PATHFNDR WORKSHOP

List of posters
Version 12.09.2022
Lea Ruefenacht

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PATHFNDR

The PATHFNDR consortium

Pathways to an efficient future energy system through flexibility and sector coupling (2021-2027)

In line with the national vision of net-zero GHG emissions PATHFNDR imagines an **efficient, flexible, resilient, cost-effective, and sustainable Swiss energy system by 2050.**

Within this future, the main goal of PATHFNDR is to develop and analyze **energy transition pathways for renewable energy integration in Switzerland.**

Main objectives

1. **Improve performance**
   Identify synergies and tradeoffs between efficiency, resilience, sustainability and cost-competitiveness of energy systems

2. **Foster sector coupling**
   Evaluate technologies, business models, innovation strategies, policies and end-user acceptance for sector coupling

3. **Enable flexibility**
   Assess system flexibility options across various sectors and along various spatiotemporal scales

Expected outcomes

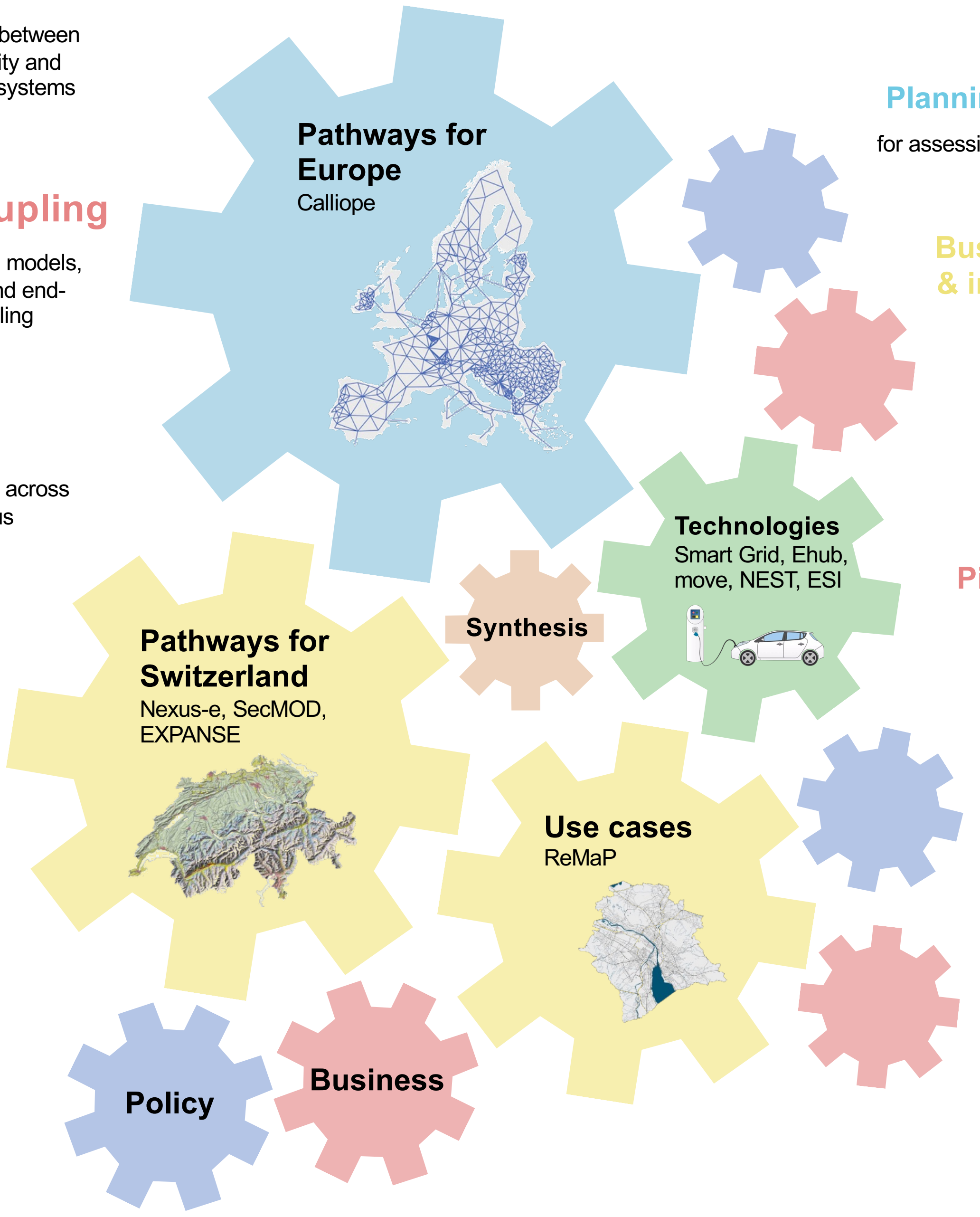
Feasible pathways
for enabling renewable energy integration

Planning & operation tools
for assessing pathways and technologies

Business opportunities & innovation strategies
at value chain and firm levels

Potential policies
for the energy transition

Pilot & demonstration (P&D) projects
for testing market designs and technologies



WP 1
Quantification of large-scale **energy pathways for Switzerland** (embedded in its European context)

WP 2
Assessment of energy pathways at **local-scale uses cases** (cities, villages, districts, site, networks)

WP 3
Analysis of **technologies** from multiple **energy sectors** (thermal, electrical and gas)

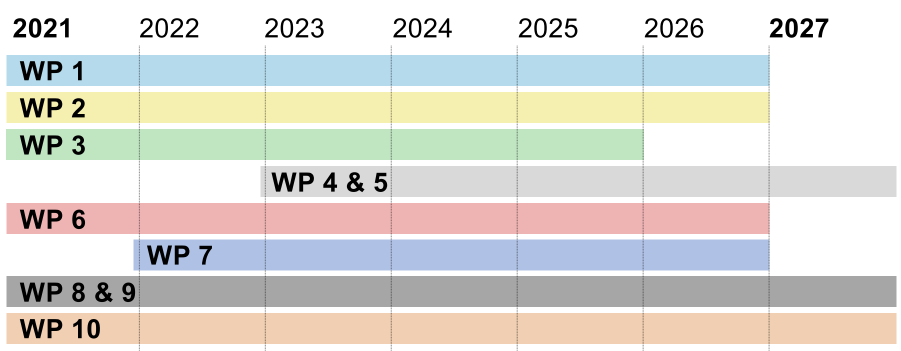
WP 4 & 5 (P&D)
Implementation of **pilot & demonstration projects** to test market designs and technologies

WP 6
Identification of **disruptions and business interests** as well as strategies to address them

WP 7
Analysis of political feasibility, **public acceptance**, and effects of **policies in Switzerland**

WP 8 & 9
Management of project activities and results, and **KTT** to the various stakeholders

WP 10
Coordination of **scenarios** as well as **integration and synthesis** of research results



CONSORTIUM

ETH zürich, Empa, PSI, zhaw, Hochschule Luzern, Université de Genève, EPFL, TU Delft

+ industry partners

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CROSS

Energy Science Center

SWEET-CROSS

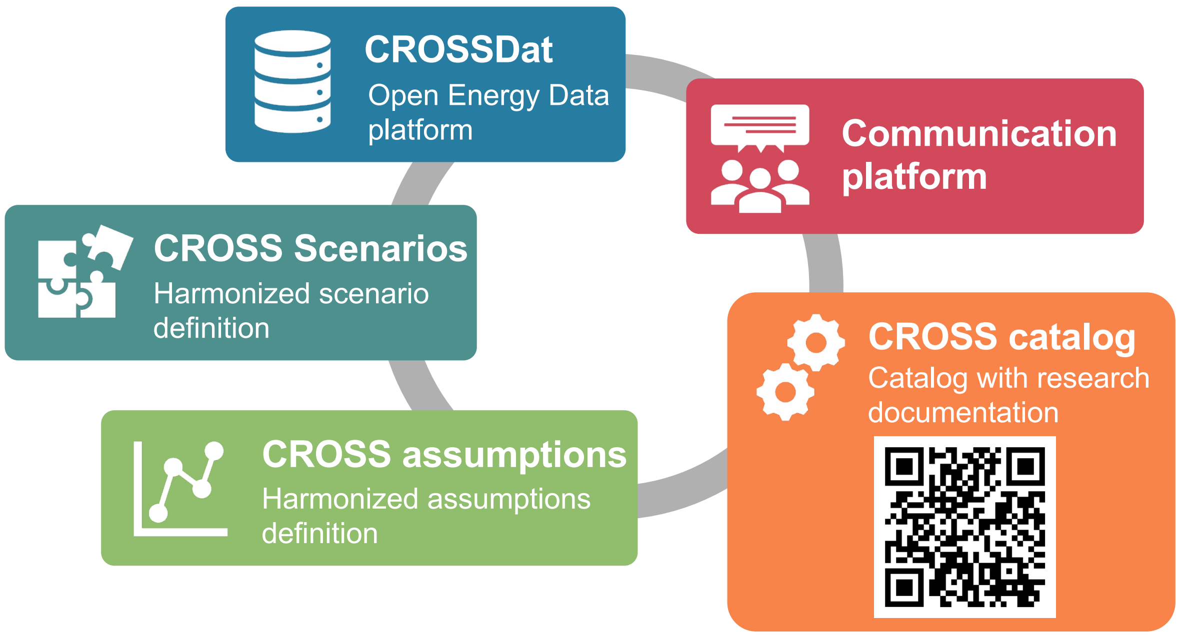
CooRdination Of Scenarios and Data in SWEET

What is CROSS?

CROSS is an activity of the Swiss Federal Office of Energy's "SWEET" programme that aims at:

- **increasing comparability** of the simulations and
- **incresing credibility** of the results

from the simulations from the SWEET consortia DeCarbCH, EDGE, PATHFNDR and SURE



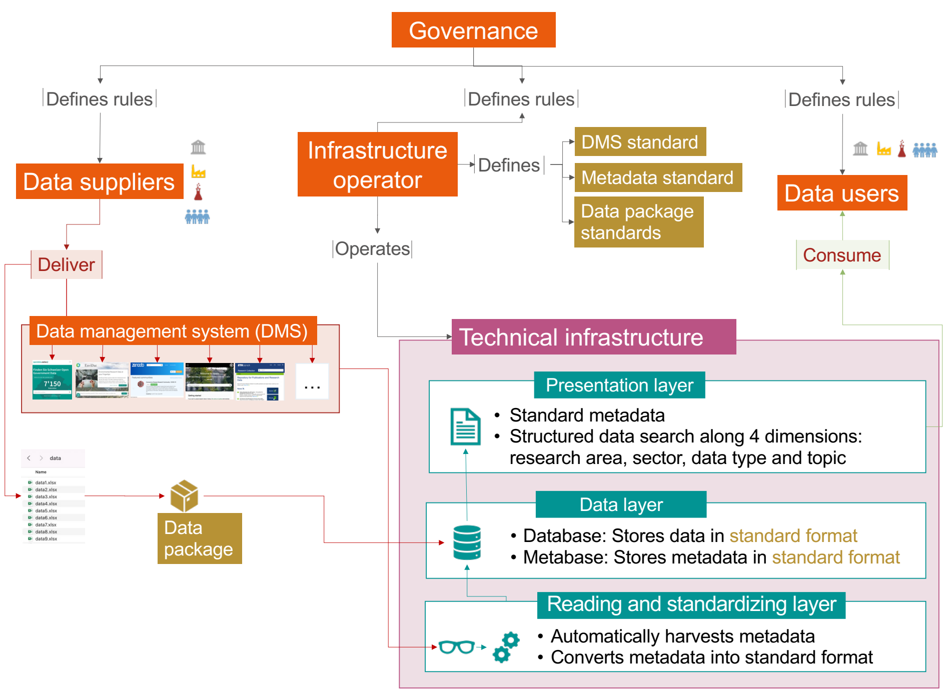
CROSSDat

Platform with unified access to SWEET and **energy** related (research) data, **irrespective of where it is stored and curated.**

Features

1. It is both a metabase and a database
2. CROSSDat uses Frictionless standards for data packages and metadata
3. CROSSDat principles: Unified data access, Distributed research data management, Findable, Accessible, Interoperable, Reusable

Structure



CROSS Scenarios

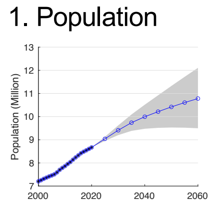
- Scenarios are **alternative developments** of the future energy system
- CROSS scenarios are defined along two dimensions: Climate policy and energy market integration

Climate policy	Energy market integration
Net-zero without compensation abroad	Moderate integration
	Low integration
Net-zero with compensation abroad	Moderate integration
	Low integration

CROSS assumptions

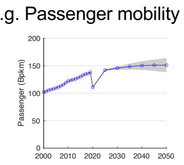
Harmonization of uncertain drivers, including, socioeconomic development, demands, global climate change and resources

1. Population

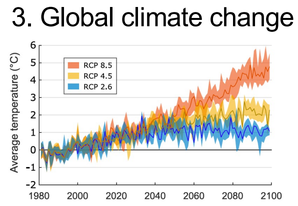


2. Demands

E.g. Passenger mobility



3. Global climate change



4. Resources

	Renewable potentials (TWh/a)		
	Hydropower	Solar	Wind
Low	34.8	30	1.7
Reference	36.4	45	4.3
High	38.4	88	15

COORDINATION

Energy Science Center

ETH zürich

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EPFL

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PAUL SCHERRER INSTITUT PSI

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PATHFNDR

PATHFNDR scenarios

Work package 1

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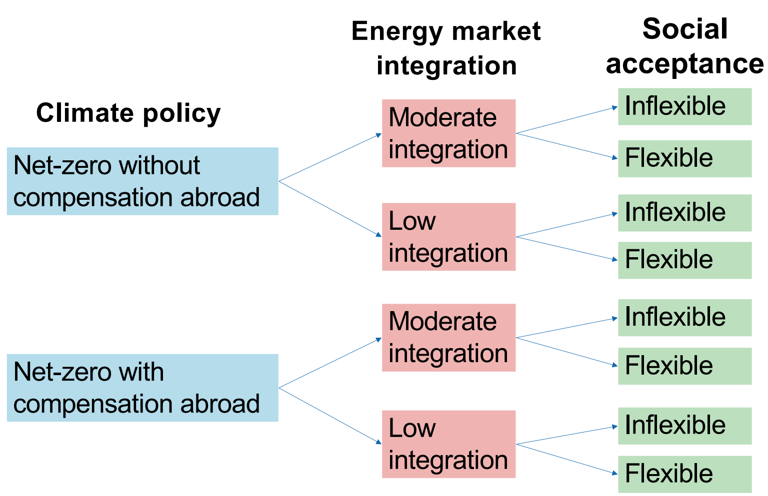
[2] Faculty of Technology, Policy and Management (TPM), Delft University of Technology, Delft, the Netherlands

What are PATHFNDR scenarios?

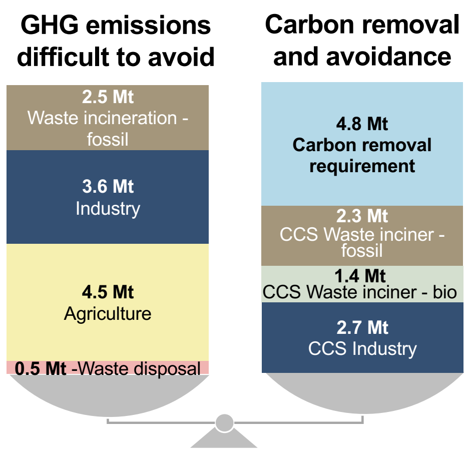
- Scenarios are **alternative developments** of the future energy system
- Quantifying these scenarios helps us with understanding the role of **flexibility** and **sector coupling** in achieving the Swiss net zero GHG goal

Scenario dimensions

- PATHFNDR scenarios are defined along 3 dimensions on which Swiss citizens and policymakers **can** exert direct influence



Climate policy dimension: Net zero GHG target



Carbon removal requirement is 4.8 MtCO2, which can be compensated by the energy sector and abroad

	Energy emissions (MtCO2)	Carbon removal abroad (MtCO2)
Net-zero without compensation abroad	-4.8	0
Net zero with compensation abroad	-2.4	-2.4

Energy market integration dimension

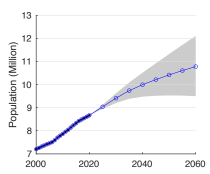
Degree of self-sufficiency for different commodities

	Electricity	Biofuels and biomass	Hydrogen
Low integration	30% net transfer capacity	No imports	No imports
Moderate integration	100% net transfer capacity	56 PJ by 2050 from EP2050+ [1]	Upper limit from EP2050+ [1]

Uncertain drivers

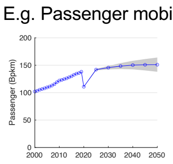
- Uncertainties: Affect the energy system directly or indirectly

1. Population

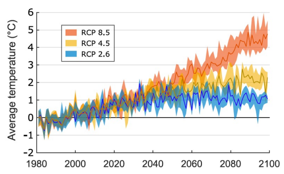


2. Demands

- E.g. Passenger mobility



3. Global climate change



4. Resources: Hydropower, solar, wind, biomass, etc.

Social acceptance dimension

- Public acceptance of new infrastructure

Renewable potentials (TWh/a)

	Hydro-power	Solar	Wind
Inflexible	34.8	30	1.7
Flexible	38.4	88.2	15

- Willingness to change consumption patterns

Time by which use can be shifted

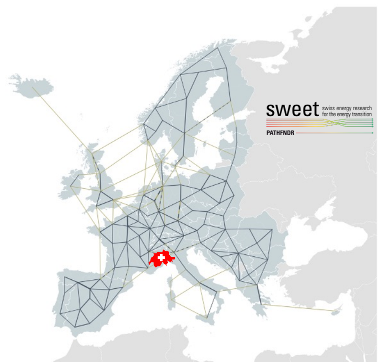
	Appliances	Vehicle charging
Inflexible	0	0
Flexible	24 hours	72 hours

PATHFNDR Scenarios – Europe

Scenarios' descriptions

Import of fuels from outside Europe	a) No fuel imports allowed. b) Fuel imports are allowed but available starting from 2035 [2]. c) Fuel imports are allowed but available starting from 2045 [2].
Import of electricity from outside Europe	a) No electricity imports allowed outside Europe. b) Electricity imports are allowed but available starting from 2035. c) Electricity imports are allowed but available starting from 2045.
CO_2 compensation abroad (within Europe)	a) Allowed to sequester emissions abroad within Europe. b) Net-zero emissions carbon budgets are imposed on each country.
Interconnections between European countries	a) Restrict the transmission networks according to development plans' levels at different points in time (now, 2030, 2045, etc.) [3]. b) No transmission constraints.
Continent-scale hydrogen transport	a) Restrict the availability of hydrogen transport to European Hydrogen Backbone's projections [4]. b) No hydrogen transport capacity constraints.
Actions of neighbouring countries of Switzerland	a) No asymmetry in European countries' behaviours. b) Germany divergent. E.g.: Germany depends on massive hydrogen imports from outside Europe. c) France goes rogue: France, for example, could go for a nuclear renaissance.

What are the impacts of European policies on Switzerland energy system planning?



Additional sensitivity analyses and scanning of alternative configurations with different flexibility options will be performed.

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[4] EHB. 2022, *European Hydrogen Backbone* report

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PATHFNDR

Flexibility potentials across Europe

WORK PACKAGE 1 (Task 2)

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[1]Urban Energy Systems Laboratory, Swiss Federal Laboratories for Materials Science and Technology, Empa, Dübendorf, Switzerland

1 OBJECTIVES

The use of flexibility in terms of seasonal energy storage and demand shifting will play a vital role in the future European energy system that mainly relies on intermitted and stochastic renewable generation from solar and wind.

The flexibility options include power-to-X (hydrogen, methane, heat, etc) and demand side management (DSM). While DMS mainly relies on the share of energy demands that can be shifted within short-terms (hours to days), power-to-X needs seasonal storage capacities such as salt caverns, etc. for gaseous energy carriers such as methane or hydrogen. Moreover, for renewable carbon-based energy carrier (i.e., methane) nearby CO2 sources are required for economically viable operation.

2 CONTRIBUTION TO PATHFDNR

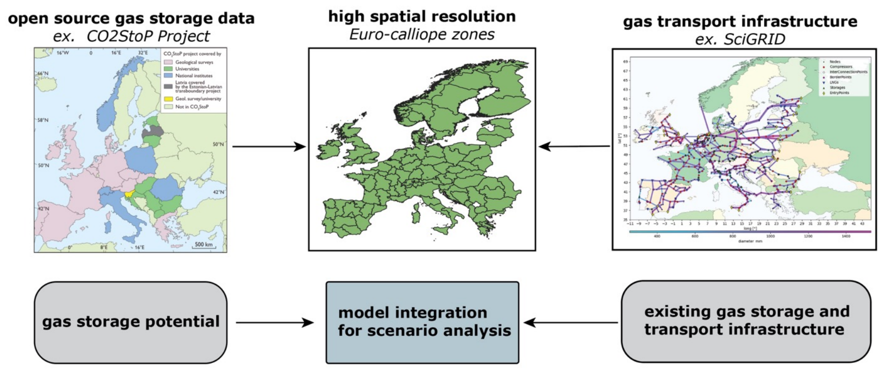
The flexibility options found here are used as inputs in the Euro-Calliope model for the modelling of scenarios at the European scale.

Due to the high spatial (NUTS-3) and temporal (hourly) resolution of the Euro-Calliope model, all parameters of these flexibility options need to be at this spatial and temporal granularly, too.

Results from the modelling at the European scale will then be used as inputs for NEXUS-E to model the Swiss energy system in detail.

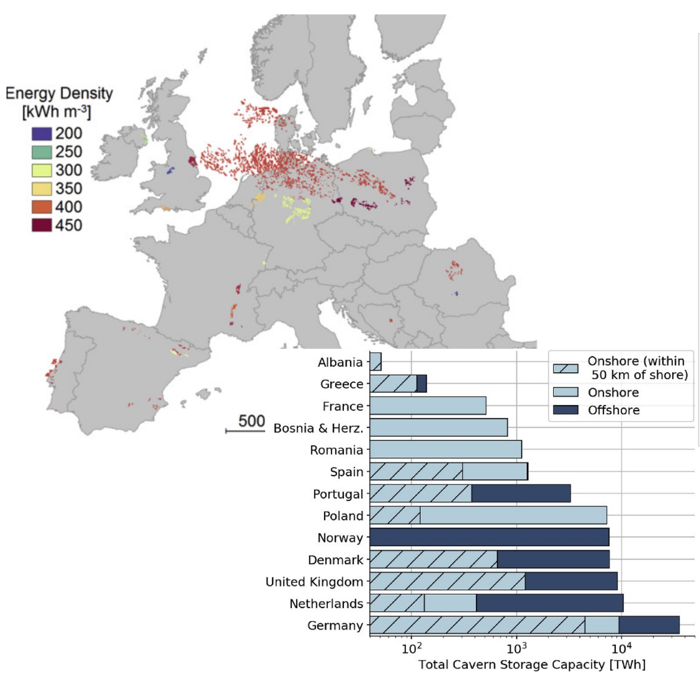
2 METHODOLOGY

- Existing data flexibility options at the European Scale from past projects (e.g. CO2SToP, etc.) are gathered
- The gathered data is assessed with respect to its applicability as inputs for the Euro-Calliope model
- With GIS this data is aggregated and converted to the required spatial and temporal granularity of the Euro-Calliope model
- Results from Euro-Calliope model runs are used as feedbacks to improve the quality of input data for successive runs

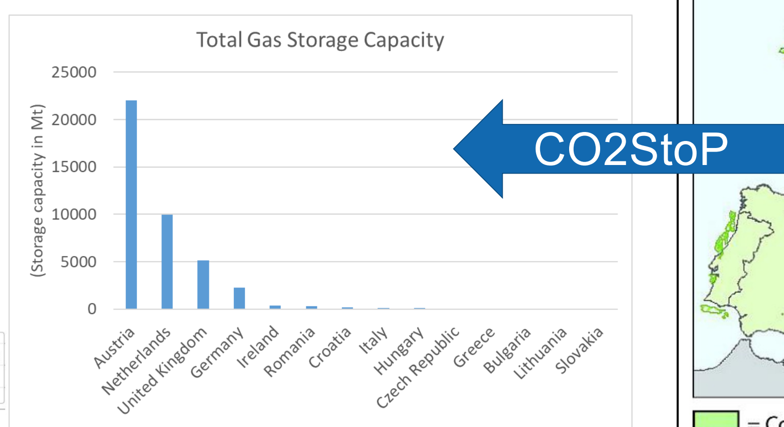


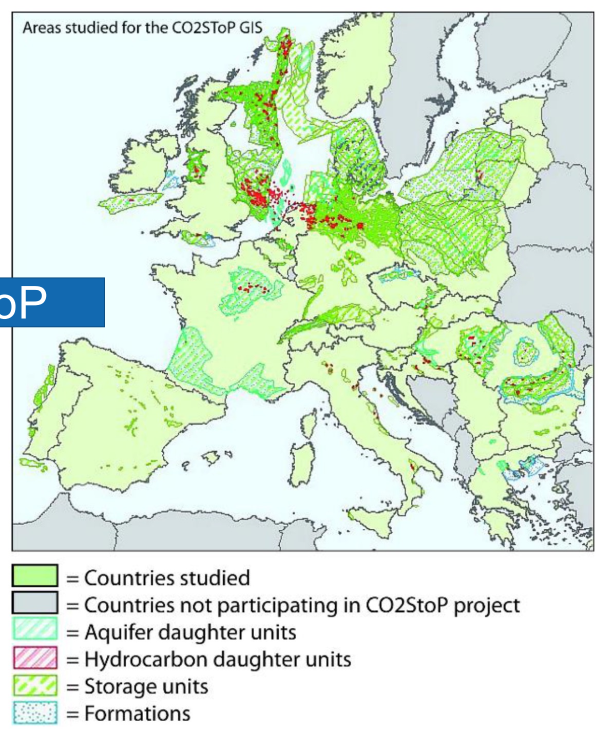
3 RESULTS

Hydrogen storage potential



CO2 storage potential





Reported reservoirs in CO2StoP

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3 PyPSA-Eur-Sec: A Sector-Coupled Open Optimisation Model of the European Energy System. Hydrogen potential data.

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PATHFNDR

Work package 1

How dependent is the Swiss energy transition on developments abroad?

Marius Schwarz[1], Pranjal Jain[1], Arijit Upadhyay[1], Jared Garrison[2], Elena Raycheva[13], Blazhe Gjorgiev[4], Turhan Demiray[2], Giovanni Sansavini[4], Christian Schaffner[1], Gabriela Hug[3]

[1]ESC, Energy Science Center, ETH Zurich;
[2]FEN, Research Center for Energy Networks, ETH Zurich
[3]PSL, Power Systems Laboratory, ETH Zurich
[4]RRE, Reliability and Risk Engineering, ETH Zurich

Nexus-e

1 Importance of electricity trading

The Russian invasion of Ukraine this February revealed how dependent Switzerland's security of energy supply is on developments abroad. To reduce such dependency, Switzerland aims at an extensive electrification of the economy while simultaneously increasing the domestic, renewable electricity generation [1]. However, electrification of heating and transport and the expansion of solar power are leading to a seasonal electricity demand and supply imbalance. Therefore, electricity trading with neighboring countries is becoming increasingly important.

Whether electricity imports will remain possible in the future depends on the development of electricity generation and demand in neighboring countries as well as the regulatory and political framework. Like Switzerland, the EU aims at climate neutrality by 2050 as part of the European Green Deal [2]. In response to the uncertainty of Russian gas deliveries, the EU outlined the REPowerEU [3] plan which includes higher share of renewables in the energy mix (from today 17.4% to 45% in 2030) and a solar strategy (to achieve 600GW by 2030). While there is no explicit expansion target, wind power is expected to exceed 1000 GW by 2030 [4].

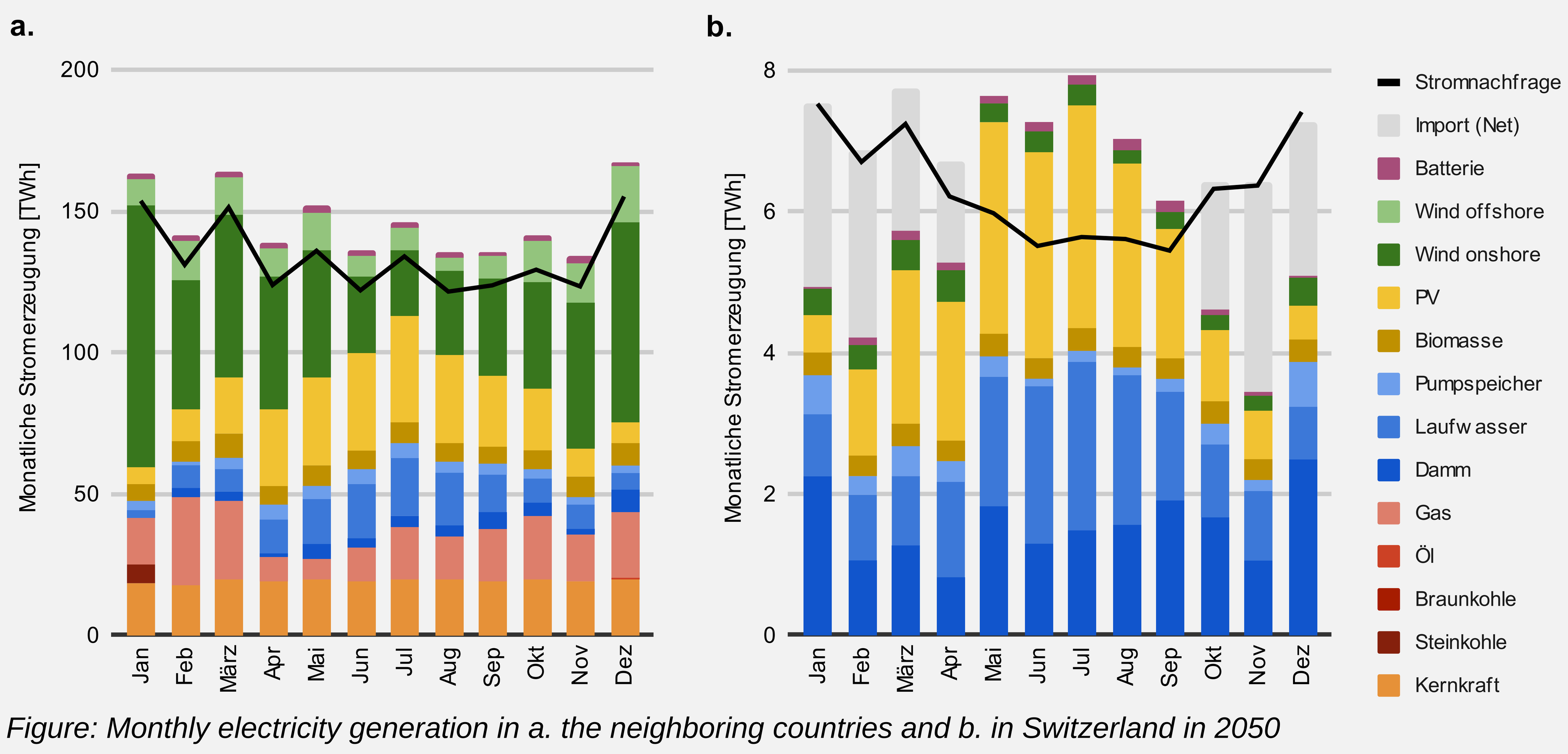
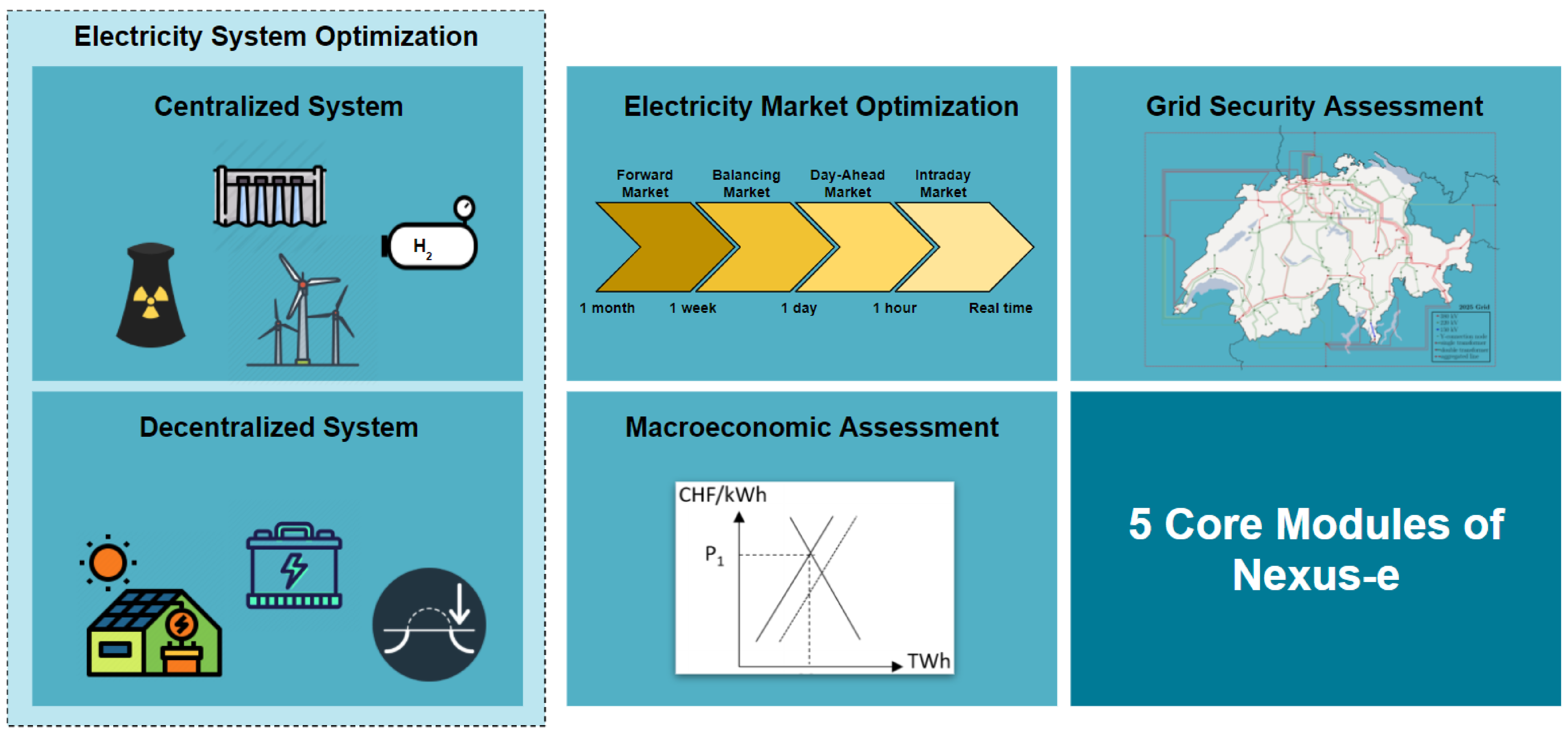


Figure: Monthly electricity generation in a. the neighboring countries and b. in Switzerland in 2050

At Energy Science Center of ETH Zurich, we use the Nexus-e platform to look at the impact of EU developments on Switzerland. In our scenarios, the 2050 Swiss electricity system, which is based on hydropower, PV, wind, biomass, and electricity trading, is sufficient to supply domestic demand. Electricity trading with neighboring countries is aided by the planned massive expansion of wind parks in Europe, which harmonizes seasonally with solar PV in Switzerland.



2 Gas prices affecting the Swiss electricity system

Gas prices have already been rising in Europe since last summer. Our scenarios outline four short-term effects of high gas prices on the Swiss electricity system:

- When increasing gas prices from €30/MWh (price before 2021) in the baseline scenario to €100/MWh (price at the beginning of 2022), electricity prices double in our scenarios. Compared to the historical day-ahead prices, we even underestimate the prices in the model (see Figure 3a.). One reason for this is that we do not consider the current downtime of French nuclear power plants and the drought that is affecting the hydro power generation
- With higher gas prices the utilization of other flexibility options such as pumped hydro increases as they replace expensive peak load gas units abroad.
- The overall costs of the Swiss electricity system are decreasing slightly, as domestic electricity producers can take advantage of high prices.
- In the neighboring countries, electricity generation from gas units is substituted by lignite and hard coal units, despite higher CO_2 costs.

The main long-term impact we observe is that more domestic generation capacity is installed as high electricity prices increase the profitability of these investments.

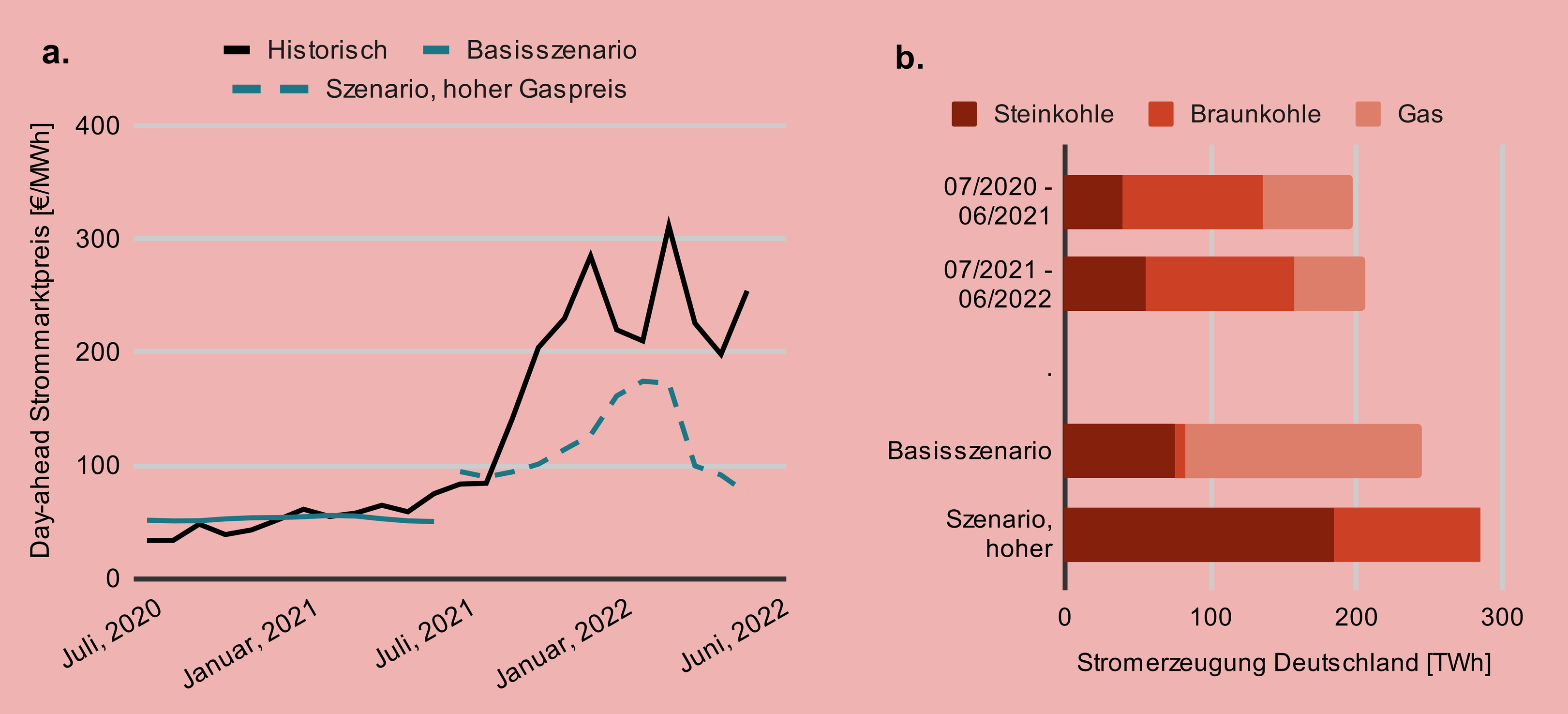


Figure: Impact of high gas prices on a. Electricity market prices and b. Electricity generation from fossil fuels in Germany [5]

3 Gas as a transition fuel

Despite the current crisis, natural gas has just been added to the EU guidelines as "green" investments since July 2022 [6]. If neighboring countries rely heavily on gas as a transition fuel (with or without CCS), electricity prices (higher marginal costs) and overall system costs (as Swiss generation is driven out of the market) are increasing.

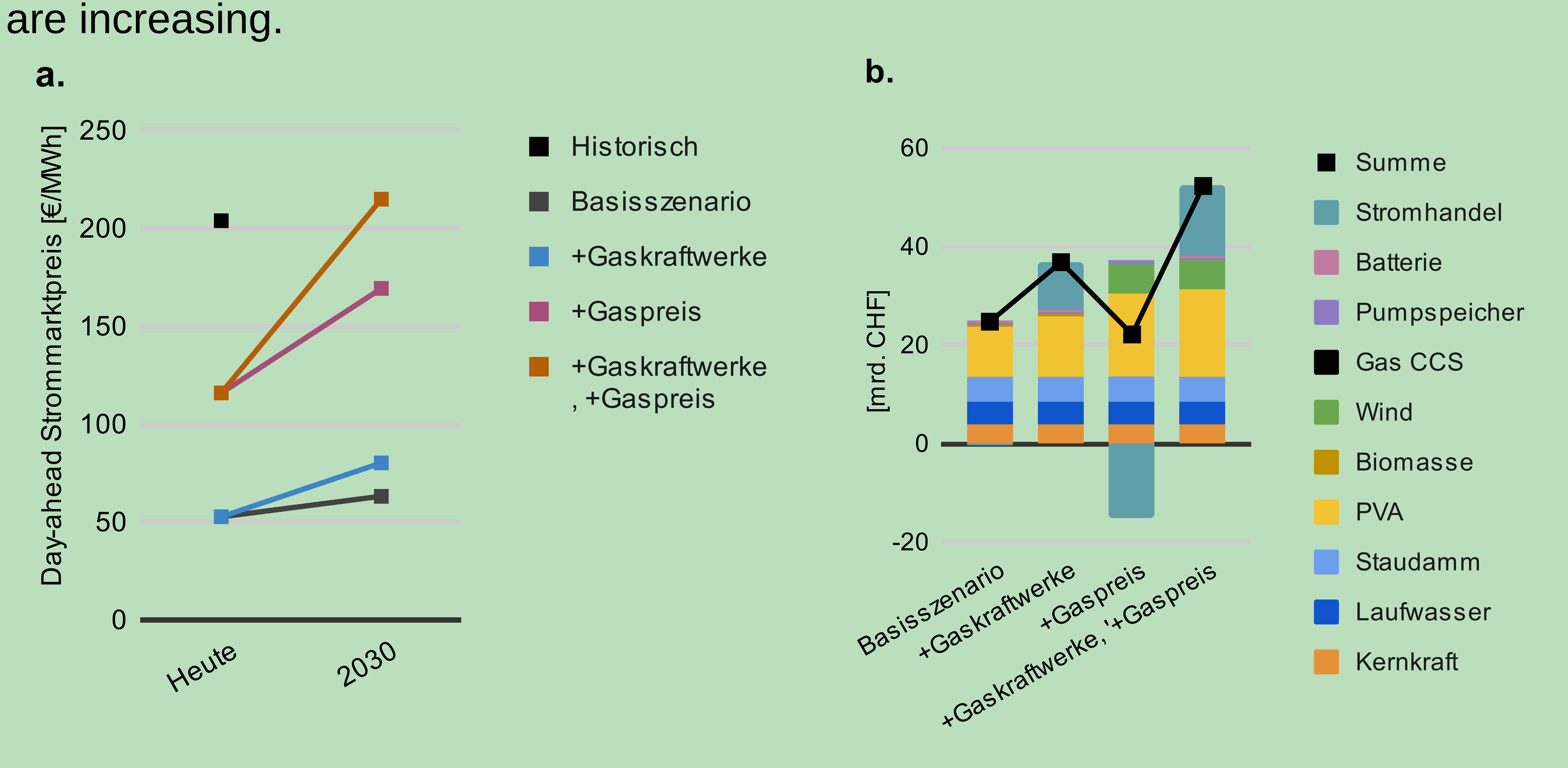


Figure: a. Electricity prices 2020 and 2030, b. Total system costs by 2030.

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Have a look at additional results and scenarios of this project directly in our webviewer!

Storage reserve for Switzerland

Is it necessary and (how) would it work?

Ingmar Schlecht, Jonas Savelsberg, Moritz Schillinger, and Hannes Weigt

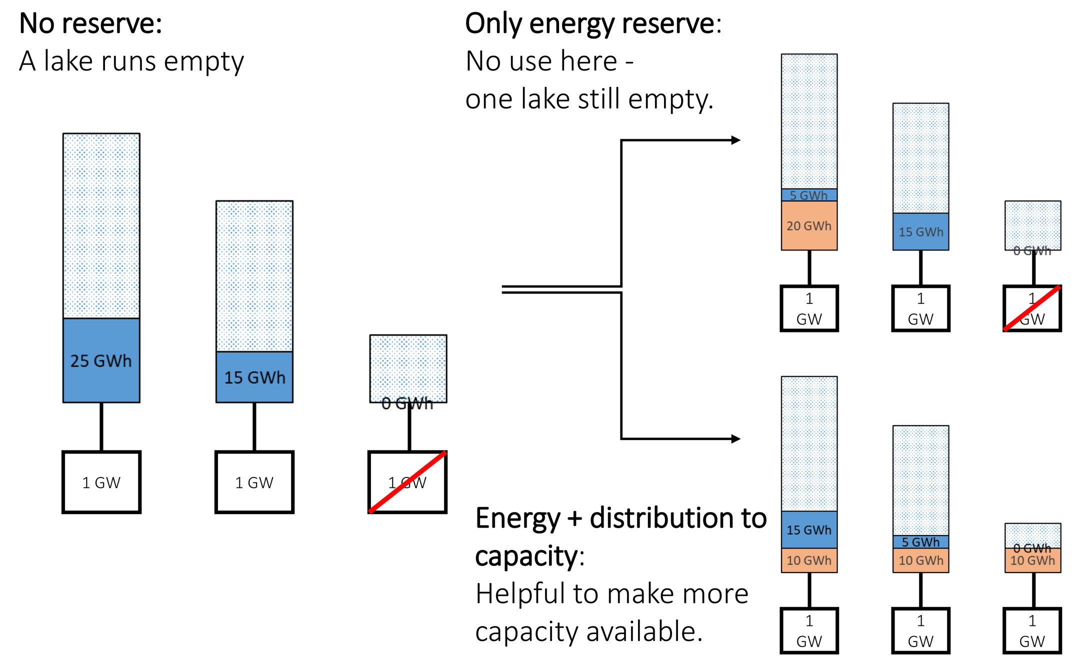
ZHAW Winterthur / ETH Zurich / University of Basel

Background and objectives

A large part of Switzerland's generation capacity (>10 GW) is based on storage or pumped storage power plants, which can only produce when the reservoirs are not empty. In order to increase security of supply in winter, the SFOE has therefore proposed a storage reserve. This would pay storage operators to maintain a minimum water level in their reservoirs and thus leave part of the stored energy unused during normal operation in order to be prepared for critical situations.

In this research paper, we first present the theory of a storage reserve and explain the economic basis of storage reserve pricing. Second, we use Swissmod, a DC load-flow electricity market model for Switzerland with a high level of detail in hydropower, to model an electricity market with a storage reserve. We endogenously derive a competitive procurement of storage reserves at the lowest cost and then test the reserves in different shock scenarios where we specify autarkies with different lengths.

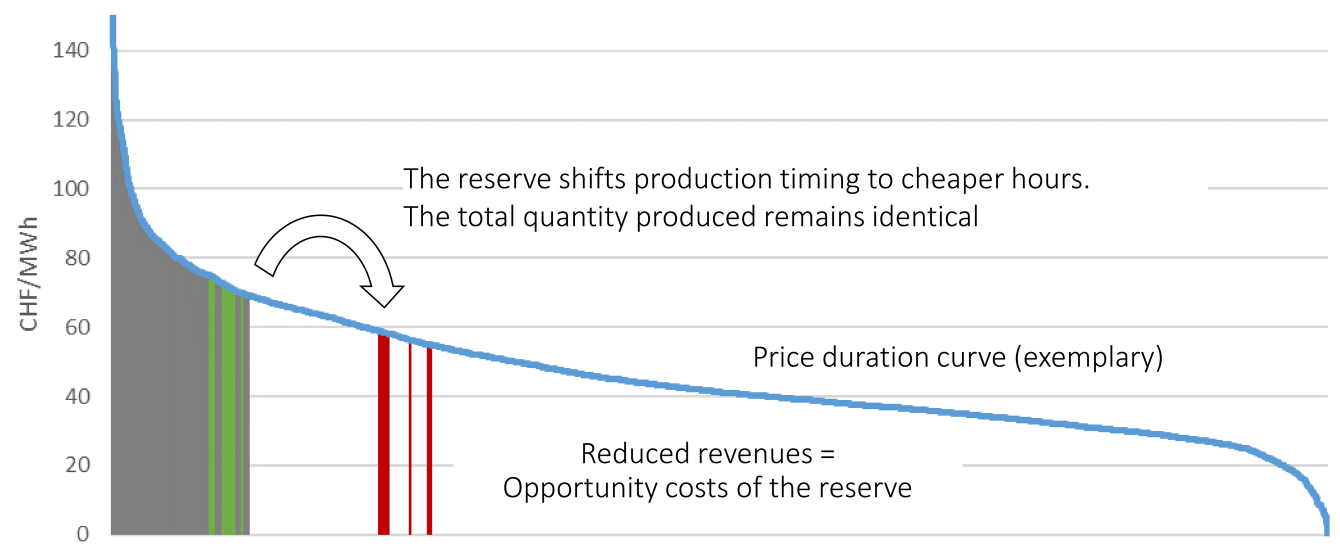
Mechanics of a storage reserve



- Power plants with a large lake volume relative to turbine output have low opportunity costs of storage provision
- They would therefore submit the cheapest bids in a tender
- However, power plants with a smaller storage volume relative to turbine output are often decisive for security of supply.
- Only with a capacity requirement in the tender would these power plants (which are more expensive to reserve) also participate.

Economic costs of storage reserve reservation

(in normal operation, without call-up costs)

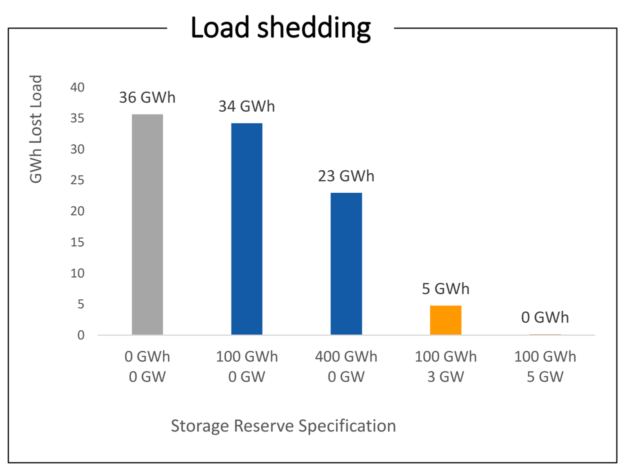


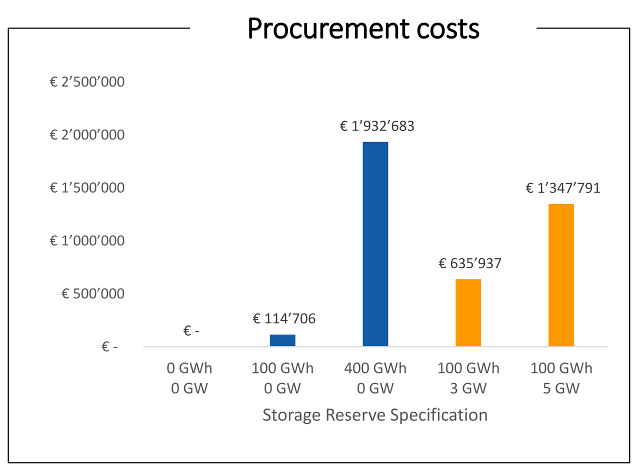
A storage reserve...

- ...reduces usable storage volume for normal operation
- ...therefore incurs costs in the form of lost revenues...
- ...but does not reduce the annual energy production (except in first year)

Results for short import crises (24h autarky)

■ Energy-focused reserves
■ Capacity-focused reserves

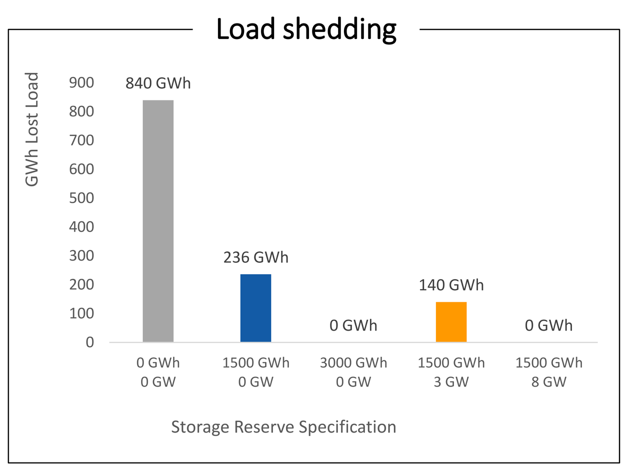


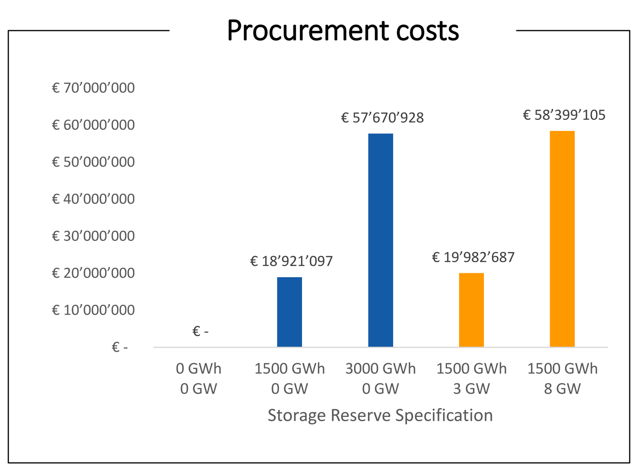


- Capacity (GW) is decisive to solve short import crises
- High energy levels reduce load shedding only slightly

- 100 GWh / 3 GW specification most efficient
- Overall manageable cost framework
- Assumption: perfect competition

Results for long import crises (1 week autarky)





- Significant load shedding during 1 week import crisis (autarky)
- Capacity of the reserve less decisive for long autarkies

- High energy volumes cause significantly higher costs
- Assumption: perfect competition (but excessive bids to be expected at high capacity, then more expensive)

Conclusion

- **Distribution over sufficient capacity necessary**. Not only the specification of an energy quantity, but also the distribution over sufficient underlying power plant capacity is decisive for the effectiveness of a storage reserve. This applies in particular if short-term, strong shocks are also to be mitigated.
- **Cost-benefit difficult to assess**. The cost-benefit ratio of a storage reserve depends heavily on events at the political level (in connection with the allocation of cross-border capacities and Switzerland's participation in the European internal electricity market). It is therefore not possible to estimate it from a technical-economic point of view alone.
- **Market power problematic**. In particular if the storage reserve is designed with a capacity requirement, individual suppliers will be able to exercise market power (excessive prices). This should be taken into account when designing the procurement system.

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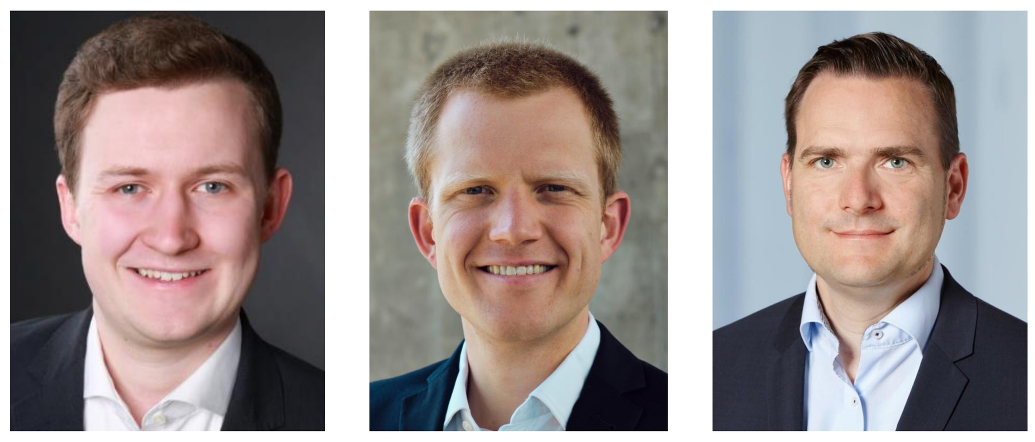


Integrating Scheduling of Multi-Energy Systems and Industrial Processes

Work package 1: Pathways on a national and international scale

Florian Joseph Baader[1], Ludger Leenders[1], André Bardow[1]

[1]Energy and Process Systems Engineering, Department of Mechanical and Process Engineering, ETH Zurich

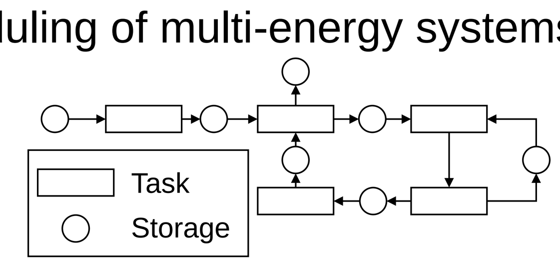
1 Harvesting flexibility by scheduling optimization

Idea: Coordinated scheduling provides flexibility through sector-coupling and allows to

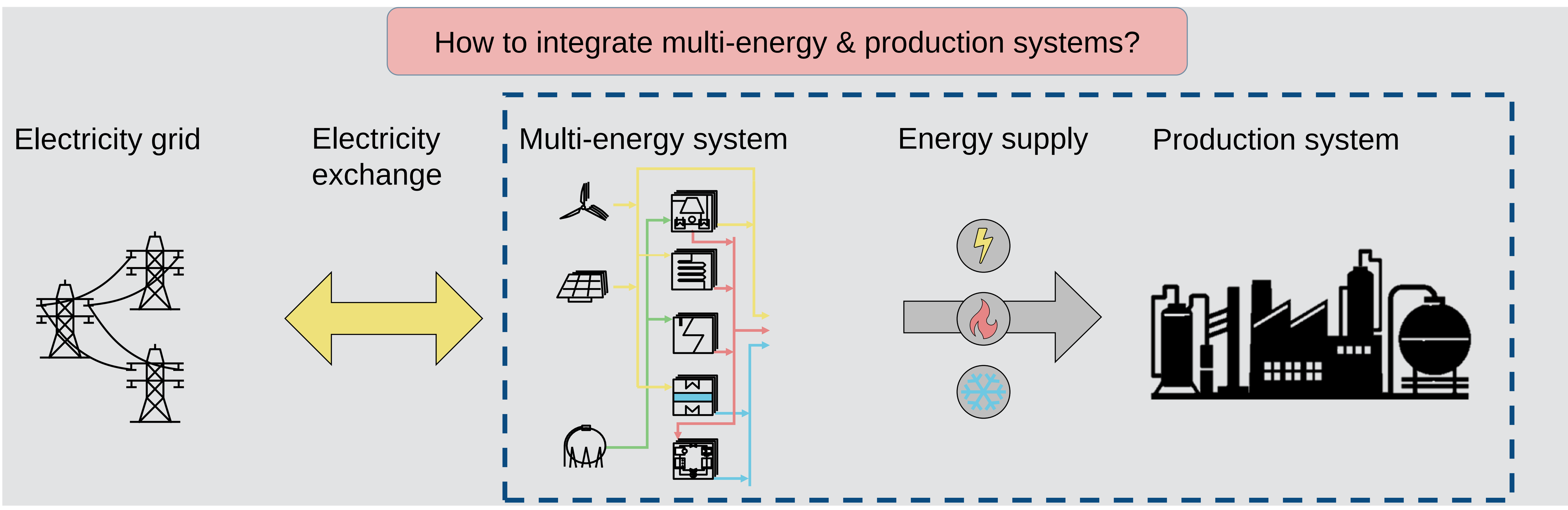
- Minimize costs
- Stabilize the electricity grid

Challenge: Real-time scheduling of multi-energy systems and

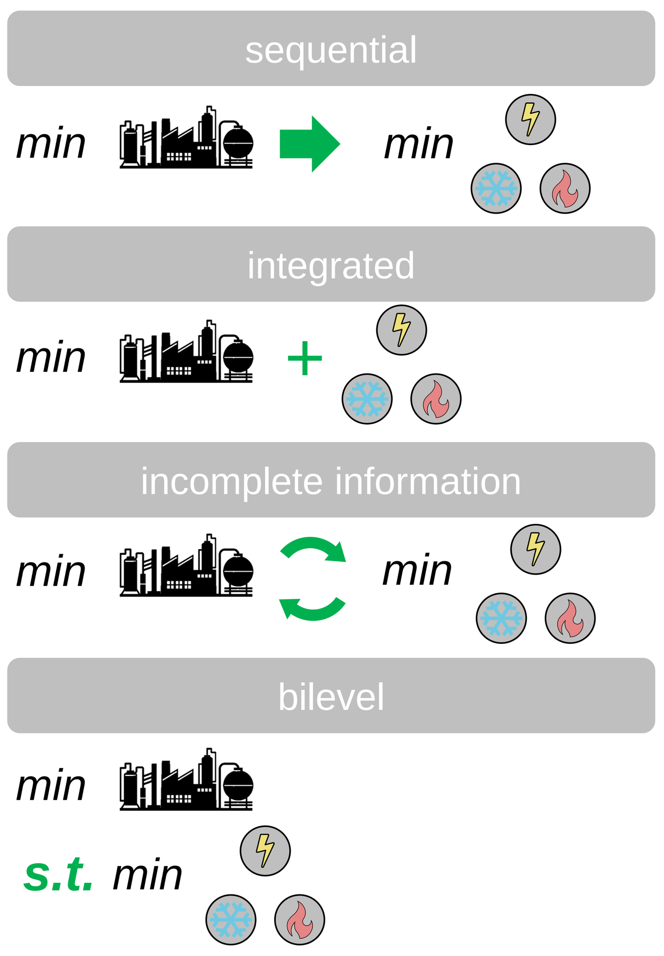
- Batch process networks
- Dynamic Processes



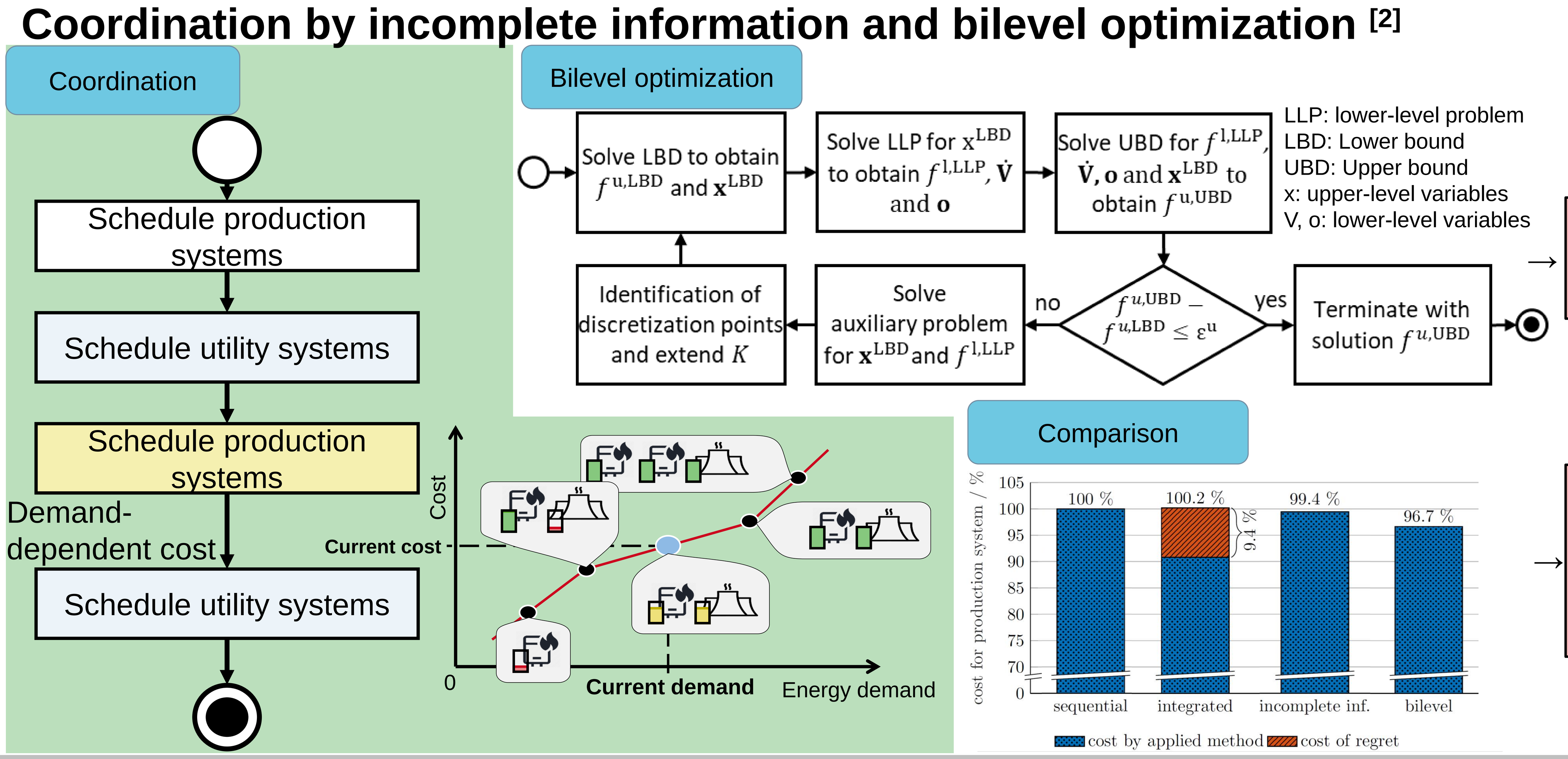
$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u})$$



2 Relationship between systems defines optimization method [1]



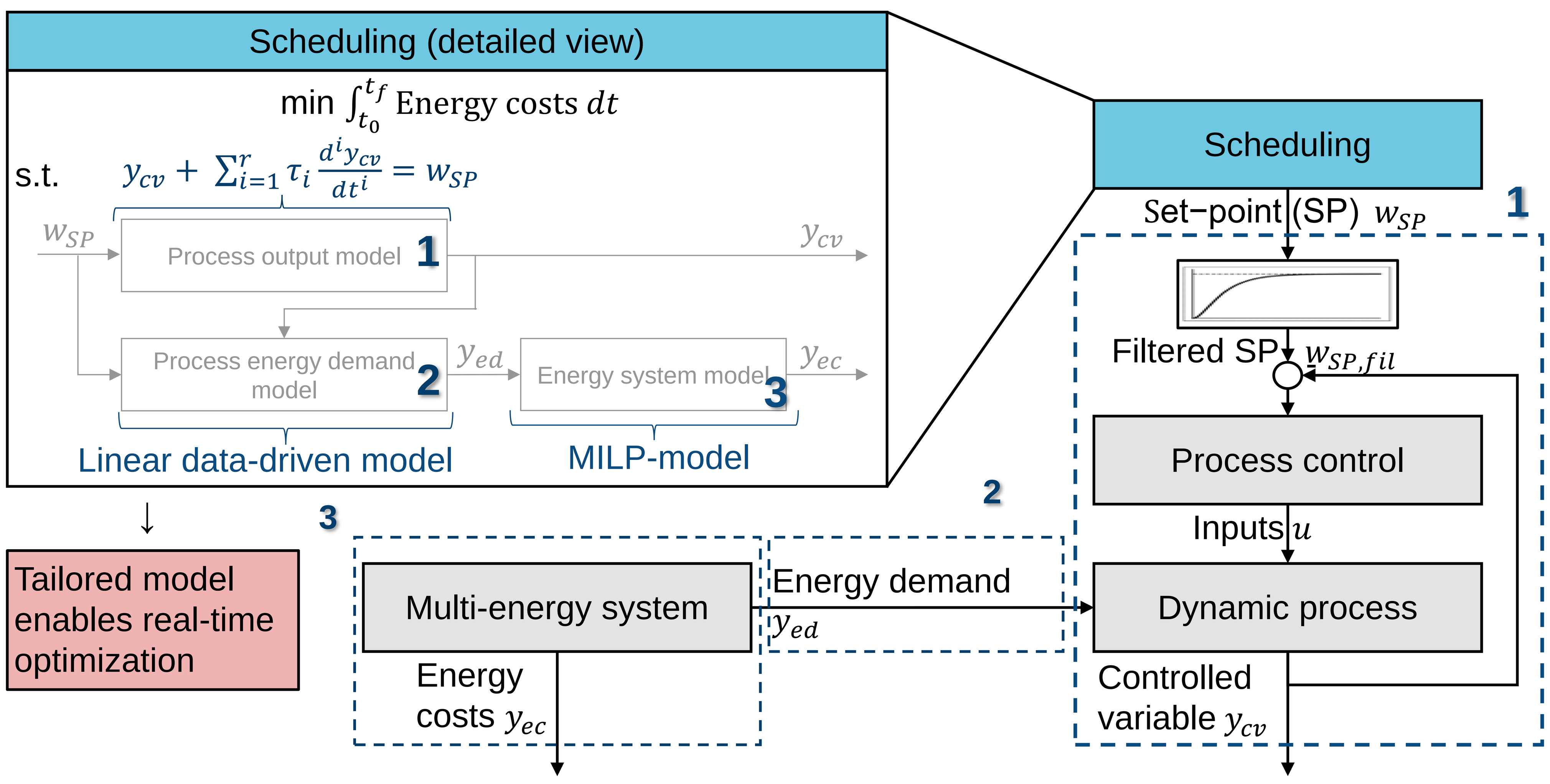
3 Optimization for misaligned objectives: Coordination by incomplete information and bilevel optimization [2]



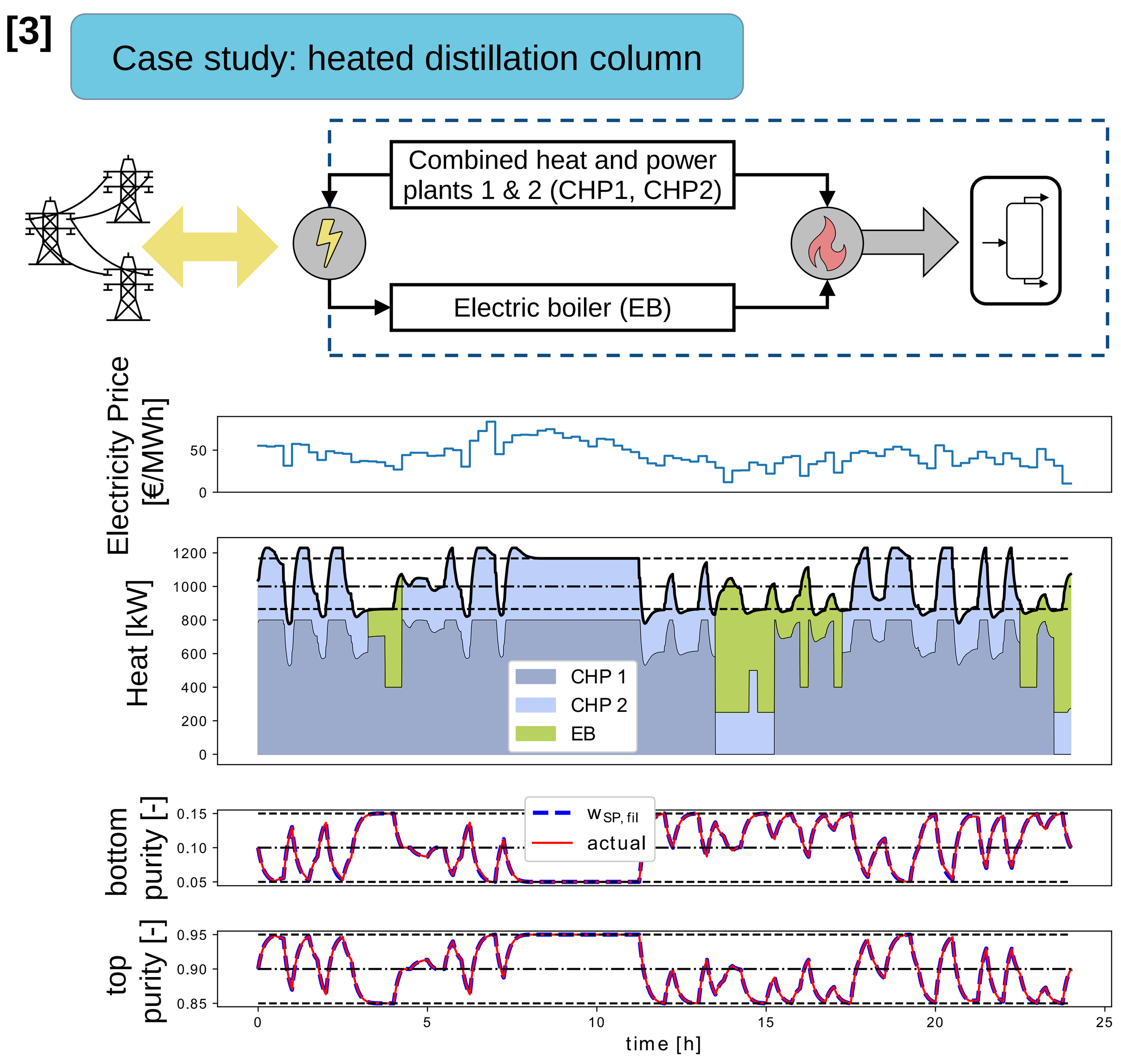
→ Lowest costs for competing objectives

→ Competing objectives lead to additional costs

4 Integrated scheduling of dynamic processes and Energy systems [3]



↓ Tailored model enables real-time optimization



→ Heat coupled with electricity

→ Heat demand flexibility is used for flexibility on electricity side

5 Conclusions

- Integrating multi-energy and production system scheduling results in large benefits
- Relationship between the system defines the optimization method
- Dynamic process increases challenge for integrated scheduling

6 Outlook

- Experimental validation
- Application to sector-coupled multi-energy systems within PATHFNDR?

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Integration of Detailed Electricity Grid and Sector-Coupled Energy System Models: Nexus-e Engages with SecMOD

Work package 1: Pathways on a national and international scale

Ludger Leenders[1], Jared Garrison[2], Florian Joseph Baader[1], Marius Schwarz[3], 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
[3]Energy Science Center, ETH Zurich

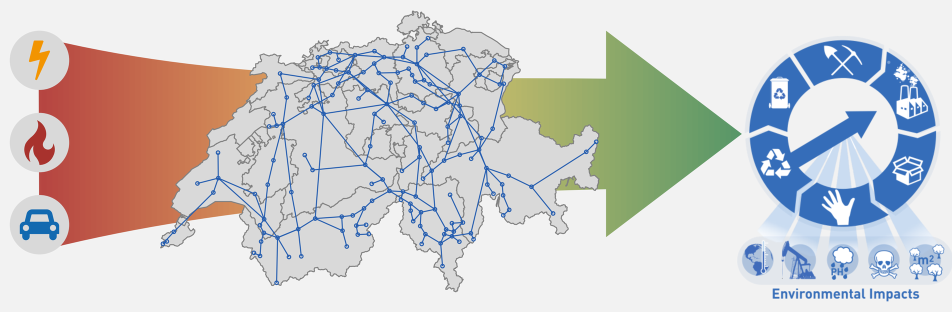
Energy and Process System Engineering, Research Center for Energy Networks and Energy Science Center proudly announce the engagement of

Input/Output Database

Webviewer

SecMOD [1]

Multi-sector energy system model

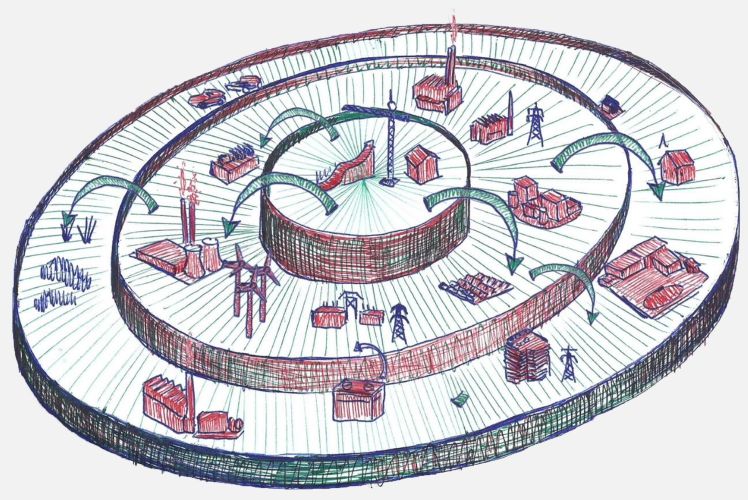


- Time series of electricity demands of heat, mobility, and industrial sectors
- Installed sector-coupling technologies

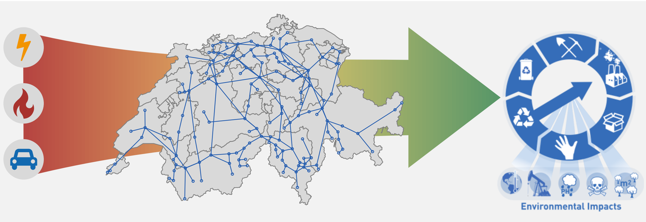
- Installed capacity of power generation technologies

Nexus-e [2]

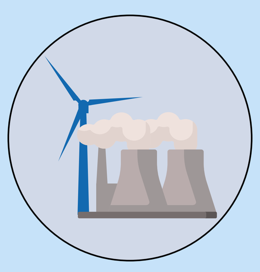
Detailed electricity grid and market model



SecMOD [1]



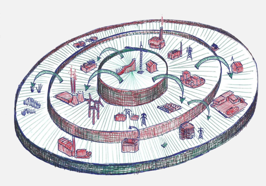
Multi-energy systems optimization

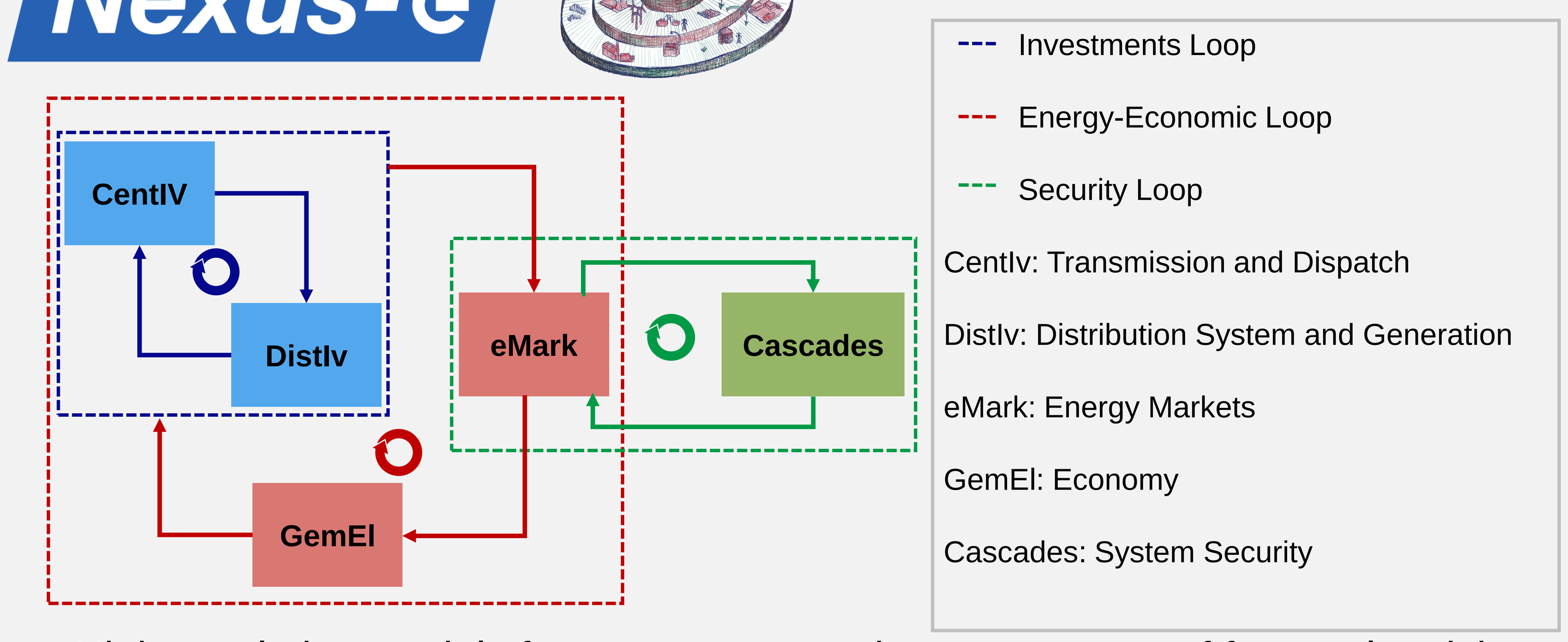


Life cycle assessment

- Framework for optimization & life cycle assessment of sector-coupled energy systems
- Multi-sector energy demands: electricity, residential, transport, industry
- Investment decisions & operation
- Holistic assessment of environmental impacts
- Open-source available
- Case study for Germany, Switzerland, EU steel plant, etc.

Nexus-e [2]





- High-resolution models for energy-economic assessments of future electricity systems
- Interdisciplinary electric systems modeling platform
- Integration of top-down and bottom-up models of the energy-economic system
- Coordinated investments in centralized and distributed resources
- Holistic analysis of the transition of electric power systems

Next steps

- Alignment of data
- Technical connection of the models
- Determine sector-coupled energy system pathways
- Evaluate Pathways regarding holistic assessment of environmental impacts

Questions to be answered by the connection

- How can supply and demand be balanced? What flexibility options are needed?
- How does an increased sector coupling effect the electricity system in future energy systems in detail?
- How do the results of a detailed electricity system model differ from the results of a less detailed but sector-coupled energy system model?
- Are there environmental co-benefits or environmental burden shifting in a transition to net-zero?

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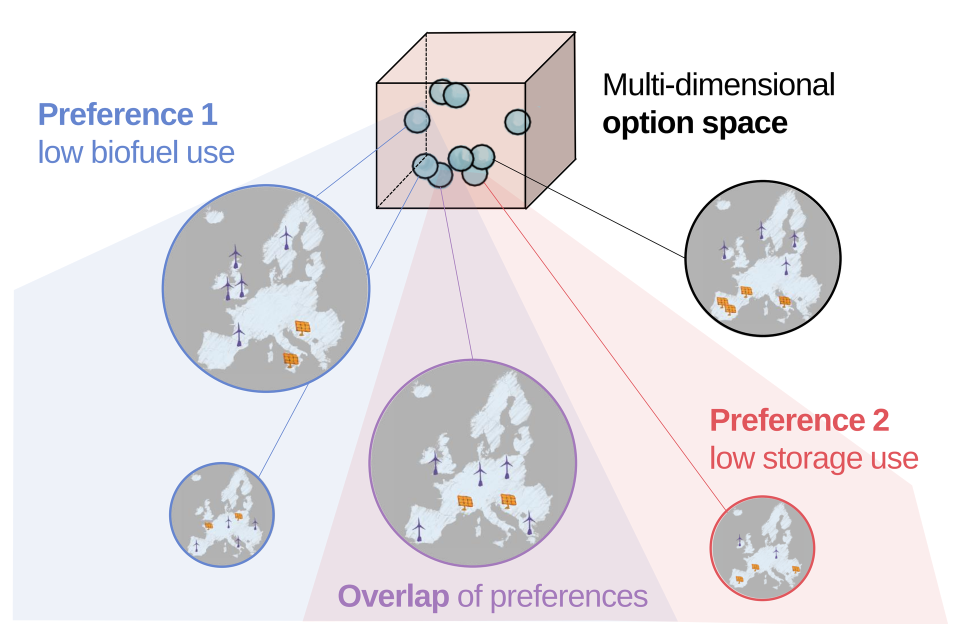
Work Package 1
Euro-Calliope and the integration of Smart Charging Mechanisms into Calliope framework

Francesco Davide Sanvito[1], Francesco Lombardi[1], Bryn Pickering[2], Stefan Pfenninger[1]

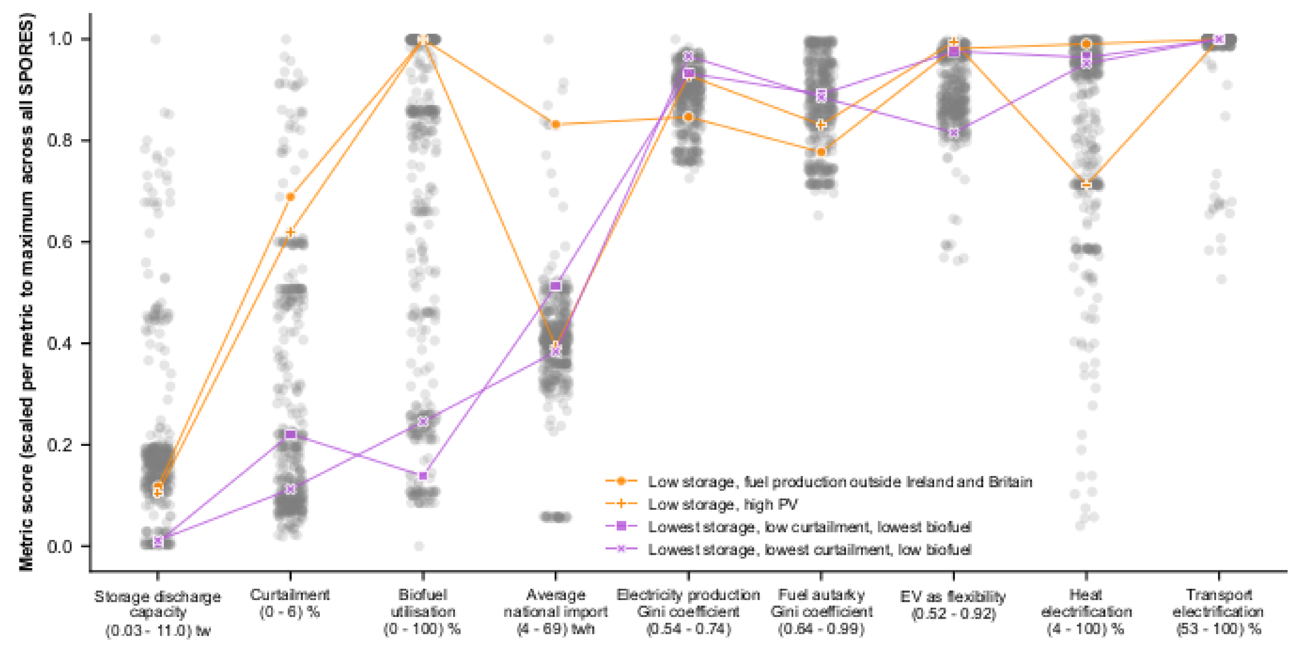
[1] Faculty of Technology, Policy and Management (TPM), Delft University of Technology, Delft, the Netherlands
[2] Institute for Environmental Decisions, Department for Environmental Systems Science, ETH Zürich, Zürich, Switzerland

Diversity of options to achieve carbon-neutrality and energy self-sufficiency in Europe[1]

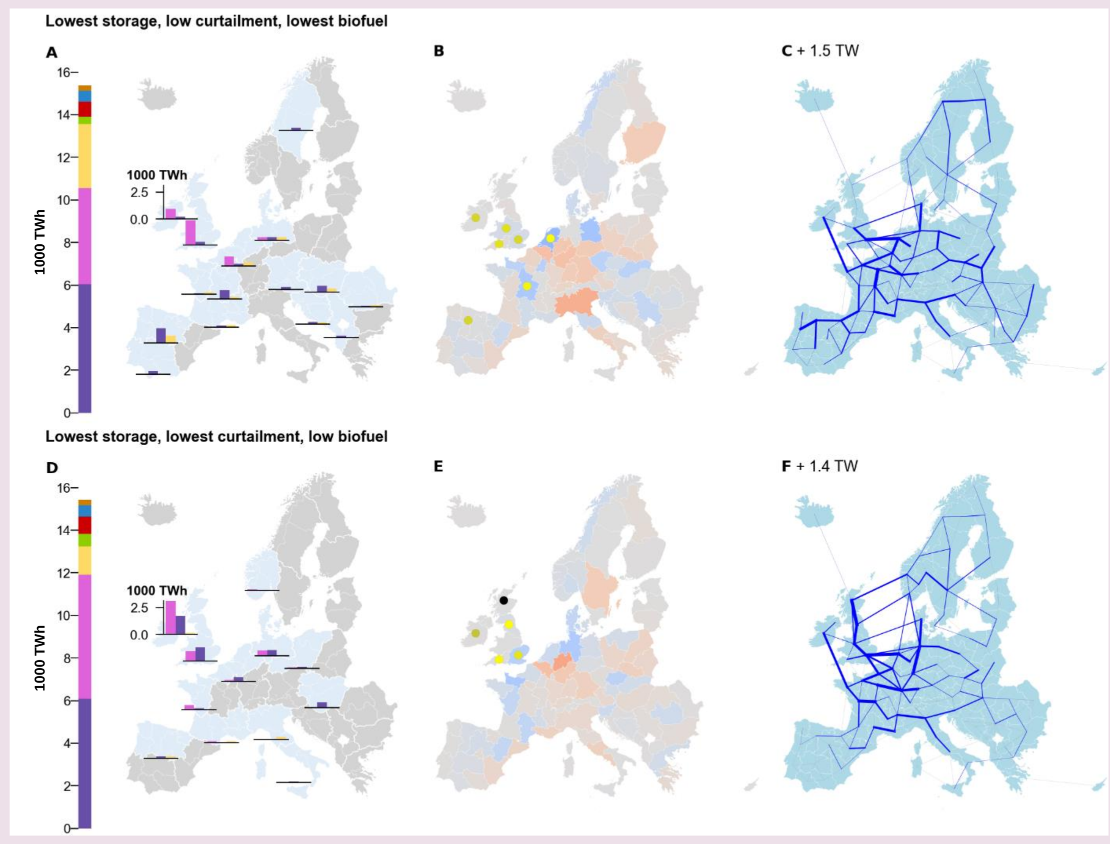
With the **SPORES** method and the **Euro-Calliope** model**,**
we generate 441 technically feasible and cost-effective options (○)
for an energy self-sufficient, carbon-neutral Europe



With **4 example SPORES** we illustrate here the synergies and trade-offs that may open up between plausible real-world competing stakeholder goals across a number of pre-defined metrics



Explore further trade-offs yourselves, with our interactive data explorer! explore.callio.pe

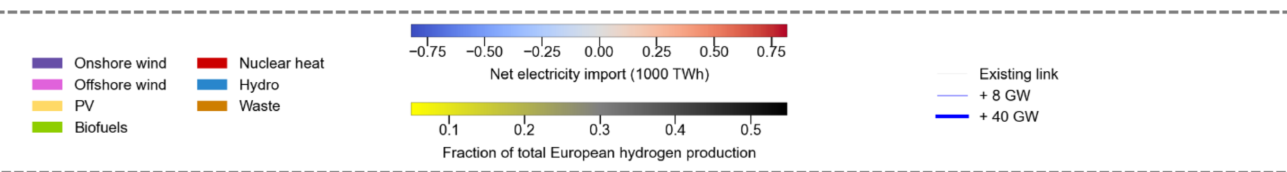


Overlap of preferences

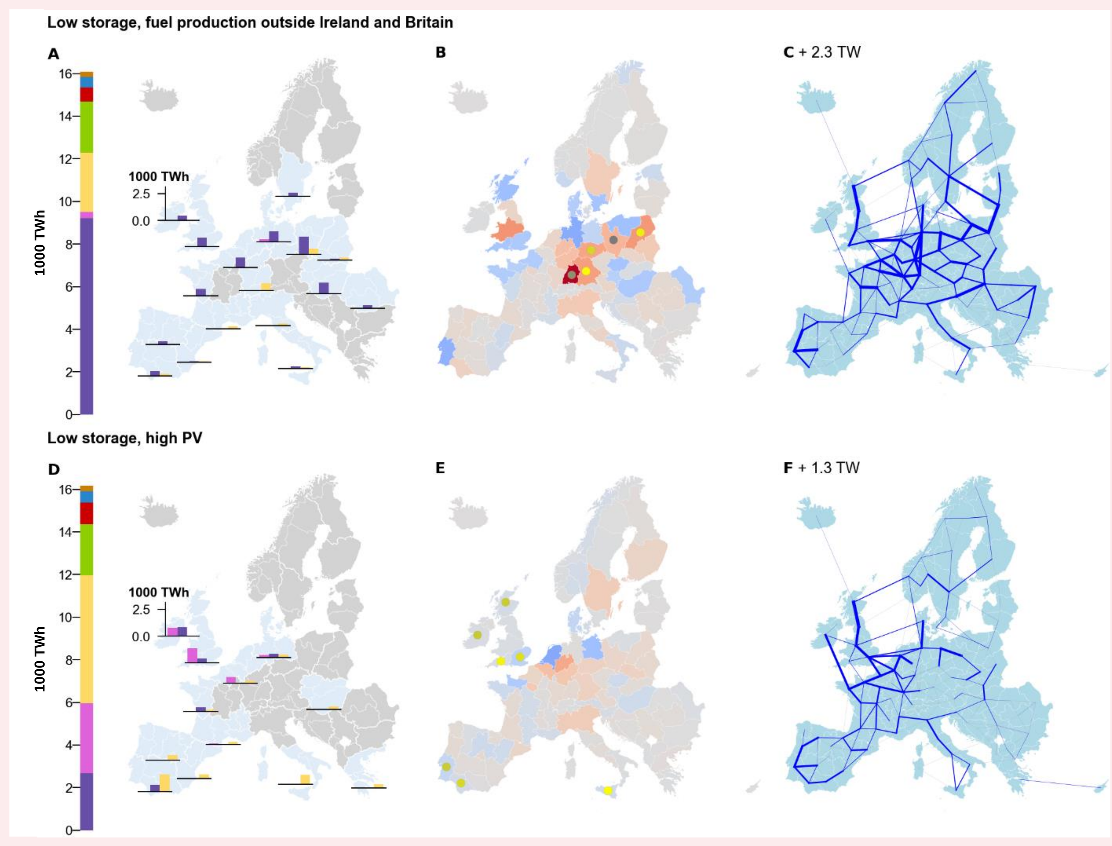
Almost anything is technically possible, but **preferences** restrict the spatial and technical **maneouvering space**

When many preferences overlap, such as **'low storage use'** and **'low biofuel use'** some features become must-haves

For instance, a strong deployment of wind generation in Britain and Ireland



Calliope



Preference 2 only

More relaxed preferences, say not limiting the use of (residual) biofuels, lead to **radically different spatial configurations**

Hubs for the production of **hydrogen** and synthetic fuels could be moved to **Eastern Europe**; or to the **Mediterranean** alongside a larger deployment of solar generation

Integrating Smart Charging Mechanisms into Calliope energy system modelling framework

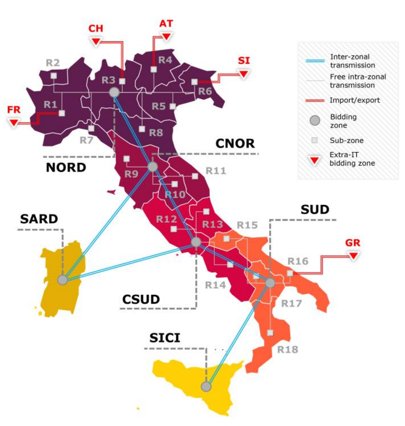
The integration of **Smart Charging Mechanisms** into **Calliope** which has been first tested on a national case study will be extended to the **European context**.

Methodology

We add novel constraints into Calliope to model the deployment of both unidirectional (**V1G**) and bidirectional (**V2G**) charging infrastructures as **competing technologies**.

Case Study

We consider the Italian **power sector-only** model projected to 2050 assuming **100% EV** car fleet.



	BESS (GWh)	CCGT syngas (GW)	Electrolyzers (GW)	Inter-zonal transmission (GW)	Methanation + DAC (GW)	PV farm (GW)	PV rooftop (GW)	Wind on-shore (GW)	Wind off-shore (GW)
UNCOORDINATED CHARGING	283	13	21	86	17	46	302	95	33
V1G – high cost	90	7	8	78	7	46	149	78	20
V1G – low cost	68	12	8	79	7	46	152	74	18
V1G + V2G – high cost	90	7	8	78	7	46	149	78	20
V1G + V2G – low cost	43	14	7	79	6	46	156	70	17
V1G + V2G – cost parity	0	6	7	80	6	46	162	66	17

Capacity deployment variation: +100% / 0% / -100%

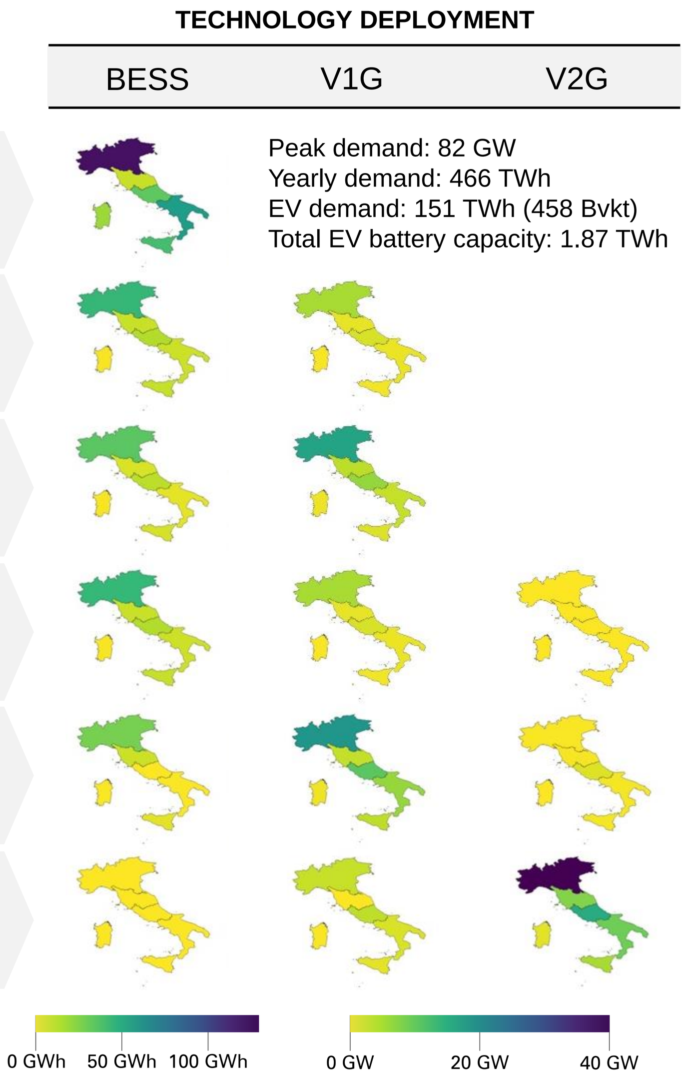
Installed capacity [GWh or GW] — 3 — Installed capacity in the Reference case; Installed capacity relative change with respect to the Reference case

Results

- V2G shows the potential of completely displacing BESS techs
- Reduction of installed capacity of VRES techs.
- Reduction of electricity curtailment (-40%/-50%)

TECHNOLOGY DEPLOYMENT

Scenario	V1G €/kW	V2G €/kW
UNCOORDINATED CHARGING	-	-
V1G – high cost	368[3]	-
V1G – low cost	60[4]	-
V1G + V2G – high cost	368	485[3]
V1G + V2G – low cost	60	115[4]
V1G + V2G – cost parity	60	60



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UNIGE RES

Electric vehicles in a spatial-explicit EXPANSE electricity system model

Work package 1

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Renewable Energy Systems, Institute for Environmental Sciences (ISE), Section of Earth and Environmental Sciences, University of Geneva, Switzerland

INTRODUCTION

Currently, Switzerland plans to phase out its nuclear power plants and hence needs to invest more in new renewable electricity generation [1]. To achieve the goal of net zero emissions by 2050, Switzerland also needs to decarbonize its transport sector by increasing the uptake of electric vehicle (EV), e.g., reaching 50% of plugged-in vehicles in new registration by 2025 [2]. Electricity demand for EVs will hence increase the requirement for renewable electricity generation.

If EV charging behaviors are uncontrolled, they would be temporally homogeneous, and the high charging demand peak could challenge the grid. With controlled charging, EV's load shifting flexibility can be utilized to promote renewable generation integration [3].

Compared with conventional centralized powerplants, renewable generation (such as solar PV and wind) is more constrained in space and generation capacity is thus spatially uneven in cost-efficient future scenarios or in real systems [4, 5]. In addition, the level of EV adoption registration is also spatially uneven (whether by EV registration number or by market share) [6].

Therefore, the heterogeneous spatial allocation of renewable generation and EV calls for the development of a spatially-explicit electricity system model to explore the potential synergy between renewable investment and EV flexibility for Switzerland.

Electric vehicle charging strategy

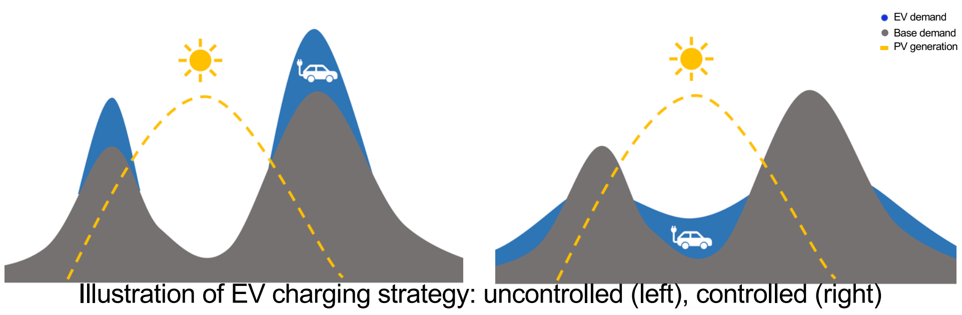

Illustration of EV charging strategy: uncontrolled (left), controlled (right)

With uncontrolled charging, EV demand can be temporally homogenous, and further increase demand peak. With controlled charging, EV demand could be shifted to the mid-day or nighttime in order to flatten the demand curve or better utilize renewable energy generation.

Here, we aim to see how EV charging flexibility may promote PV generation in Switzerland. With EXPANSE, we could explore such potential transition from a systematic view for the whole country but with municipality level detail.

Scenarios of EV charging strategies (or modes) may consider: 1) charging at home or workplace, i.e., EV demand would not only shift temporally but also spatially among municipalities; 2) EV development in the future, including market share, charging power, EV battery capacity and energy efficiency; 3) user acceptance of different EV charging schemes: 4) further interaction with stationary battery storage to see whether there may be some synergy or substitution effect between EV and stationary battery technologies.

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METHODOLOGY

The EXPANSE modeling framework

EXPANSE is a spatially-explicit, bottom-up, technology-rich electricity system model. EXPANSE models the Swiss electricity system at the municipal level (2148 municipalities) with an hourly resolution to explore the scenarios of electricity sector transition for the single year 2035 or 2050 [5, 8].

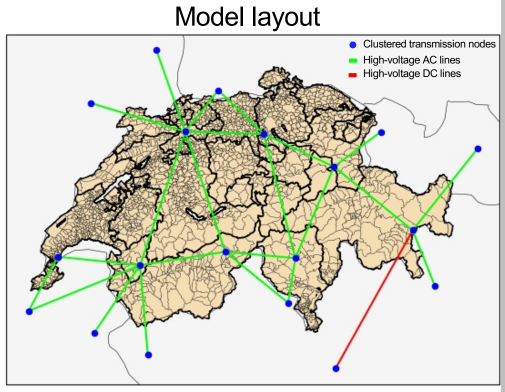
The key feature of EXPANSE is municipality-specific decisions for renewable generation allocation instead of having a central planner at the federal level.

EXPANSE includes spatially-refined data for key centralized generation technologies (e.g., large hydro power dams and gas power plants) and distributed renewable generation technologies (e.g., solar, wind turbines and biomass).

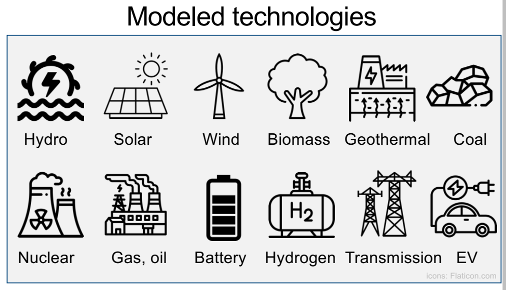
In addition to analyzing the least-cost transition pathway, EXPANSE explores hundreds or thousands of near-optimal spatial allocation scenarios with Modeling to Generate Alternatives (MGA) technique [9].

Additional impacts of these scenarios are further analyzed from the environmental and societal aspects, including regional equity, greenhouse gas emissions, particulate matter emissions, land use, investment and divestment, price, and employment.

Model layout



Modeled technologies



Input data

- Costs
- Electricity demand
- Resource availability
- Generation parameters
- Storage parameters
- Transmission parameters

Results

- Generation portfolio
- System capacity
- Total system costs
- Regional impacts
- Regional equality score
- Trade-off curves

NEXT STEPS

Disaggregate the EV sector of EXPANSE to the municipality level

Refine EV uncontrolled charging profiles based on available research (e.g., differentiate profiles for weekdays and weekends)

Further develop the EV module to enable different EV controlled charging strategies (unidirectional or bidirectional) to endogenously determine EV charging behaviors

Include EV data to support the modeling of controlled charging strategies above (e.g., EV temporal and spatial usage profiles, EV's access to charging infrastructure, users' acceptance for controlled charging)

Explore how EV's load shifting flexibility may influence PV adoption in Switzerland under different EV scenarios (e.g., adoption level, charging strategies, technology development)

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Transition Paths towards a CO_2-based Chemical Industry within a Sector-Coupled Energy System

Patricia Mayer[1], Ludger Leenders[1], David Yang Shu[1], Benedikt Winter[1,2], Christian Zibunas[2], Christiane Reinert[2], André Bardow[1]

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[2]Institute of Technical Thermodynamics, RWTH Aachen University, Germany

1 Challenge: Chemical Industry Decarbonization

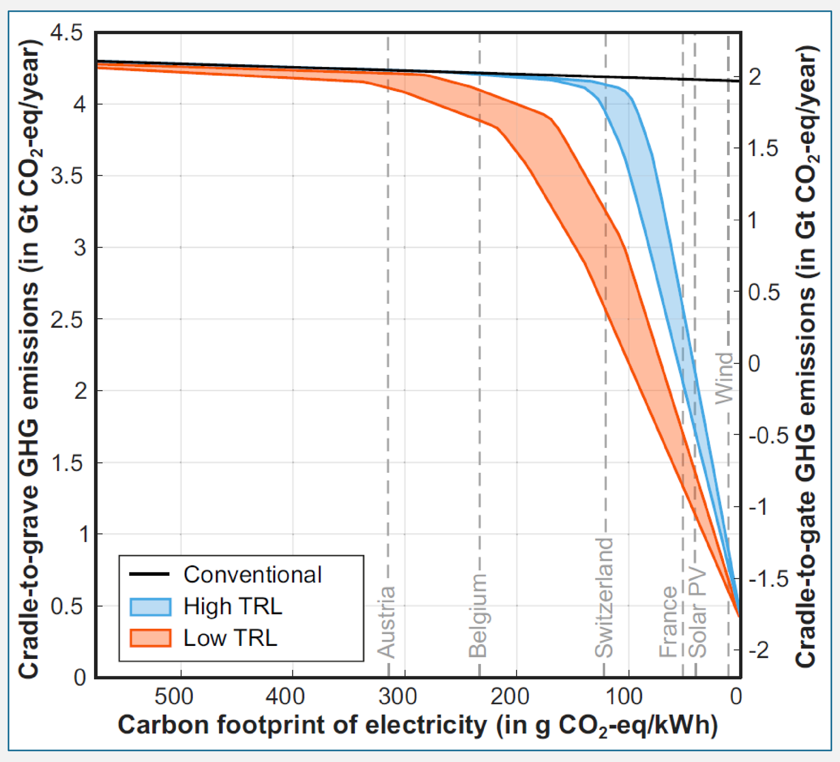
5.8% of global energy demand for chemicals [1]

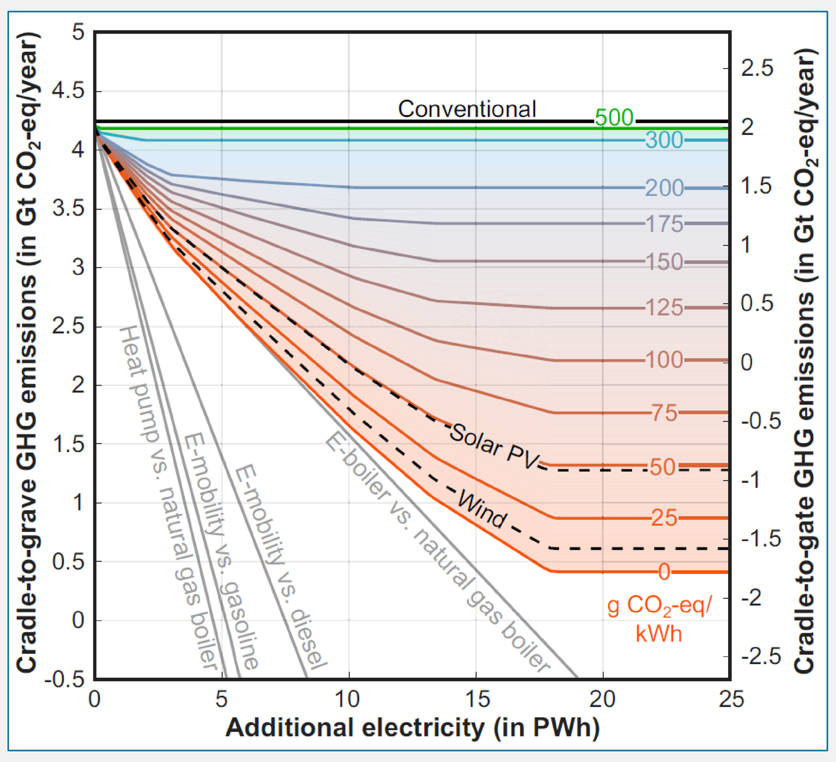
Chemicals will be the largest driver for increased oil demand [2]

Chemical industry 10% of global GHG emissions in 2030 [3, 4]

Net-zero chemical industry needed for net-zero GHG targets

CCU for net-zero chemicals?



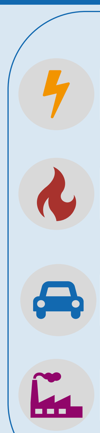


CCU enables net-zero chemicals [4]

CCU requires a lot of clean electricity – in competition with other sectors [4]

Need to evaluate CCU potential within a sector-coupled system

2 Methods: German Energy System Optimization



electricity

heating

mobility

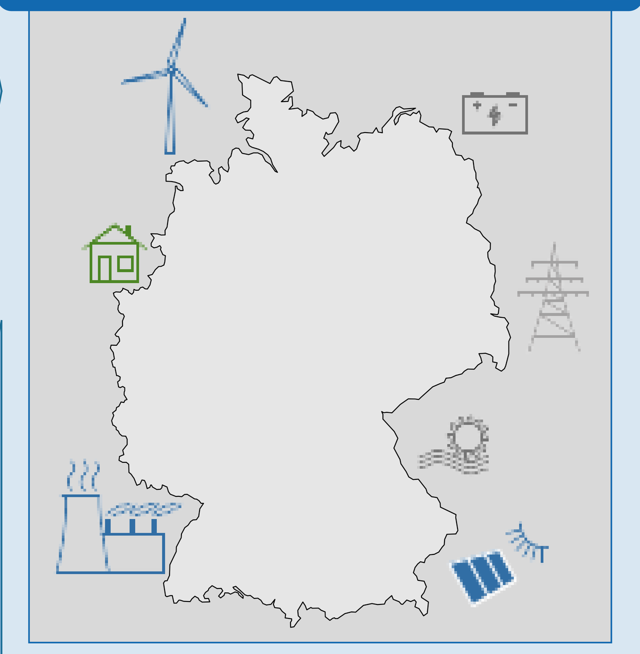
chemicals

Main Inputs

technology parameters
efficiencies, costs, environmental impacts

time series
demands, weather/availability, imports

SecMOD Framework [5]



Transition Pathway

Costs

Environmental Impacts

4 Conclusions

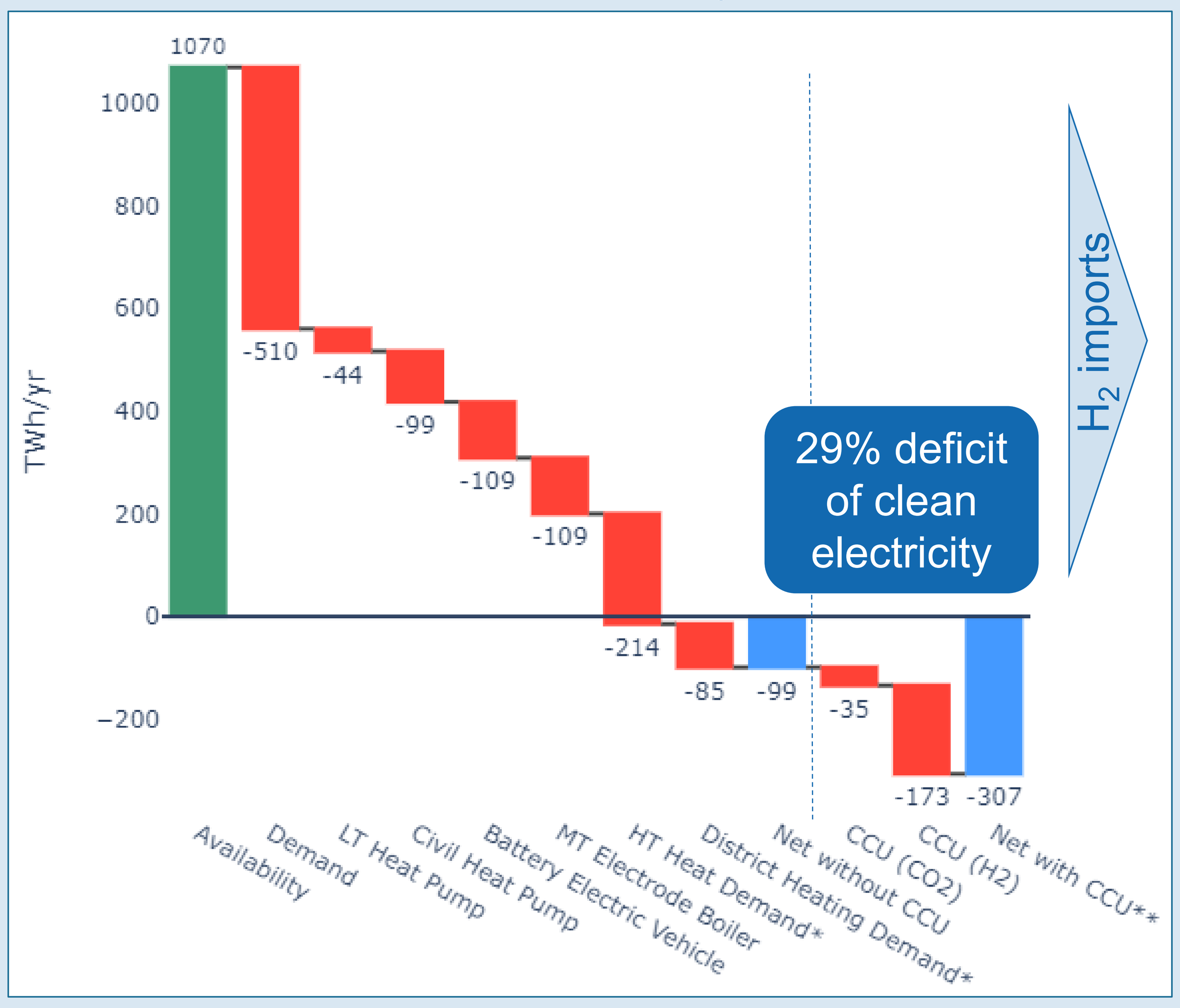
Clean electricity deficit for net-zero island German energy system → imports required

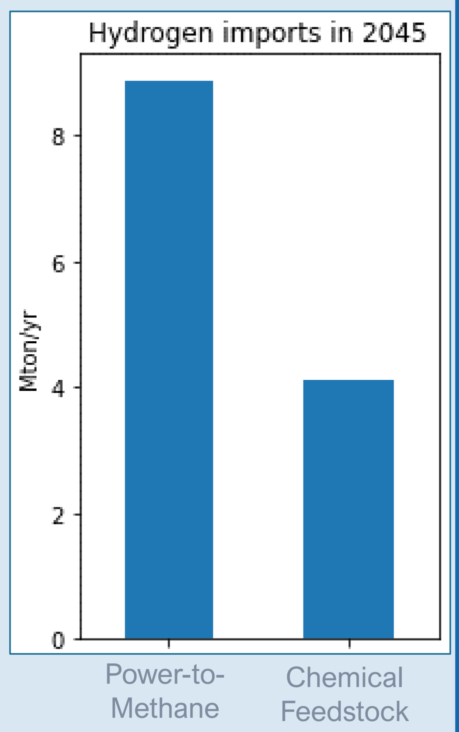
CO_2-based chemical industry transitions last along with high-temperature heat

Methanol important intermediate for CO_2-based chemicals

3 Results and Discussion

German Clean Electricity Balance for Net-Zero System

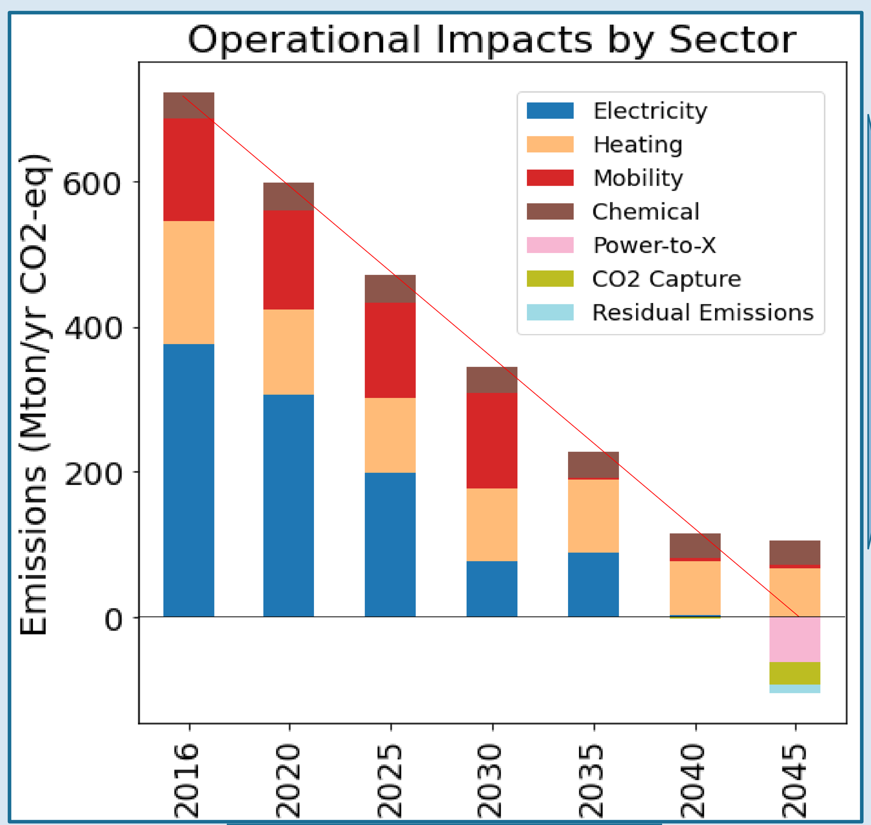


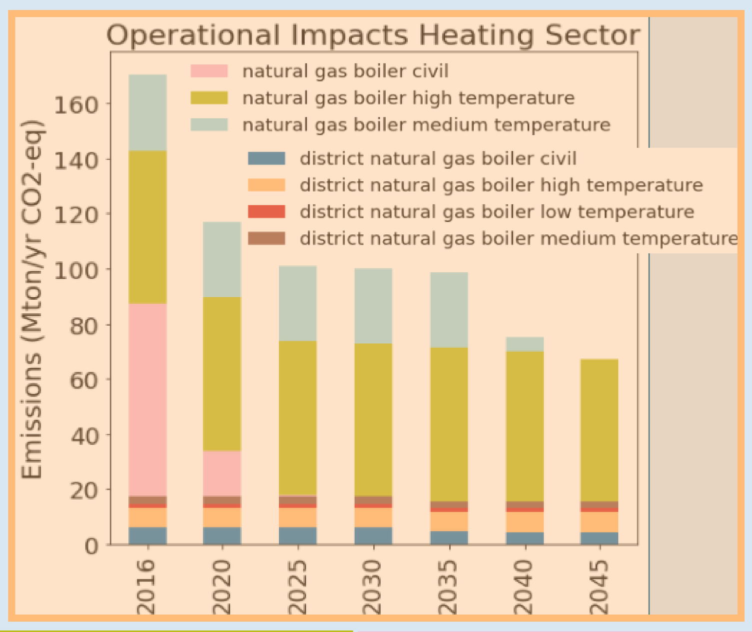


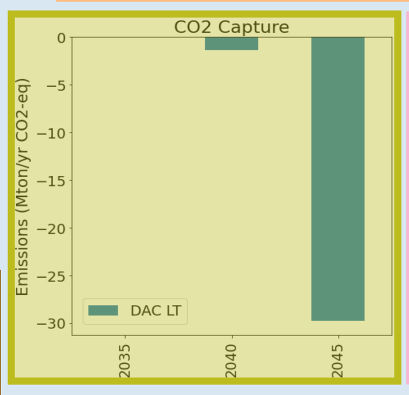
13 Mton H_2 imports per year required

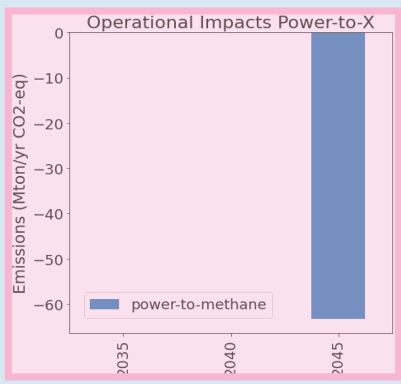
*Raw heat demand without conversion from heat-generating technology
**CCU demands do not include direct process electricity or heat demands

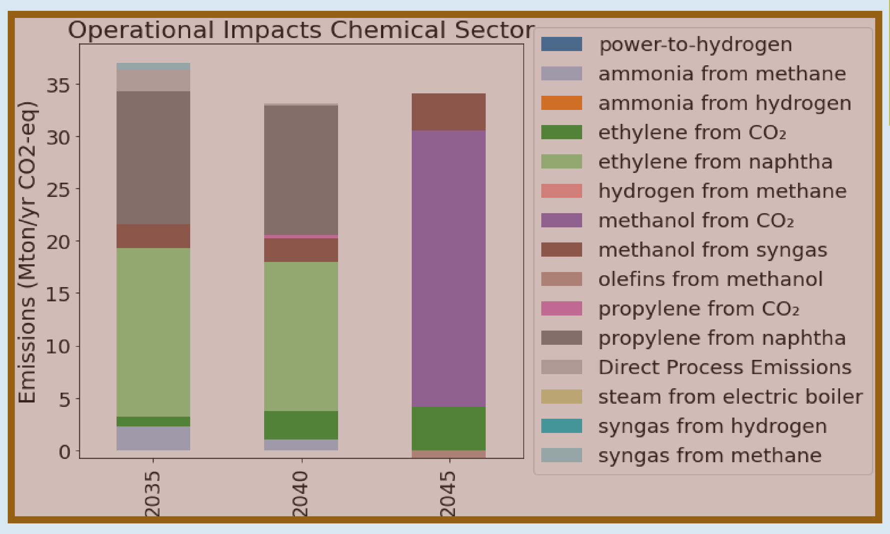
Sector-Coupled System Transition







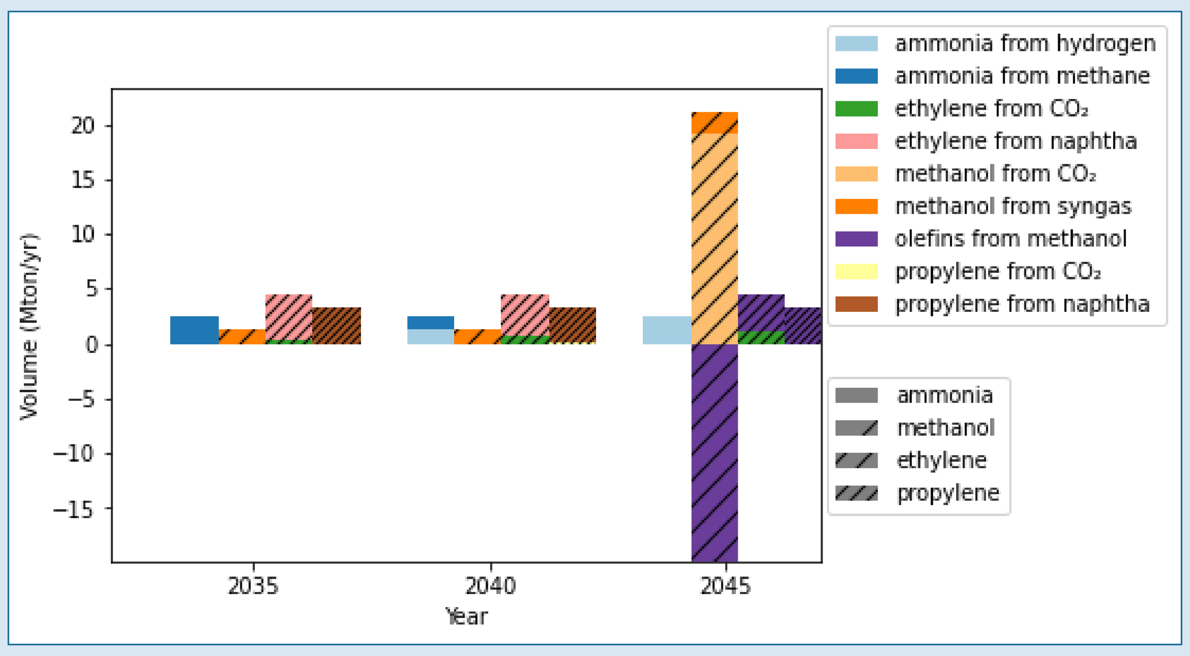




Chemical industry transitions last along with high-temperature heat

Direct air capture and power-to-methane important for net-zero system

Chemical Industry Transition



Chemical industry transition begins only in 2040…

… but fully CO_2-based in 2045

Methanol important intermediate product

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Acronyms

CCU: Carbon Capture and Utilization
LT: Low Temperature
MT: Low Temperature
HT: High Temperature
DAC: Direct Air Capture

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Cyber-physical platforms: conceptual foundations and empirical case study

Work package 6

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1 ABSTRACT

Platforms are one of the most discussed topics in recent management literature, and for good reasons. Some of the world's most successful companies are platforms, thanks to their abilities to generate network effects and foster innovation. However, research mostly focuses on digital platforms, creating the misconception that only companies relying on software-based technologies can establish platform ecosystems. To the contrary, cyber-physical platforms already find many innovative applications in various industries. We first investigate the characteristics of cyberphysical platforms, evaluate the effects of these characteristics on their mechanisms of value creation and innovation, before comparing them to those of digital platforms. We provide a first definition of cyber-physical platforms and highlight that the mechanisms of value creation and innovation of cyber-physical platforms significantly differ from those of digital platforms.

2 CONTRIBUTION TO PATHFDNR

Contribution to work package 6, Task 3: Technological innovation and the interplay between firms at value chain level.

- Milestone M6.3.1:
  Strategically important technologies (physical vs. digital; core vs. peripheral) identified and analyzed

- Deliverable D6.3:
  Submission of two peer-reviewed papers on response innovation processes, and business models and decision-making tools. ➔ Writing process for paper contribution.

2 RESEARCH QUESTION AND METHODOLOGY

In the last 30 years, researchers of various disciplines have investigated the topic of platforms. In recent years there have been several new platforms that rely on technologies such as automated control systems, cloud computing, additive manufacturing, machine-to-machine communication and the internet of things (IoT). Meuer et al. (2019) identifies these platforms as "cyber-physical", for they are made of both physical and digital components. Despite their various applications and socio-economical relevance, researchers studied cyber-physical platforms only from a technological perspective (Cusumano et al., 2019; Gunes et al., 2014; Sanislav & Miclea, 2012). Research has failed to examine in detail the nature of cyber-physical platforms and their innovation and value creation dynamics. Therefore, we ask:

- *What are cyber-physical platforms?*

- *What are the effects of their physical features on innovation and value creation patterns and how do these patterns compare to those of digital platforms?*

We divided the research process in two stages; a theoretical study and an empirical in-depth case study. First, we collected data through literature review. For the second stake, we collected data from our case Enel X, the customer solutions unit of a global utility provider. Enel X provides services from urban application such as e-city, smart home and electrical mobility. We conducted 15 interviews as primary data and collected company documentation as secondary data. We analyzed the case study following an inductive methodology.

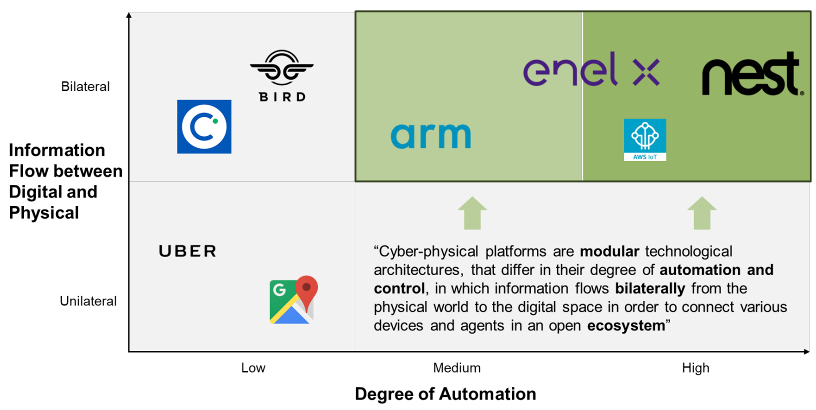
3 RESULTS

Platform literature started in the early 90s with the product design view. This stream of literature on platforms focused on innovation, looking at the modularity of design. In the first half of 2000, the economic view on platform was developed. Using the concepts of network effects and multi-sided platforms, the research stream focused on competition and competitive advantage. Baldwin and Woodard (2009) introduced the 'unified view,' defining that all platforms are made of a core and a periphery. Gawer (2014) introduced the openness of platforms. While the engineering and economic focus dominated the literature on platforms, the context was mainly on purely digital platforms, leaving out the discussion on cyber-physical platforms. From the literature analysis and our interview, we define cyber-physical platform as follows:

"Cyber-physical platforms are modular technological architectures, that differ in their degree of automation and control, in which information flows bilaterally from the physical world to the digital space to connect various devices and agents in an open ecosystem"

Key Elements of a cyber-physical platform are:
Modularity, automation & control, connectivity & information flow, and inclusion into ecosystem.

We learned that cyber-physical platforms differ from digital platforms in terms of innovation pattern, value creation & competition, and unique challenges they face.
- Cyber-physical platforms require only incremental innovation to build the infrastructure but rely on radical innovation for platform adoption.
- Cyber-physical platforms rely on a high density of device to constitute the platform and range of service. Competition of new entrants from both physical and digital side makes it very hard recognize potential threats as competitors are most of the times unknown.
- Cyber-physical platforms face unique challenges such as high capital requirements and long sales cycles creating difficulties in scaling the business.



What makes a cyber-physical platform?

	CYBER-PHYSICAL PLATFORMS	DIGITAL PLATFORMS
Innovation Pattern	• Incremental innovation to build infrastructure • Radical innovation to make shift towards platform adoption	• Same core technological features, new linkages of knowledge • Architectural innovation pattern
Value Creation & Competition	• Density of devices constituting the platforms is major driver to give great range of services • Competition of new entrants from both physical and digital side makes hard recognizing threats	• Importance of network effects as source of competitive advantage • Low capital requirements allow scalability
Unique Challenges	• High capital requirements and long sales cycles creating difficulties in creating scalable businesses • More varied data result in greater data management and enrichment efforts needed	• Possibility of platform partners to become competitors for control • Lack of infrastructure requirements facilitates interplatform competition

Comparison cyber-physical platform vs. digital platforms

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Cross-sectoral collaboration for a green hydrogen value chain

Work package 6

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1 ABSTRACT

The development, diffusion, and use of sector coupling technologies such as green hydrogen play an integral role in achieving the climate targets of the Paris Agreement. To ensure a reliable transition towards a sector-coupled energy system, many actors from diverse sectors need to collaborate. However, the characteristics of cross-sectoral collaboration in sector coupling technologies have yet been underexplored. In this study, we analyze 125 European projects which jointly cover the entire green hydrogen value chain. Using fuzzy-set Qualitative Comparative Analysis, we identify four project feature configurations that are associated with cross-sectoral diversity in collaborations: the Mega, the Big & Local, the Non-International, and the Commercial Project archetype. The occurrence of these archetypes varies along the green hydrogen value chain. Our findings suggest that cross-sectoral diversity should be fostered in industry and cross-cutting (standardization, safety, education, recycling) projects and that it can be addressed by policymakers through the targeted promotion of certain project features.

2 CONTRIBUTION TO PATHFDNR

Contribution to work package 6, Task 2: Technological innovation and the interplay between firms at value chain level.

- Milestone M6.2.1:
  Technology value chains identified and understood, linkages due to sector coupling identified and analyzed.

- Deliverable D6.2:
  Submission of three peer-reviewed papers on business interests, value chain processes, and innovation strategies. ➔ Writing process for paper contribution.

2 RESEARCH QUESTION AND METHOD

As sector coupling technologies like those deployed in the field of green hydrogen will serve multiple established sectors simultaneously, they will become integral elements across several sectors. This distinct characteristic goes beyond those of traditional (i.e., non-sector-coupling) technologies, and is likely to require substantially different innovation processes. On the one hand, studies in this field have analyzed regulatory framework conditions but have provided limited insights into innovation processes. On the other hand, more general innovation studies have examined innovation in individual technologies for single sector applications, but innovation processes for sector coupling remain widely unexplored. Therefore, we ask:

- *What configurations of project features are associated with cross-sectoral diversity in collaborations for green hydrogen?*
- *How do these collaborative patterns vary along the value chain?*

Method: fuzzy-set Qualitative Comparative Analysis (fsQCA), expert interviews

Data: 125 green hydrogen projects from FCH JU database, 7 expert interviews

3 RESULTS

We analyzed the hydrogen value chain, which is end-used in the three areas: Transport, industry and building heat.
The highest participation of project partners for green hydrogen stems from Germany, France, Italy, and the UK. An overall high involvement of research and education institutions exists in the projects (see total project participation). This involvement is more distinct at some value chain stages (cross-cutting, generation, storage, fuel cell development) than at others. This indicates that an overall high level of early-stage innovation in green hydrogen exists, especially in the mentioned value chain stages.

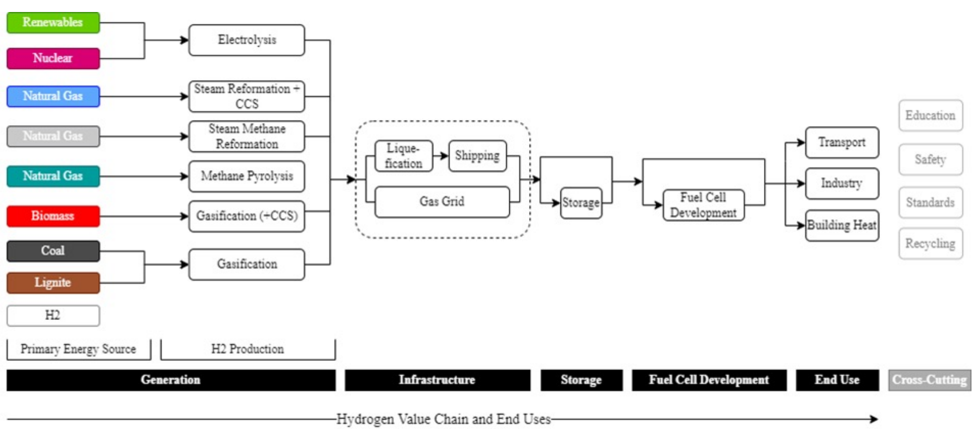
We identified 4 archetypes of green hydrogen projects with different permutation.

1. **The Mega Project**
   Hight project cost, many project partners.

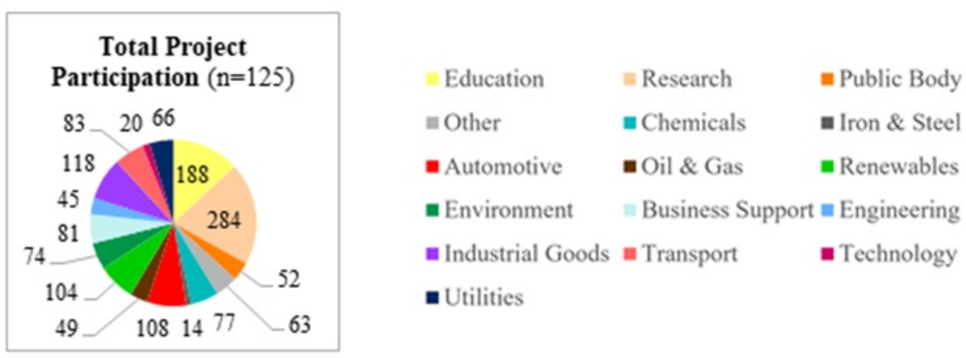
2. **The Big Local Project**
   Many project partners, very local project consortium. Not long project duration.

3. **The Few Nationalities Project**
   Two subtypes:
   3a Local: Very local project consortium. Not very international project consortium.
   3b Big, short-term: Many project partners, not very international project consortium, no long project duration.

4. **The commercial project**
   Three subtypes, all high share of commercial partners and following and additional:
   4a Local: Very local project consortium.
   4b Expensive, international: High project costs, very international project consortium.
   4c Short-term, international: no long project duration, very international consortium.



Hydrogen value chain



Sectoral involvement of project partners of the green hydrogen value chain

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Optimal design of hydrogen supply chains to decarbonize hard-to-abate industry in Europe

Work package 1.2

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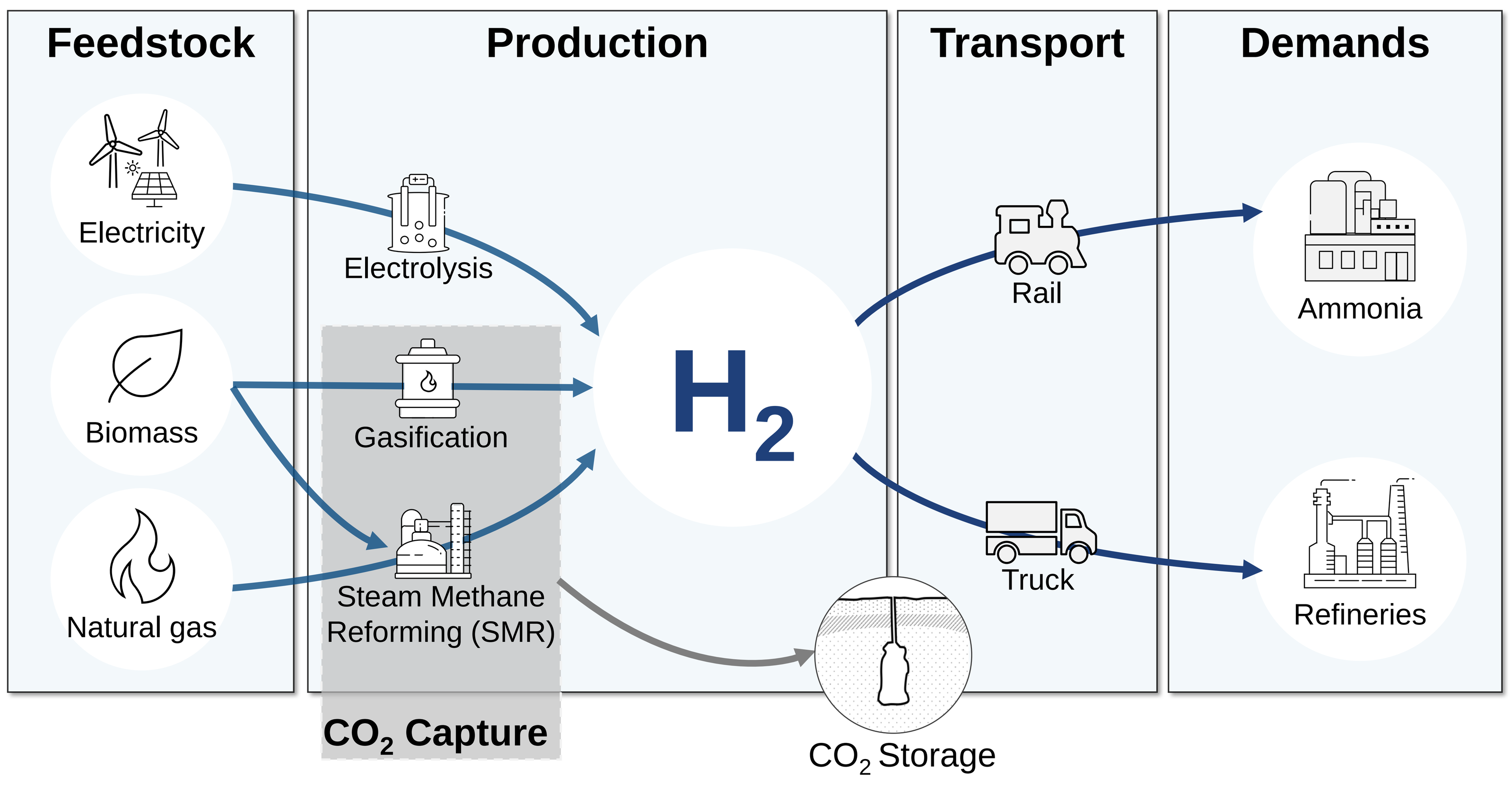
Institute of Energy and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland

1 INTRODUCTION AND MOTIVATION

Opportunity: Hydrogen have the potential to decarbonize hard-to-abate industrial sectors such as ammonia production and refineries[1]

Challenge: The lack of a European hydrogen supply chain infrastructure prevents the widespread use of low-carbon hydrogen[2,3]



2 PROBLEM FORMULATION

Input Data

- Hydrogen demands for ammonia production and refineries[2]
- Resource availabilities[3] and cost
- CO_2 storage locations and capacities
- Technology data (capital, operational expenditures, conversion efficiencies)

Mixed integer linear program[4]

$$\begin{aligned} \min_{x,y} \quad & c(x,y) \\ \text{s.t.} \quad & g_i(x,y) \leq b, \forall i \in I \\ & h_j(x,y) = 0, \forall j \in J \\ & x \in \mathbb{R}^N,\ y \in \{0,1\}^M \end{aligned}$$

Objective: Minimize total costs

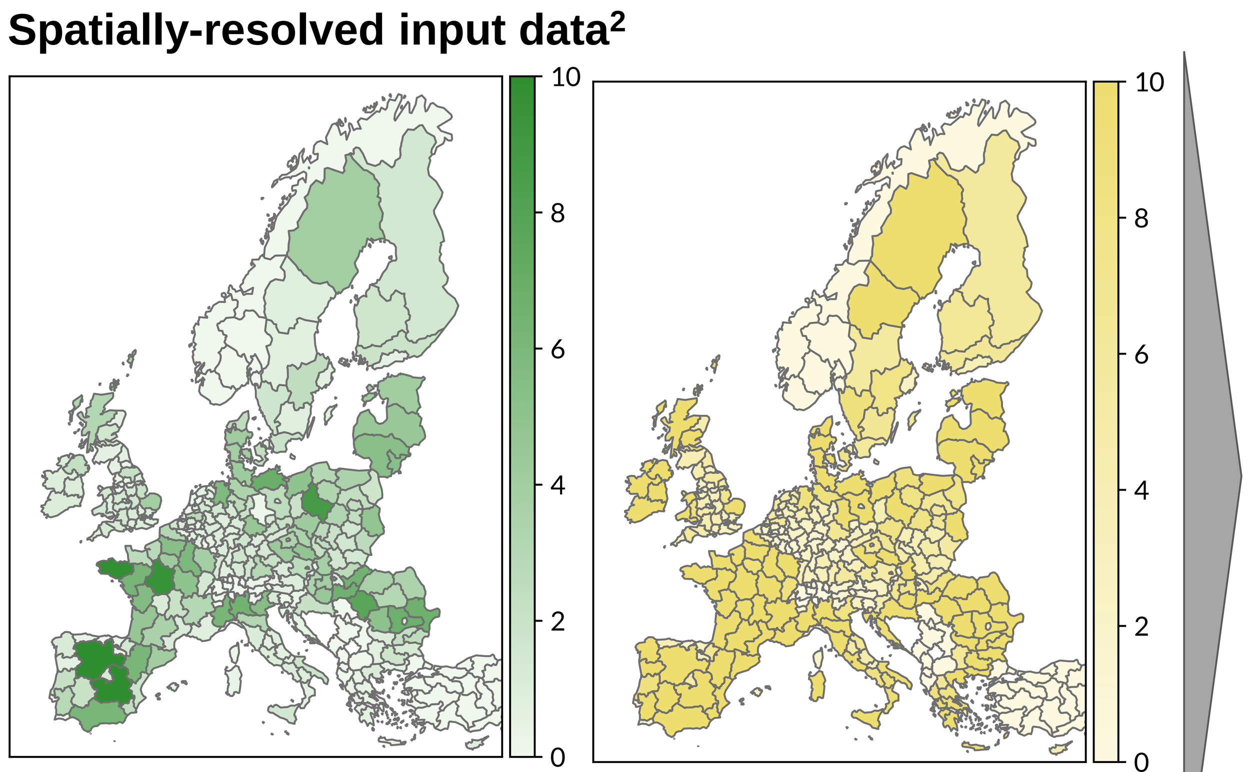
Constraints: Mass and energy balances
Carbon emissions constraint
Technology constraints

Model output

Optimal type, size, and location of the hydrogen production and transport technologies over a multi-year time horizon with respect to decarbonization targets

3 OPTIMAL HYDROGEN SUPPLY CHAIN DESIGN

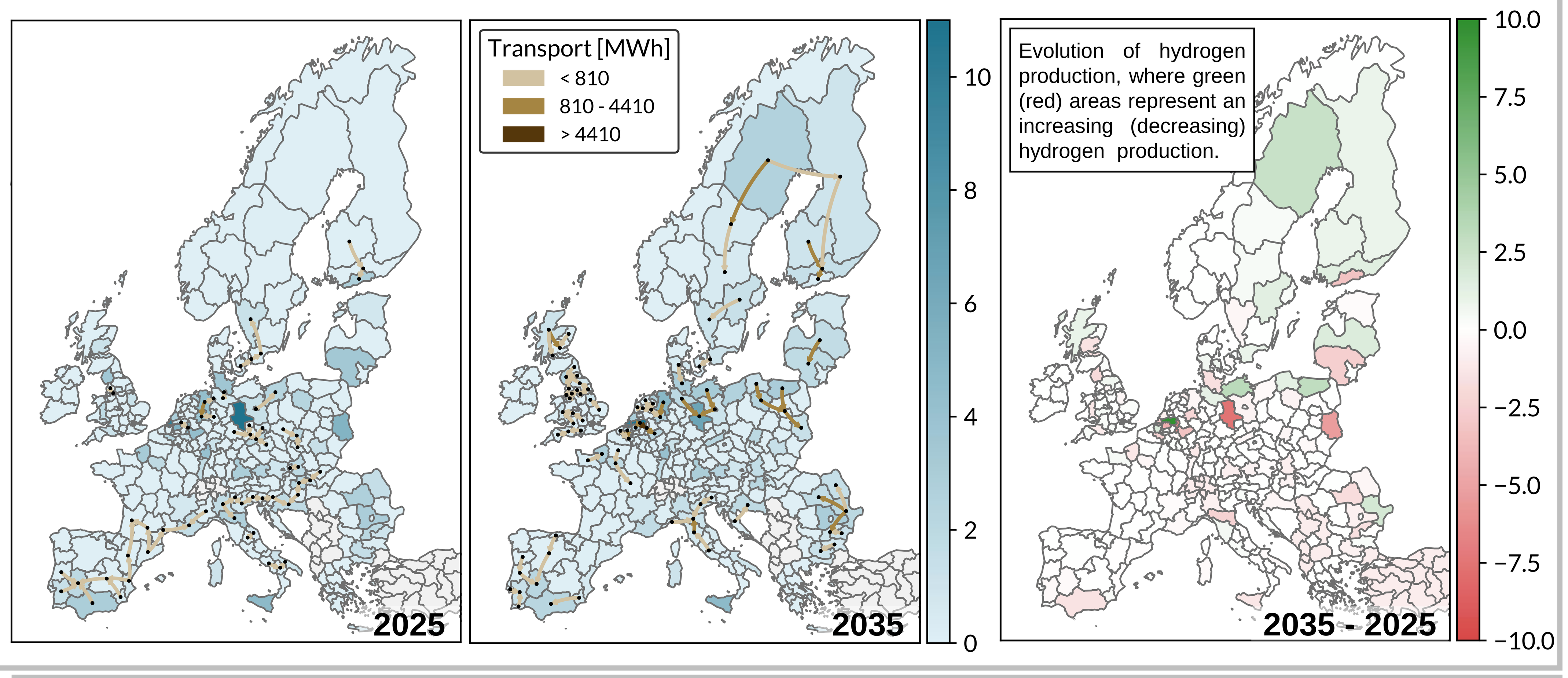
Spatially-resolved input data[2]



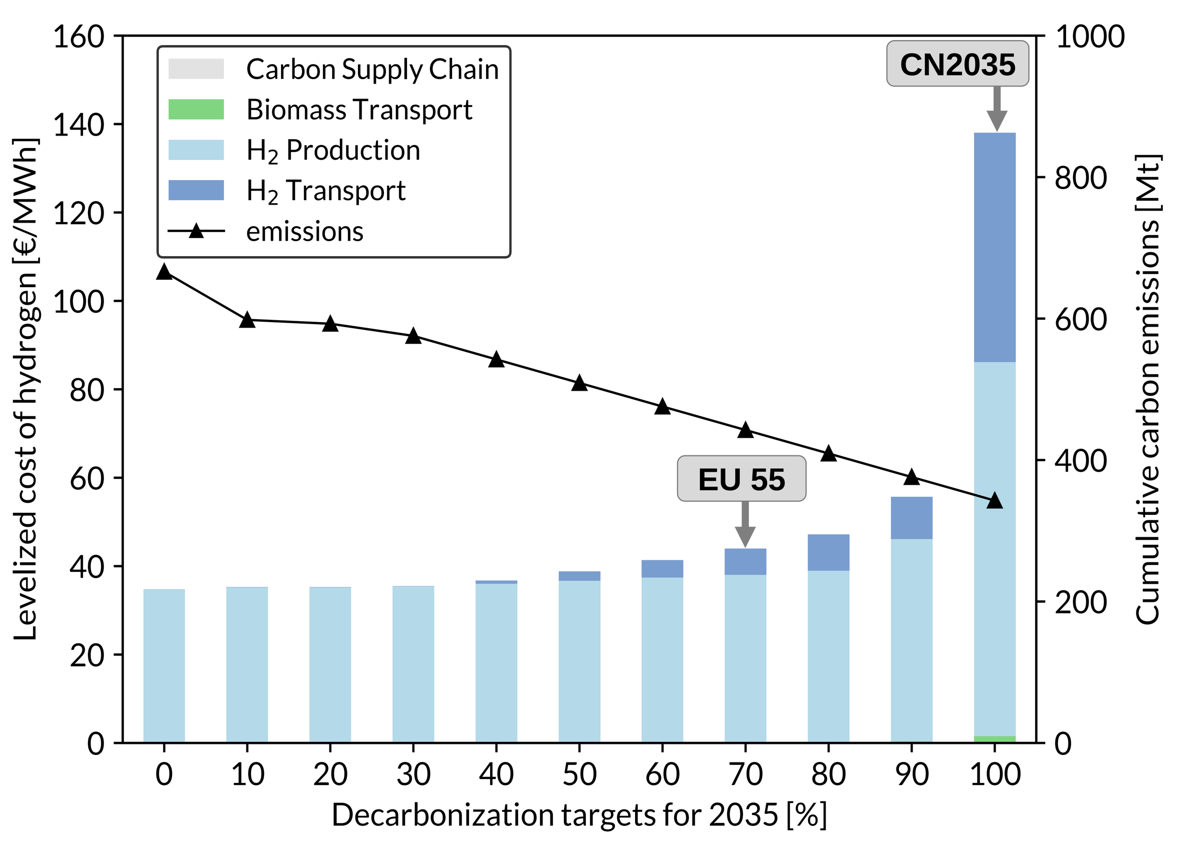
Wet- and dry-biomass potential in Europe [TWh][3]

Wind and solar energy potential in Europe [TWh][3]

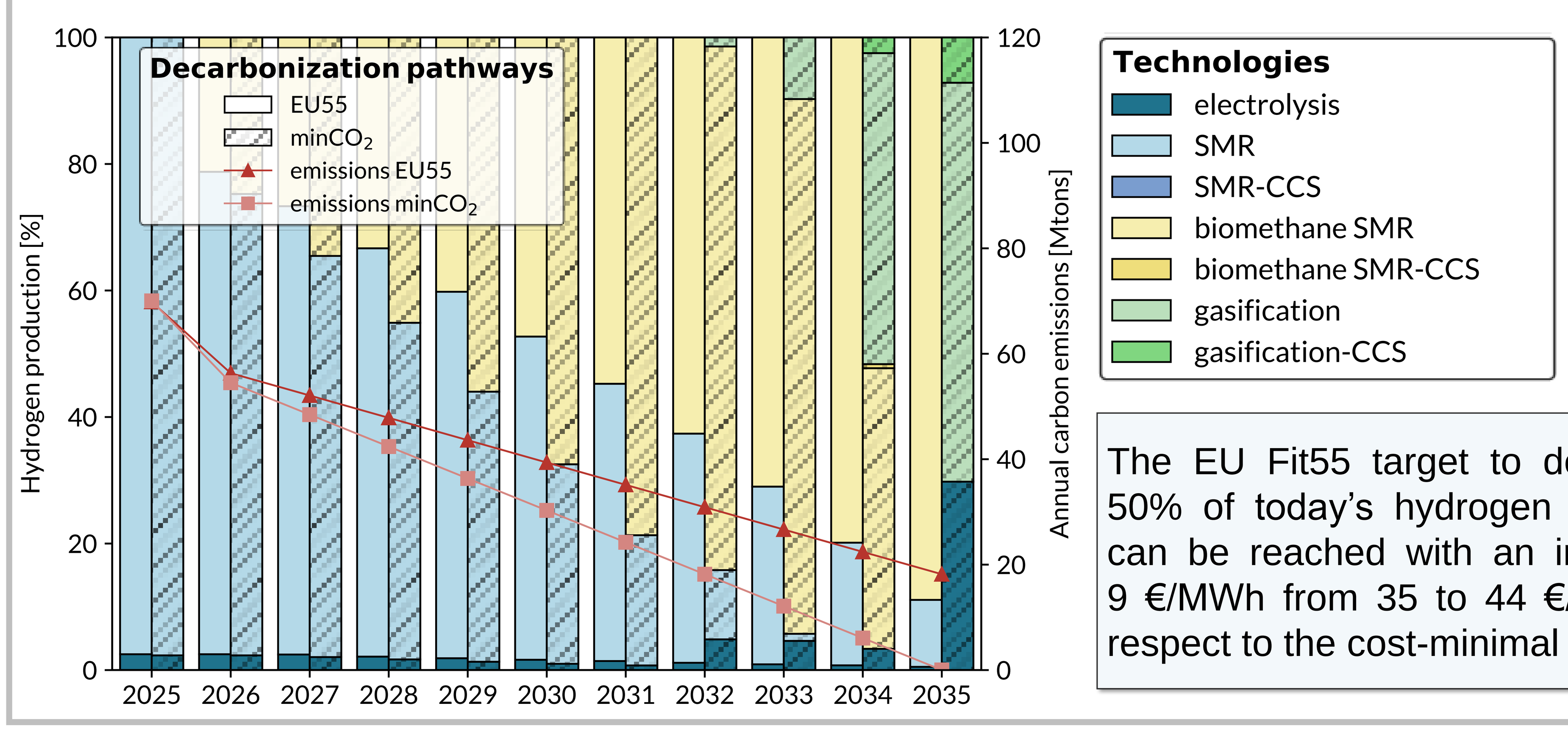
Hydrogen production [TWh] and transport to reach carbon neutrality by 2035 (CN2035)



Levelized cost of hydrogen and cumulative emissions



Optimal hydrogen production technology mix from 2025 to 2035 for EU55 and $minCO_2$



The EU Fit55 target to decarbonize 50% of today's hydrogen production can be reached with an increase of 9 €/MWh from 35 to 44 €/MWh with respect to the cost-minimal solution[5]

4 CONCLUSIONS

- The levelized cost of hydrogen increases by 150%, from 35 €/MWh to 138 €/MWh, when increasing the decarbonization target from 90% to 100%
- The results highlight the importance of biomass-based hydrogen production in the transition from fossil-based hydrogen production to low-carbon hydrogen production
- A clear ranking of low-carbon hydrogen production technologies can be derived with biomass gasification being the preferred option. Biogas reforming serves as a transition technology. The role of water-electrolysis and CCS is low, due to high system costs.

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PSI's Energy System Integration Platform (ESI)

Work package 3 – Technology and model development

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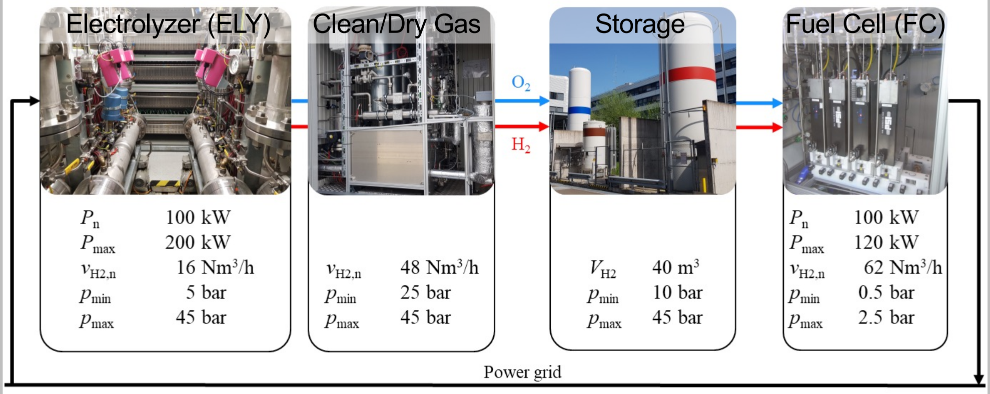
1 OVERVIEW ESI – RENEWABLE ENERGY STORAGE[1]

- PEM based
- Pure O_2 based
- Intermittent operation

Fig. 1: Energy System Integration Platform – Technology demonstration on the sub MW level.



- Fully automated
- ReMaP[2] access

Fig. 2: Hydrogen path as the backbone of ESI and the future energy system.

2 DYNAMICS OF PEM TECHNOLOGIES

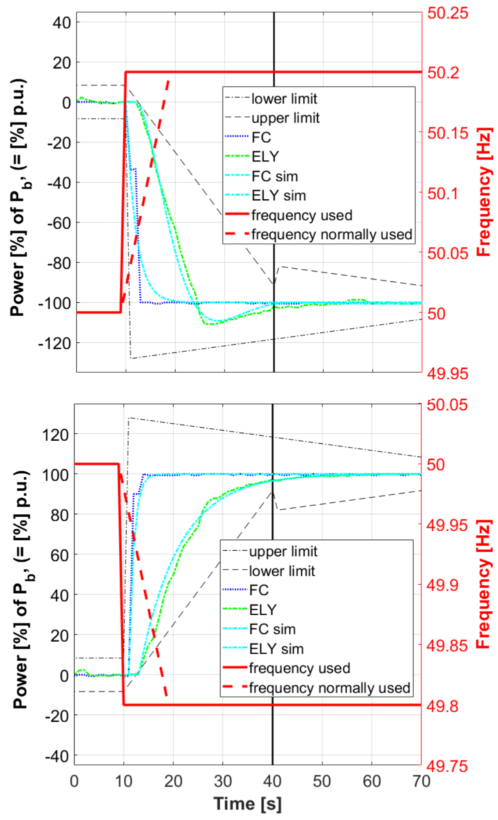
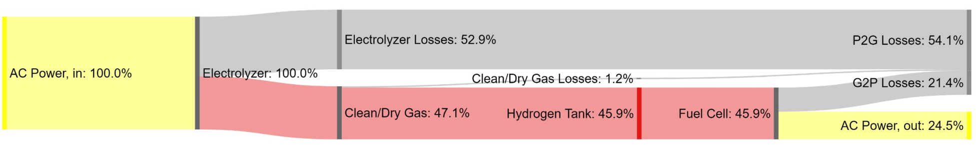


Fig. 3: Primary frequency control results for frequency increase (top) and frequency decrease (bottom).

- Tests conducted with **polymer electrolyte membrane (PEM)** technologies.
- Demonstrated synchronous grid frequency control capability.[3]
- Fast dynamics using pure oxygen in the processes.
- Collaboration with Swissgrid using relevant technology level.
- PEM Electrolyzer system (TRL 7) +/- 8 % p.u. / s.
- PEM Fuel cell system (TRL 5) +/- 33 % p.u. / s.
- Coming with a small droop – high controllability per unit of installed power.

3 EFFICIENCIES OF PEM TECHNOLOGIES

PEM technologies on ESI (TRL 5 – 7), measured in 2019[3]:



PtH_2tP PEM technologies in 2040, estimated:

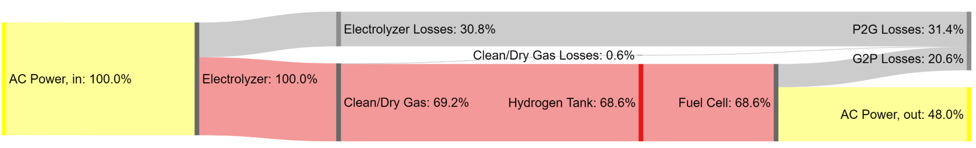


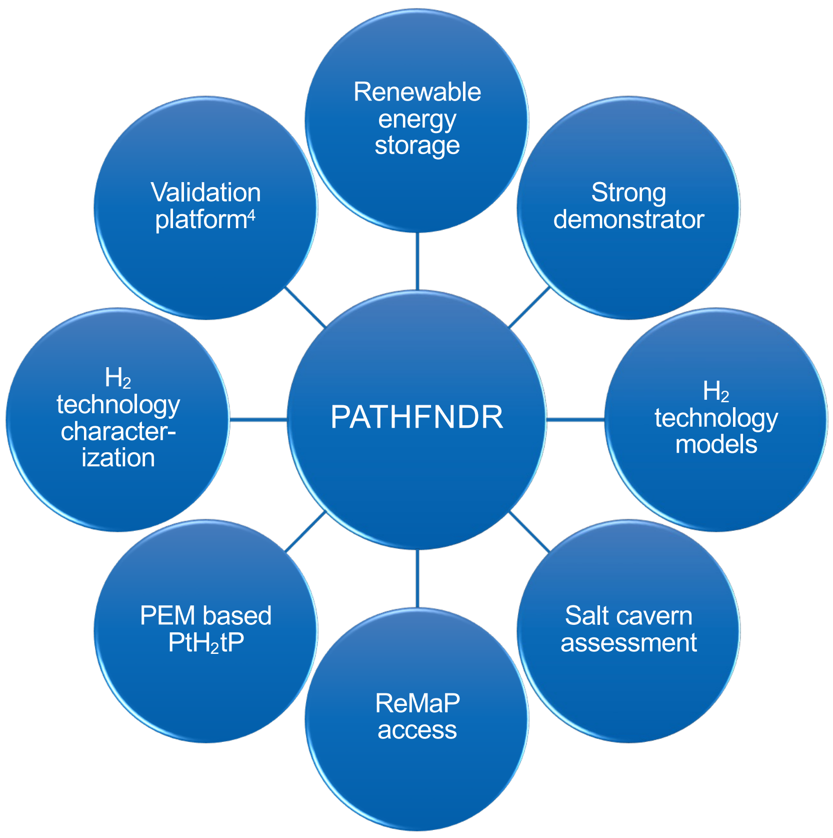
Fig. 4: Roundtrip efficiency for hydrogen path on ESI (top) and for the future energy system (bottom).

- Fundamental efficiencies determined.
- Base for techno-economic assessments.
- PtH_2tP using pure oxygen.
- Higher roundtrip efficiency than with air (+ 7.5 % in near future).

	Losses in % of system feed entity:					
	PtG			GtP		
Category	2011	2040	Δ	2017	2040	Δ
BoP	5.8	3	2.8	5.6	1.2	4.4
Converter	8.0	0.5	7.5	4.0	1.4	2.5
EC	38.5	26.8	11.7	33.5	27.2	6.3
GC	0.5	0.5	0	–	–	–
GUL	–	–	–	3.6	0.24	3.4
Tot. EL	52.9	30.8	22.1	–	–	–
CDG	1.2	0.6	0.6	–	–	–
Total	54.1	31.4	22.7	46.7	30.1	16.6

Fig. 5: Development of the different losses investigated. (Balance of plant (BoP), electro-chemical (EC), gas-crossover (GC), and gas utilization (GUL)).

4 CONTRIBUTION TO PATHFNDR



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2 https://remap.ch//platform
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MODEL DEVELOPMENT FOR ADVANCED CONTROL ALGORITHMS

Work package 3 – Technology and model development

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1st USE CASE: OPTIMIZED HYDROGEN PRODUCTION[1]

Goal: cost efficient hydrogen production for refilling fuel cell cars using PEM electrolyzer.

- PEM electrolyzer considered.
- System Identification.
- Modelling input / output relations.
- Determine system limitations.
- PEM electrolyzer model.

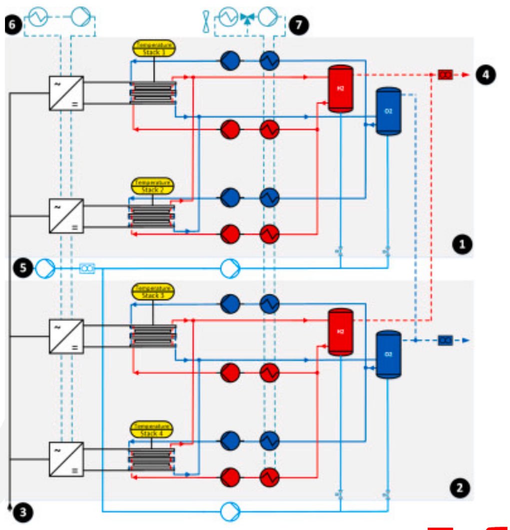
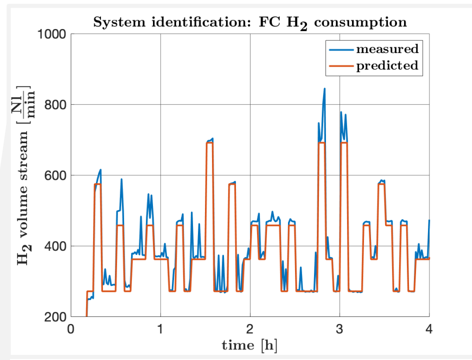


Fig. 1: Process & Intstrumentation Diagram of Silyzer 100 electrolyzer.

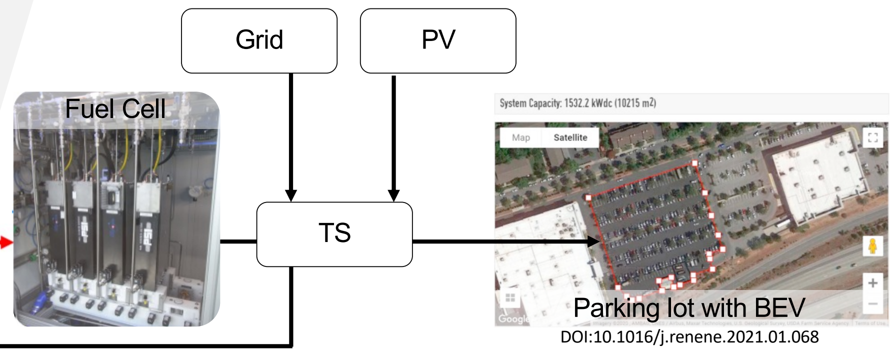
Fig. 2: Energy System Integration Platform's hydrogen path providing various testing possibilities.

2nd USE CASE: PEAK SHAVING BEV DEMAND[2]

Goal: reduce the daily power peak drawn from the grid to charge the incoming EVs on a parking lot.



- PEM PtH$_2$tP considered.
- System Identification.
- Modelling input / output relations.
- Determine system limitations.
- Electricity supply by grid & onsite PV production.
- PEM PtH$_2$tP model.



DOI:10.1016/j.renene.2021.01.068

Results

- Deterministic model predictive control carried out.
- Realistic setup considered.
- Fuel cell hydrogen refilling demand & EPEX SPOT SE.
- Realization of software framework with HIL.

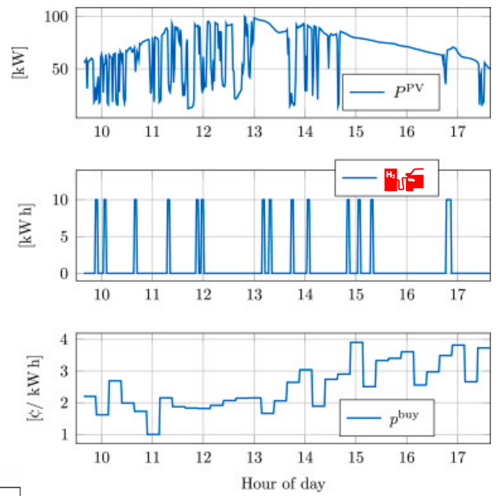


Fig. 3: Scenario settings: photovoltaic power generation (top), hydrogen demand (middle) and dynamic prices (bottom) over time considered.

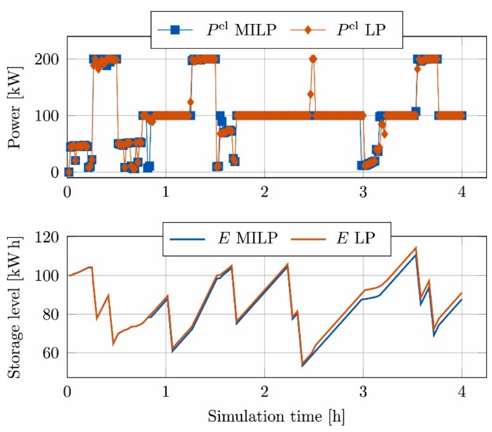


Fig. 4: HIL data with electrolyzer power and storage level over time according to the applied control algorithm.

- PEM electrolyzer model validated.
- Advanced control algortihms validated.
- Performance comparison mixed-integer linear programming problem (MILP) versus LP.
- MILP performed more cost-efficient.

Results

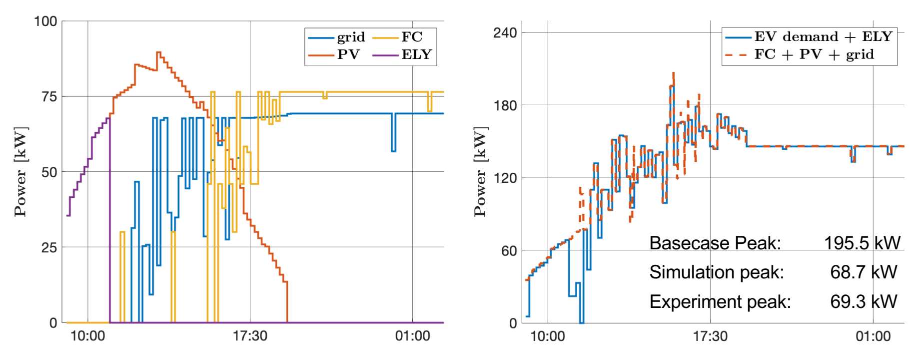


Fig. 5: HIL data with grid, fuel cell (FC), PV and electrolyzer (ELY) powers (left) – power balance check (right).

- Deterministic & stochastic model predictive control.
- Fully automated tests with HIL.
- Advanced control algortihms validated.
- Performance comparison between different algorithms.
- Simulation environment developed.

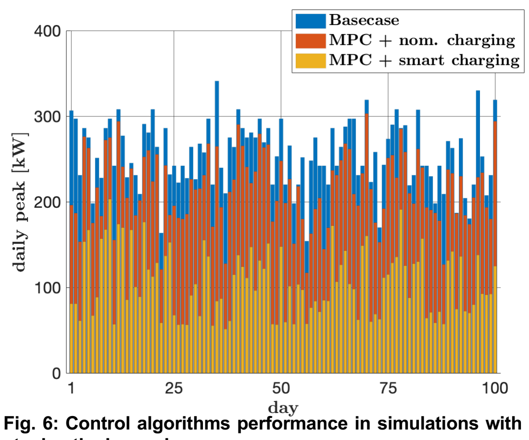


Fig. 6: Control algorithms performance in simulations with stochastic demand.

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2 https://remap.ch/project_t3-9

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Planning & operation of multi-energy systems

Work package 2 (ST1, 3.2 & ST4.1)

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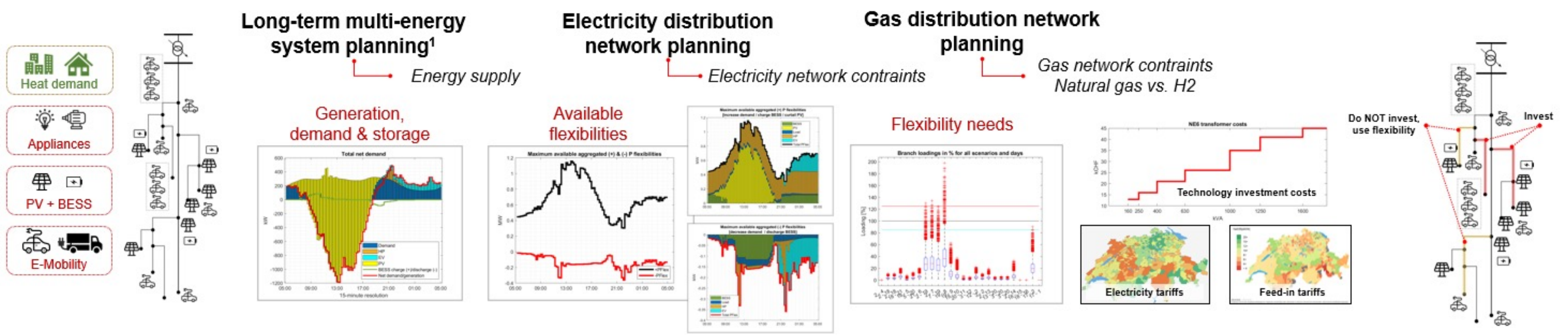
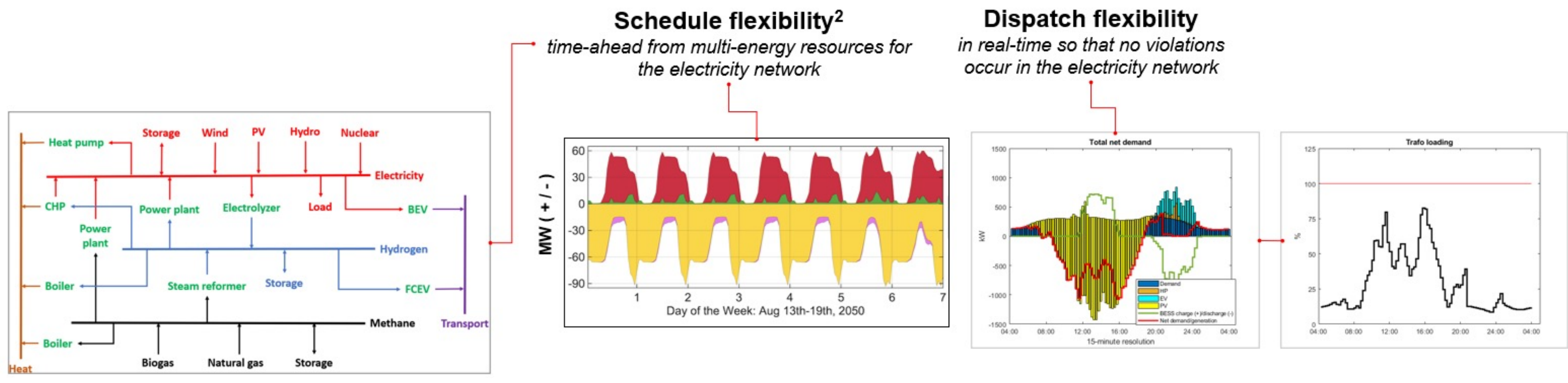
ETH zürich FEN

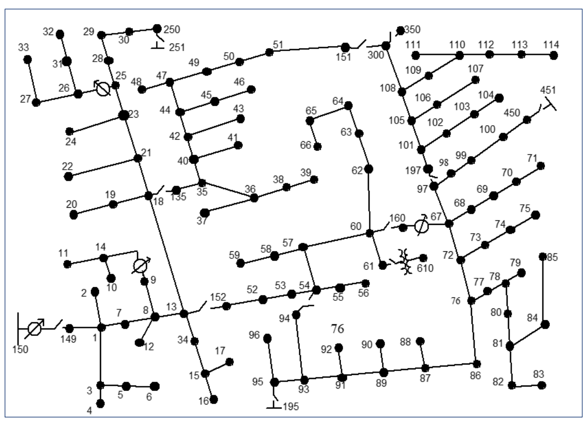
INFRASTRUCTURE PLANNING FOR MULTI-ENERGY SYSTEMS (CITY, VILLAGE ETC.)



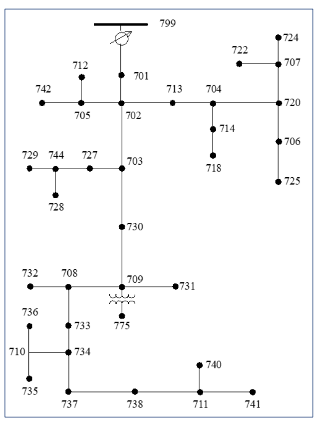
NETWORK OPERATION: SCHEDULING & UTILIZATION OF FLEXIBILITY



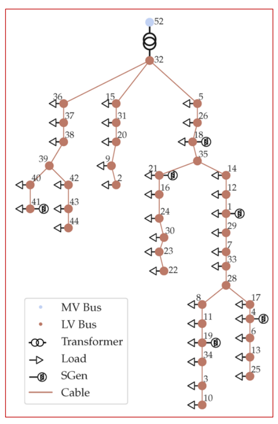
IDENTIFICATION OF USE-CASES: REPRESENTATIVE GRIDS (ELECTRICITY, GAS, HEATING) & ENERGY SCENARIOS



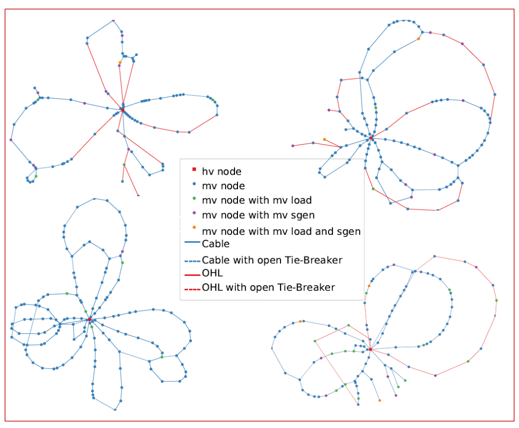
IEEE 123-node



IEEE 37-node



SimBench[3] 44-node



SimBench[3] MV grid analysis

Rural, urban, mountainous regions; electricity, gas and district heating networks; type of sites / end-users; resource availability

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Optimal integration of Borehole Thermal Energy Storage in district heating and cooling networks

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1 Motivation

Integrating a borehole thermal energy storage (BTES) into district heating and cooling networks enables cost-effective seasonal storage of waste and renewably-generated heat. The operation of such a district heating and cooling network involves a large number of decision variables and is affected by boundary conditions[1], such as the CO2 intensity of the electricity, which varies seasonally. For this reason, an optimization formulation needs to be developed. To predict the performance of such systems, two modelling approaches are normally employed:

- High fidelity models, which simulate the detailed behavior of the networks and components for predefined parameters. (such as in TRNSYS or Modelica)
- Optimization formulations, using simplified, mostly linearized, models, to calculate optimal decision variables affecting these systems.

Due to high computational costs, no numerical approaches with detailed high-fidelity models can be solved in a reasonable time, but it is at the same time unknown how well the simplified approaches can represent these systems.
This leads to the research questions of this work:

How does the optimal solution of operational parameters managing a BTES, which has to be found with simplified models, compare to the same inputs given in a high-fidelity platform?

Considering the seasonality of the CO2 intensity of the electricity, what is the best operating temperature of the BTES, and when should be air be used as a source?

3 Methods

In a first step, a detailed model of the heating and cooling network with a time step of $^1/_4$ hour was created in TRNSYS. With this, two baseline simulations were created. One with a low temperature BTES, with a starting temperature ($T_{BTES,initial}$) of 12 °C and a high temperature BTES at 25 °C. These two simulations serve as a benchmark. In a second step, an energy hub approach formulated as a non-convex MILP formulation was developed with Gurobi and Yalmip in Matlab. The objective was to minimize the annual CO_2 emissions, by optimally operating the network. The following 2 optimization parameters were selected.

- $T_{BTES,initial}$ (initial BTES temperature in spring)
- $T_{air,set}$ (daily mean air temperature at which the air source is prioritized over the BTES source heat pump)

This formulation takes the annual CO_2 intensity of electricity into account and approximates the BTES as a steady-state cylindrical ground storage with a uniform temperature. In addition, the maximum energy transfer rate in and out of the BTES was assumed by a constant UA value, as follows:

$$T(i{+}1) = T(i) + \frac{\Delta t}{M_g V_g}\Big[\underbrace{\dot{Q}}_{\text{Net heat flow}} - \underbrace{U_A A_g (T(i) - T_a(i))}_{\text{Top losses}} - \underbrace{k_g h \frac{D_g}{2}(T(i) - T_g)}_{\text{shell losses}}\Big] \qquad \dot{Q}_{BTES,i} \leq UA_i \Delta T_i$$

To further reduce the calculation time, a daily time step was chosen.

2 Case Study

A generic district heating and cooling system, analogous to Fig. 1, was used as a case study. It has 3 networks:

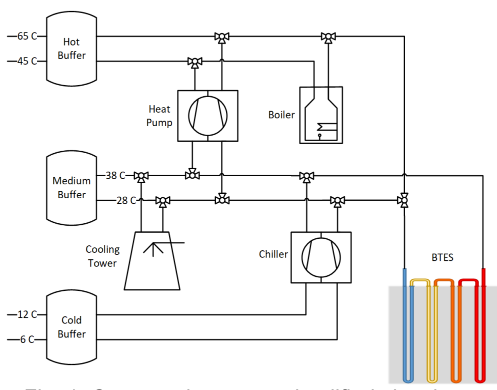

Fig. 1: Case-study system simplified sketch

- High-temperature network at 68/45°C, which is dedicated to supply the heating load. The heat is provided by 3 different heat pumps, namely an air, a waste heat and a BTES source heat pump. In case the heating demand cannot be covered by the heat pumps, a boiler is switched on as a backup.
- Medium-temperature network at 38/28 °C, is used to receive and store the rejected heat inside the BTES. In case of excess of heat during summer, the heat can also be released to the environment via a cooling tower.
- Cold network, providing cooling via a single chiller in the cooling network and has a temperature level of 6/12 °C.

A buffer is integrated within each temperature level, which enables short-term storage of heat and thus simplifies the control of the entire system.

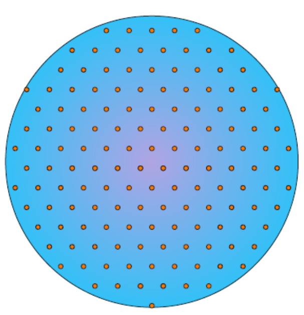
Fig. 2: BTES boreholes placing[2]

The BTES, on the other hand, is used as long-term storage and has a diameter of 50m, a depth of 100m and consists of 144 double-U ground heat exchangers (GHXs) (Fig.2)
An annual load profile of the EMPA research campus was used as input to the models. The network provides an annual heating demand of 6850 MWh and a cooling demand of 3490 MWh.

4 Results

- Comparing the high and low-temperature BTES baseline results in TRNSYS, the high temperature solution (Fig.3) reduces CO2 emissions by 5%, despite having a lower thermal efficiency of the storage (~70% vs ~80%).
- Optimal solution was found to be 22°C for $T_{BTES,initial}$ and 4.5°C for the average daily mean temperature trigger $T_{air,set}$. In TRNSYS, the reduction in yearly CO2 emissions compared to the baseline low-temperature increased to 7.2% (Fig.4).

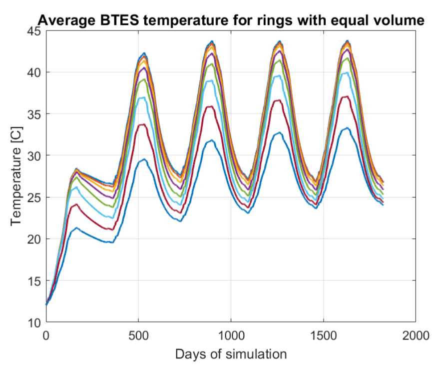

Fig. 3: Temperature evolution of the ground, high-temperature baseline

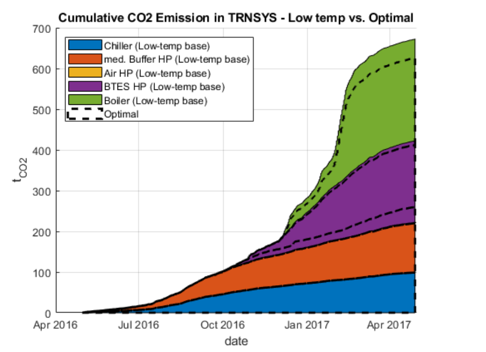

Fig. 4: Comparison of cumulative emissions, baseline low temperature vs Optimal (TRNSYS).

While the optimal solution is better than the two baselines when implemented in the high-fidelity model, the expected emissions by the optimizer is 10% lower than the more realistic one with the same setting.
The mismatch is mainly due to the limitations of the different time steps of the models, removal of buffers, and interaction between components, which is simplified in the optimization.

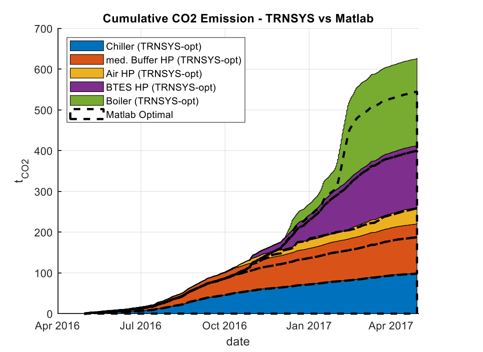

Fig. 5: Comparison of cumulative emissions, Optimal (TRNSYS) vs. Optimal (Matlab).

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Model development for integrated systems: example application and preliminary results

Work package 3

Edward Lucas[1], Esther Linder[1], Marcel Troxler[1], Philipp Schütz[1], Willy Villasmil[1]

[1]Lucerne School of Engineering and Architecture, Technikumstrasse 21, 6048 Horw

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.

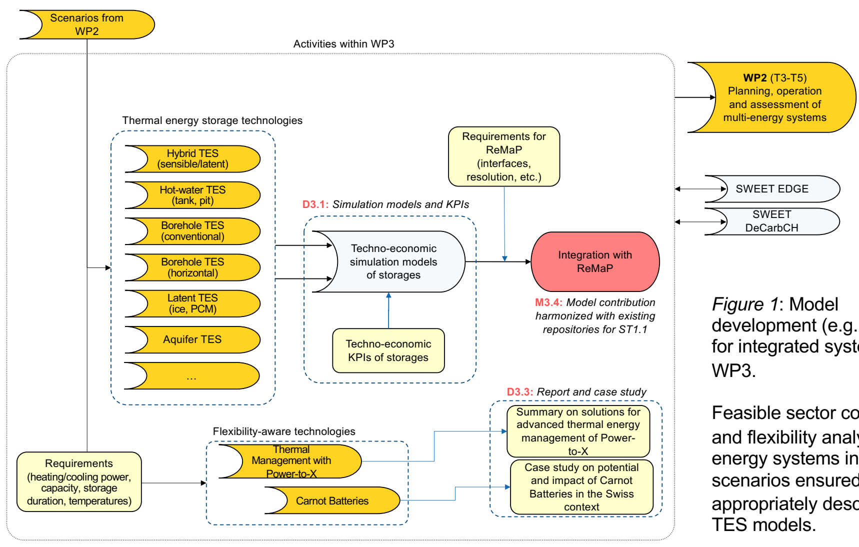

Figure 1: Model development (e.g. TES) for integrated systems in WP3.

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.

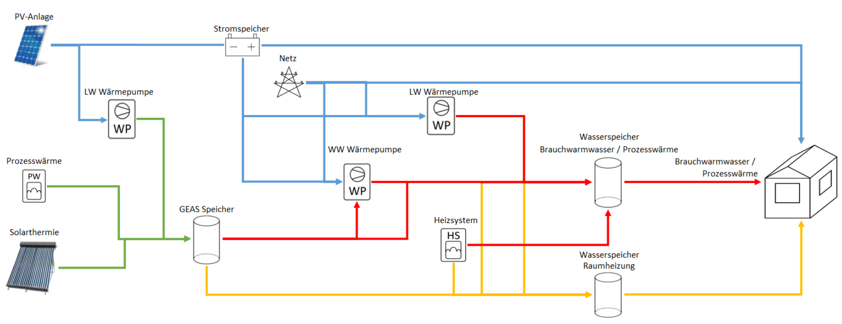

Figure 2: A conceptual layout for an integrated energy system for a residential application, including some example key performance indicators of the chosen storage technology.

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)

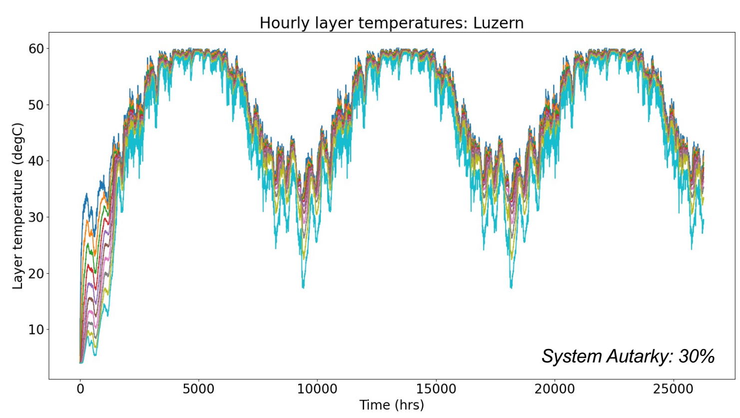

Figure 3: Simulated temperature profile of the water-based seasonal thermal energy storage showing how tank temperatures develop and change throughout the year in accordance with seasonal charging and discharging behaviour. The modelled location used weather data from the city of Luzern.

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4 GEAS Project, Luzern University of Applied Sciences

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Hochschule Luzern Technik & Architektur

THERMAL ENERGY STORAGE

HSLU Lucerne University of Applied Sciences and Arts

Estimating heat demands of residential buildings

Work package 2

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1 OBJECTIVES

In Switzerland, **the residential sector spends nearly a third of the total energy** consumption of which almost 50% is from oil and gas burning[1]. To reduce the CO_2 emissions significantly, oil and gas based heating systems need hence to be replaced with renewable options such as heat pumps, especially also to reach the net zero goal by 2050 of the Swiss climate strategy[2].

To analyse how heat demands can be covered with renewable energy sources and to quantify the flexibility contribution from space heating system, it is necessary to estimate the heat (and cooling) demands for the Swiss building park reliably. This demand depends for example on the geographic location, size, and insulation of the building and its neighbourhood.

2 CONTRIBUTION TO PATHFNDR

To quantify the flexibility between demands and energy sources, a necessary input are demand estimation. These demands concern electricity, but also heat/cooling demands. Through conversion technologies such as a heat pump, the heat demand can be supplied by electricity and hence is a provider of potential sector coupling and flexibilities.

An estimation of **heat demands for residential buildings** is therefore a crucial input to Pathfndr and serves as the **basis for the estimation of the flexibility and sector coupling potential**. In this poster, heat demand estimation for residential buildings are presented.

2 METHODOLOGY

Two approaches to estimate the heat demand of residential buildings are presented. Both of them are based on public building properties such as size or building age (which are taken from the Federal Register of Buildings and Dwellings[3](RBD)), assume a constant room temperature of 20°C and take into account weather data. The RBD data has to be used with caution, as it is for same cases incomplete or outdated. However, due to its wide coverage, it is a valid starting point for this analysis. The weather data is taken from Agrometeo[4], which provides weather data from more than 150 stations in Switzerland with a resolution of 10min. Important for this analysis are the measured ambient temperatures.

One of the approaches uses the **building class to estimate the heat demand based** on the SIA norm[5]. The other one calculates the **heat transmission factor from the building properties directly**, as was also done by Peru Elguezabal *et al* 2019[6]. The heat demand estimation is multiplied, depending on the age of the building and the ambient temperature. In a refined version, the scaling factor is fitted based on clustered real-world consumption.

3 RESULTS AND NEXT STEPS

The distribution of the actual consumption values and the estimated values from the refined method from above is shown in *Figure 1*.

Figure 1 shows the distribution of the specific space heat demands for a city where also the actual heat demands were available. Shown is the number of buildings per specific space heat demand in kWh/m²/a, for the actual measurement as well as the prediction from the model. The three peaks which are present in the measurement at roughly 50, 60, and 80kWh/m²/a are recovered by the modelling. Also, the peak height is satisfyingly similar in the predicted and actual measurement, with an overshoot at the peak around 80kWh/m²/a, which is compensated with a low number of buildings on the right wing of this same peak for the predicted data. A difference occurs with some high consumers at more than 160kWh/m2/a, which are not present in the actual data. Overall, **a satisfying agreement with actual measurement data and the models** was achieved.

The calculation of the heat demand is now **automatized for calculating the yearly heat demand of every building of a complete community**. An example is shown in *Figure 2*, which displays the coordinates of the buildings together with the colour-coded estimated heat demand. We are currently in exchange with different communities to have **more possibility for validation** for the presented approaches.

Next steps are also to **calculate the heat demand on a daily basis**, taking into account the weather data at a specific location.

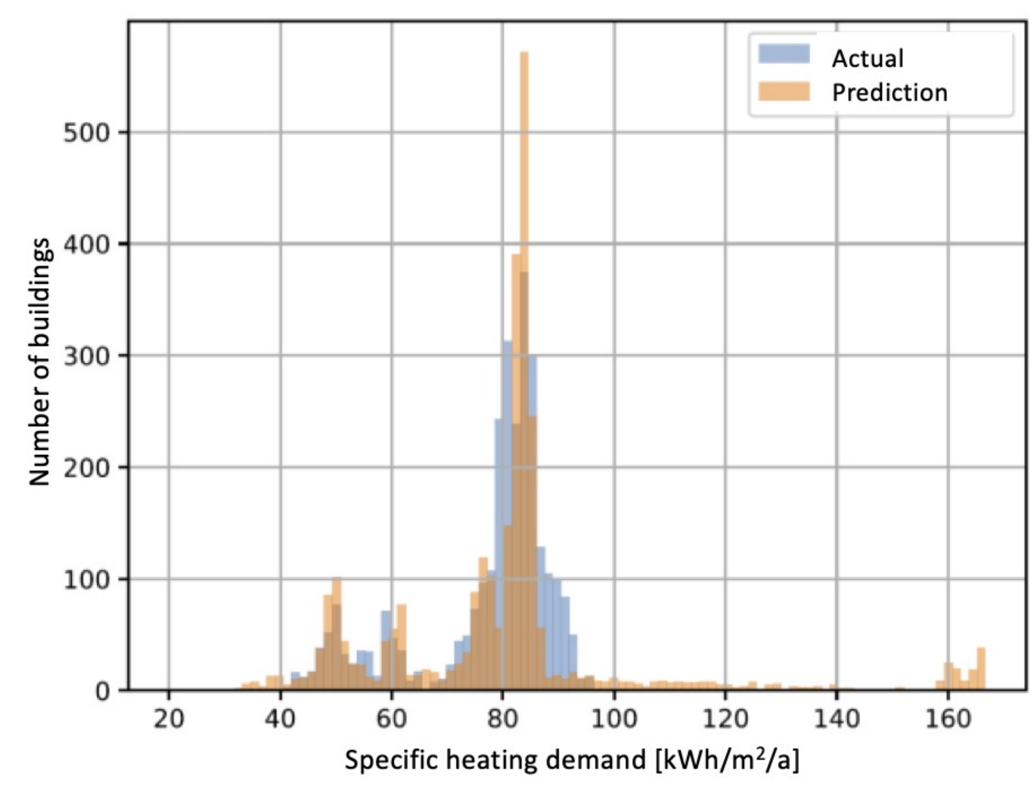

Figure 1: Distribution of heat demands, actual and predicted, for a specific community.

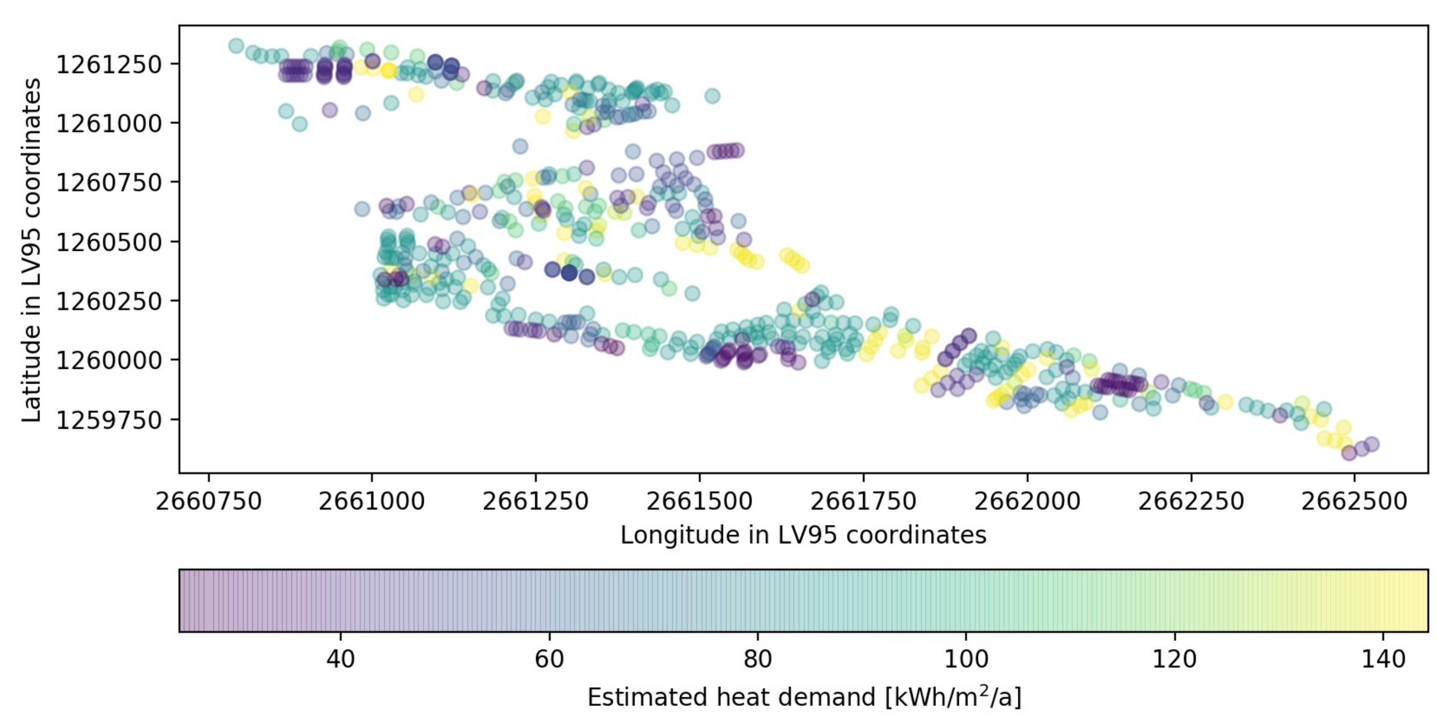

Figure 2: Specific space heat demands calculated for a specific community.

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Flexibility assessment of E-mobility in Multi-energy Systems

Work package 2

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[2] Sympheny
[3] ETH Singapore

1 BACKGROUND AND OBJECTIVES

- Decarbonization of the mobility sector is increasingly becoming important.
- E-mobility emerging as major source of power demand in urban energy system.
- This work studies the flexibility of e-mobility in a multi-energy system.

2 CONTRIBUTION TO PATHFDNR

- Enhancement of Ehub tool with e-mobility module.
- Contribution to T3.1 on site planning considering multi-energy flexibility.
- Techno-economic parameters as well as modelling assumptions.

3 METHODOLOGY

- E-hub Tool of Empa is used to perform the planning and operation of multi-energy system.

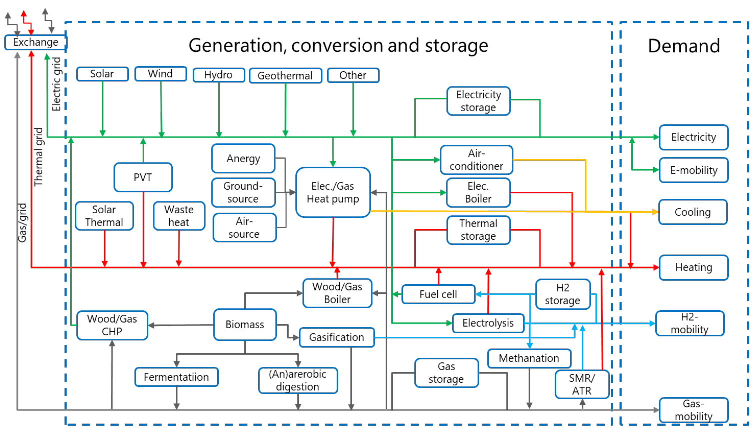

Figure 1: Multi-energy system in Ehub Tool

- An e-mobility module is developed and integrated into the E-hub Tool.

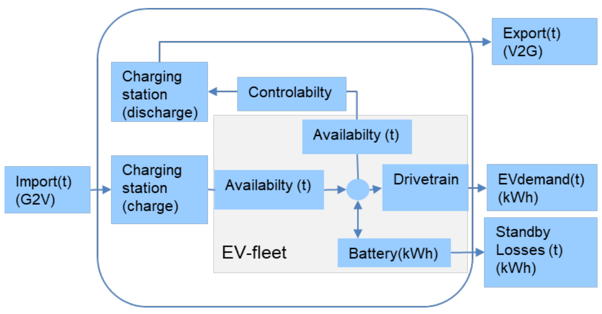

Figure 2: E-mobility module

- The module captures the fleet size, charger size, transport demand, vehicle availability, controllability and battery size.
- The module is tested in the e-hub tool using the multi-energy system in Chur, Switzerland.

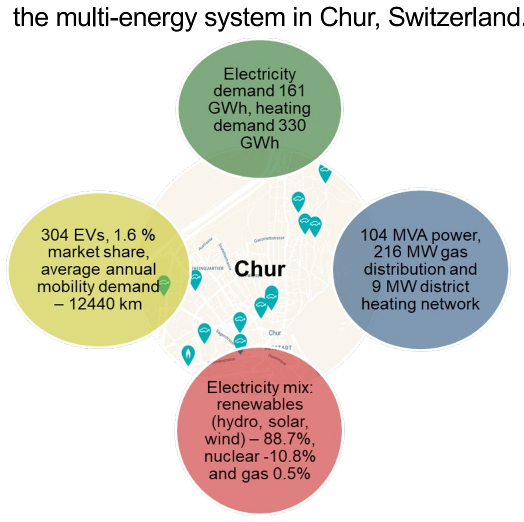

Figure 3: Case study of Chur, Switzerland

3 RESULTS

- E-mobility can provide demand and supply-side flexibility in the multi-energy system, see Fig. 4.
- Under the given boundary conditions and energy-mix, V2G is an attractive solution in a cost optimization over a CO_2 optimization scenario.
- Sensitivity analysis on input parameters as well scenarios will be useful to obtain further insights on the value of e-mobility flexibility.

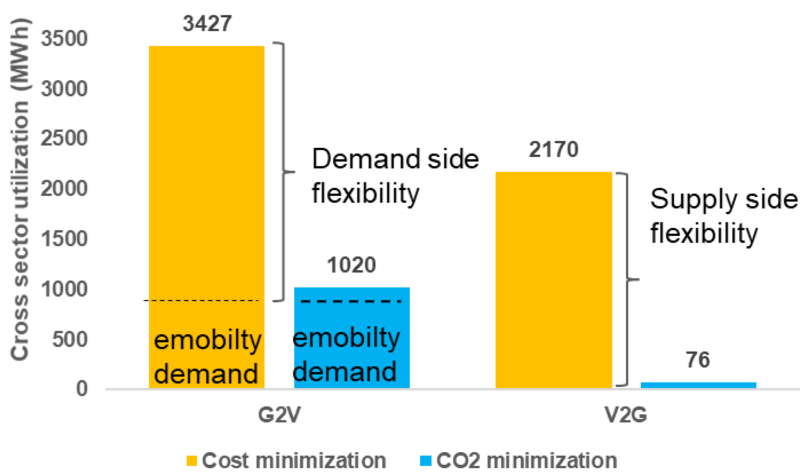

Figure 4: *Cross-sector utilization and flexibility between power and e-mobility sector with cost and CO2 minimization objectives.*

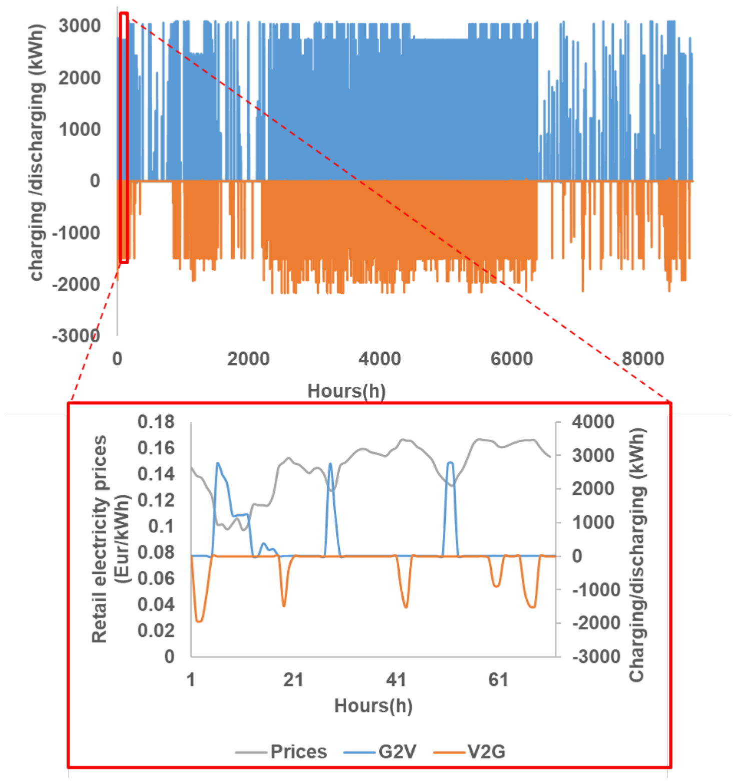

Figure 5: Optimal V2G/G2V profiles of Chur EV fleet with cost minimization and their correlation with electricity prices

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Modeling and Control of Multi-energy System in a Microgrid

Work package 3

Rahul Gupta, Fernando Soria, Mario Paolone

Distributed Electrical Systems Laboratory, EFPL

1 Objectives

Model predictive control (MPC) of a multi-energy systems in a microgrid – optimization across electrical + gas + thermal grids.

- **Objectives**
  - Minimize cost of operation (electricity from the grid)
  - Optimize dispatch plan of energy resources
- **Constraints**
  - Fuel cell system
  - Electrolyzer
  - Battery storage

Challenges: Fuel cell (FC) + Electrolyzer (EL) systems are inherently non-linear. It makes the optimization problem **non-convex**.

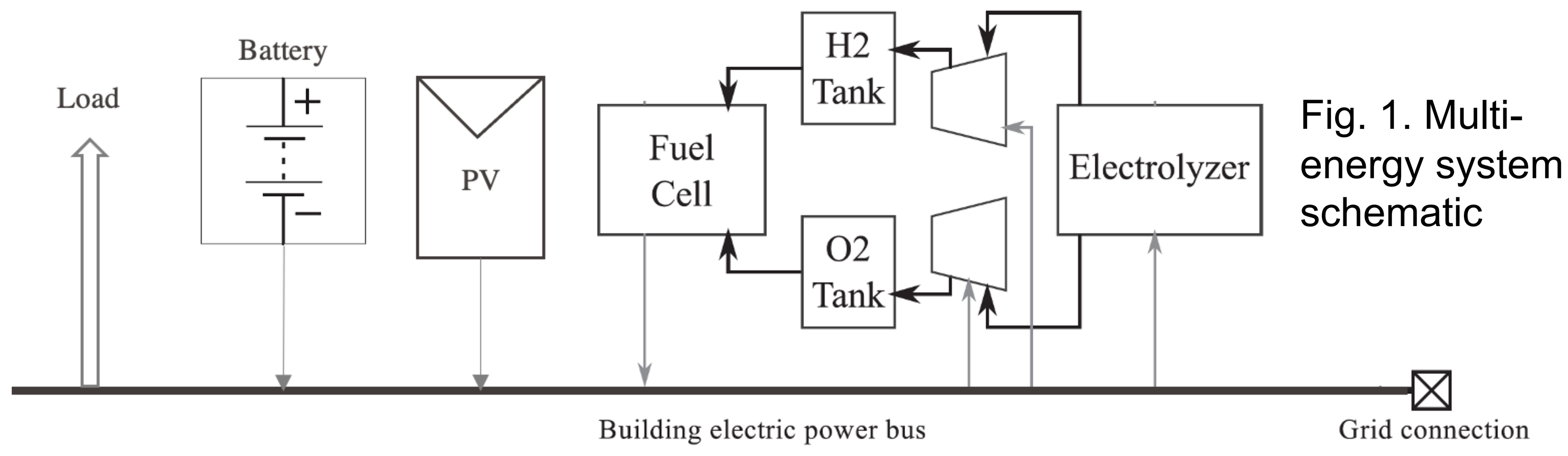

Fig. 1. Multi-energy system schematic

Assumption: all the resources are connected at the same node, so electrical grid is not modeled (It will be considered in future work).

2 Linearization of FC and EL Models

Voltage dependency with stack temperature and current.

$$v_{FC}(k) = \left(OCV - (\alpha \boldsymbol{T_{FC}} + \beta)\sqrt{\boldsymbol{i_{FC}}} - (\gamma \boldsymbol{T_{FC}} + \delta)\boldsymbol{i_{FC}}\right)$$

Heat-flow dependency with stack temperature and current.

$$Q_{FC} = \left((\alpha \boldsymbol{T_{FC}} + \beta)\sqrt{\boldsymbol{i_{FC}}} + (\gamma \boldsymbol{T_{FC}} + \delta)\boldsymbol{i_{FC}}\right)\boldsymbol{i_{FC}}$$

First order Taylor's approximation

$$\boldsymbol{f}(\boldsymbol{x},\boldsymbol{y}) = f(\hat{x},\hat{y}) + \frac{\partial f}{\partial x}\Big|_{(\hat{x},\hat{y})}(x-\hat{x}) + \frac{\partial f}{\partial y}\Big|_{(\hat{x},\hat{y})}(y-\hat{y})$$

$$\frac{\partial v_{FC}}{\partial T}\Big|_{(\hat{T},\hat{\imath})} = \alpha\sqrt{\hat{\imath}} - \gamma\hat{\imath} \qquad \frac{\partial v_{FC}}{\partial i}\Big|_{(\hat{T},\hat{\imath})} = \frac{\alpha\hat{T}+\beta}{2\sqrt{\hat{\imath}}} - (\gamma\hat{T}+\delta)$$

$$\frac{\partial Q_{FC}}{\partial T}\Big|_{(\hat{T},\hat{\imath})} = \alpha\hat{\imath}^{3/2} + \gamma\hat{\imath}^2 \qquad \frac{\partial Q_{FC}}{\partial i}\Big|_{(\hat{T},\hat{\imath})} = (\alpha\hat{T}+\beta)\frac{3}{2}\hat{\imath}^{1/2} + (\gamma\hat{T}+\delta)2\hat{\imath}$$

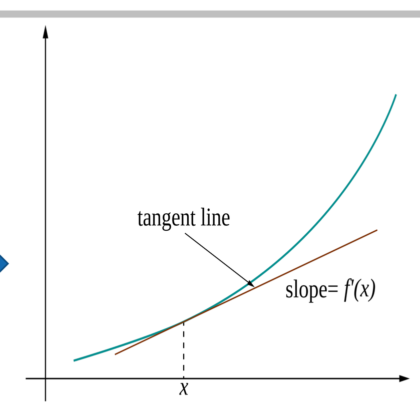

Fig. 2. First-order Taylors approx.

Power from the FC and EL: bilinear terms

$$P_{FC}(k) = v_{FC}(k)i_{FC}(k)$$

$$P_{EL}(k) = v_{EL}(k)i_{EL}(k)$$

Relaxing by McCormick Envelopes – relax the hyperbolic constraints by a bigger polytopic constraints.

$$P \geq \underline{x}y + x\underline{y} - \underline{x}\underline{y} \qquad P \leq \overline{x}y + x\underline{y} - \overline{x}\underline{y}$$

$$P \geq \overline{x}y + x\overline{y} - \overline{x}\overline{y} \qquad P \leq \underline{x}y + x\overline{y} - \underline{x}\overline{y}$$

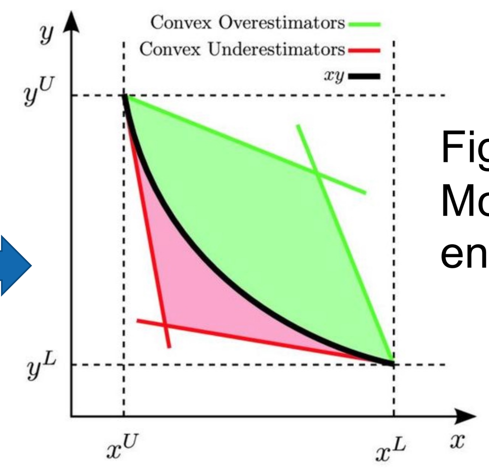

Fig. 3. McCromick envelopes

3 Simulation setup

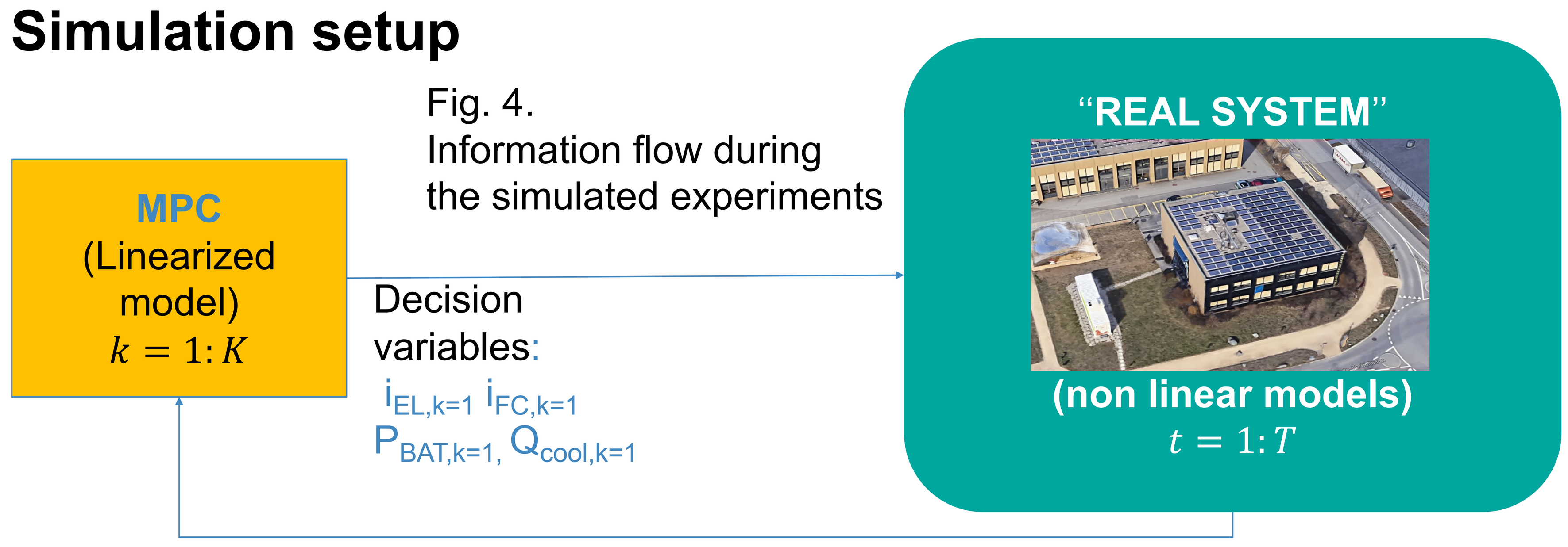

Fig. 4. Information flow during the simulated experiments

- State variables: $E_{bat}(t)$, $p_{H2}(t)$, $t_{FC}(t)$
- Sensitivity coefficients: $\frac{\partial v_{FC}}{\partial T}\big|_{(\hat{T},\hat{\imath})}(t)$, ...
- (Deterministic) forecasts: P_{PV}(t:t+K-1), Price(t:t+K-1), P_{Load}(t:t+K-1)
- McCormick envelopes: moving limits

3 Minimize electricity cost

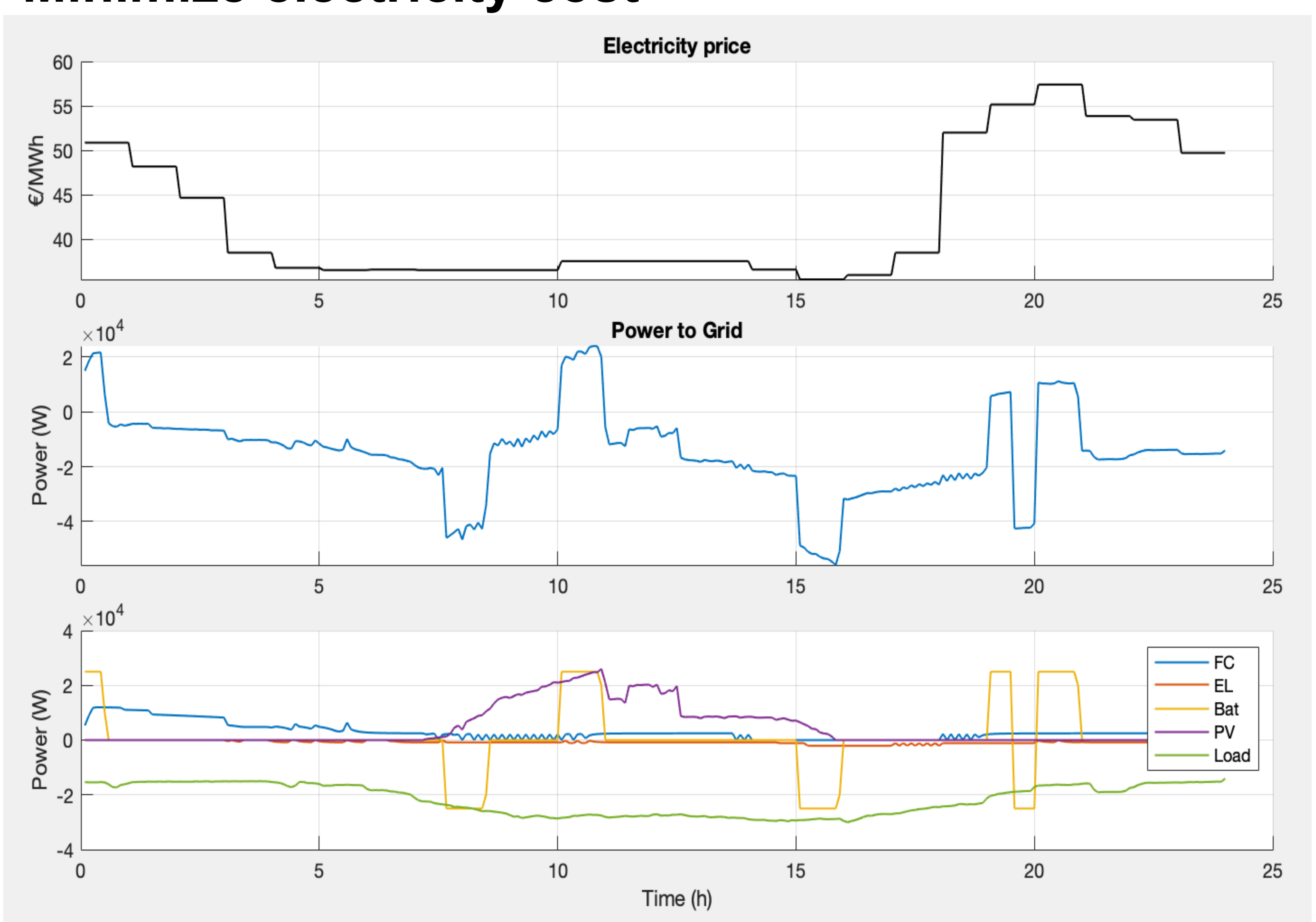

Fig. 4. Optimized power from different resources.

4 Track dispatch plan

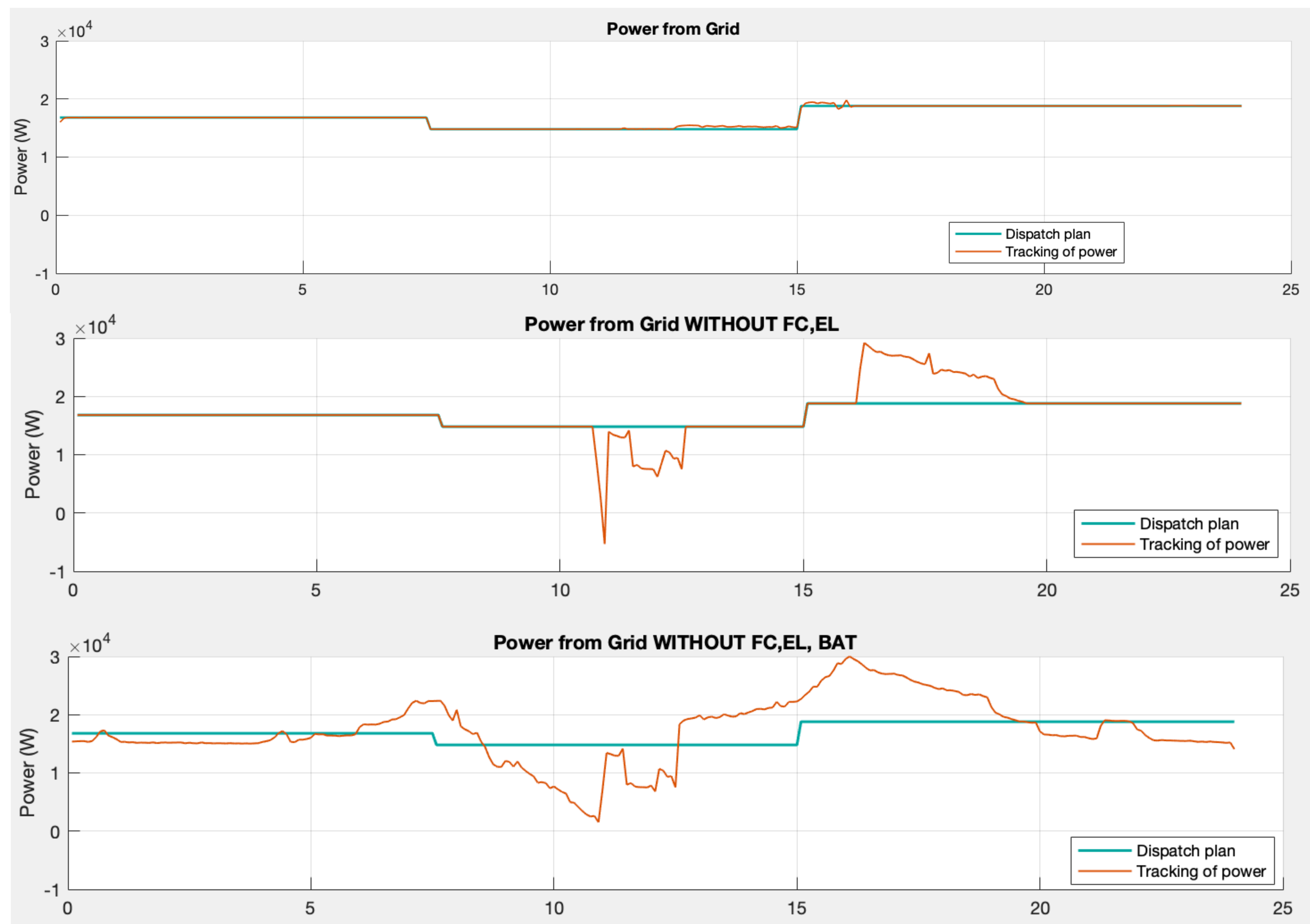

Fig. 5. Dispatch plan tracking by different resources.

5 Cost comparison

	COST (operation)	Dispatch error
With FC, EL	14.25 €	22 kWh
Without FC, EL	16.60 €	365 kWh
Without FC,EL, Battery	17.68 €	1112 kWh

6 Conclusions

- Model predictive control of multi-energy system connected to a microgrid is proposed.
- A linear model of fuel cell and electrolyzer is developed for obtaining tractable control formulation.
- The simulated results show lower costs when fuel cell and electrolyzer are considered in the control.

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EPFL

Coordinated Multi-grid Dispatch Framework

Work package 3
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1 Motivation

- ❑ Balancing Groups (BGs) are responsible for coordination between the generation and the demand.
- ❑ They are not constrained geographically (in Switzerland).
- ❑ Distributed energy resources (DERs) at different sites in distribution systems can be used in aggregated way (**crowd balancing**) to provide **ancillary services** to the transmission network e.g. for *Dispatching, primary frequency regulation etc.*

2.1 Objective

- ❑ Flexible resources across different sites are controlled to provide aggregated flexibility to the upper-layer transmission grid.
- ❑ By coordinating microgrids at different sites (e.g., EPFL and PSI) to have aggregated response.
- ❑ Local constraints of the grid and DERs to be accounted.

2.2 Aggregation Platform

- ❑ Objective: Compute day-ahead dispatch plans of a multi-grid setup.
- ❑ Constraints:
  - ❖ Stochasticity of electricity demand and generation (forecasting).
  - ❖ Flexibility of the controllable resources.
  - ❖ Grid constraints (via a linearized grid model.

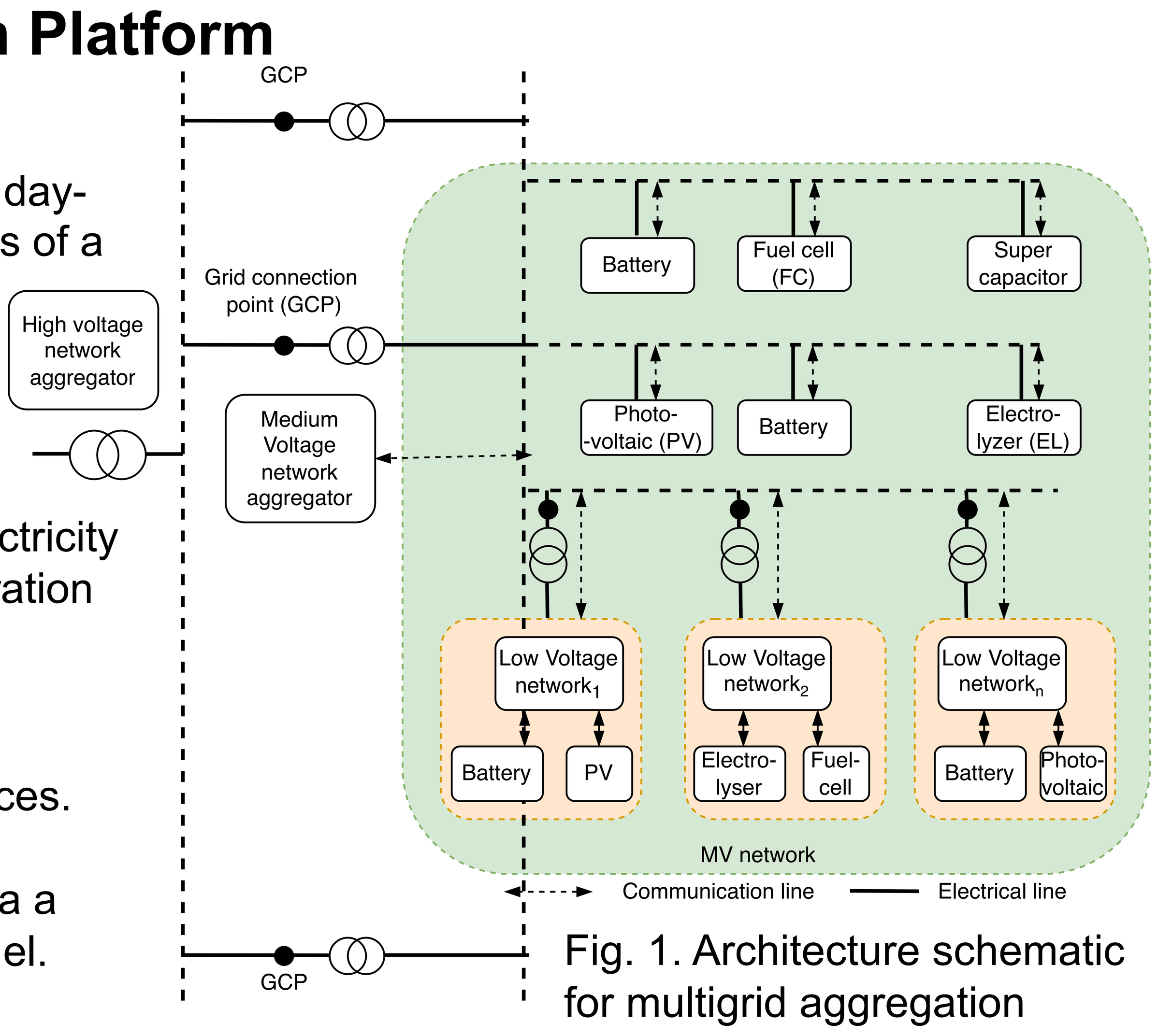


Fig. 1. Architecture schematic for multigrid aggregation

3 Distributed Optimization

- ❑ Solved as distributed optimization using Alternating Direction Method of Multipliers (ADMM).
- ❑ Allows scalability and decoupling of the models of networks and resources.

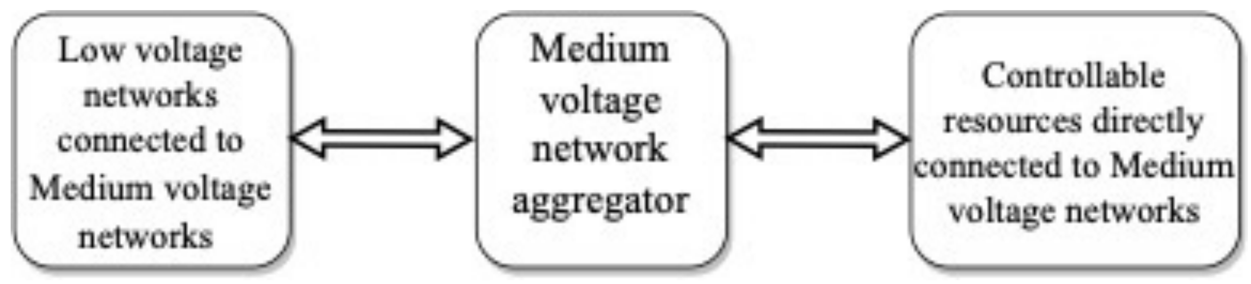


Fig. 2 Information exchange flow-diagram

4 Simulation Setup

- ❑ CIGRE MV grid connected to CIGRE LV grids at node N_5 and N_6.
- ❑ CIGRE MV: PV – 1.25 MWp, BESS – 1MWh/0.75MW.
- ❑ CIGRE LV1 and 2 – PV – 100 + 50 kWp, BESS – 750kWh/250kW.

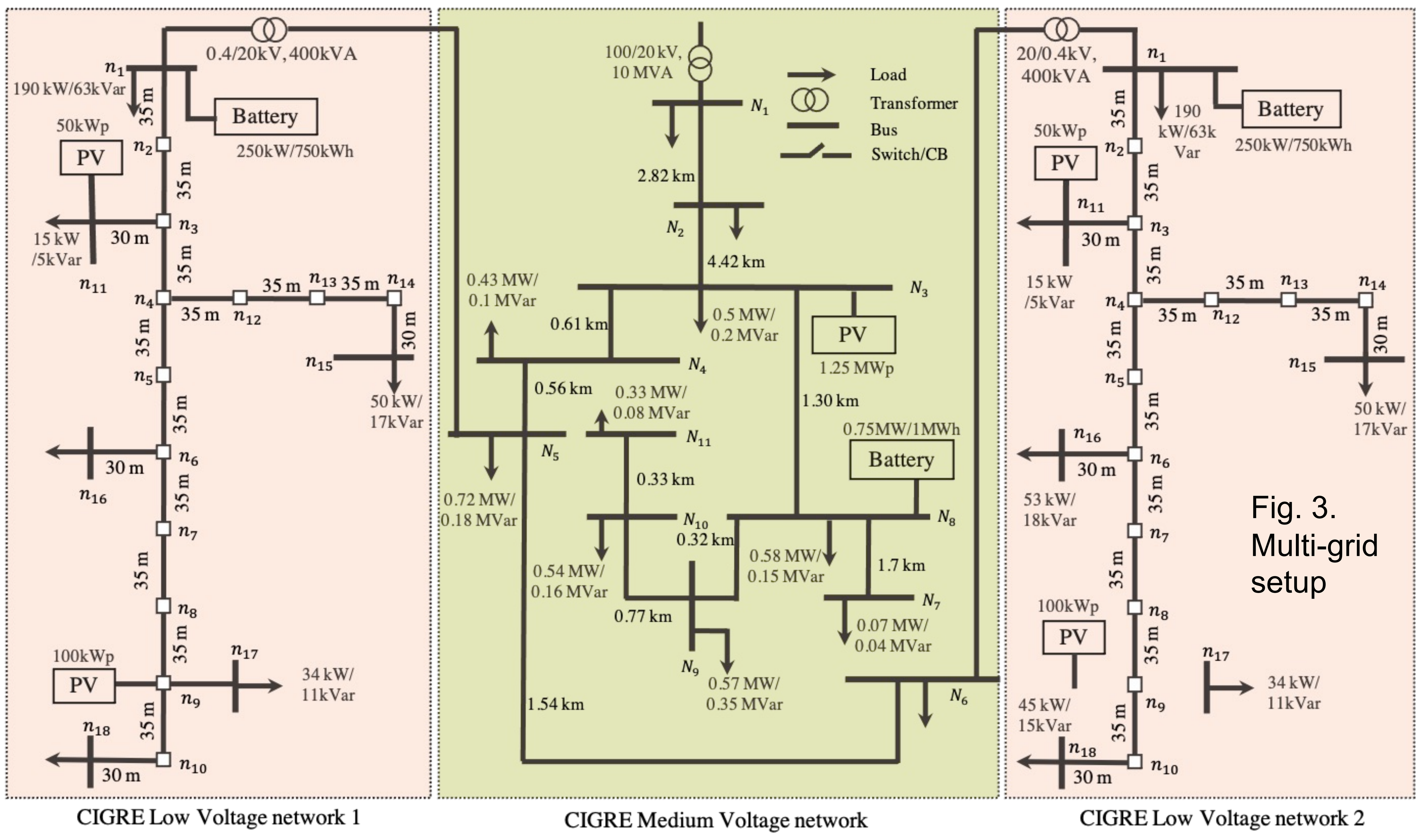
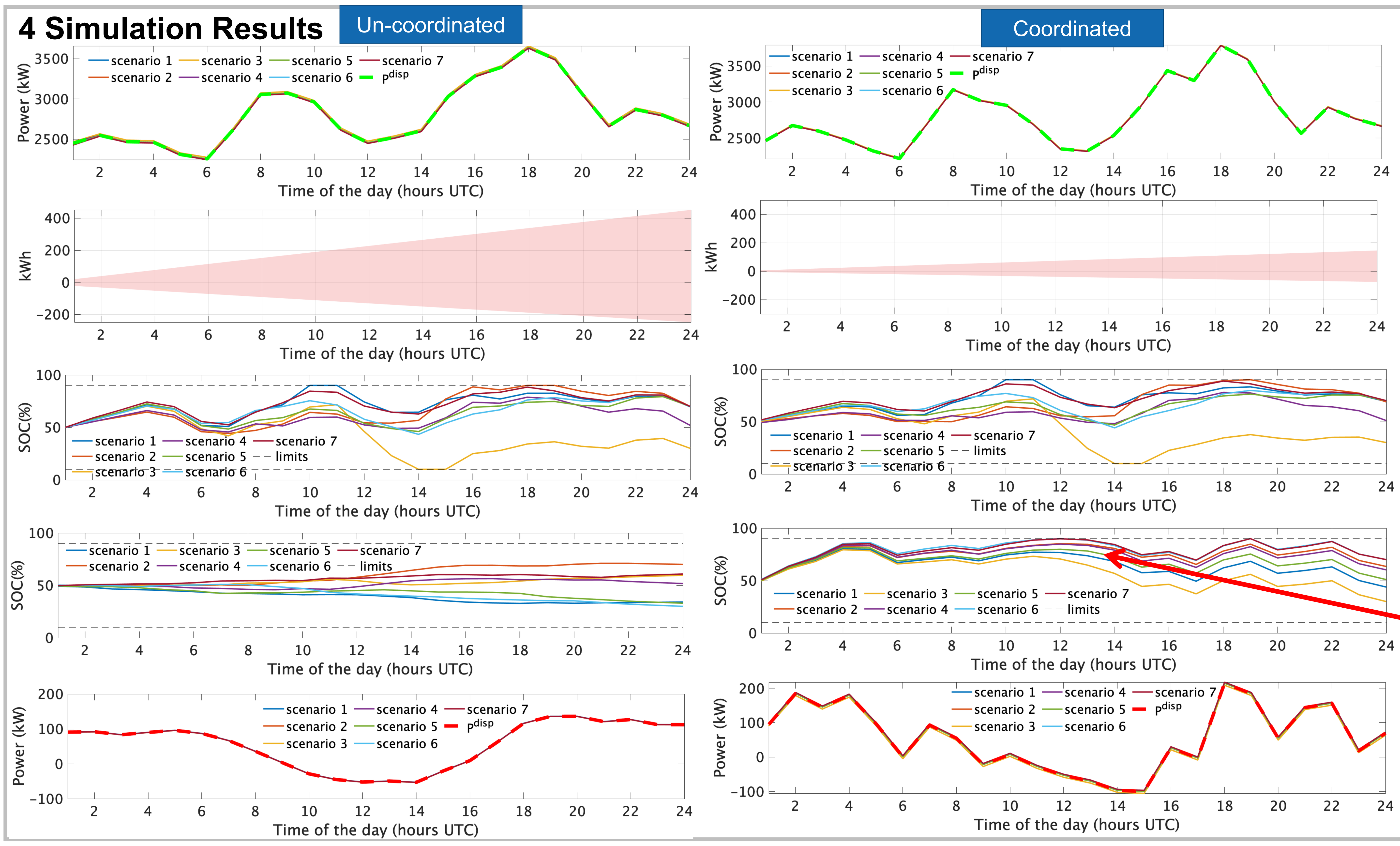


Fig. 3. Multi-grid setup

4 Simulation Results



Maximum absolute error (MAE)

$$\text{MAE} = \max_{\omega \in \Omega, t \in T} |P_t^{\text{disp}} - P_{0,t}^{\omega}|$$

Uncovered energy error (UEE)

$$\text{UEE}^{+} = \frac{T_s}{3600} \sum_{t \in T} (\max_{\omega \in \Omega} P_{0,t}^{\omega} - P_t^{\text{disp}})$$

$$\text{UEE}^{-} = \frac{T_s}{3600} \sum_{t \in T} (\min_{\omega \in \Omega} P_{0,t}^{\omega} - P_t^{\text{disp}})$$

Un-coordinated

MAE (kW)	UEE+ (kWh)	UEE- (kWh)
22	451	-247

Coordinated

MAE (kW)	UEE+ (kWh)	UEE- (kWh)
6.5	146	-75

LV BESS is providing regulation to the MV grid resulting in BESS saturation as well as change in LV's dispatch plan.

Fig. 4: day-ahead Dispatch computation Without coordination (left) With coordination (right)

For more details, please access the Full paper here:

Conclusions

- A framework is developed for coordinating the flexibilities (power and energy) from different distribution grids while accounting for network constraints.
- The developed framework is applied to day-ahead dispatch computation for a multi-grid system.
- It shows better dispatch performance (tracking) when flexibility and uncertainties of the downstream distribution systems are considered in computing the dispatch plan.

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Network tariffs for flexible loads (NETFLEX*)

Authors: Patrick Ludwig and Christian Winzer (winc@zhaw.ch)

Abstract

Dynamic grid tariffs can incentivize grid-serving behavior of load without requiring direct load control by grid operators. However, they need to be designed appropriately to avoid rebound peaks and welfare losses due to unnecessary demand response activations. We analyze the performance of 9 different dynamic tariff designs with regard to their impact on household consumption behavior and grid utilization. In a linear optimization model, we determine the optimal operation of electric vehicles, heat pumps, batteries and PV systems based on four result metrics: (i) Effectiveness (ii) Efficiency, (iii)) Profitability of technologies & (iv) equity. We find that in a system with a large share of flexible devices, direct load control and capacity prices effectively reduce load peaks. Time variable grid tariffs create problematic new rebound peaks, however, this could be avoided, by a novel approach where the tariff is charged proportional to the grid-load, rather than as a function of time.

Inputs

We model 9 different tariff scenarios for 300 housholds in 2 different years.

Infrastructure in 2020 is based on the current penetration of new technologies according to the Swiss Household Energy Demand Survey (SHEDS).

Infrastructure in 2050 is based on the "Energy perspectives" Szenario ZERO Basis.

Tariff scenarios

SQ: Energy, Grid and other tariffs: constant price per kWh (=Basecase)
Capacity Grid: Capacity charge on individual peak
DLC: Grid: Direct Load Control
ToU: Grid: High-/Low Tariff
CPP_h: Critical-Peak Price (dynamic hours)
CPP_d: Grid: Critical-Peak Price (fixed hours; dynamic days)
Gridload: Grid: Proportional to grid-load
Gridload&spot: Energy: Spot-pricing & Grid: Proportional to grid-load
Spot: Energy: Spot-pricing

Infrastructure Scenarios

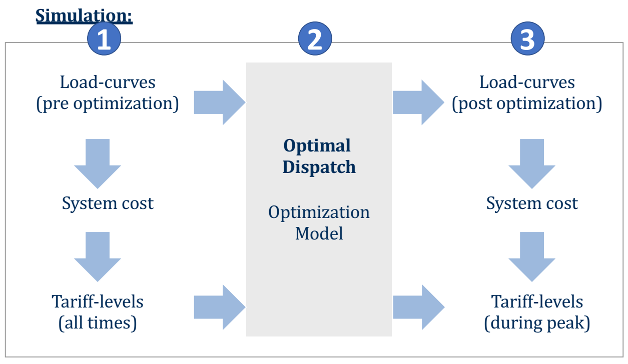
	Household Features				Household Count		Simulation	
HH-Type	HP	EV	Battery	PV	2020	2050	2020	2050
type1	0	0	0	0	211	66	70.3%	22.0%
type2	1	0	0	0	57	0	19.0%	0.0%
type3	0	1	0	0	5	29	1.7%	9.7%
type4	0	0	0	1	4	0	1.3%	0.0%
type5	1	1	0	0	3	4	1.0%	1.3%
type6	1	0	0	1	3	0	1.0%	0.0%
type7	0	1	0	1	0	1	0.0%	0.3%
type8	0	0	1	1	8	0	2.7%	0.0%
type9	1	1	0	1	1	60	0.3%	20.0%
type10	1	0	1	1	6	0	2.0%	0.0%
type11	0	1	1	1	1	0	0.3%	0.0%
type12	1	1	1	1	1	140	0.3%	46.7%
Total					300	300	100%	100%

Simulation

The simulation model consists of three steps:

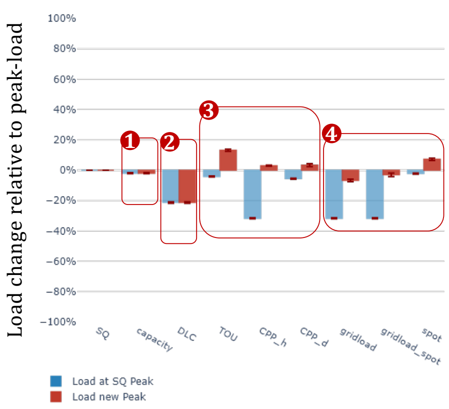
1. Calculate system costs based on infrastructure scenario and calibrate tariffs to ensure cost recovery
2. Optimize dispatch of flexible loads to minimize consumer bill for the given tariff, while avoiding discomfort
3. Recalibrate tariff levels to ensure cost recovery

Simulation:



Results for 2020

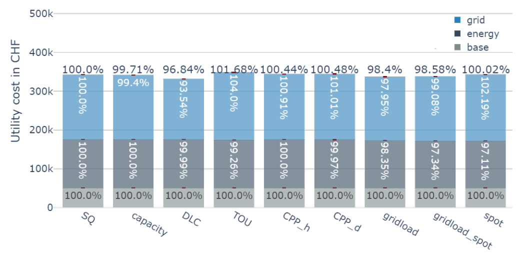
Tariff impact on peak-load of the grid

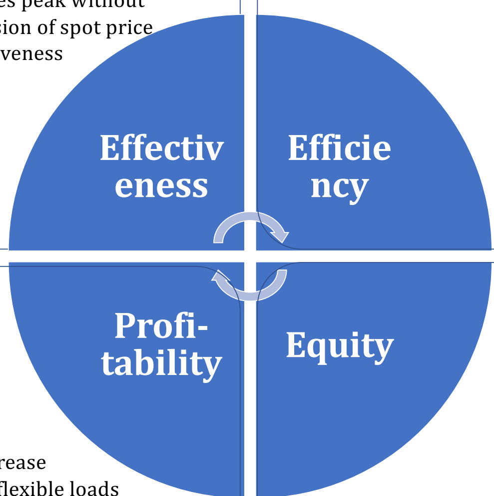


1. Capacity tariff avoids rebound peak, but hardly lowers original peak
2. DLC achieves strongest peak reduction without rebound
3. Time-dependent tariffs lead to rebound peak
4. Gridload reduces peak without rebound; inclusion of spot price weakens effectiveness

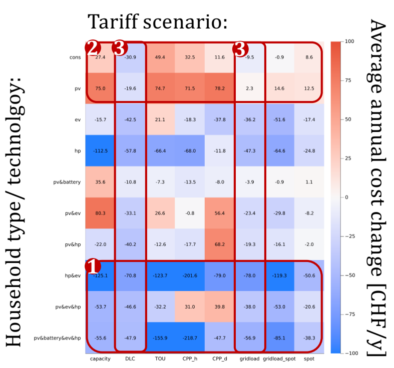
Tariff impact on average system cost

- Cost impacts small, as only 30% of grid cost, and 0% of base-cost are variable, and peak is reduced by less than 20% (DLC)
- DLC achieves strongest grid-cost reduction, but ignores energy costs



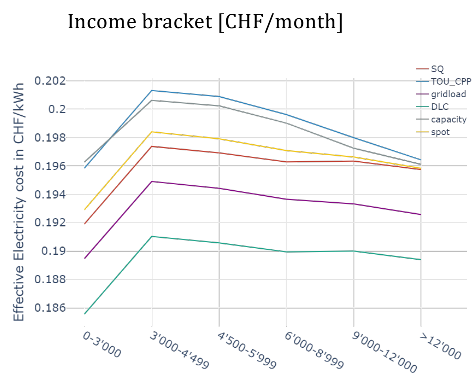


Tariff impact on average annual cost of households with different technologies



1. Most tariffs increase profitability of flexible loads
2. ...while increasing cost of unflexible customers
3. Tariffs proportional to grid-load and DLC reduce the cost for (almost) all household types

Tariff impact on average annual cost of households from different income brackets



- A capacity tariff, gridload tariff and Direct Load Control (DLC) reduce the average cost for households in all income brackets
- DLC achieves strongest grid-cost reduction, but ignores energy costs

Disclaimer

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