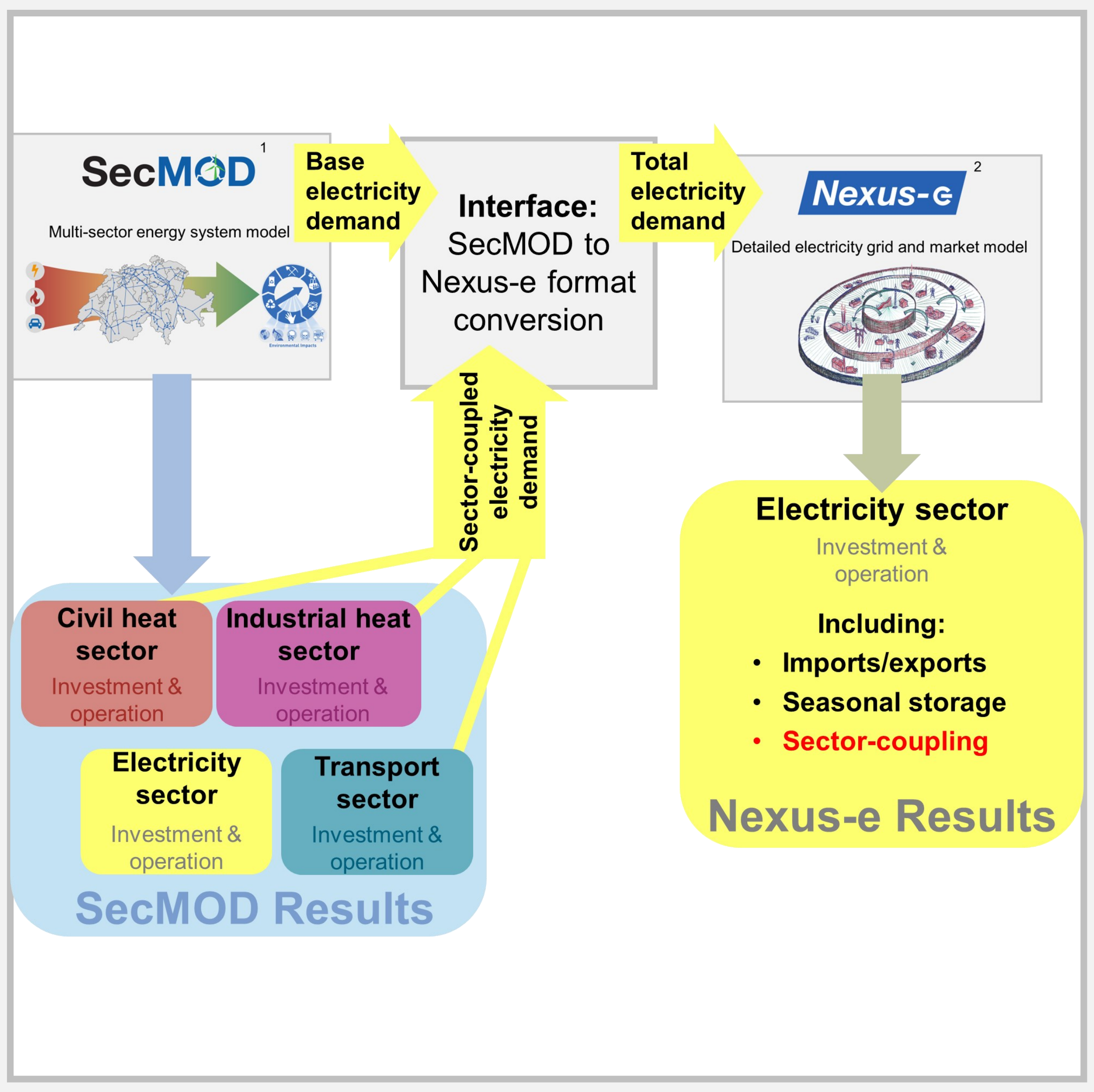
Investment period

- Installed capacity of power generation technologies

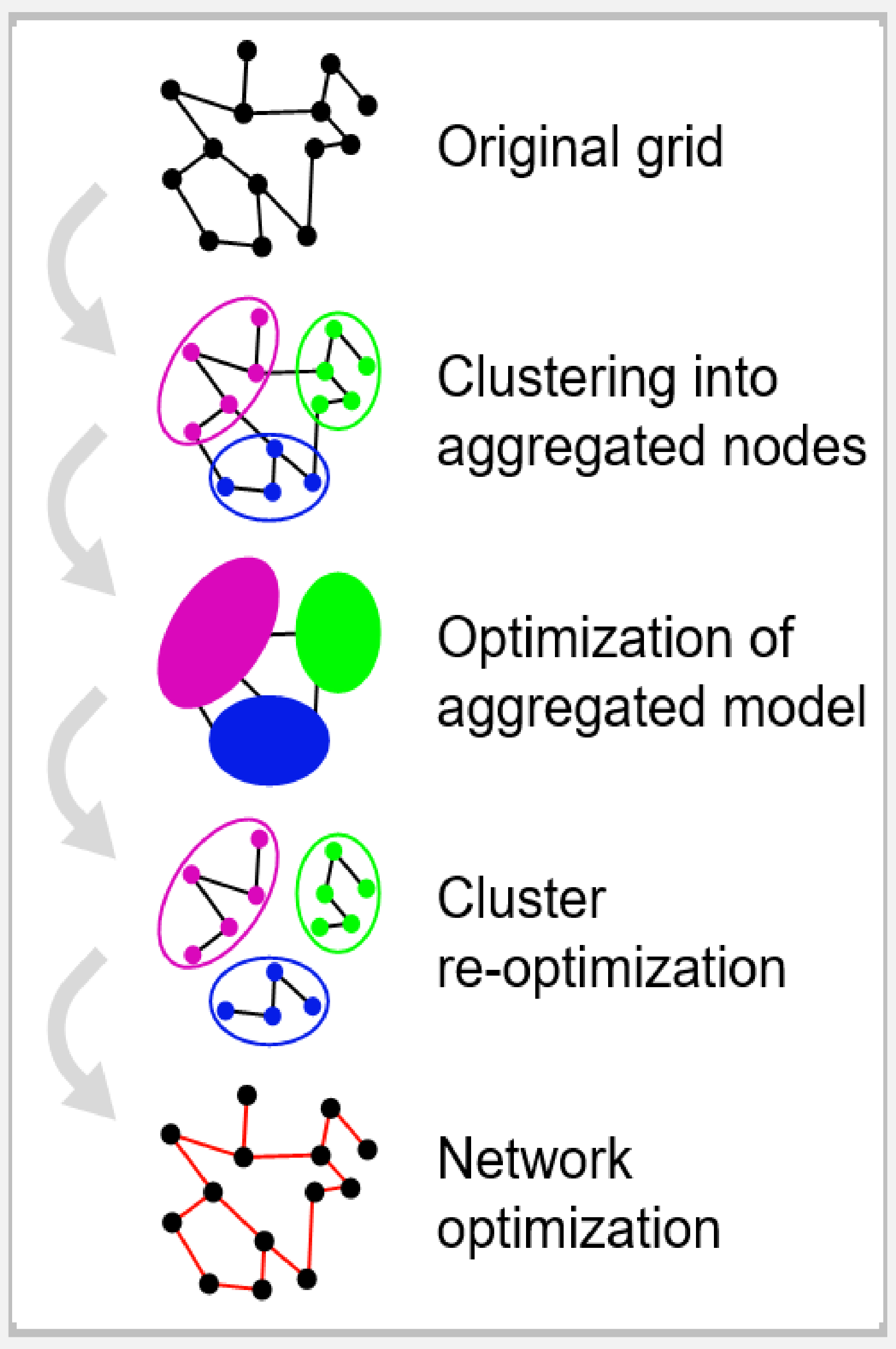
Detailed electricity grid and market model

Progress of the integration

Phase 1: One-way connection



Tailored spatial aggregation and disaggregation in SecMOD[3]



Original grid

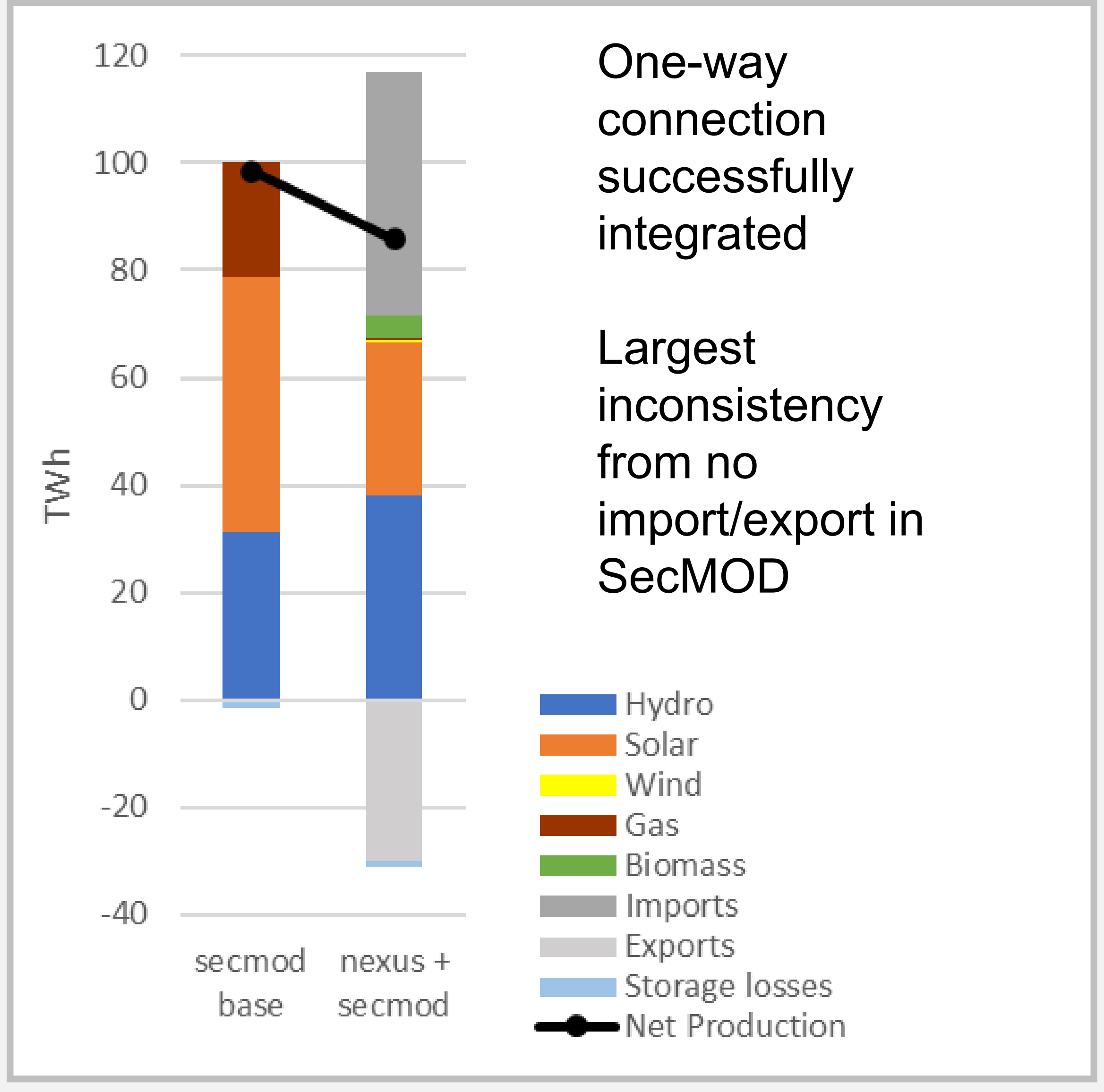
Clustering into aggregated nodes

Optimization of aggregated model

Cluster re-optimization

Network optimization

First results:
2050 Electricity Consumption

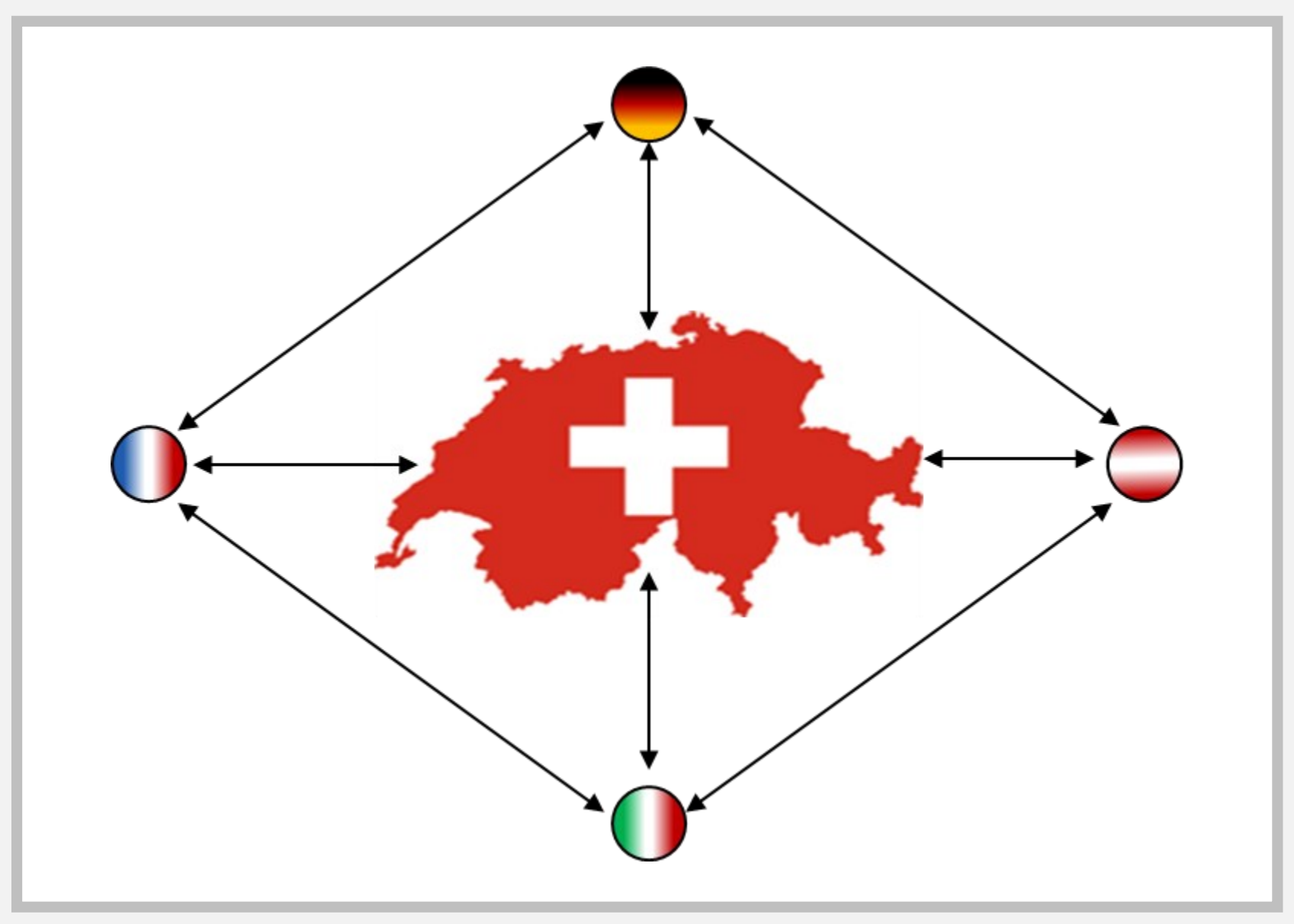


One-way connection successfully integrated

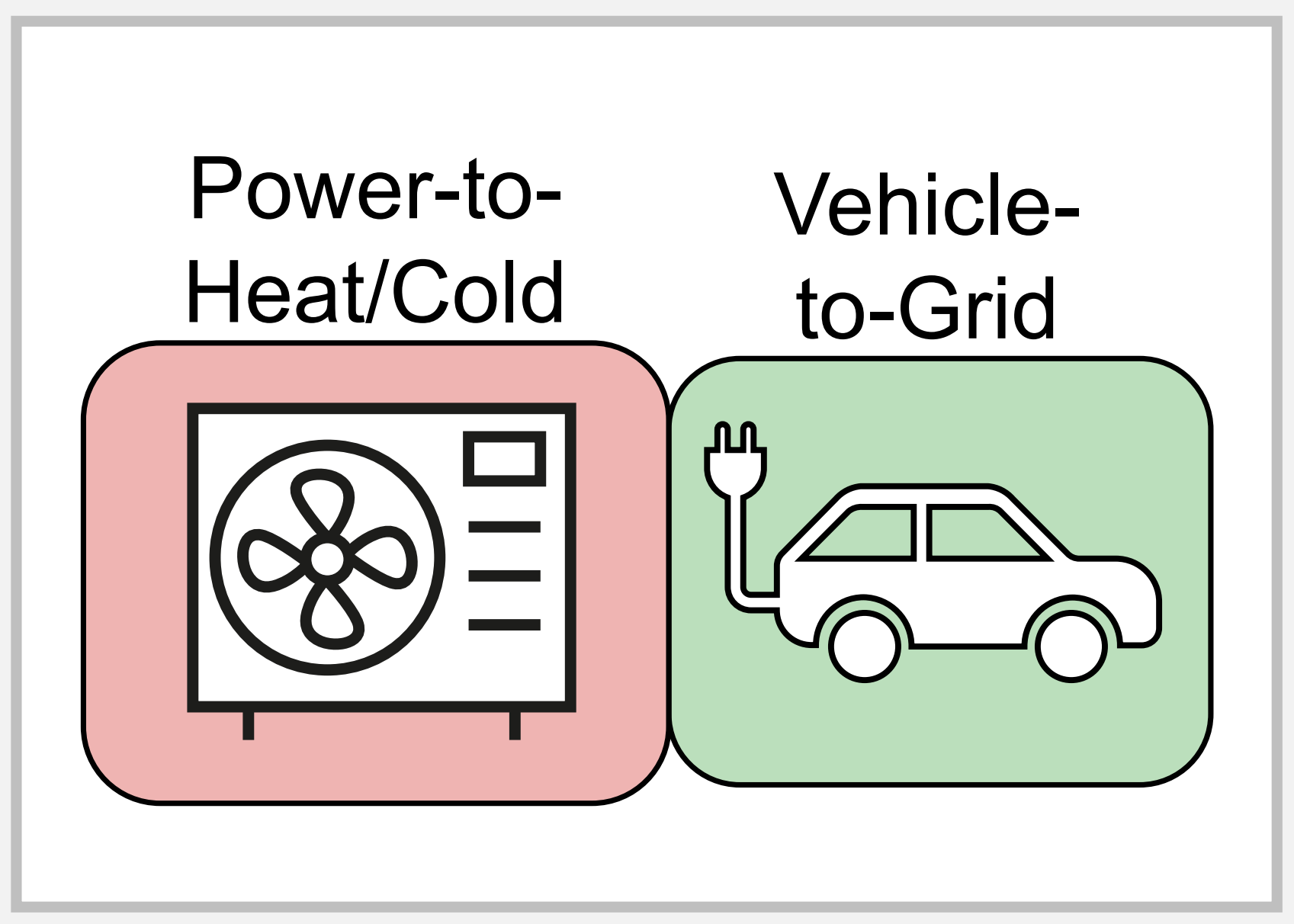
Largest inconsistency from no import/export in SecMOD

Next steps → Phase 2 for the integration

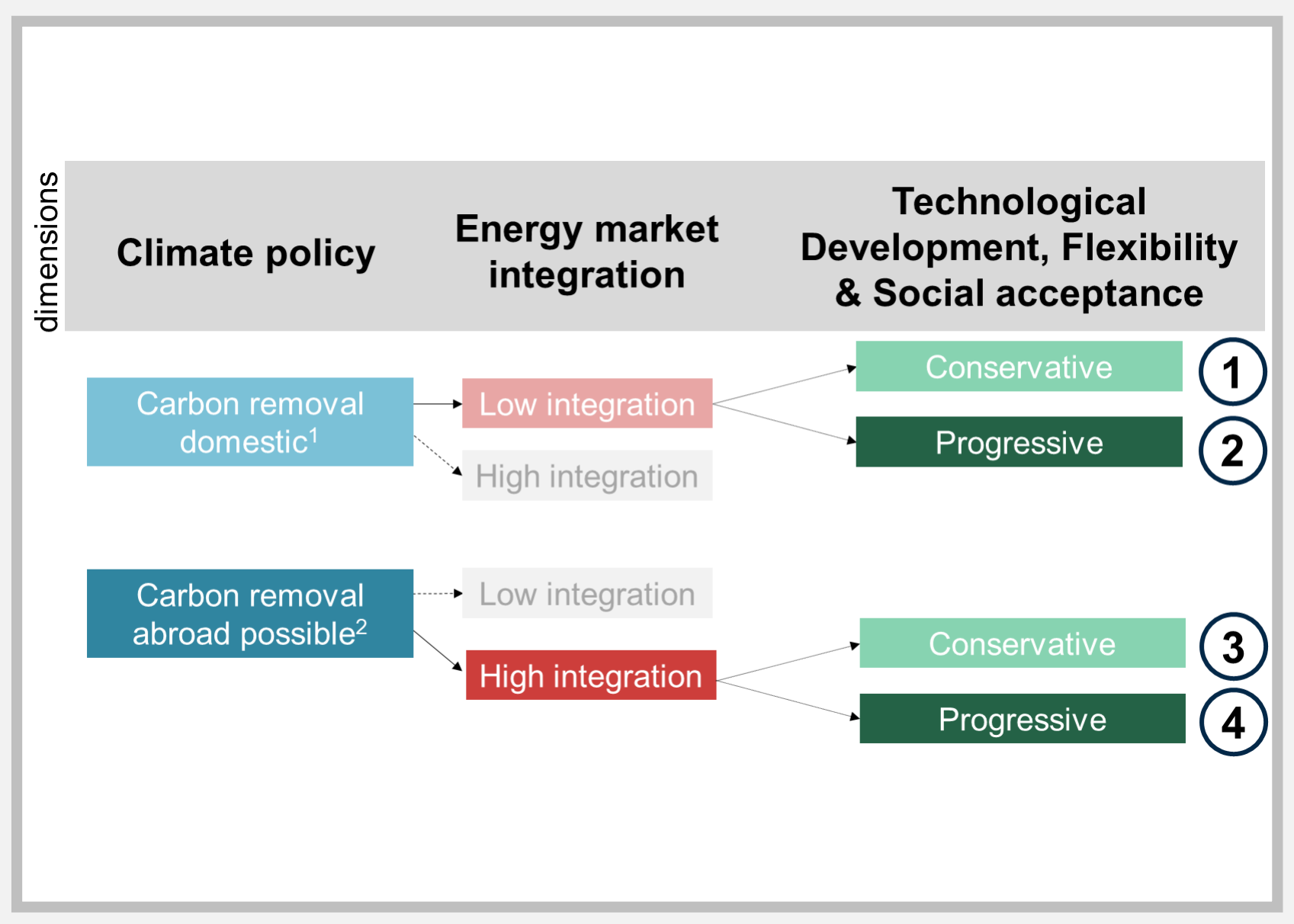
Add import/export to SecMOD



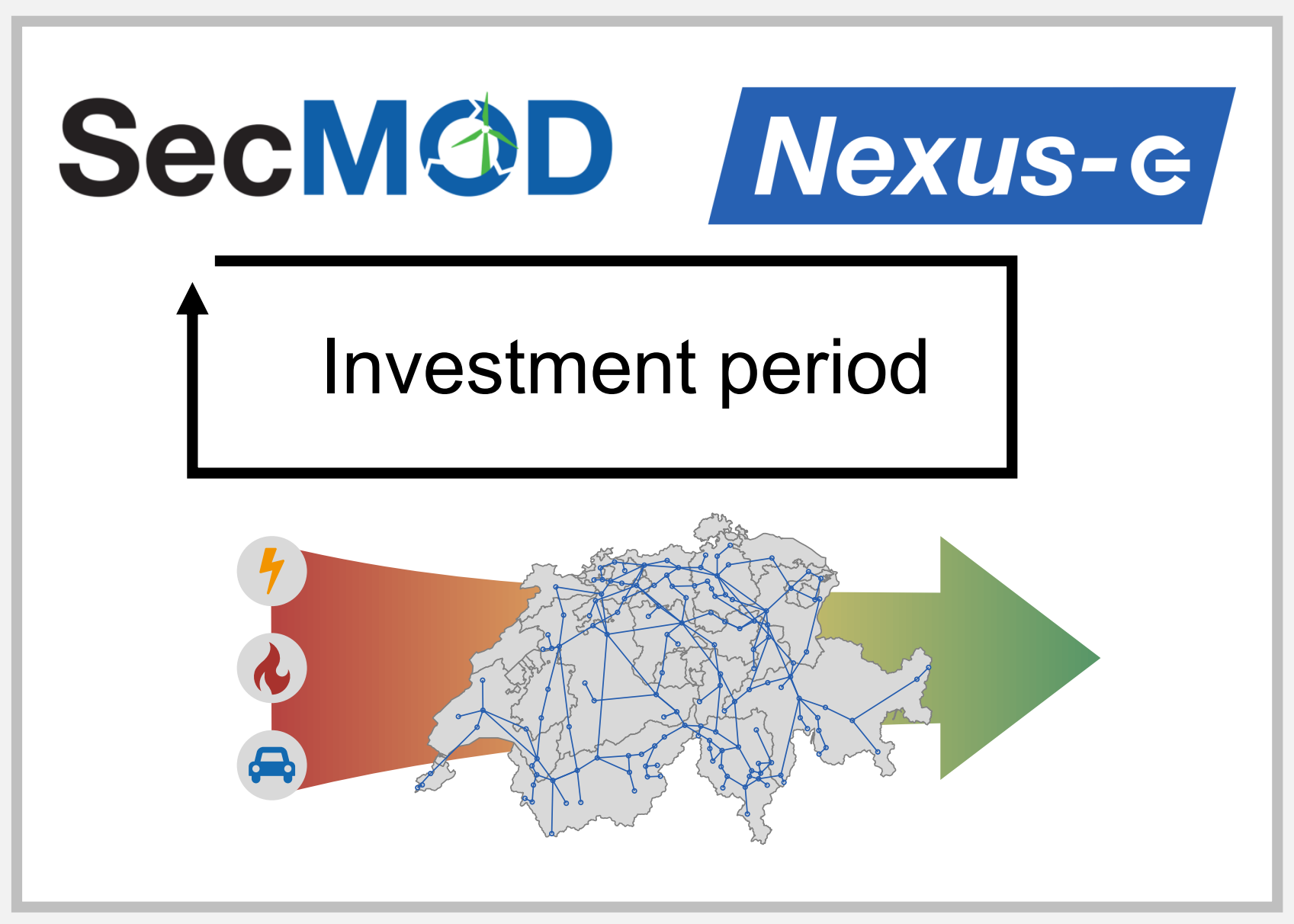
Introduce flexibility options in sector-coupled system



Incorporate PATHFNDR scenarios



Two-way connection for transition pathway



REFERENCES

1 Reinert C., Schellhas L., Mannhardt J., Shu D. Y., Kämper A, Baumgärtner N., Deutz S., Bardow A. (2022). SecMOD: An Open-Source Modular Framework Combining Multi-Sector System Optimization and Life-Cycle Assessment. Frontiers in Energy Research, 10, 884525.

2 Gjorgiev B., Garrison J. B., Han X., Landis F., van Nieuwkoop R., Raycheva E., Schwarz M., Yan X., Demiray T., Hug G., Sansavini G., Schaffner C. (2022). Nexus-e: A platform of interfaced high-resolution models for energy-economic assessments of future electricity systems. Applied Energy, 307, 118193.

3 Reinert, Christiane; Nilges, Benedikt; Baumgärtner, Nils; Bardow, André (2023): This is SpArta: Rigorous Optimization of Regionally Resolved Energy Systems by Spatial Aggregation and Decomposition.

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Energy system model integrating with building simulation and PV estimation for Swiss municipalities

Work package 2

Yi-Chung Barton Chen, Binod Prasad Koirala

Urban Energy Systems Laboratory, Empa

1 BACKGROUNDS

Energy systems modelling can study the impact of the implementation of decarbonisation technologies and measures in multiple sectors, and therefore provide quantitative evidences to decision-making processes in the transition to a sustainable energy system by optimising selected objective functions such as minimising the costs and/or environmental impacts.

To identify the potential pathways to decarbonise the energy system in the municipalities in Switzerland, the demand and potential generation based on buildings in a region are estimated and then integrated with a multi-energy system model. The suitable technology mix and timeline are investigated in this framework.

2 CONTRIBUTION TO PATHFDNR

A energy system modelling framework for a modelling a municipality or a region in Switzerland is developing to support the Losone case study in WP2, and later be able to apply to any regions in Switzerland.

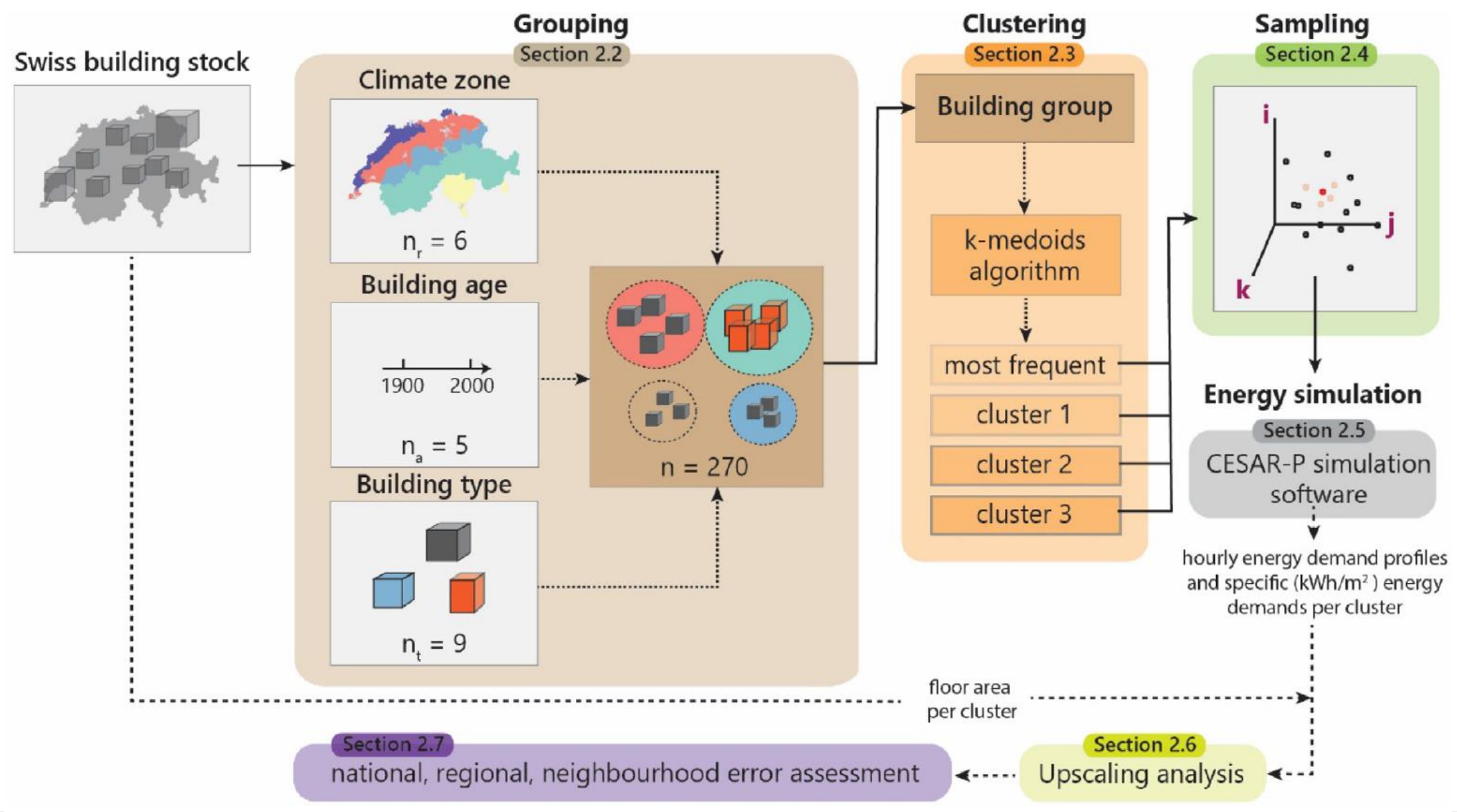
This framework is expected to evaluate the impact of integrating low-carbon technologies (e.g. PV panels, EVs, heat pumps) and storage technologies (e.g. batteries, thermal energy storage) on overall costs and carbon emissions by considering climate and geographical conditions.

2 METHODOLOGY

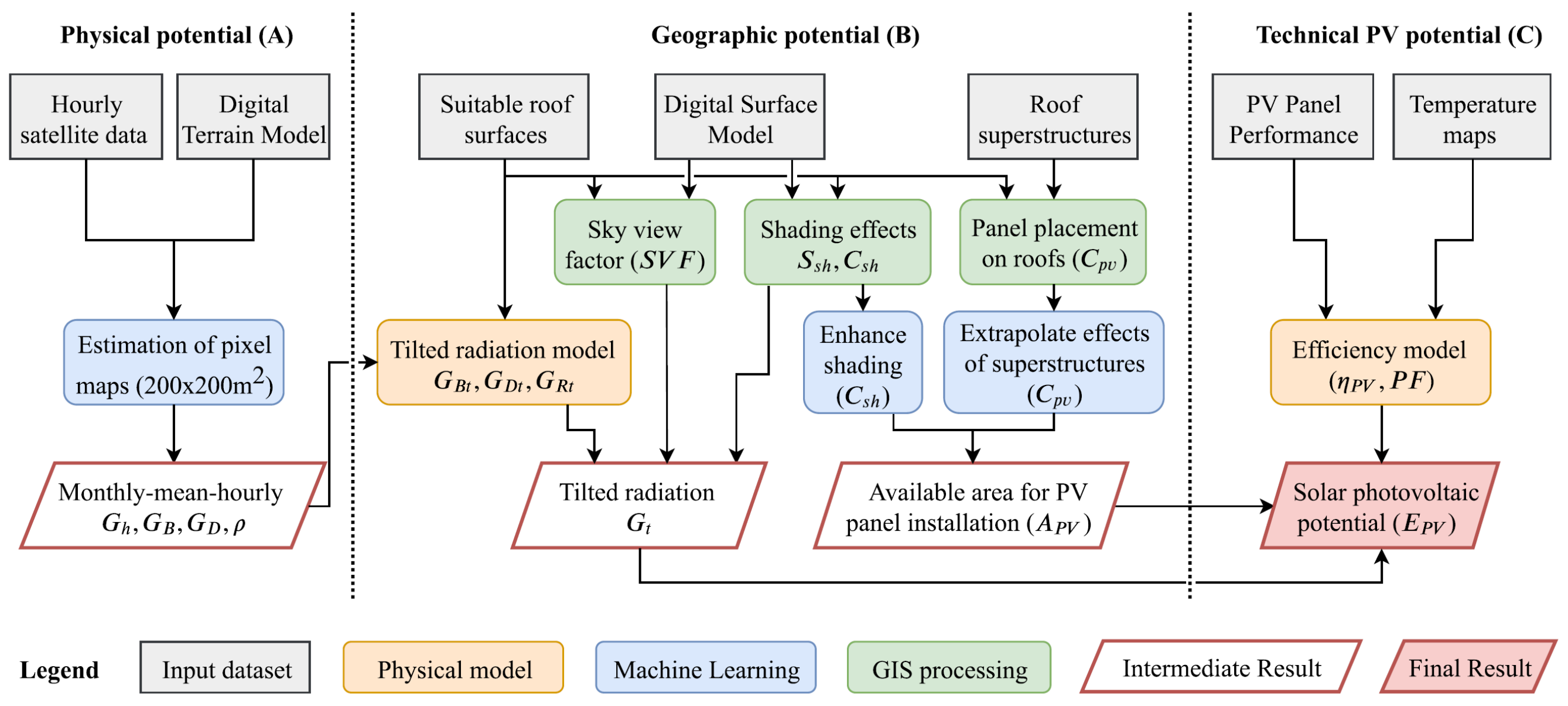
Ehub optimisation tool, a multi-energy system modelling tool developed by Urban Energy Systems Laboratory in Empa, is integrated with the building renovation model CESAR-P (Combined Energy Simulation And Retrofitting – Python)[1] and a Swiss-based PV potential estimation model developed by EPFL[2].

Firstly, the building demand data (i.e. electricity, heating, and cooling) and potential building renovation strategies are simulated based on Swiss building database. Secondly, the PV generation potential and time-series profiles are estimated based on the building, meteorological data, and satellite images.

Building modelling[1]

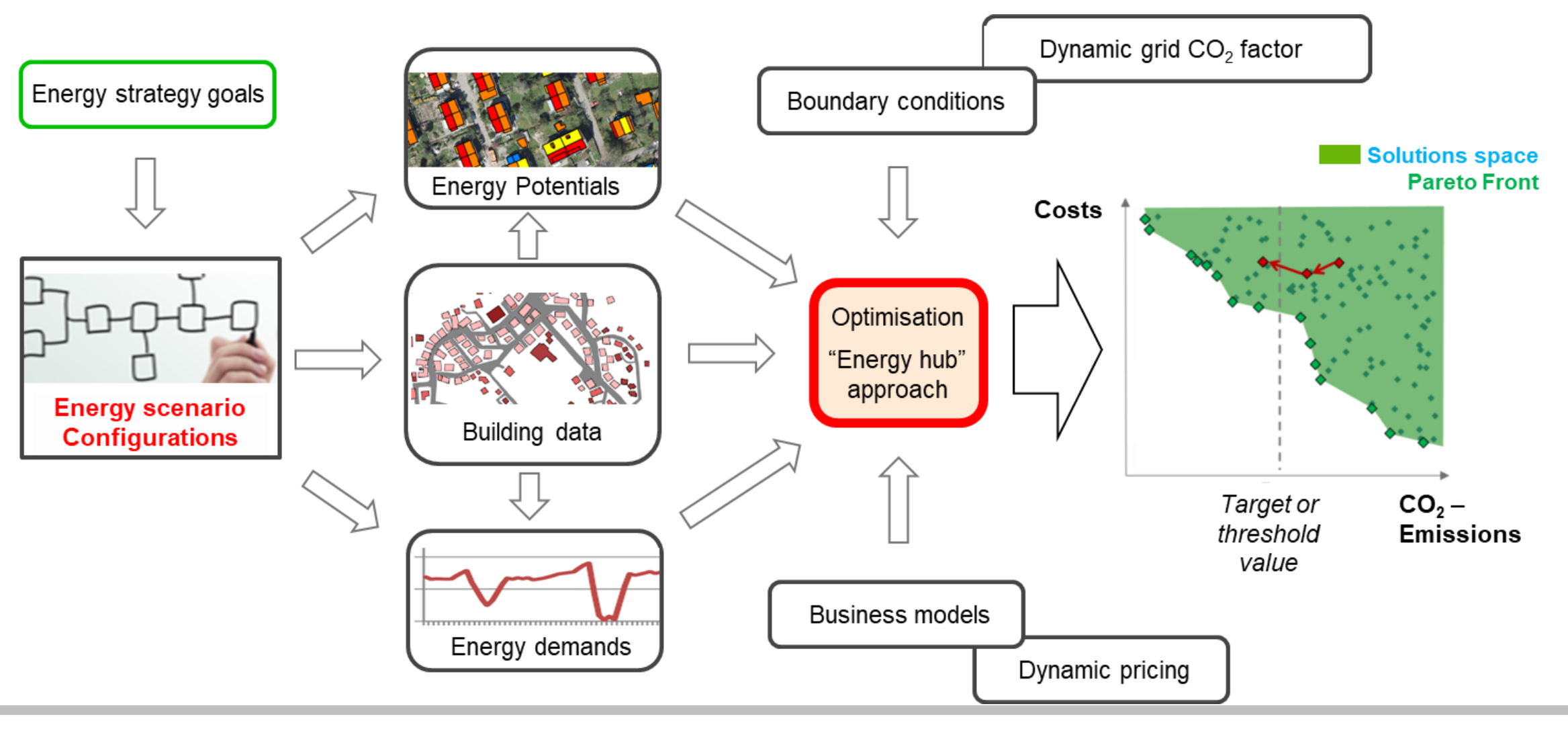


PV estimation[2]

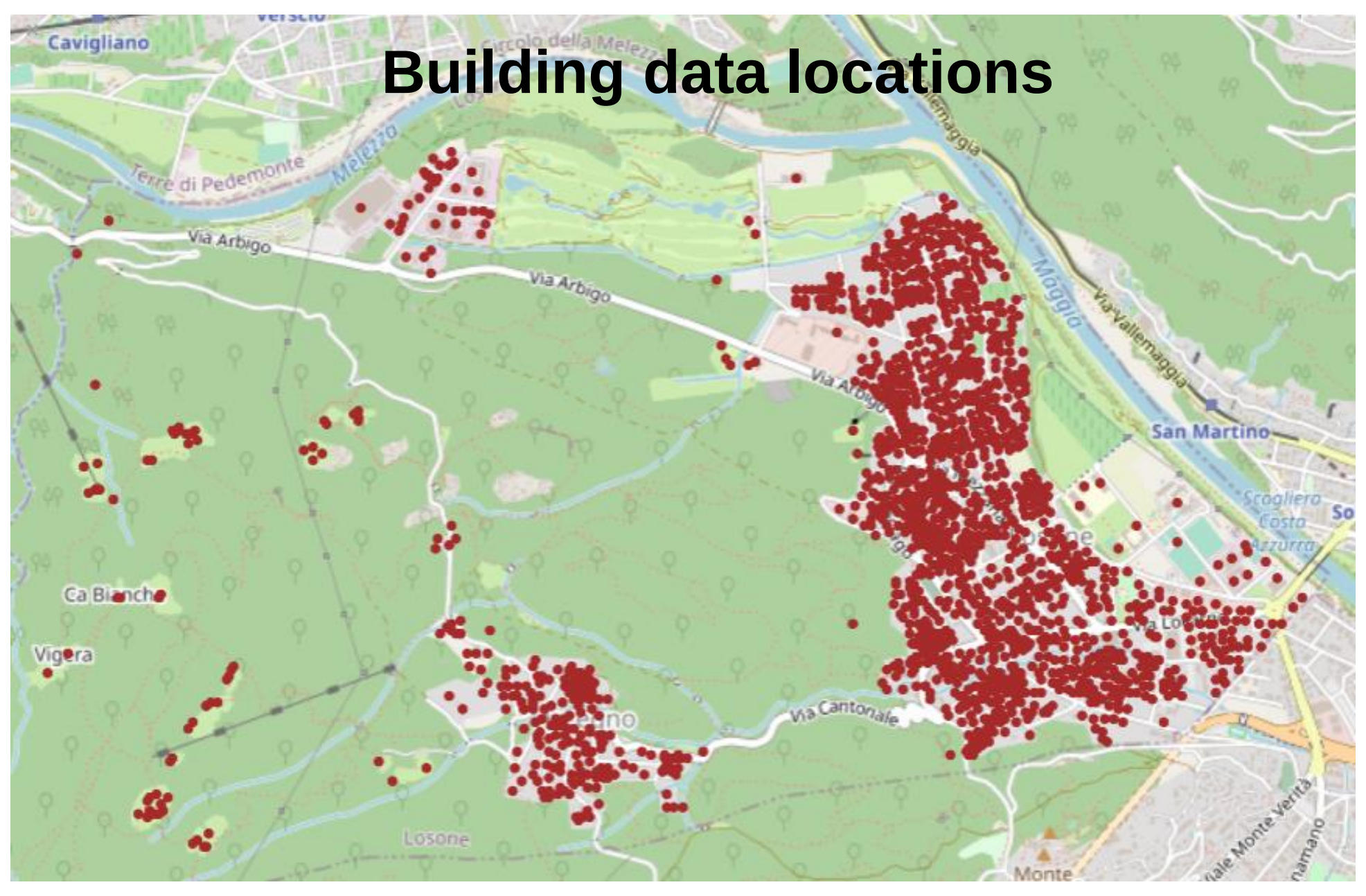


At the end, the data obtained from previous two steps and the data from other sources (e.g. technology data, energy commodity prices, emissions data…etc.)[3] are fed into ehub tool for costs and carbon emissions optimisation.

Energy system simulation

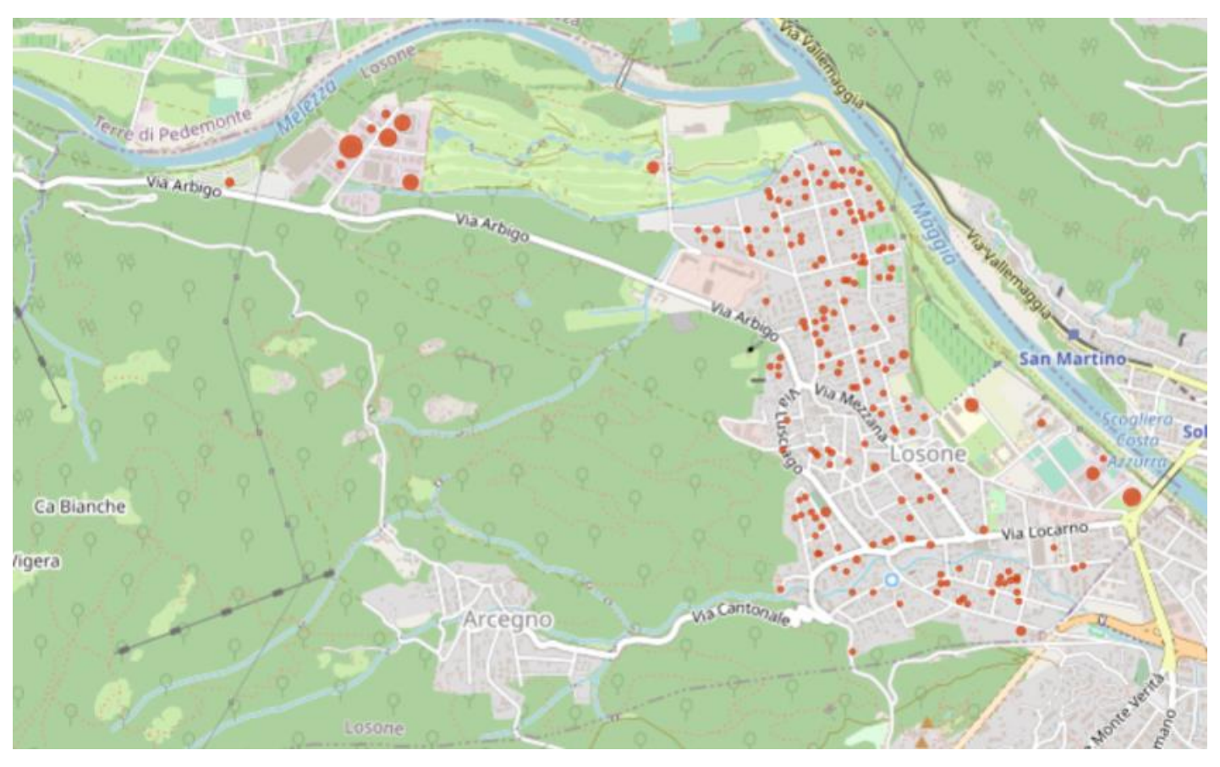


3 PRELIMINARY RESULTS: Losone



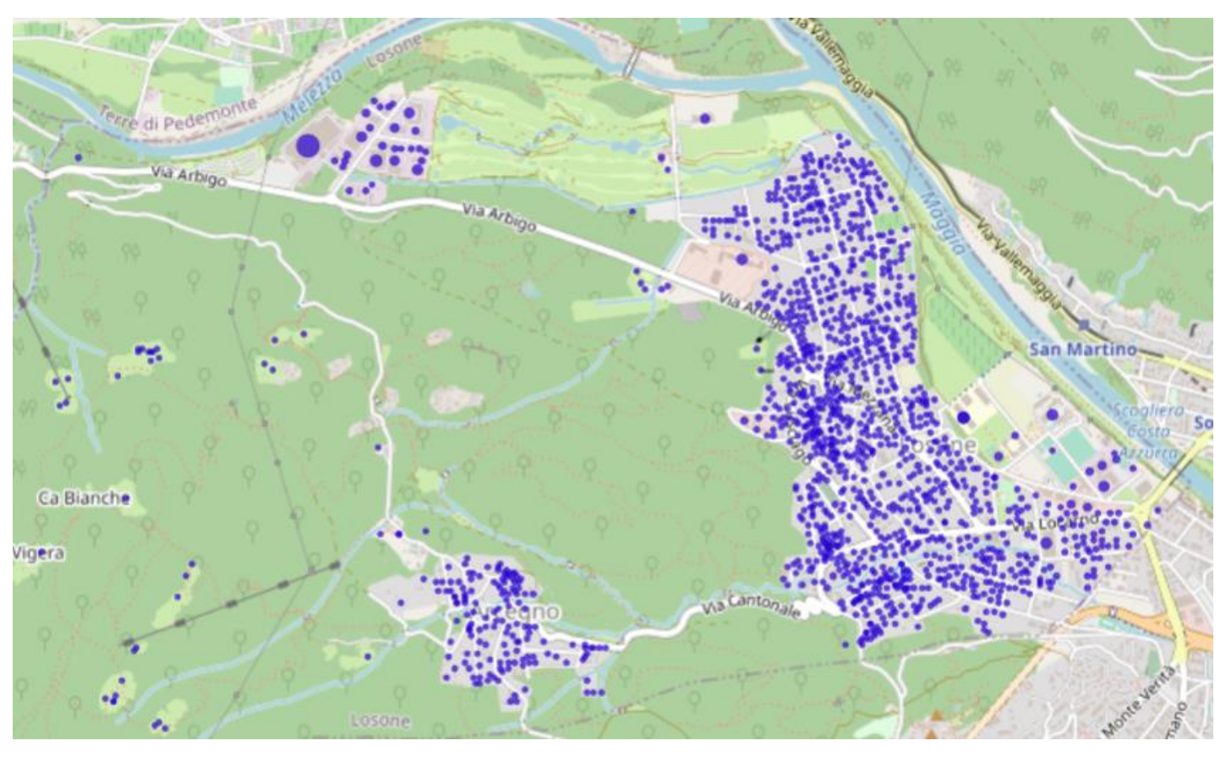
Municipality: Losone
Number of buildings: 1’879; number of roofs: 7’511

Available data: Building category/type, age, ground surface, number of floors, gross area…



PV installation (BFE, 2023)

- Installed capacity: 3.5 MW
- No of plants: 187
- Average capacity: 19 kW
- Min. capacity: 1.75 kW
- Max. capacity: 351 kW



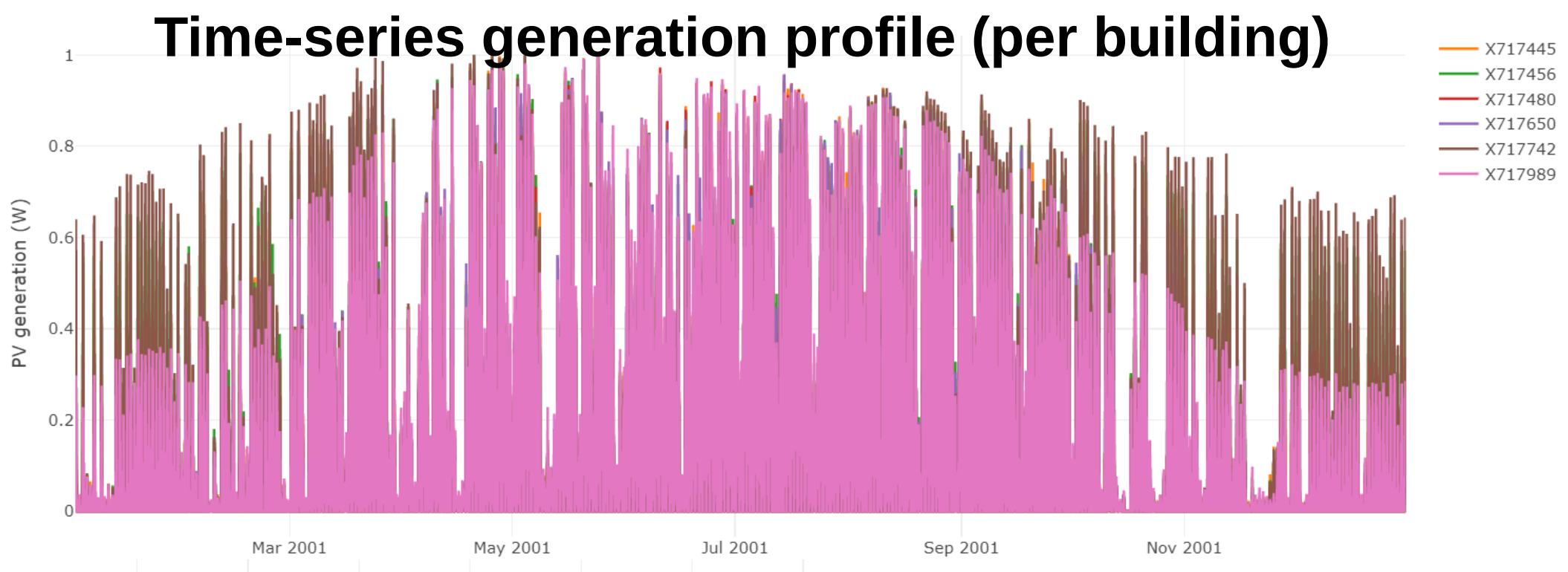
PV potential estimation

- Suitable PV area: 91’705 m^2
- Potential capacity: 17.4 MW
- No of suitable building: 1’368
- No of suitable roofs: 1’648

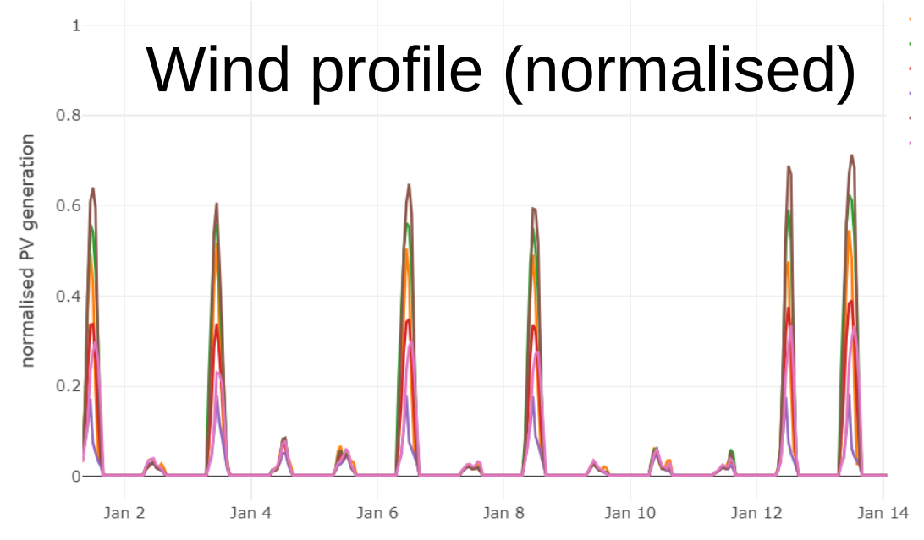
Assumptions:

- Available area > 8 m^2
- Exclude north-facing roofs with an aspect angel > 90°

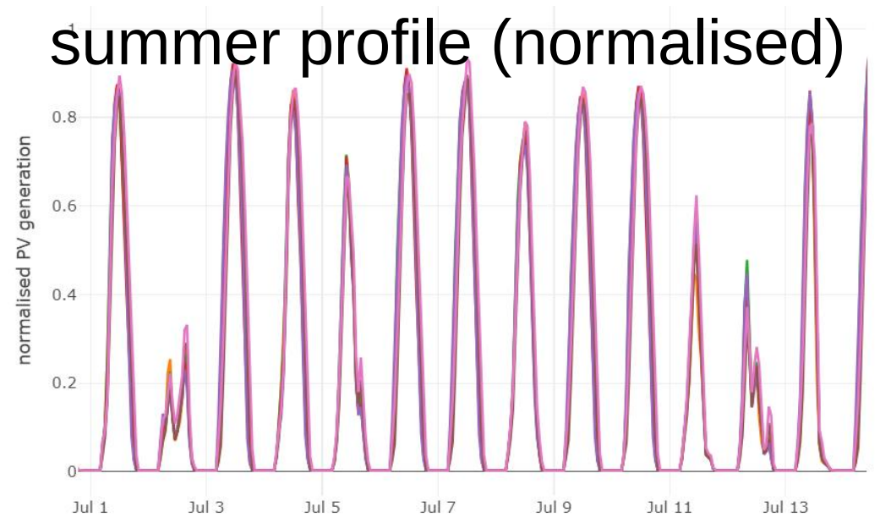
Time-series generation profile (per building)



Wind profile (normalised)



summer profile (normalised)



Estimation vs. reality

Estimation: 10 kW
Installed: 1.75 kW (2016)

Estimation: 6 kW
Installed: 17.55 kW (2020)

REFERENCES

1 Eggimann et al., Spatiotemporal upscaling errors of building stock clustering for energy demand simulation, Energy & Buildings (2022)
2 Walch et al., Big data mining for the estimation of hourly rooftop photovoltaic potential and its uncertainty, Applied Energy (2020)
3 2050 Energiezukunft: Energieversorgung Der Schweiz Bis 2050, VSE (2022)

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Network Tariffs for Decentral Load Control (NEDELA)

Work package 4

Christian Winzer [1]

[1] ZHAW Zurich University of Applied Sciences

1 BACKGROUND

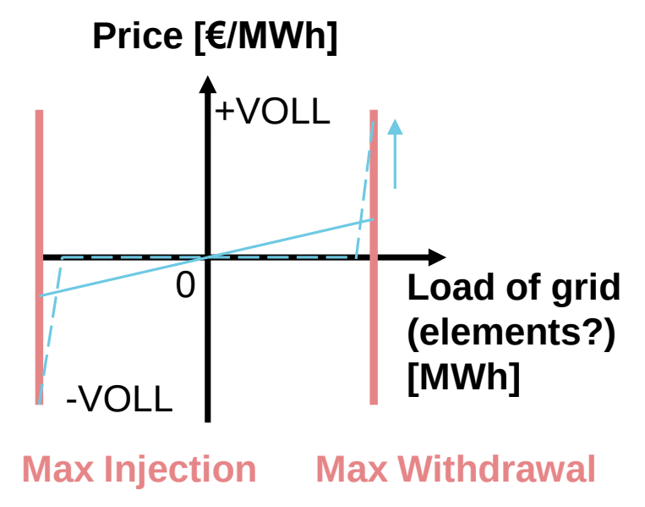
- Decentral renewables production and electrification of transport and heat sectors may lead to increasing peak-load and therefore an increasing grid-expansion need
- Network tariffs could provide incentives for loads to reduce grid peak-load
- Network tariffs need to be designed appropriately to avoid rebound peaks or increasing energy production cost.

2 CONTRIBUTION TO PATHFDNR

- Simulation of tariff impacts on grid peak-load (EMPA, ZHAW and Siemens) which can be used to compare the efficiency of tariffs against market based flexibility procurement in PATHFNDR WP2.
- Field-test of tariff designs in Groupe-E grid to identify and solve technical implementation issues and test the acceptance of tariff designs developed in PATHFNDR WP7.

2 WORK-PLAN

WP2) Simulation of different tariff grid designs:

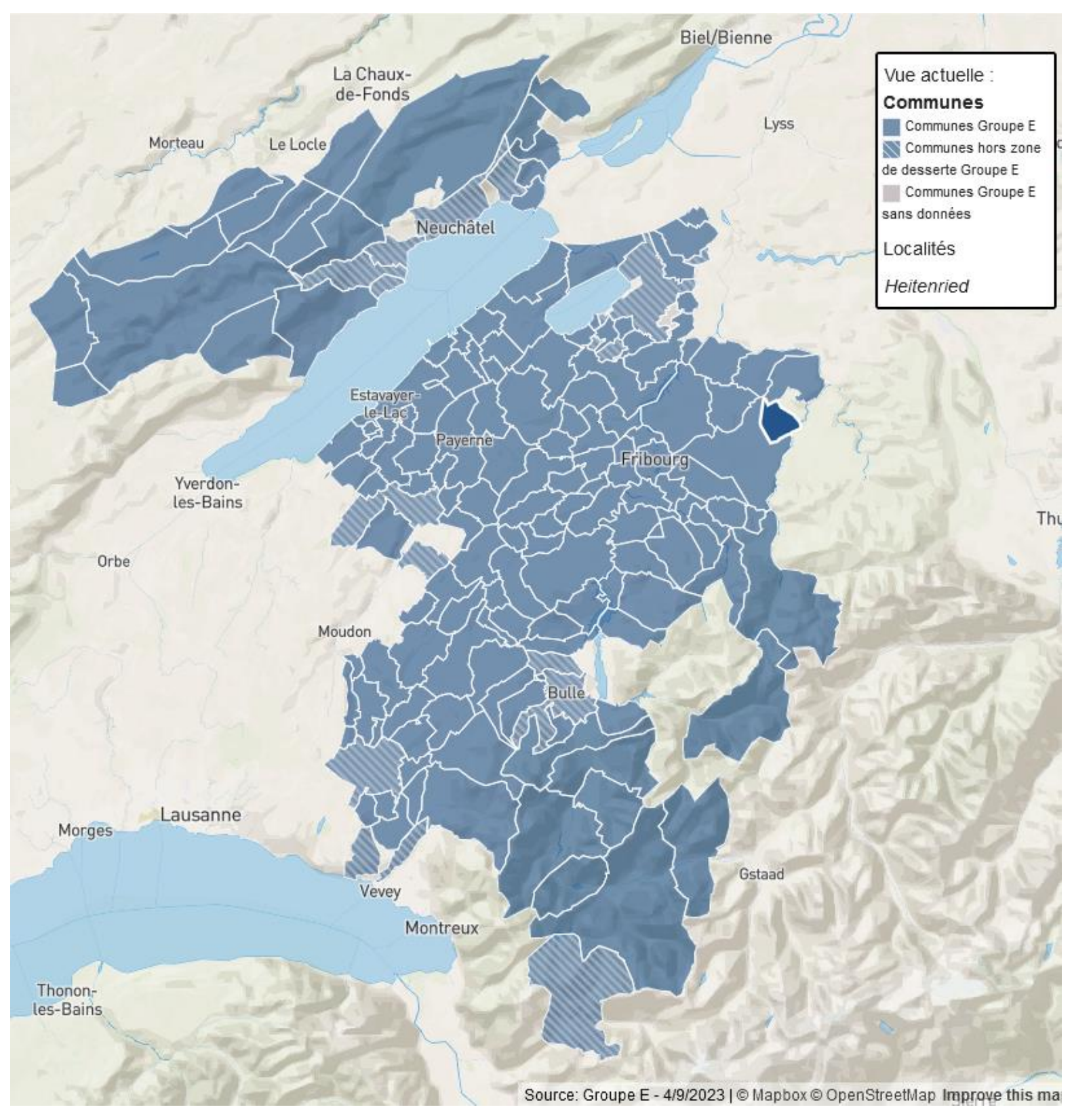


Simulations may include the following grid **tariff design variations**[1]:

- proportional to d-1 load forecast
- increase "constant price range" and "max price“
- proportional to real-time load
- synchronize tariff for feed-in and withdrawals
- add price signal for spotprice
- Locational differentiation
- ...

WP1) Field test of tariff designs:

- Selected tariff designs from the simulation, will be tested during a field-study with a **pilot group** of Groupe-E customers.
- Based on the results of the simulations and the pilot group, Groupe-E’s will adjust its **“vario” tariff**, which can be selected by any of residential customers in their grid area.



Source: Groupe E - 4/9/2023 | © Mapbox © OpenStreetMap Improve this ma

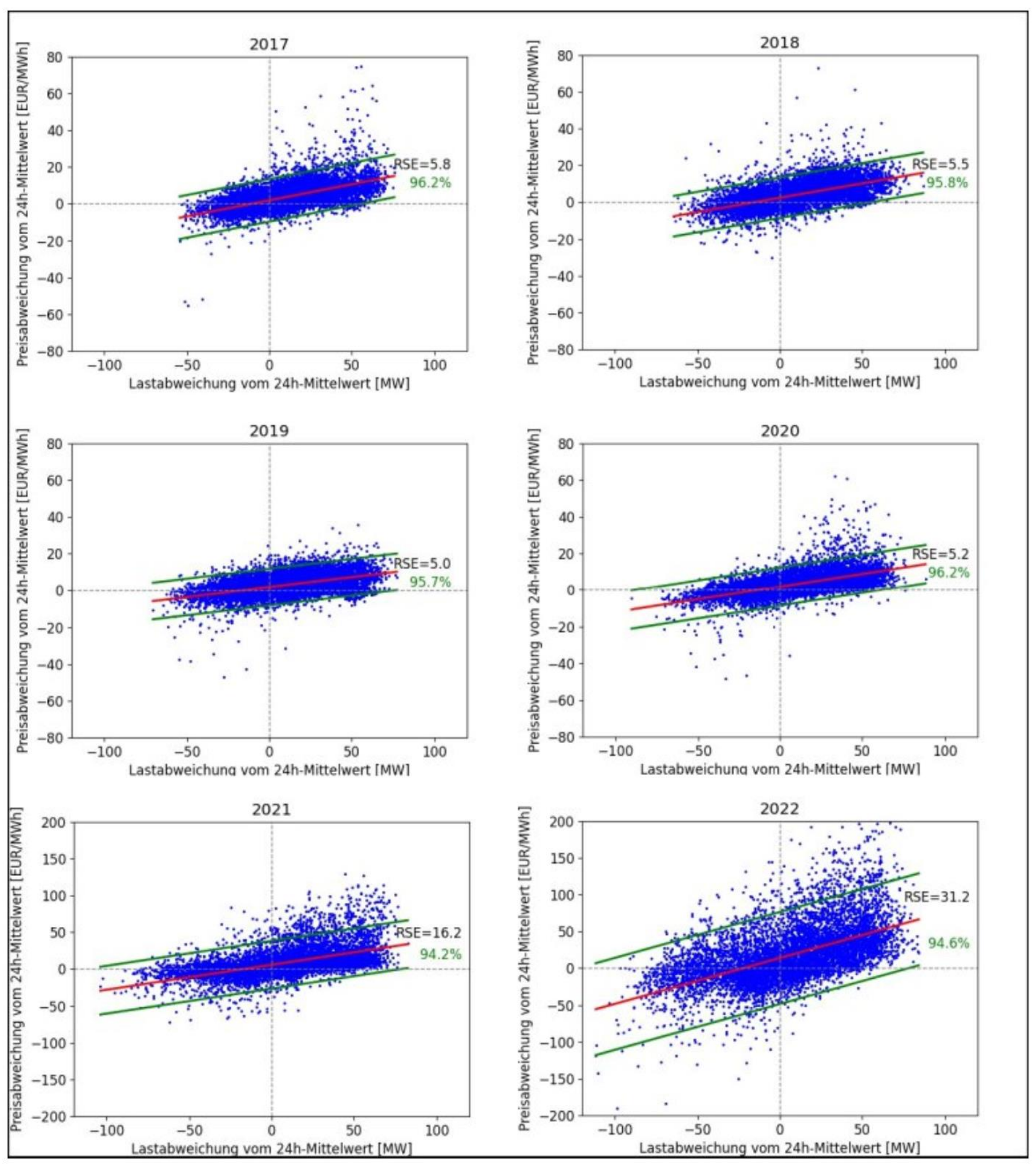
3 TIME-LINE

	Tasks	2023				2024				2025				2026			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	Handing in P&D proposal	🟩 X															
AP1: Implementation	1.1 Pre-test preparation		🟦														
	1.1 Pre-test implementation		🟦	🟦	🟦												
	1.2 Vario tariff preparation			🟦	🟦	🟦	🟦	🟦	🟦								
	1.2 Vario tariff implementation					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
AP2: Design & Simulation	2.1 Pre-test preparation		🟩														
	2.1 Pre-test implementation		■	■	■												
	2.2 Vario tariff preparation		🟩	🟩	🟩	🟩 U	🟩	🟩	🟩	U							
	2.2 Vario tariff implementation					■	■	■	■	■	■	■	■	■			

Lead: 🟩 ZHAW ■ EMPA 🟦 Groupe-E

- Pre-test: focus on designing and testing WebAPI for communicating tariff signals.
- Vario tariff & pilot group: testing performance of different tariff designs.

4 INTERIM RESULTS



- Groupe-E Grid-load strongly correlated with spot price.
- Tariff proportional to grid-load could reduce both grid peak-load and energy production cost[2].

REFERENCES

1 Winzer, Christian, Conceptual Recommendations for Optimal Grid Tariff Design (June 19, 2023). http://dx.doi.org/10.2139/ssrn.4484167

2 Cuony, Peter, Federica Bellizio, Cédric Chanez, Philipp Heer, and Christian Winzer. 2023. “Dynamische Tarife für ein effizientes Stromsystem | VSE,” July 19, 2023. https://www.strom.ch/de/nachrichten/dynamische-tarife-fuer-ein-effizientes-stromsystem

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Comparison of price caps and tariffs to counter a foreign monopoly

Work package 7

Karl-Martin Ehrhart[1], **Ingmar Schlecht**[2], Jan Schmitz[3], Runxi Wang[1]

[1] Karlsruhe Institute of Technology KIT
[2] ZHAW Winterthur
[3] European Commission, DG Trade

1 EUROPEAN GAS IMPORT PRICES SKYROCKETED

- Fossil gas prices in Europe exceeded 300 €/MWh in 2022, this is 15 times the previous long-term average of 20 €/MWh.
- As a residual monopolist, Russia benefited from price increases following its supply reductions of fossil gas to Europe to the detriment of Swiss and other European customers. This is also a result of price formulas in long-term supply contracts that reference spot prices.
- Many scholars pointed to tariffs to reduce Russian oil and gas profits. We compare tariffs to the alternative of import price caps.

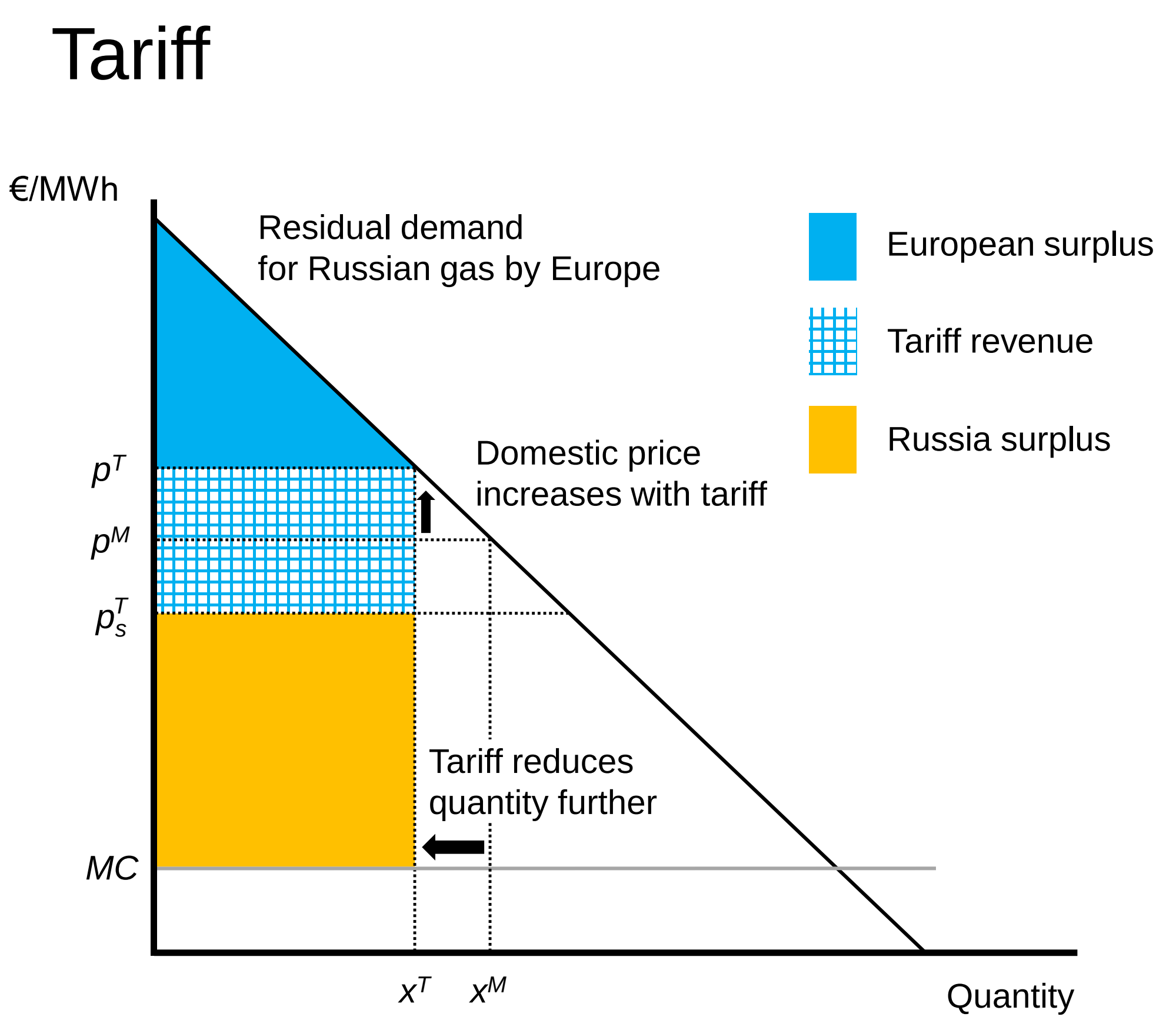
2 TACKLING THE ENERGY CHALLENGE

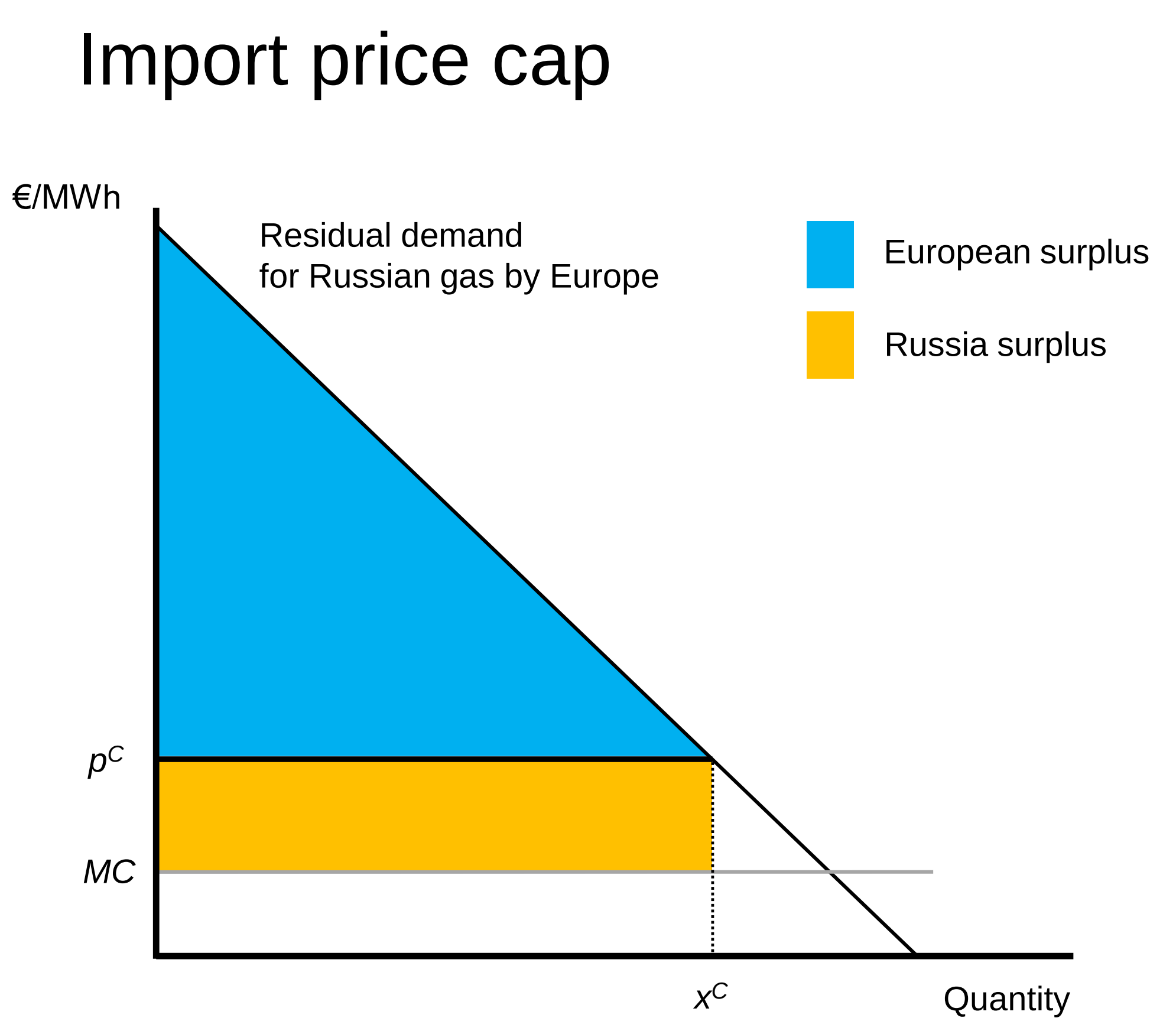
- The PATHFNDR Consortium is concerned about the current energy crisis.
- The consortium aimed to provide policymakers and the media with science-based insights that can help address the current challenges.
- The findings presented are results that are conducted within PATHFNDR and with co-authors outside of PATHFNDR to tackle the energy crisis.

2 THEORETICAL ANALYSIS

In a theoretical paper, we show that:

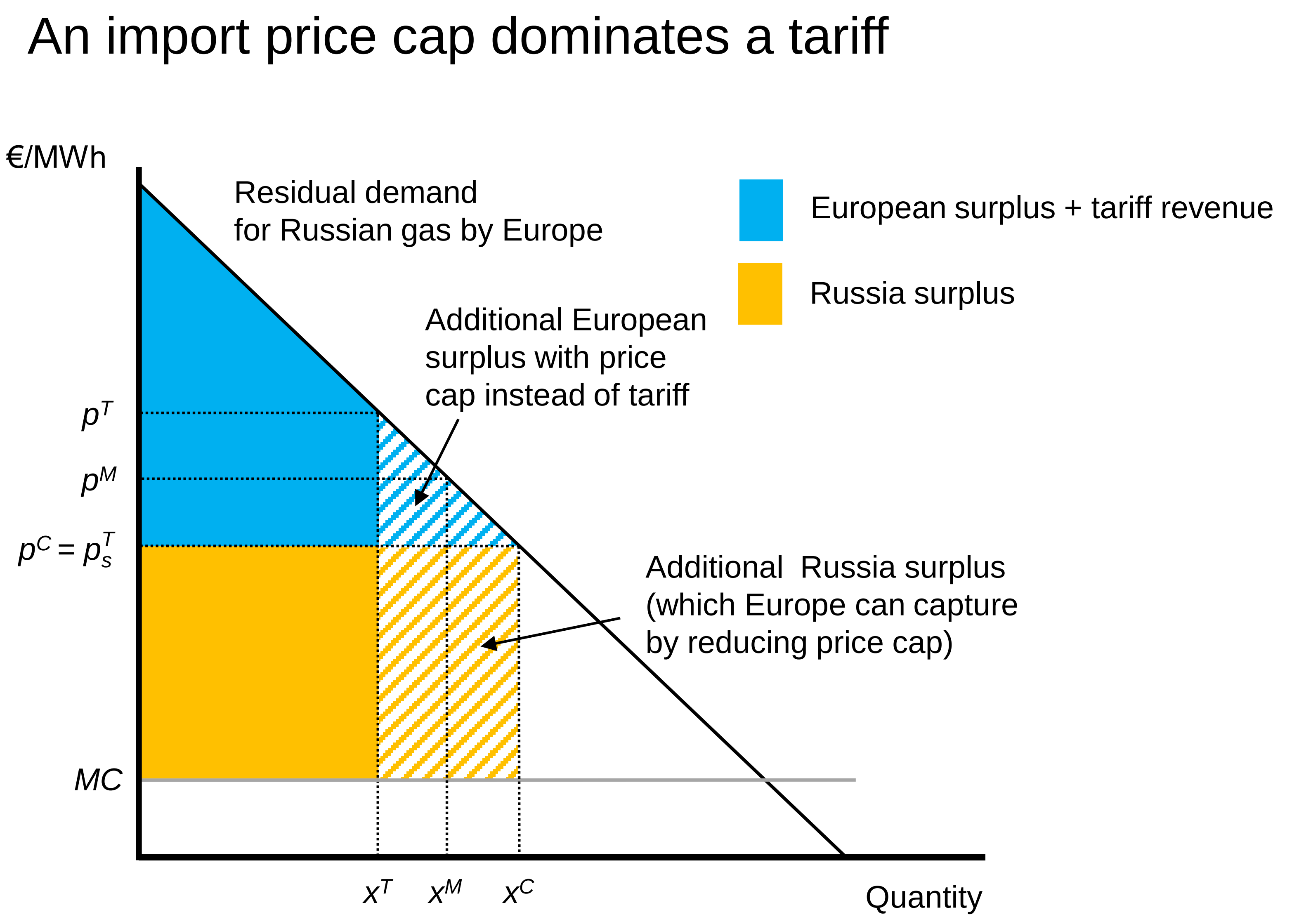
- A foreign monopoly reduces quantity to increase prices
- It increases the quantity even further after the introduction of a tariff on imports
- An import price cap removes the monopolist's incentive to reduce quantities
- Compared to any tariff, there exists a price cap that makes both parties better off


Tariff


Import price cap

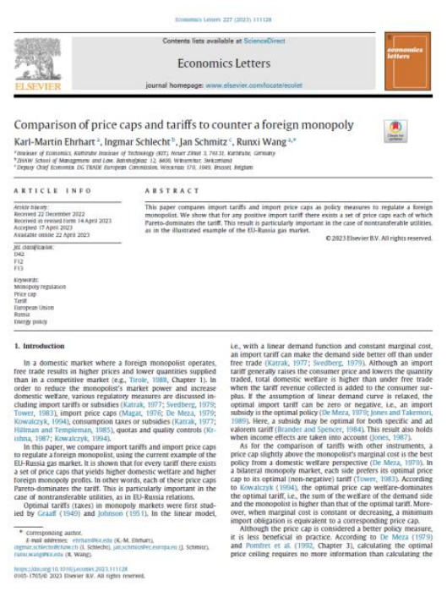
3 RESULTS

- We find that an import price cap on Russian gas is advantageous compared to a tariff.
- This is due to Russia's (residual) monopoly power over Europe's residual gas demand.
- We show that for any tariff there exists a price cap that makes both Europe and Russia better off.
- Consequently, compared to imposing a tariff, Europe could always design a price cap that could have given Russia the same welfare (so it is equally likely to accept), but makes Europe better off.
- To impose a price cap, Europe should exercise its own market power, appointing a single European entity buying gas from Russia and re-selling domestically in European spot markets.


An import price cap dominates a tariff

PAPER

1 Ehrhart, Karl-Martin, Ingmar Schlecht, Jan Schmitz, Runxi Wang (2023). Comparison of price caps and tariffs to counter a foreign monopoly. Economics Letters, Volume 227. https://doi.org/10.1016/j.econlet.2023.111128



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Modeling of heat pumps and thermal storage units to exploit thermal energy flexibility

Work package 3

Matthias Brandes[1], Hanmin Cai[1], Jacopo Vivian[1,2], Lorenzo Croci[3], Philipp Heer[1], Roy Smith[4]

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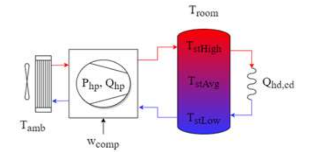
[2] Dept. of Industrial Engineering, University of Padova, Padua, Italy
[3] Dept. of Power System Development, Ricerca Sistema Energetico SpA, Milan, Italy
[4] Automatic Control Laboratory Department of Electrical Engineering and Information Technology, ETH, Zurich, Switzerland

1 INTRODUCTION AND OBJECTIVES

Heat pumps (HP) coupled with thermal energy storages (TES) can be optimized to reduce carbon footprint and used as a source of flexibility to support energy system operation when combined with model predictive control. However, to scale in a multitude of buildings, the transferability of the modeling and control policies into heterogeneous systems is crucial. To this end, data-driven approaches have received considerable attention as they can reduce modeling efforts and support a cost-efficient implementation.

2 CONTRIBUTION TO PATHFDNR

Systematic comparison of models calibrated with real-world variable-speed HPs combined with TES units. The transferability of the modelling approach is evaluated using two facilities (NEST, RSE Lab) with heterogeneous sizing and configuration (Table 1) for both heating and cooling operations.



System	RSE Lab	NEST
HP capacity (electric power) [kW]	7 (2)	100 (24)
Heat source	Air	Ground & District Grid
TES volume for heating/cooling [L]	300	2200

Table 1: Characteristics of case studies

2 MODEL SCREENING AND SELECTION

Two dynamic regression-based state-space modeling techniques, namely Sparse Identification of Non-Linear DYnamics with control (SINDYc) and Dynamic Mode Decomposition with control (DMDc) are used to identify first-order dynamic models [1]. For model variables with negligible dynamics, static models, identified with LASSO regression, have been evaluated. A screening of model characteristics, such as model type (Static/Dynamic, Linear/Non-Linear), sampling time (1 minute, 15 minutes) and the prediction horizon (1 hour, 5 hours), was conducted to identify suitable models and combinations for HP and TES variables. Figure 2 shows all feasible combinations of model variables, methods, sampling time, and model types that result in stable models.

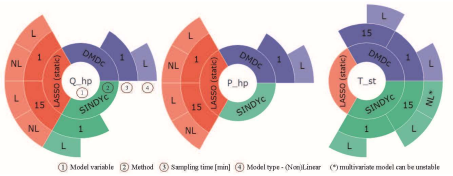


Figure 2: Screening results of feasible models

The screening process led to the identification of two feasible HP-TES system models, both linear: a hybrid (grey-box) and a fully data-driven model (black-box). The models are presented in a generic descriptor state-space representation:

$$Ex_{k+1} = Ax_k + B_u u_k + B_d d_k \ , \ y_k = Cx_k$$

where matrix E allows for the formulation of combined static and dynamic models.

I) Coupled fully data-driven and dynamic model

$$E = \mathbb{I}, \ A, \ B_u, \ B_d, \ C = \mathbb{I}$$

II) Decoupled hybrid static and dynamic (mixed) model

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \ A = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & -1 & 0 \\ a_{31} & 0 & -1 \end{bmatrix}, \ B_u = \begin{bmatrix} 0 \\ b_{u,21} \\ b_{u,31} \end{bmatrix}, \ B_d = \begin{bmatrix} 0 & b_{d,12} & b_{d,13} \\ b_{d,21} & 0 & 0 \\ b_{d,31} & 0 & 0 \end{bmatrix}, \ C = \mathbb{I}$$

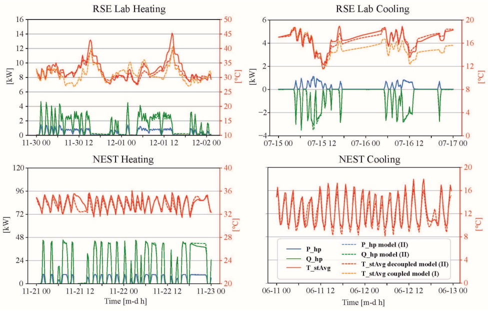
With the following definition:

$$x = [T_{\text{st}}, Q_{\text{hp}}, P_{\text{hp}}]^T \ , \ u = [w_{\text{comp}}] \ , \ d = [T_{\text{amb}}, T_{\text{room}}, Q_{\text{hd,cd}}]^T$$

3 SIMULATION AND MULTISTEP-AHEAD PREDICTION RESULTS

To facilitate the comparison of the prediction performance for different systems in Figure 3, the RMSE is normalized with the standard deviation of the respective measurements. Linear and non-linear dynamic average tank temperature models as well as linear two-state models with a coupled upper and lower tank temperature perform well for both case studies and heating and cooling operations. The coupled fully data-driven model identified with DMDc performes poorly for NEST and is therefore not depicted. This is mainly due to the faster and therefore less observable dynamics compared to the RSE Lab.

Figure 4: Simulation results for both case studies and operation modes



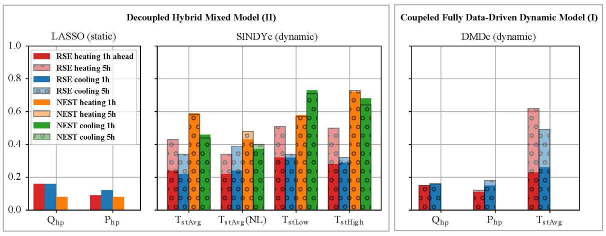


Figure 3: Prediction performance of selected 15 minutes sampling time models

Key to the model design and evaluation process was the ease of model interpretation provided by the methods used. The transparency ensures the choice of stable and intuitive models.The results show that the methodology can be applied to systems with different scales which indicates transferability. The decoupled hybrid model has proven to be more suitable for use in an optimal control framework. It provides good performance for short-term prediction and long-term simulation. In contrast, the fully data-driven dynamic model, which only applies to the RSE Lab, suffers from a delay of the HP dynamics, leading to a drift of the tank temperature for long-term simulations.In the future, extended tank temperature two-state models would allow for a more accurate state-of-charge estimation.

REFERENCES

1 E. Kaiser, J. N. Kutz, and S. L. Brunton, Sparse identification of nonlinear dynamics for model predictive control in the low-data limit," Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 474, no. 2219, 2018.

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PATHFNDR

EV Charging Infrastructure Deployment

Work package 6

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[1]SusTec, D-MTEC, ETH Zürich

1 The Importance of Charging Infrastructure

Electric vehicle (EV) charging flexibility is limited by:
- Driver behaviour and preferences[1],
- Charging infrastructure availability[1], and
- Implementation[1], e.g. direct vs. pricing.

Switzerland's plan to roll-out EV charging infrastructure will affect EV demand, limit EV flexibility, and affect the electricity system[2].

We aim to improve those impacts by (1) understanding the connection with EV flexibility, (2) simulating the interplay of actors deploying charging infrastructure, and (3) testing the influence of policies to inform an efficient roll-out plan.

2 Contribution to PATHFDNR

Link to WP2: To obtain the required flexibility from EVs, what is the optimal mix of home vs. work vs. public charging stations?

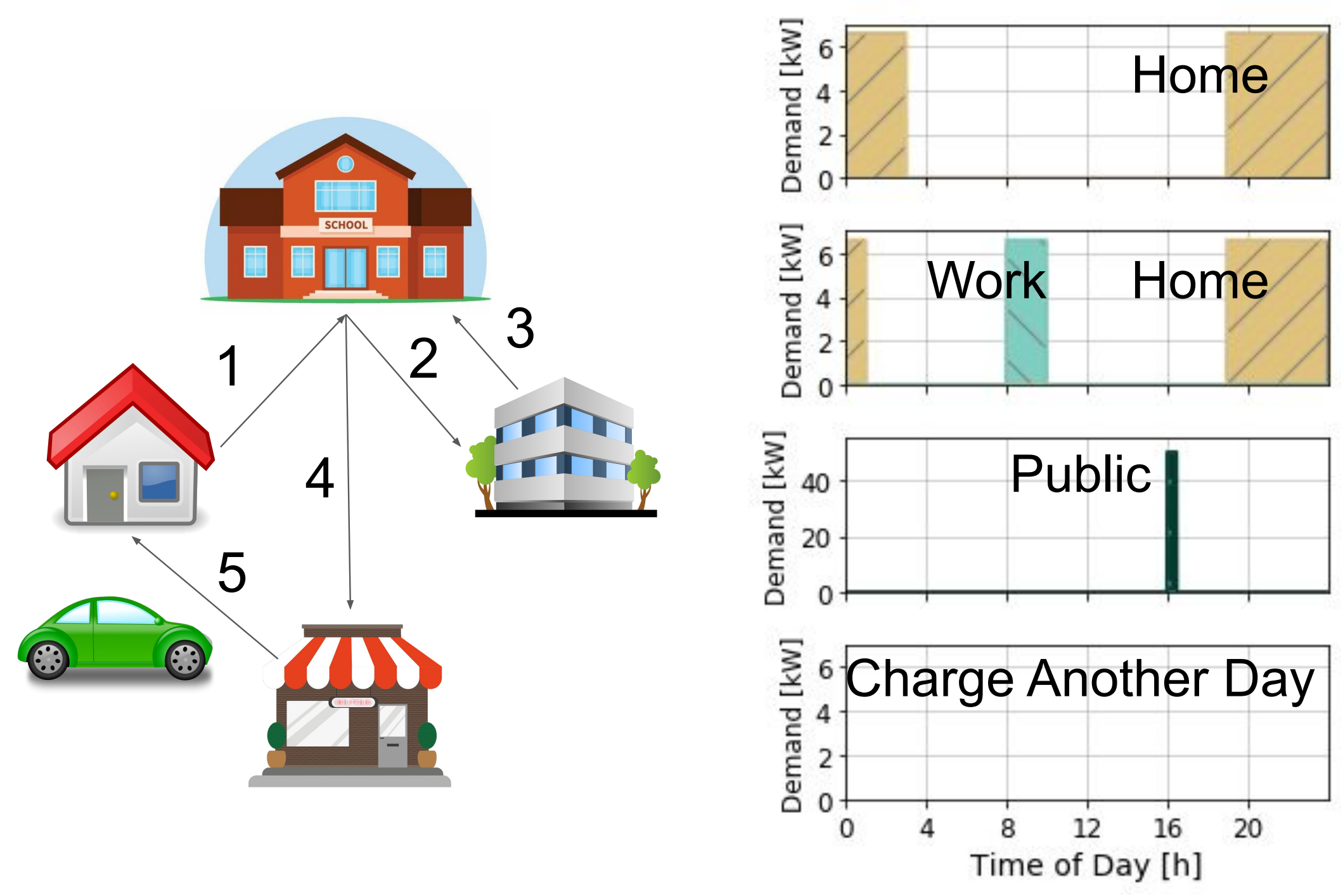
How will the deployment of stations evolve given the interplay between different charging station providers and charging network operators?

Link to WP7: How do policies impact those firms' decisions? What policies lead to that optimal mix?

This work contributes to Task 6.2: Technological innovation and the interplay between firms at value chain level.

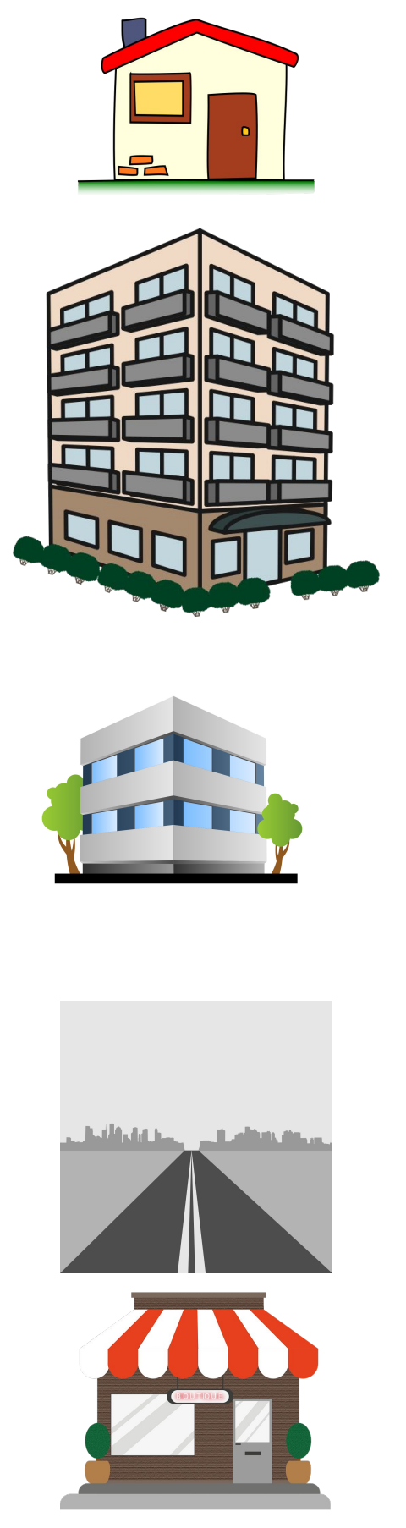
3 Methodology

i. Infrastructure ↔ Behaviour ↔ Demand Flexibility



- Agent-based model of drivers and stations[3]
- Travel survey data
- Charging infrastructure availability
- Scenarios of driver preferences and behaviours
- Flexibility potential in each case

ii. Review/Model Policies Affecting Deployment



Private - Single-family homes:
  Subsidize new installations

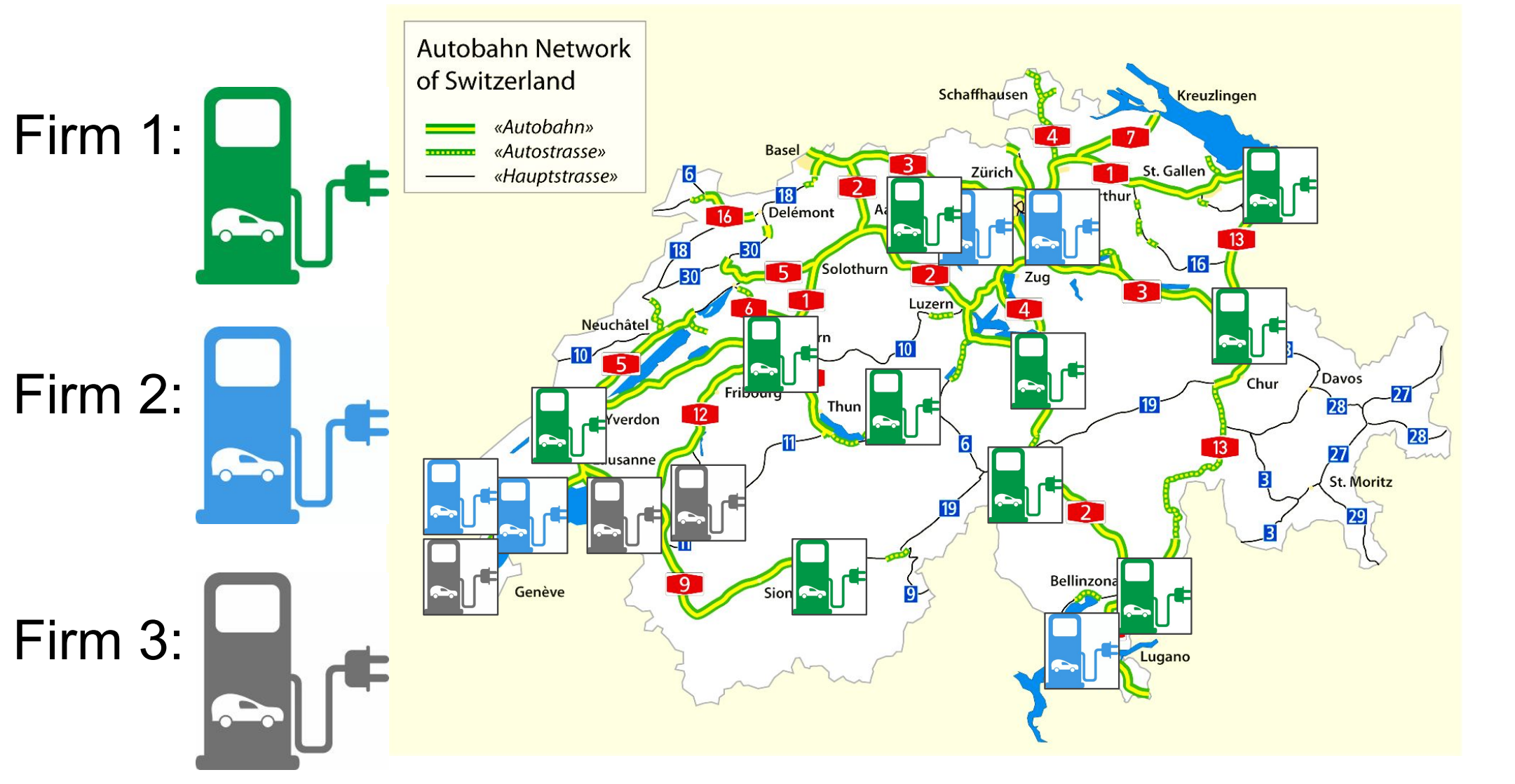
Private - Multi-unit dwellings:
  Mandate access for renters
  Mandate stations in new buildings
  Subsidize new installations

Private - Workplaces:
  Subsidize new installations

Public:
  Subsidize new installations
  Regulate coverage per EV or km
  Publicly owned networks

Any:
  Favourable electricity rate designs
  Accelerated permitting
  Reward per user or per use
…

iii. Model Interplay of Firms and Individual Decisions



https://en.wikipedia.org/wiki/Motorways_of_Switzerland

- Agent-based model of deployment for all actors[4]
- Interact month-by-month to simulate deployment
- Decision inputs include:
  - Demand by charger type and location
  - Costs (including effect of subsidies, learning)
- Influence on electricity demand and flex potential

4 Preliminary Results

i. Infrastructure ↔ Behaviour ↔ Demand Flexibility

Case 1

With high VRE and transmission congestion, Germany has high demand for intraday EV flexibility. How does shifting between home and workplace charging help?

Case 2

With large seasonal variations due to hydro and growing solar PV, Switzerland has different demands for EV flexibility. Results: work in progress.

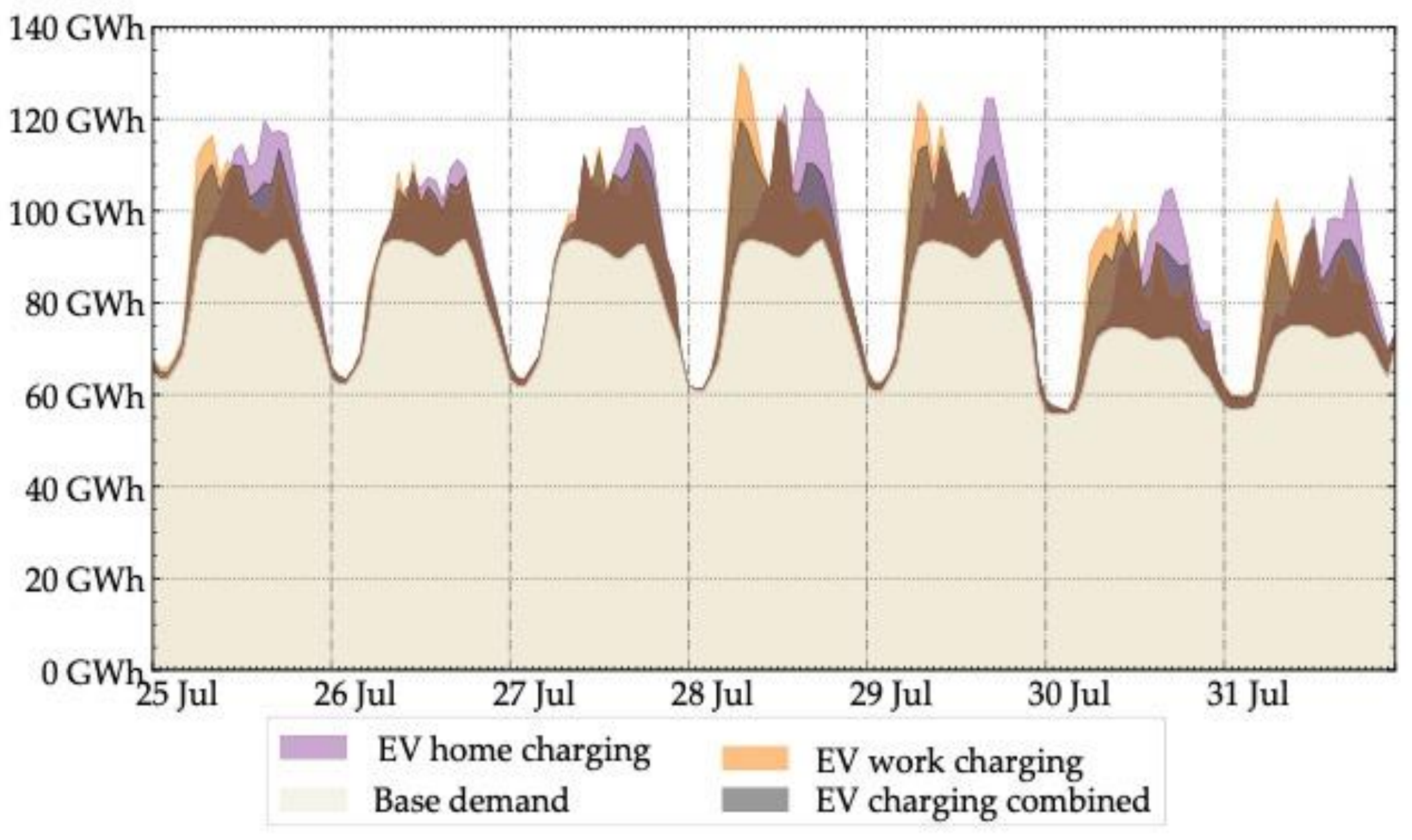


Fig 1. Influence on demand profile and flexibility.

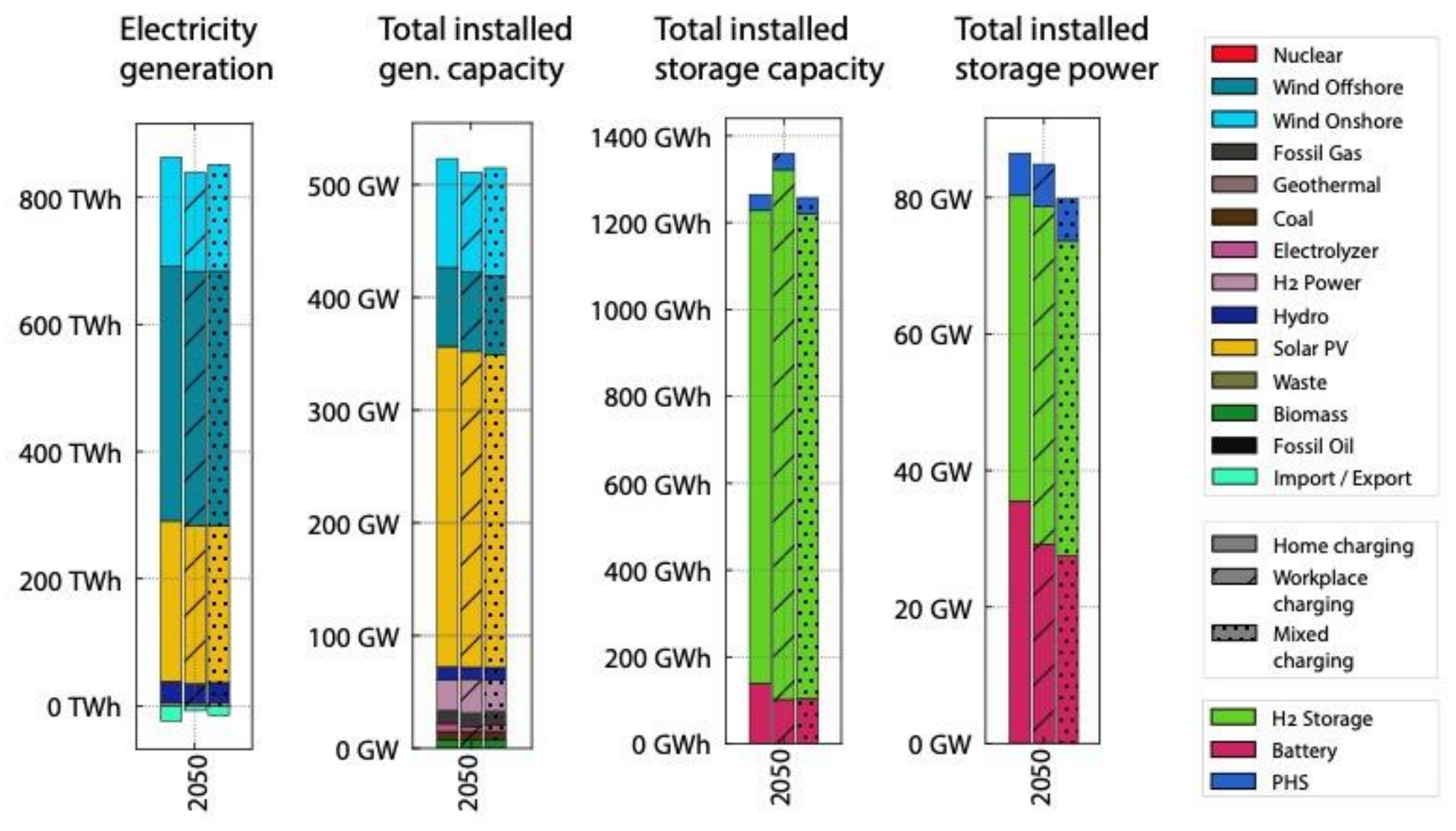


Fig 2. Impact on 2050 planning with MANGOelec model[5]. Workplace case has lower total system costs.

REFERENCES

1 Powell, S., Cezar, G. V., Min, L., Azevedo, I. M., & Rajagopal, R. (2022). Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption. Nature Energy, 7(10), 932-945.

2 Luh, S., Kannan, R., McKenna, R., Schmidt, T. J., & Kober, T. (2023). How, where, and when to charge electric vehicles–net-zero energy system implications and policy recommendations. Environ. Res. Commun.

3 Gschwendtner, C., Knoeri, C., & Stephan, A. (2023). The impact of plug-in behavior on the spatial–temporal flexibility of electric vehicle charging load. Sustainable Cities and Society, 88, 104263.

4 Nunez-Jimenez, A., Knoeri, C., Hoppmann, J., & Hoffmann, V. H. (2022). Beyond innovation and deployment: Modeling the impact of technology-push and demand-pull policies in Germany's solar policy mix. Research Policy, 51(10), 104585.

5 Thimet, P., & Mavromatidis, G. (2023). What - where - when: Investigating the role of storage for the German electricity system transition. *Under review.*

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Heating and electricity demand modeling for residential and commercial buildings

Work package 2

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[1]Hochschule Luzern, Competence Centre Thermal Energy Storage

1 OBJECTIVES

- To estimate the total electricity and heat demand for single buildings as well as aggregated at different levels, such as quarters and communities.
- Assessing the increasing share of electrified heating systems and their respective electricity demand.
- Validation of the developed estimation methods based on real-world consumption data.

2 CONTRIBUTION TO PATHFDNR

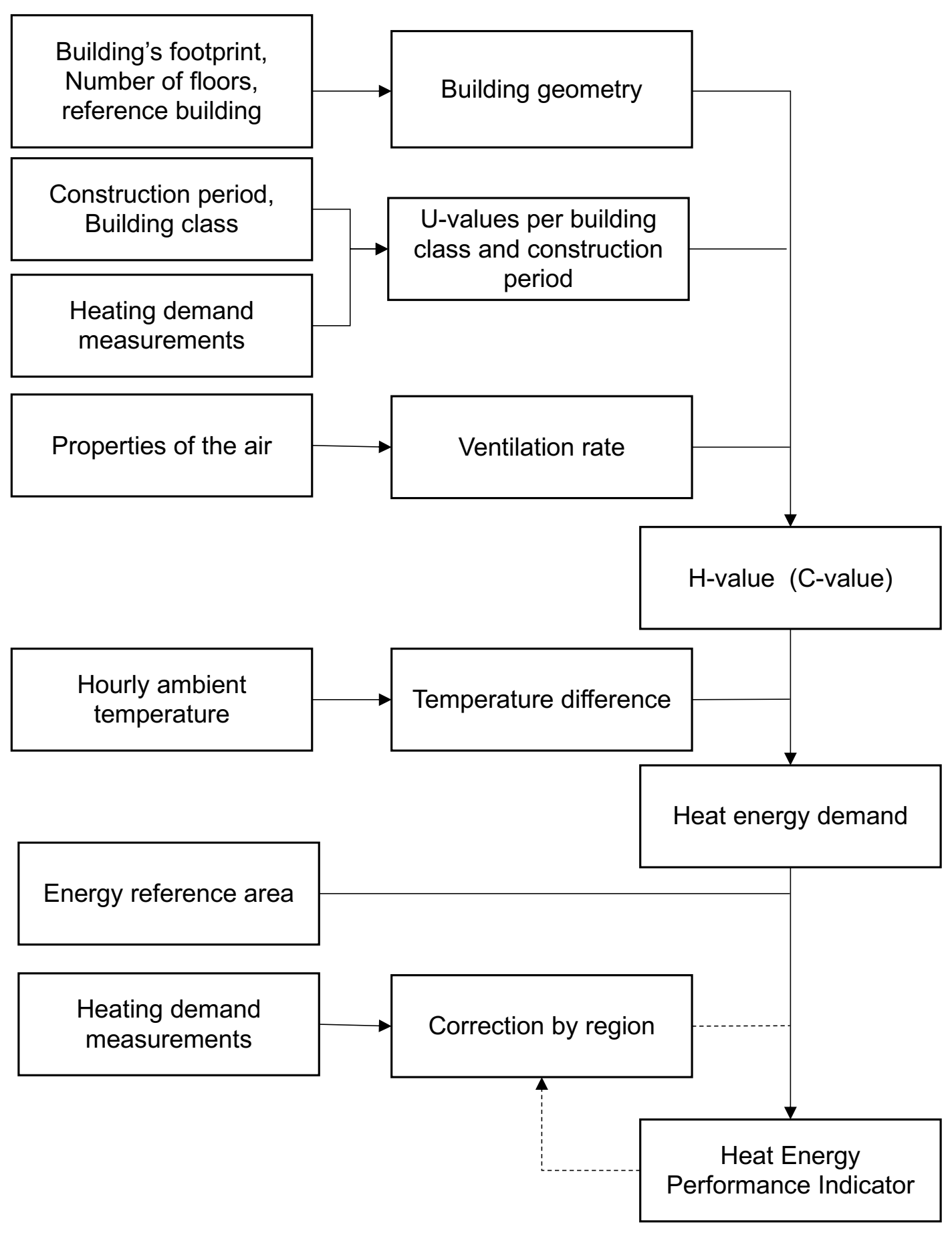
In the residential sector, space heating and domestic hot water contribute to more than 80 % of the energy demand. Based on the thermal inertia of buildings, the prediction of the heating demand/profile for buildings helps to assess its flexibility and supports future sustainable energy systems. Accurate estimation of representative electricity demand profiles for residential, and commercial sectors is essential to model and identify the peak usage periods and patterns, and underpins the development of strategies for load management and peak shaving.

2 METHODOLOGY

Heating demand estimation

- based on building characteristics from the RBD[1], weather data from the Meteostat and its Python library, and reference values from literature[2]
- calibrated and validation based on real-world consumption data[3].

The detailed workflow is displayed in the flow diagram.



Building's footprint, Number of floors, reference building

Building geometry

Construction period, Building class

Heating demand measurements

U-values per building class and construction period

Properties of the air

Ventilation rate

H-value (C-value)

Hourly ambient temperature

Temperature difference

Heat energy demand

Energy reference area

Heating demand measurements

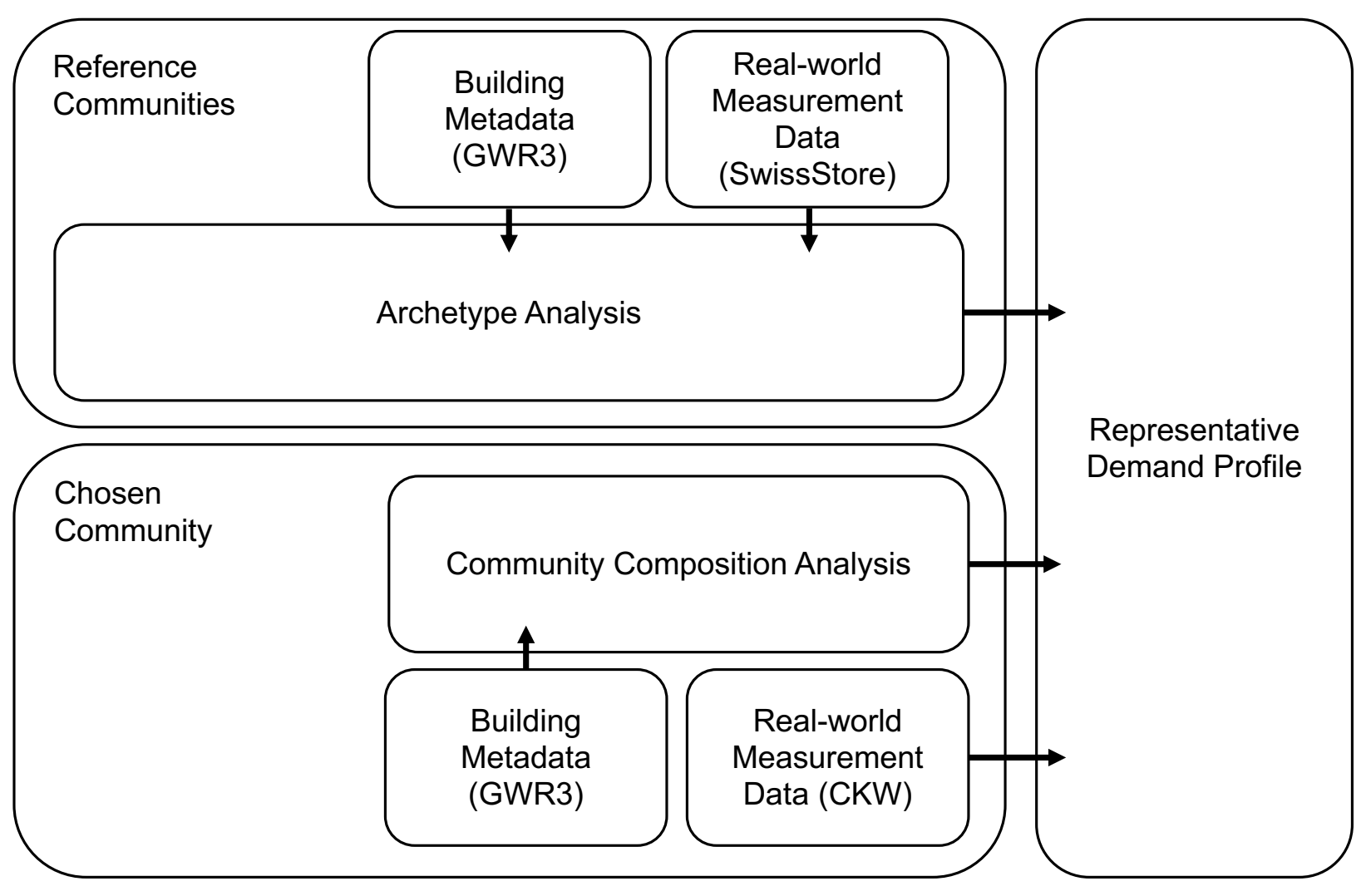
Correction by region

Heat Energy Performance Indicator

Electricity demand estimation

- based on building characteristics from the RBD[1], and multiple- and single-family household aggregated consumption data[4].
- calibrated and validation based on real-world consumption data[5].

The detailed workflow is displayed in the flow diagram.



Reference Communities

Building Metadata (GWR3)

Real-world Measurement Data (SwissStore)

Archetype Analysis

Chosen Community

Community Composition Analysis

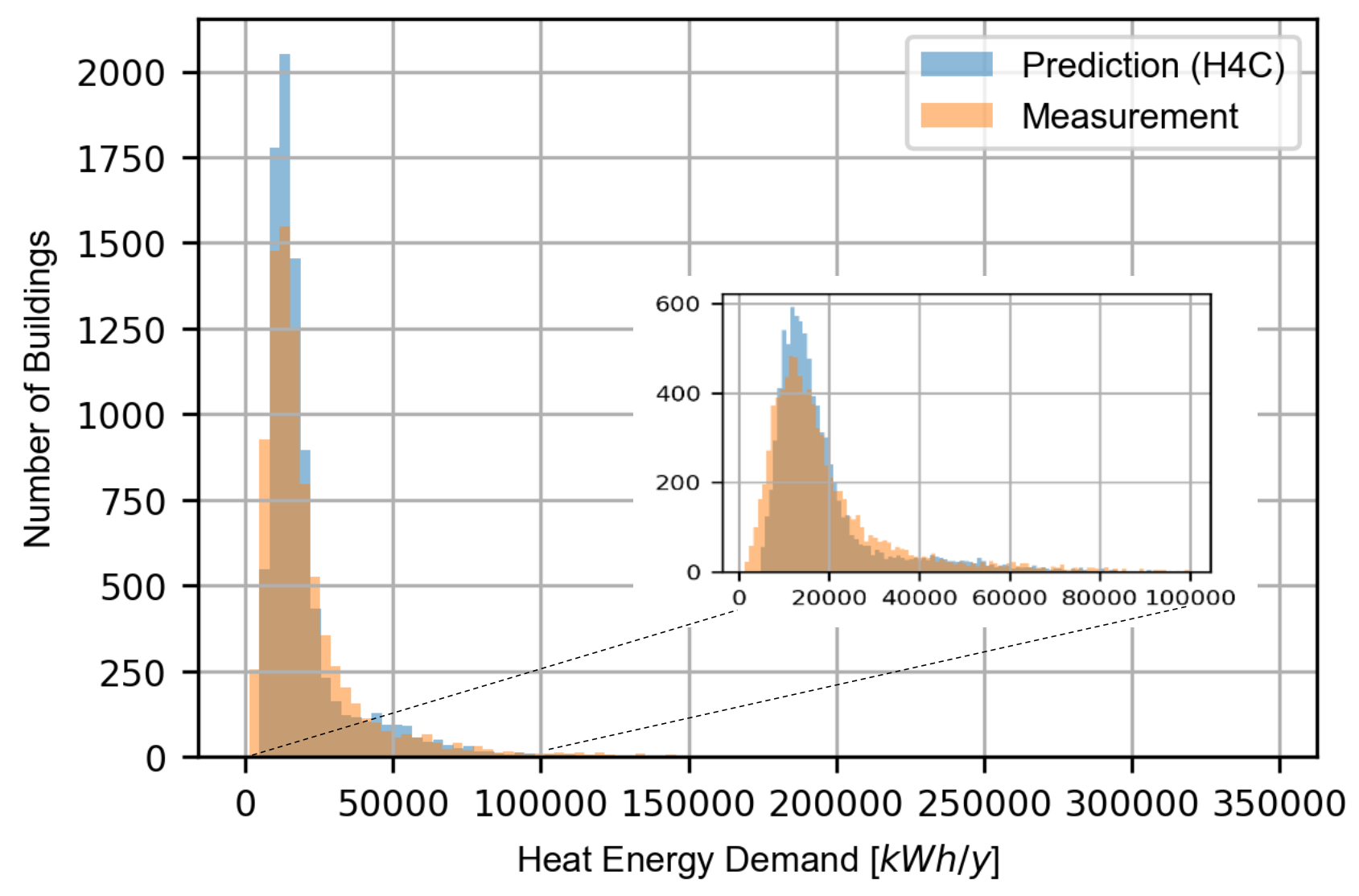
Building Metadata (GWR3)

Real-world Measurement Data (CKW)

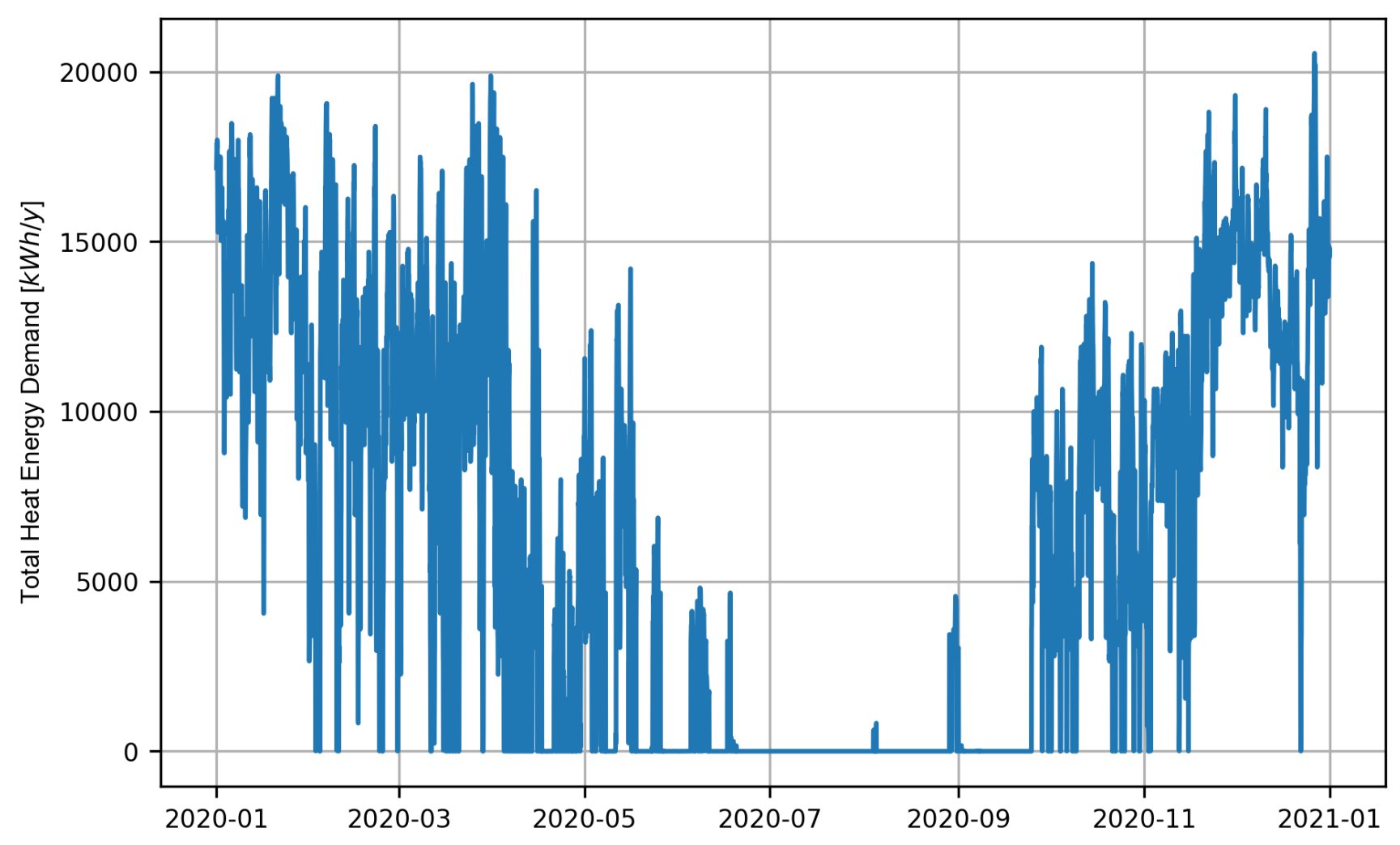
Representative Demand Profile

3 RESULTS

Heating demand estimation



- Validation of the BL-region-calibrated model on test data. In the inset, smaller bins have been used to profit from the increased resolution.

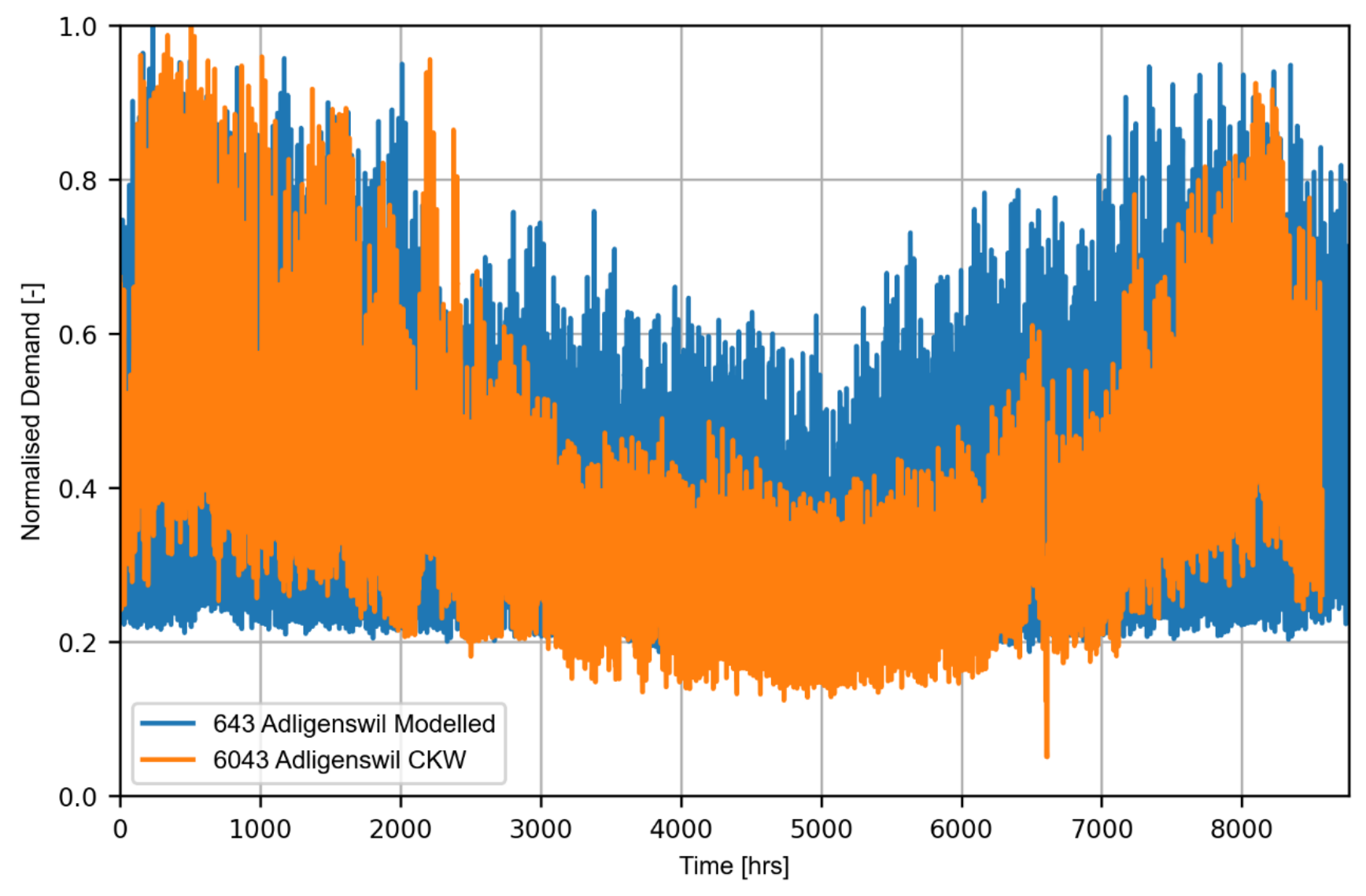


- Hourly heat demand profile for space heating for 2020 of all residential buildings in Liestal (BL).

Electricity demand estimation

PLZ	Communities	Modelled Demand (MWh/a)	Reported Demand (MWh/a)	Fraction of Reported (-)	Normalised Demand (MWh/a)	Fraction of Reported (-)
6043	Adligenswil	18'932	19'433	0.97	18'045	0.93
6212	Knutwil, Mauensee	6'977	9'890	0.71	8'461	0.86
6047	Horw	5'777	41'042	0.14	30'406	0.74
6217	Ettiswil	1'993	9'605	0.21	9'807	1.02
6243	Egolzwil	6'474	5'354	1.21	6'419	1.20
6044	Root, Udligenswil	8'630	9'429	0.92	8'469	0.90
6024	Hildisrieden, Neuenkirch	8'803	10'054	0.88	8'588	0.85
6242	Wauwil, Mauensee	9'756	8'310	1.17	8'753	1.05
6010	Kriens, Hergiswil (NW)	77'810	66'601	1.17	91'705	1.38
6231	Schlierbach	3'350	3'757	0.89	3'295	0.88
Average		**14850**	**18348**	**0.83**	**19395**	**0.98**

- Validation of the modelled demand for a range of communities in the Luzern region using reported consumption statistics from Kanton Luzern[5].



- Hourly electricity demand profile for 2022 of all residential buildings in Adligenswil, compared to CKW smart meter consumption data for the community.

REFERENCES

1 Federal Register of Buildings and Dwellings (RBD), Federal Statistical Office, https://public.madd.bfs.admin.ch

2 A. Pongelli, Y. D. Priore, J. P. Bacher, and T. Jusselme, “Definition of Building Archetypes Based on the Swiss Energy Performance Certificates Database”, 2023; and D. Klauser, “Solarpotentialanalyse für Sonnendach.ch”, 2016

3 Statistical office of BL

4 Arthur Rinaldi, Héctor Ramirez, Benjamin Schroeteler, & Marco Meier. (2022). The role of energy storage technologies in the context of the Swiss energy transition (SwissStore) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.6782179

5 Energiespiegel für Gemeinden, Kanton Luzern, https://bitly.ws/UrkV

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Economic and Environmental Assessment of Energy Strategies Designed to Mitigate the Swiss Electricity Winter Problem

Work package 7

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[1]Climate Policy Lab, ETH Zürich, Department of Environmental Systems Science, 8092 Zürich, Switzerland

1 OBJECTIVES

Switzerland historically had a '**winter problem**': an electricity production deficit over the winter months. The planned phase-out of nuclear and the roll-out of photovoltaic (PV) panels, outlined by the EP2050+ roadmap [1], will only exacerbate this problem because of PV's seasonal imbalance *(fig.1)*, reaching **net winter imports of almost 10 TWh**. However, the availability of 10 TWh of net winter imports in the future is not guaranteed, considering that neighbouring countries will face similar levels of PV penetration as they decarbonise [2,3]. In this study, we assess different strategies *(table 1)* as possible mitigation solutions to the winter problem, limiting Swiss **net electricity winter imports to 5 TWh**.

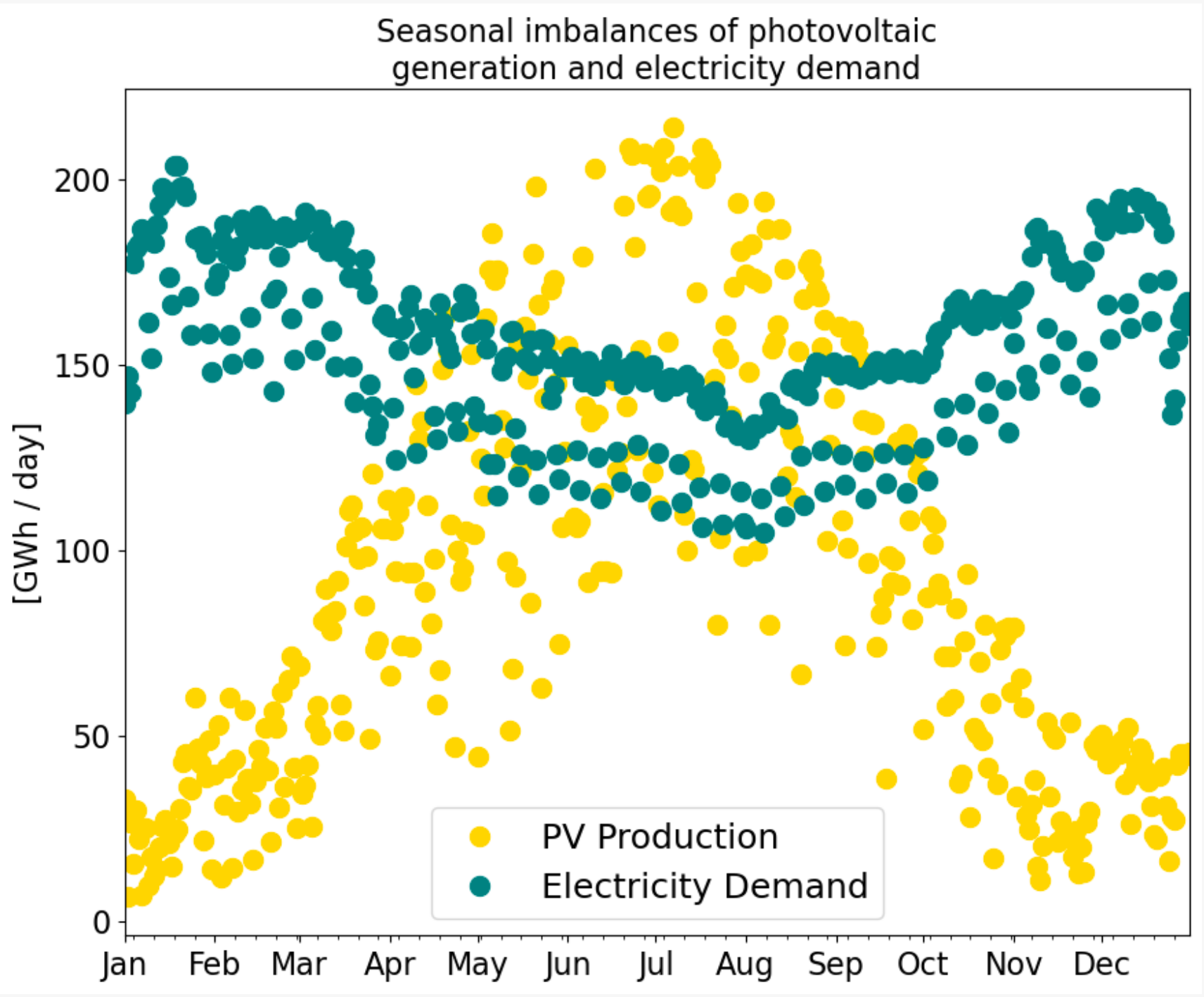

Figure 1: Seasonal fluctuations of solar energy reinforcing a seasonal supply-demand mismatch: ***the winter problem***

Table 1: Mitigation strategies assessed in this study

Scenario	Characteristic compared to Baseline
Baseline	EP2050+ Zero Basis roadmap [1]
Alpine PV	• Allow Alpine PV, up to 13.0 GW and 22.0 TWh
DACCS	• Allow natural gas imports, gas turbines with Post Combustion Capture, and use direct air capture for residual emissions
WIND	• x2 wind turbine capacity
PV++	• Allow 20% more PV
CHP	• x2 Combined-Heat & Power capacity
H2	• Allow hydrogen imports and gas turbines running on renewable methane
S/CCGT	• Allow gas turbines running on renewable methane
RE MIX	• All of the above allowed except DACCS
MIX	• All of the above allowed

2 ENERGY MODELLING

Using the *Calliope* software [4], we model a sector-coupled energy system of Switzerland and its neighbours. We re-create the EP2050+ roadmap and use it as a reference point of comparison to assess possible solutions to the winter problem. We enforce a maximum of 5 TWh of net winter imports with an additional optimisation constraint.

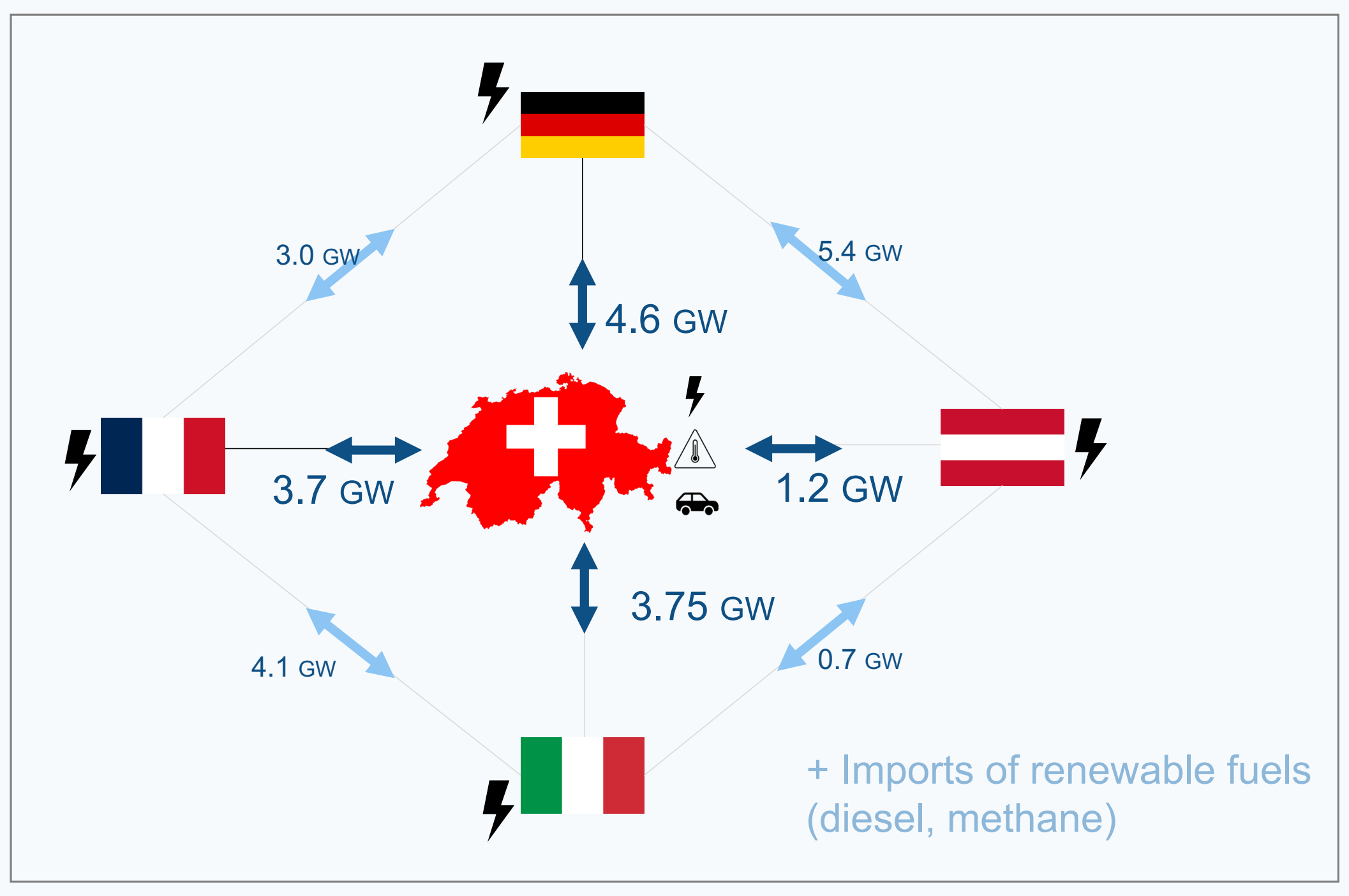

Figure 2: Model region

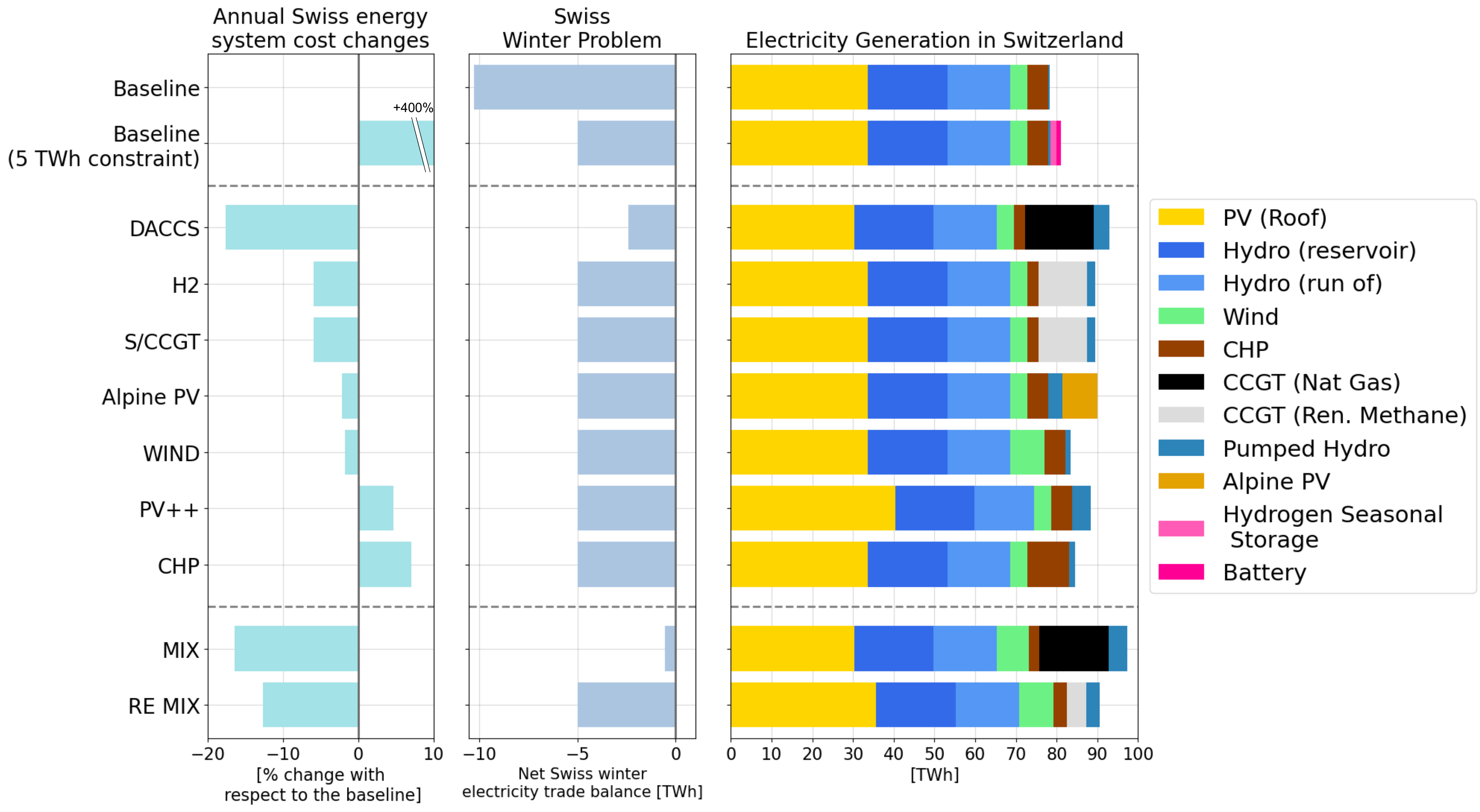

Figure 3: Economic cost, net winter imports and corresponding electricity mix in the different scenarios (preliminary results

3 ENVIRONMENTAL LCA: METAL REQUIREMENTS AND LAND USE

To evaluate the environmental viability of the solutions, we further couple the energy model with a life-cycle assessment (LCA) framework, comparing their metal and land requirements with EP2050+'s roadmap.

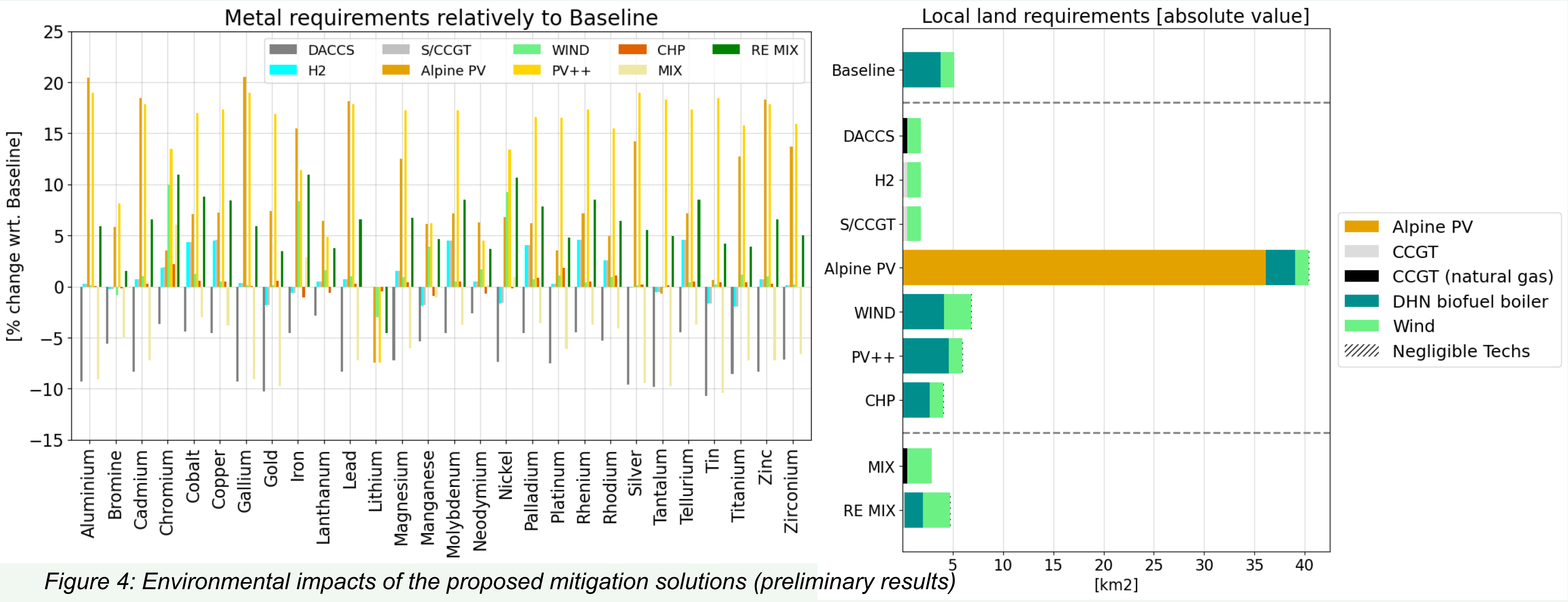

Figure 4: Environmental impacts of the proposed mitigation solutions (preliminary results)

4 CONCLUSION

- Mitigating the winter problem is feasible from technical, economic cost and environmental impacts perspectives.
- Gas turbines with CCS are the cost-optimal solution, but come with other trade-offs: social acceptance, fossil fuel imports, reliance on unproven technologies at scale.
- Mitigation is also feasible in a fully renewable scenario (RE MIX), using more wind turbines and thermal plants running on renewable fuel.
- Sensitivity analyses showed that the most impacting factors were weather patterns, notably outside temperatures and water inflows in reservoirs.

REFERENCES

[1] Prognos AG, INFRAS AG, TEP Energy GmbH, and Ecoplan AG. Energieperspektiven 2050+ - Kurzbericht. December 2022.
[2] Electricity Commission (ElCom). Versorgungssicherheit im Winter - Auslegeordnung zu den Impor- trisiken. June 2021.
[3] Nadine Lienhard, Robin Mutschler, Ludger Leenders, and Martin Rüdisüli. Concurrent deficit and surplus situations in the future renewable Swiss and European electricity system. Energy Strategy Reviews, 46:101036, March 2023.
[4] Stefan Pfenninger and Bryn Pickering. Calliope: a multi-scale energy systems modelling framework. Journal of Open-Source Software, 3(29):825, September 2018.

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