Center for Combined Smart Energy Systems (CoSES)

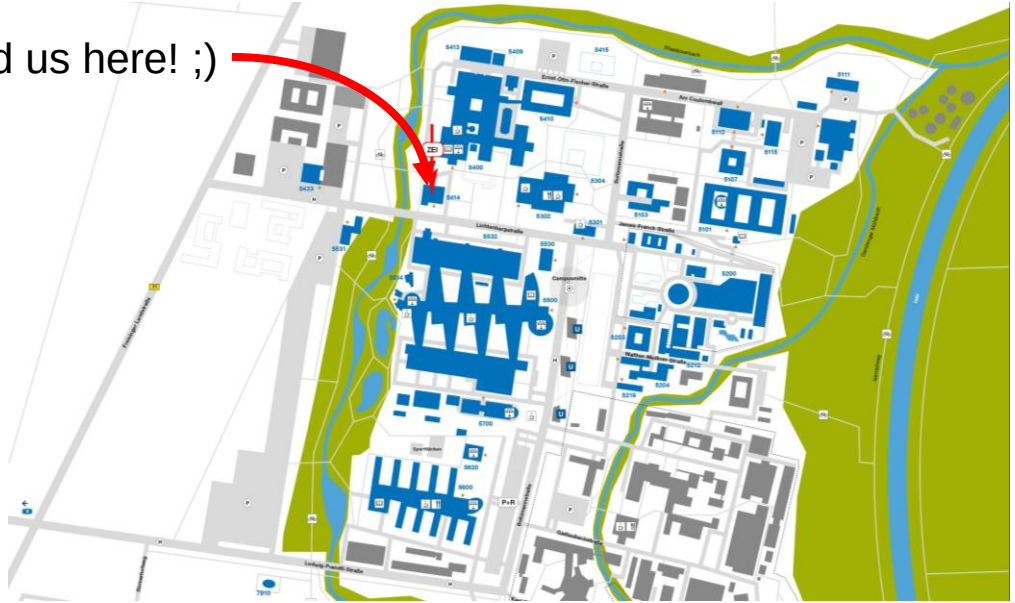
Active Distribution Grid Research Group at TUM

Located at TUM Campus Garching

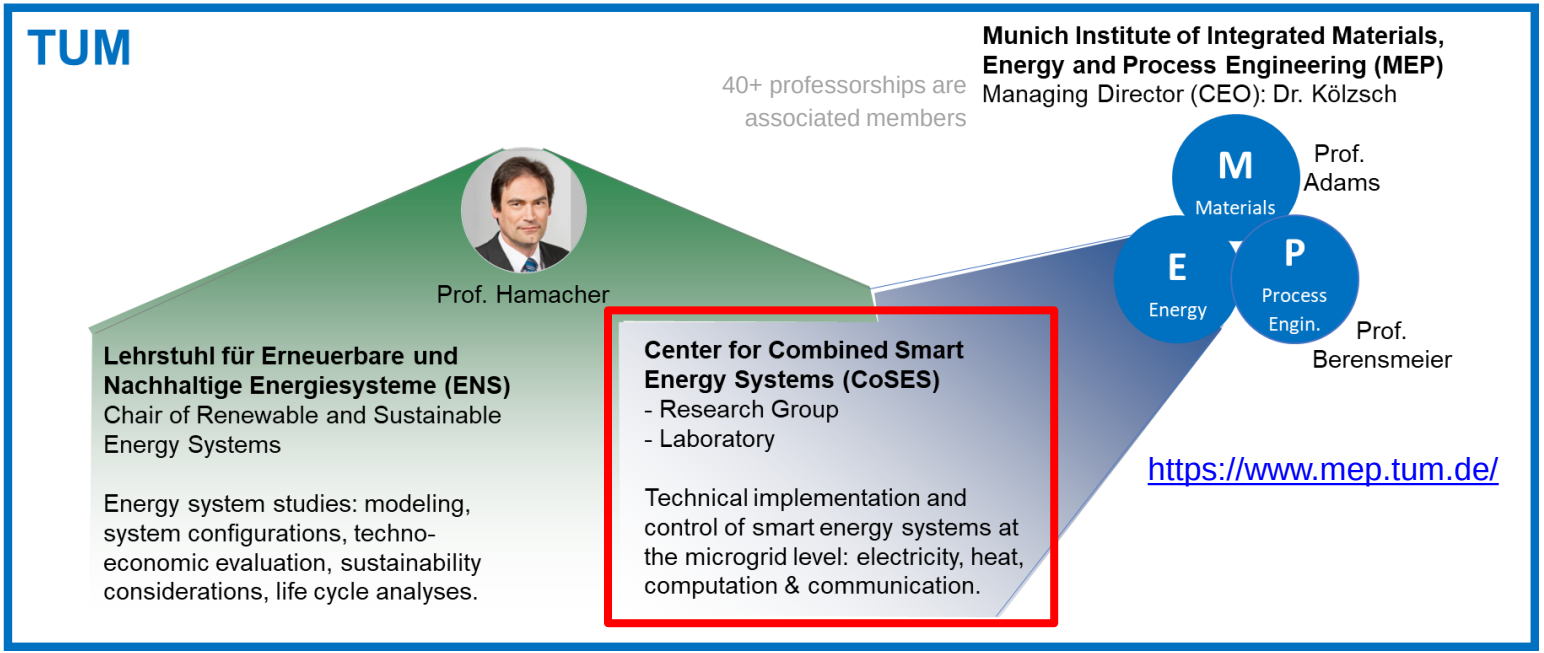
Zentrum für Energie und Information (ZEI)
CoSES Research Group
Lichtenbergstraße 4a
85748 Garching

Reachable by
- subway U6 „Forschungszentrum“
- car via highway A9

Find us here! ;)



Part of an Integrative Research Institute at TUM



CoSES at a glance

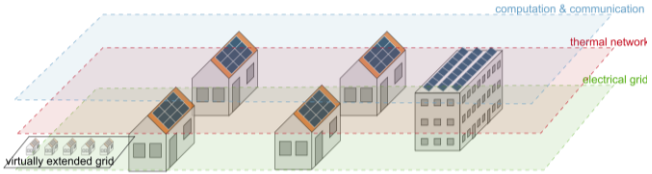
Prof. Dr.
Thomas Hamacher
Director

Dr. -Ing.
Anurag Mohapatra
Group Leader

Integrated Multi-Energy Systems

- ❑ Active Distribution Grids
- ❑ Prosumers in District Heating Grids
- ❑ Energy Management Systems
- ❑ Data-driven techniques

Simulation / Emulation



Leads

Focus

Tools

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CoSES Team

Anurag Mohapatra
PHIL, ADG control, ML Surrogates

Kun Fu
PHIL, Digital Twins for ADG

Prashant Pant
PHIL, ADG control, Ancillary service

Ulrich Ganslmeier
PHIL, Next gen. heating systems

Michael Erhart
Grid digitization, EMS infrastructure

Maximilian Hock
ML surrogates, Physics based EMS

Nermina Abdurahmanovic
Next gen. heating systems
Fraunhofer IEE

Martin Cornejo
BESS Digital Twin, Second life batteries
TUM EES

Hela Cuzic
Smart meter data and infrastructure
Fraunhofer IEE

Sebastian Eichhorn
ADG Control, ML for power systems
TUM EMT

Thomas Haupt
HEMS Benchmarking, Grid-friendly EMS
HS Ansbach

Ulrich Ludolfinger
RL and Physics based home EMS
HAW Landshut

Vivek T. Tanjavooru
BESS control, Second life batteries
HS Kempten

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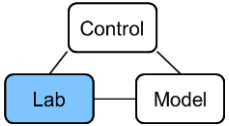
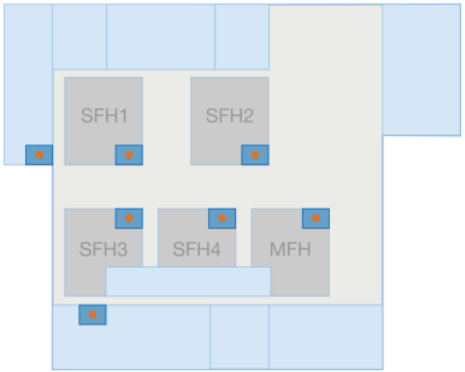


CoSES: Energy technology of five buildings in one lab



Video Presentation:

[Lickleder2022]

Detailed info in our publications on the lab:

[Zinsmeister2023]

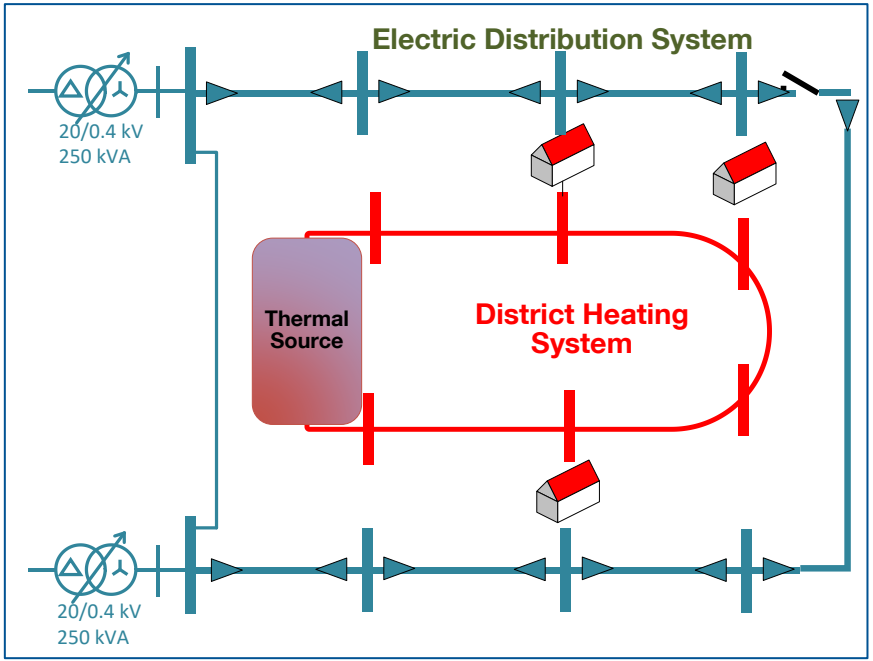
[Mohapatra2022]

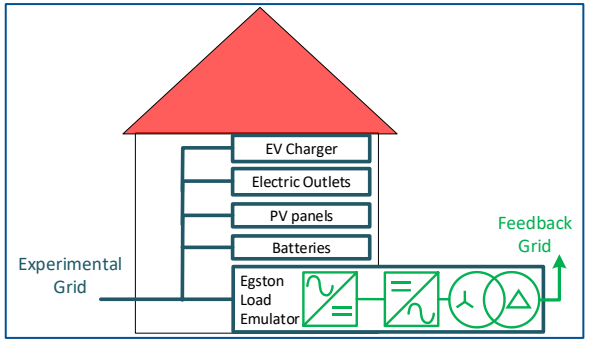
Design philosophies of the lab

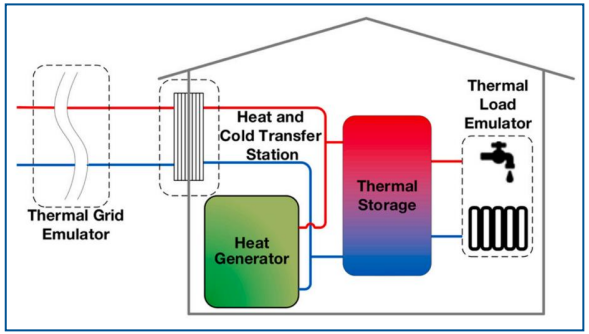
- **Realistic emulation** of a Multi-Energy-System in five-building neighborhood.
- **Independent of ambient** conditions for scenario testing and benchmarking.
- **Modular design** for interchangeable hardware and software.
- **Generic interfaces** to promote collaboration and reproducability.

➢ **„Almost-Field Test“** philosophy in a controlled lab environment.

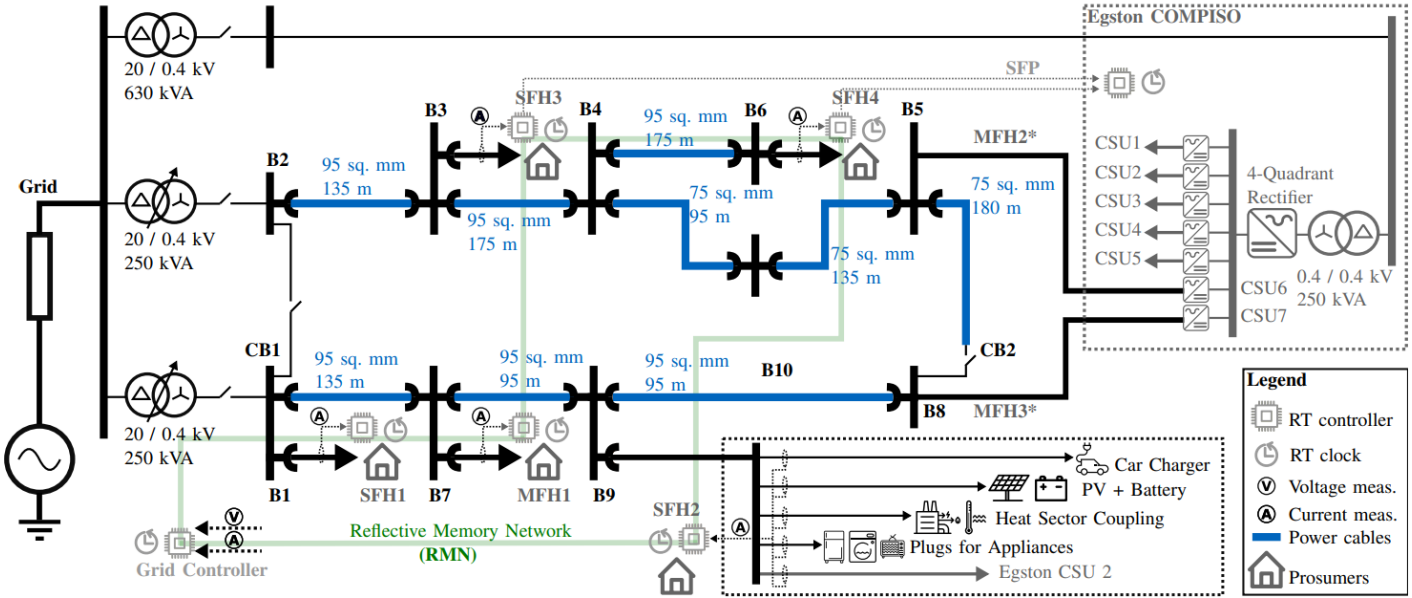
CoSES Lab - Overview

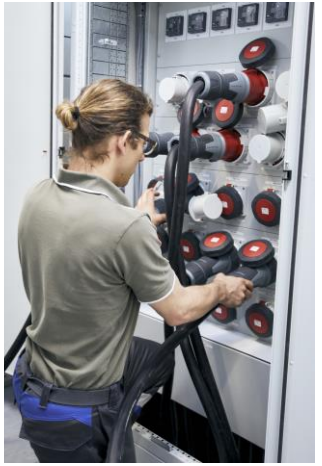




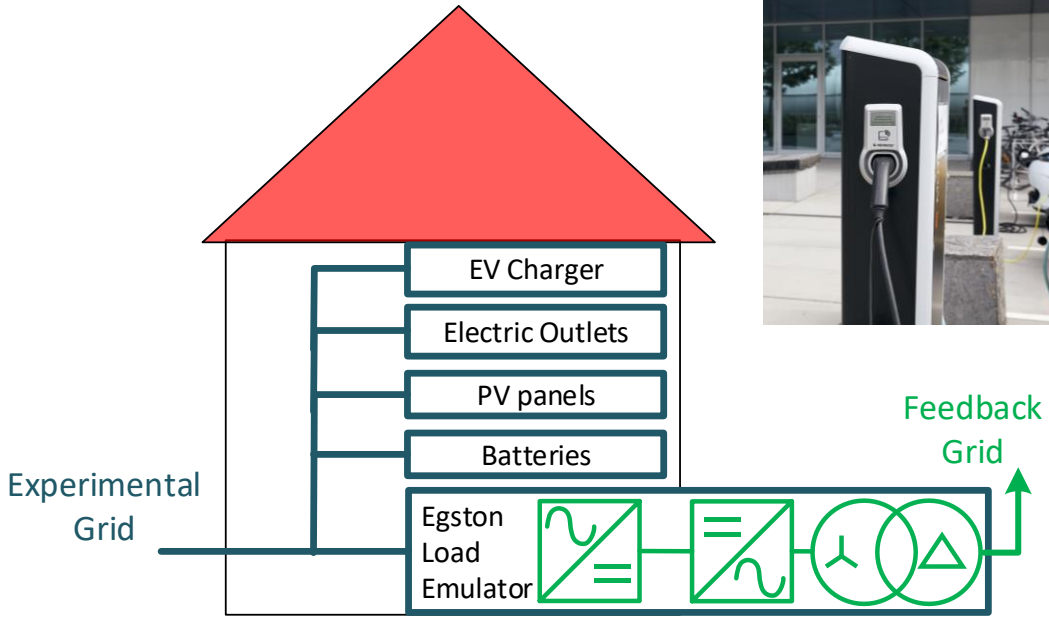


Electric Grid

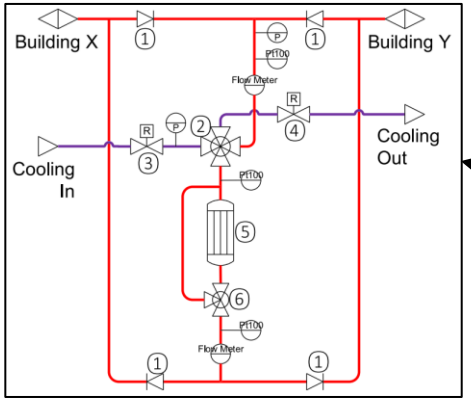




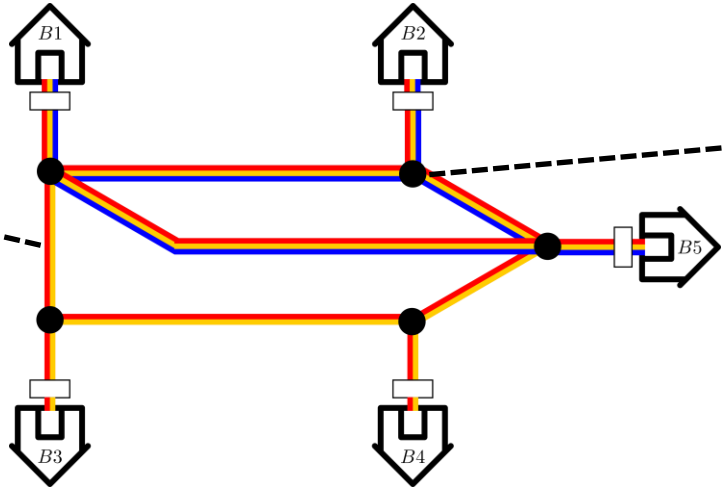
Electric Building Emulator



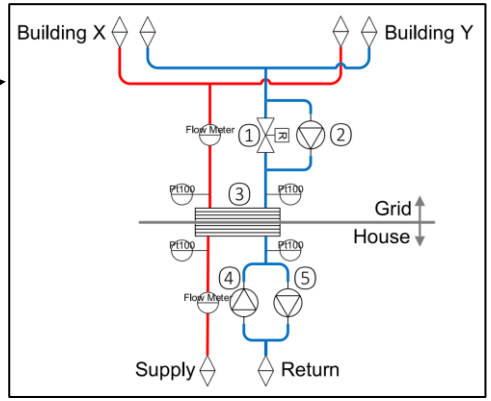
Thermal Grid



thermal network emulator / pipe emulator



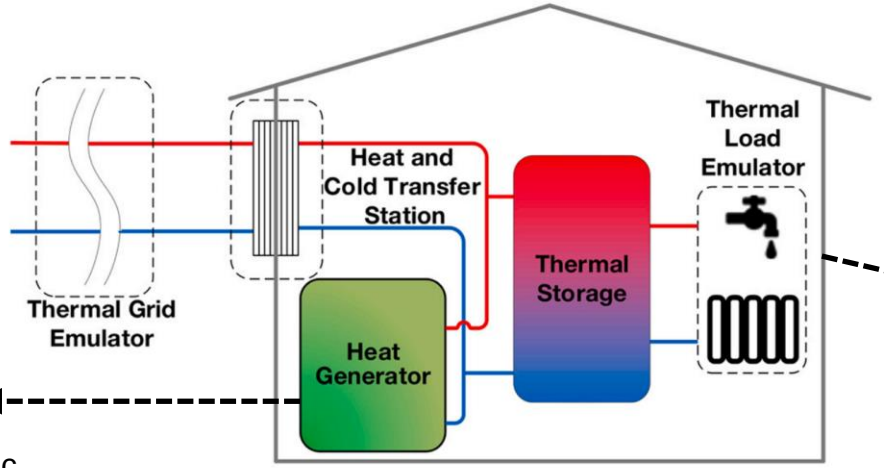
bidirectional thermal network with prosumers

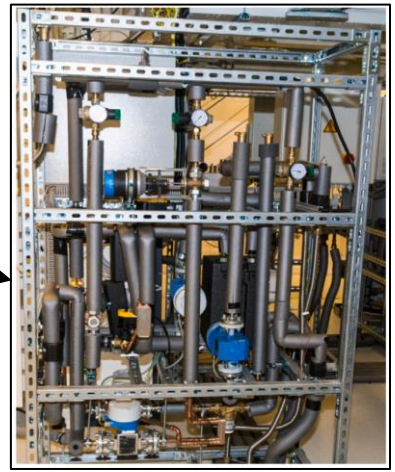


bidirectional heat transfer station

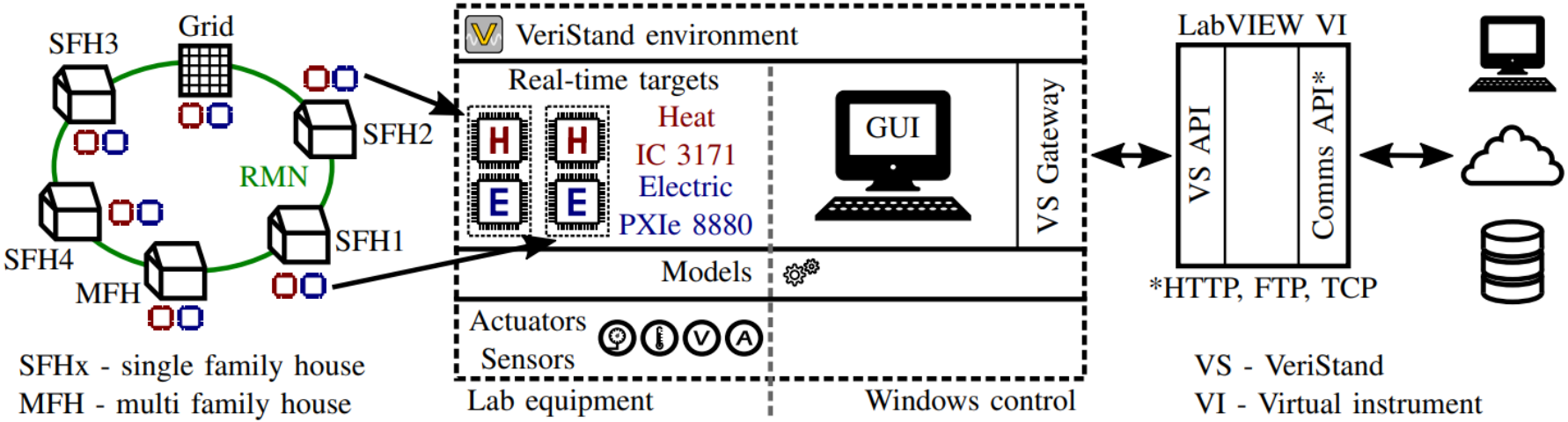
Thermal Building Emulator

e.g. air source heat pump incl. hvac system for ambient emulation





Computation and Communication



Current Projects

PhyLFlex

Physics-based, grid-friendly Home EMS – benchmarked and field tested in a real LV grid.

Funding: BMWK, April/25 - March/28

CoSES activities –

- Simulation and testing environment for the project.
- EMS Benchmarking Test Center to be established in CoSES.
- Integrating german iMSys regulations into test center.
- Sizing of a central storage unit for direct grid flexibility.
- Combining grid-friendly and customer-friendly strategy for EMS.

DirectGreenEnergy4Trains

Renewable VPP concepts for the Deutsche Bahn traction grid.

Funding: EFRE NRW, April/25 - March/28

CoSES activities –

- PHIL DER models for the VPP concept.
- Testing PHIL models for train ramping requirements.
- Theoretical framework for modeling large-scale DERs over PHIL.
- Strategies for VPP operation.

Current Projects

REx-CLi-ReS

Regional exergy-driven, climate resilient renewable energy based system.

Funding: HU-RIZON Hungary, April/25 - January/28

CoSES activities –

- Renewable integration planning for Hungarian power grid.
- Stability assesment for Hungarian transmission network.
- Impact of RE integration on Gyor region distribution grid.
- PHIL validation of distribution grid digital twin.

Heat Pump Characterisation

Proving the viability of heat pumps in combination with traditional gas boilers in residential sector.

Funding: Industry funded, April/25 - December/25

CoSES activities –

- Commissioning three air source heat pumps.
- Characterising ASHPs at different operating conditions.
- Combined ASHP + Boiler control with a predefined price signal.

Past Projects

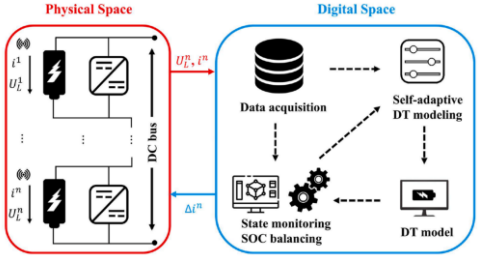
- **MEMAP (BMWK)**: A Digital Platform for Smart Multi-Energy Flow Management in Districts.
- **OSkit (BMWK)**: Optimized Sector Coupling in Neighborhoods via Smart Thermal Prosumer Networks.
- **STROM (BFS)**: Bavarian Research Consortium on "Energy - Sector Coupling and Micro-Grids".
- **IntElHeat (DFG)**: Optimal Operation of Low-Temperature Bidirectional Heat and Electric Grids.
- **Mcube (BMBF)**: Munich Cluster for the Future of Mobility in Metropolitan Regions - ComfficientShare.
- **KI-M-Bat (BFS)**: AI-Based Modular Battery Systems for Commercial and Grid Applications

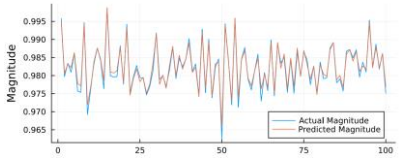
- **Decarbonisation / Energy Optimisation studies for Industry**:

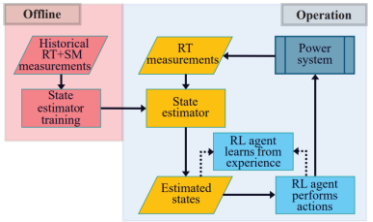
Current Research Direction

- Low Voltage grid control with large renewable penetration.
  - Reduced instrumentation grid operation [Pant2022*, ISGT Europe*]
  - System Identification Based Grid Agnostic Adaptive Droop Control Strategy [Pant 2023, *PowerTech*]
  - Grid Agnostic Droop Control Strategy for Damping Restoration and Optimal Reactive Power-Sharing [Pant 2025, *IEEE Open Journal of Power Electronics*]
  - Self Adaptive digital twin for battery monitoring and management system [Fu2024, *PSCC*]
  - A Self-adaptive Digital Twin with Broad Learning System for Heat Pumps [Fu2024, *ISGT Europe*]
  - Application-oriented digital twin for integrated energy systems: A review [Fu2025, *Preprint*]

- Data Driven Distribution Grid Control
  - RL for Demand Response Problems [Ludolfinger2023a, *PowerTech*]
  - LV Grid Control Based On Data-Driven State Estimation and RL [Özlemis2024, *PES GM*]
  - Towards Automatic Parameterization of Online Feedback Optimization for Autonomous Low-Voltage Distribution Grids [Schubert2025, *PowerTech*]
  - Grid-Connected, Data-Driven Inverter Control, Theory to Hardware [Graf2025, *PowerTech*]
  - Physics-Informed Symbolic Regression (PISR) for Predicting Power System Voltage [Eichhorn2025, *ACM E-Energy*]
  - PHIL Validation of PISR for Power System Voltage Prediction [Eichhorn2025, *ISGT Europe*]

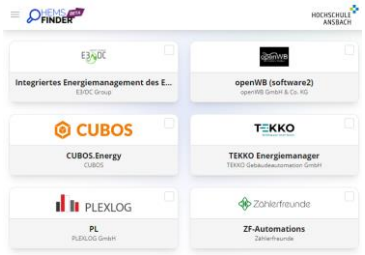






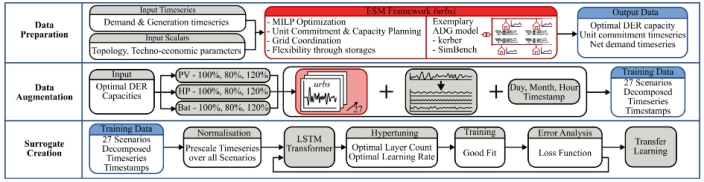
Current Research Direction

- Digitizing Low Voltage grids for sector-coupling.
  - Annual HEMS Symposium at CoSES; 100+ participants, 20+ manufacturers
  - HEMS Finder Website - https://hems-finder.org/



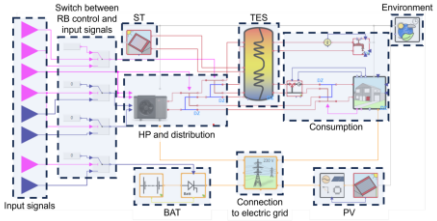
- Realistic DER Emulation with PHIL
  - PHIL infrastructure in CoSES [Mohapatra2022, *ISGT Europe*]
  - IoT integration for CoSES [Mayer2021, *WF-IoT Conf.*]
  - Online decentral OPF in PHIL [Cornejo2022, *PES GM*]
  - PHIL emulated M-Class PMU [Mohapatra2023, *PowerTech*]
  - PHIL validation of air-source heat pump for fast frequency response applications [Song2024, *PSCC*]
  - Impact of Fast Grid Ancillary Services on Weak Grid Stability: A PHIL Study [Pant2024, *PES GM*]

- Surrogate modelling for energy system modeling
  - Surrogate Framework for Energy System Modeling [Mohapatra2025, *PowerTech*]
  - Graph Neural Network Surrogates for EnergySystem Modeling [Pjetri2025, *ISGT Europe*]
  - Deep Learning Surrogates For Low-Voltage Grid Expansion Planning [*under prep.*]
  - Blending MILP and Surrogates for Smarter Energy Systems [*under prep.*]



Previous works

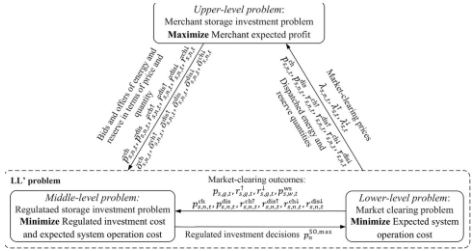
- Next gen. Sector coupled Thermal Networks with Prosumers interactions
  - Thermohydraulic model of Smart Thermal Grids with prosumers [Lickleder2021 *Energy*]
  - Libraries : [ProsNet *Github*], [ProHMo *Gitlab*], [ProHeatNet_Sim *Github*]
  - Characteristics and Challenges in prosumer-based networks [Lickleder2021, *CISBAT*]
  - Prosumer-system configurations inside the building [Zinsmeister2021, *Energy Reports*]



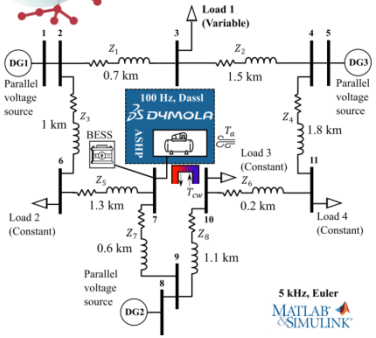
  - Stratified thermal energy storage model with constant layer volume for predictive control [Zinsmeister2023, *Renewable Energy*]
  - Control Approach for Bidirectional Prosumer Substations in Smart Thermal Networks [Lickleder2024a, *Applied Energy*]
  - A benchmarking framework for energy management systems with commercial hardware models [Zinsmeister2024, *Energy and Buildings*]
  - 5th Generation District Heating and Cooling Modelica Models for Prosumer Interaction Analysis [Angelidis2024, *Modelica Conference*]
  - Implementation of a Digital Twin of the CoSES District Heating Prosumer Laboratory [Zinsmeister2022, *Energy Proceedings*]
  - A prosumer-based sector-coupled district heating and cooling laboratory architecture [Zinsmeister2023, *Smart Energy*]
  - Experimental validation of a hybrid 1-D multi-node model of a hot water thermal energy storage tank [DeLaCruz2023, *Applied Energy*]
  - Bidirectional Substation Control for Smart Thermal Grids: PHIL evaluation [Ganslmeier2024, *ISGT Europe*]
  - Design and simulation of district heating networks: A review of modeling approaches and tools [Kuntuarova2024, *Energy*]

Previous works

- Strategic operation of storage in energy markets
  - Storage operation as an AC-bilevel problem [Guo2023, *PES GM*]
  - Merchant and regulated storage as a Stackelberg game [Guo2023, *IET Generation*]
  - Merchant transmission expansion planning on wind penetration [Guo2023, *PowerCon*]
- Flexibility in multi-energy system grids
  - Literature review: Flexibility in Multi-energy systems [Kleinschmidt2020, *EEM Conf.*]
  - Flexibility modelling in thermal-electric networks [Kleinschmidt2021, *ISGT Europe*]
  - Flexibility modelling in active distribution networks [Kleinschmidt2022, *ISGT Asia*]
- Heat pumps for demand side response
  - Modelling hydraulic faults in multi-energy systems [Song2021, *MSCPES Conf.*]
  - Data-driven modelling of heat pump dynamic model [Song2022, *PES GM*]
  - Literature review: Sector coupling for frequency control [Song2023, *Int. Journal EPES*]
  - Air source heat pumps for fast frequency response [Song2024, *Preprint*]
  - Report: A moving boundary model for air source heat pumps [Song2023, *Report*]



MESMO



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