Power Hardware-in-the-loop testing – Can it mean more?

Anurag Mohapatra

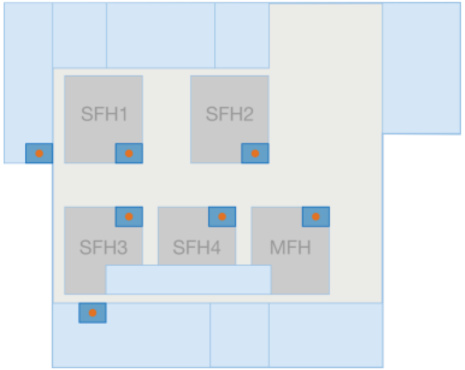
Center for Combined Smart Energy Systems (CoSES)

Technical University of Munich

SYSLAB, Technical University of Denmark

24.11.2025

CoSES: Energy technology of five buildings in one lab



Video Presentation:

[Licklederer2022]

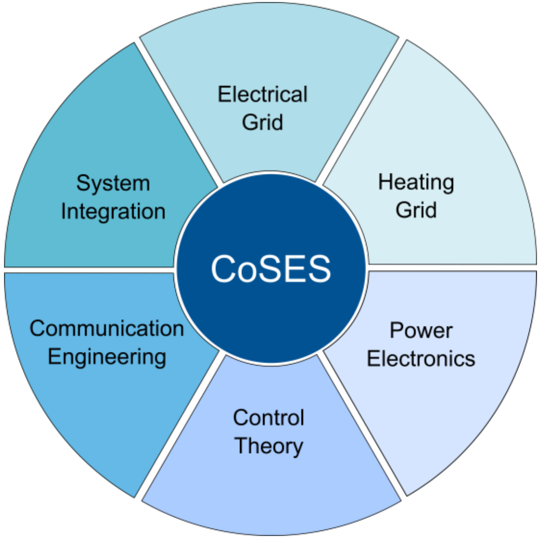
Detailed info in our publications on the lab:

[Zinsmeister2023] [Mohapatra2022]

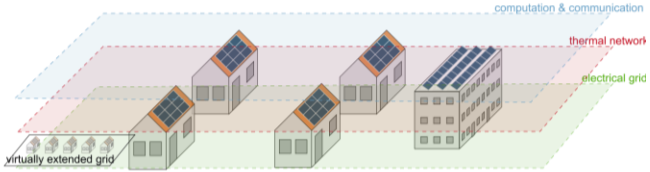
CoSES at a glance

Prof. Dr.
Thomas Hamacher
Director

Dr. -Ing.
Anurag Mohapatra
Group Leader



Simulation / Emulation



Leads

Focus

Tools

CoSES at a glance

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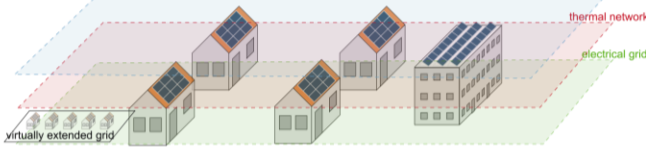
Integrated Multi-Energy Systems

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

Simulation / Emulation



Leads | Focus | Tools

CoSES at a glance

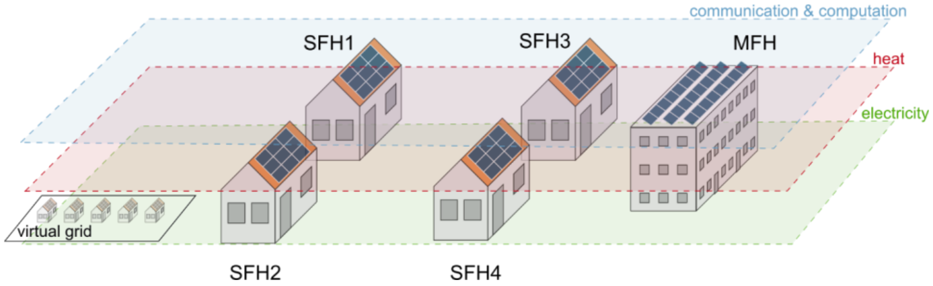
Sector-coupled microgrid at TUM

- Reconfigurable 1.5 km power grid
- Power Hardware-in-the-Loop

- Prosumer emulation - heat and power
- PV, battery and charger for electric cars

- Decentralised control systems
- Unified programming interfaces

- API access to the lab



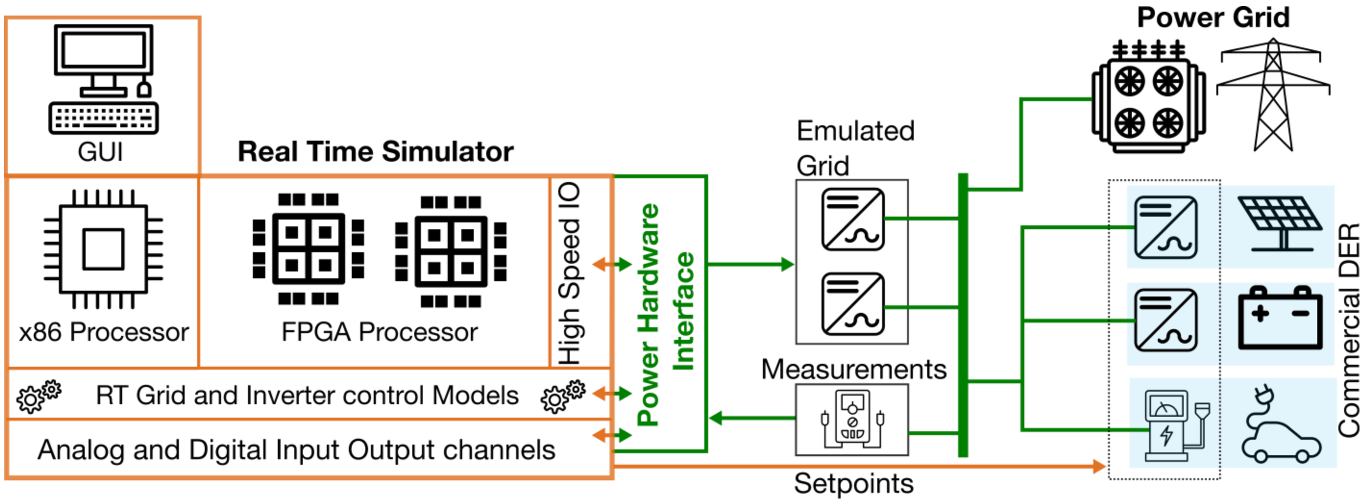
CoSES at a glance

Directly at CoSES
- 6 PhD students
- 1 Post-doc

Associated with CoSES
- 7 PhD students
- Chair of Power Transmission and Distribution.

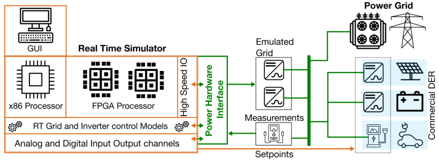
Frequent Guest Researchers

Standard Power System Laboratory

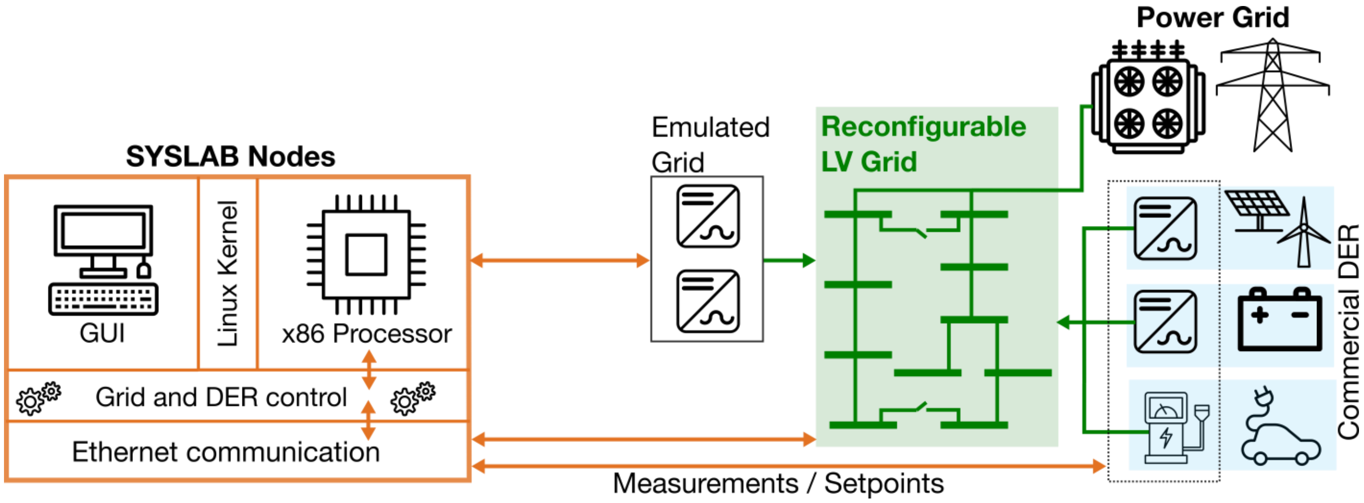


Electrical link, **Communication link**

SYSLAB, DTU

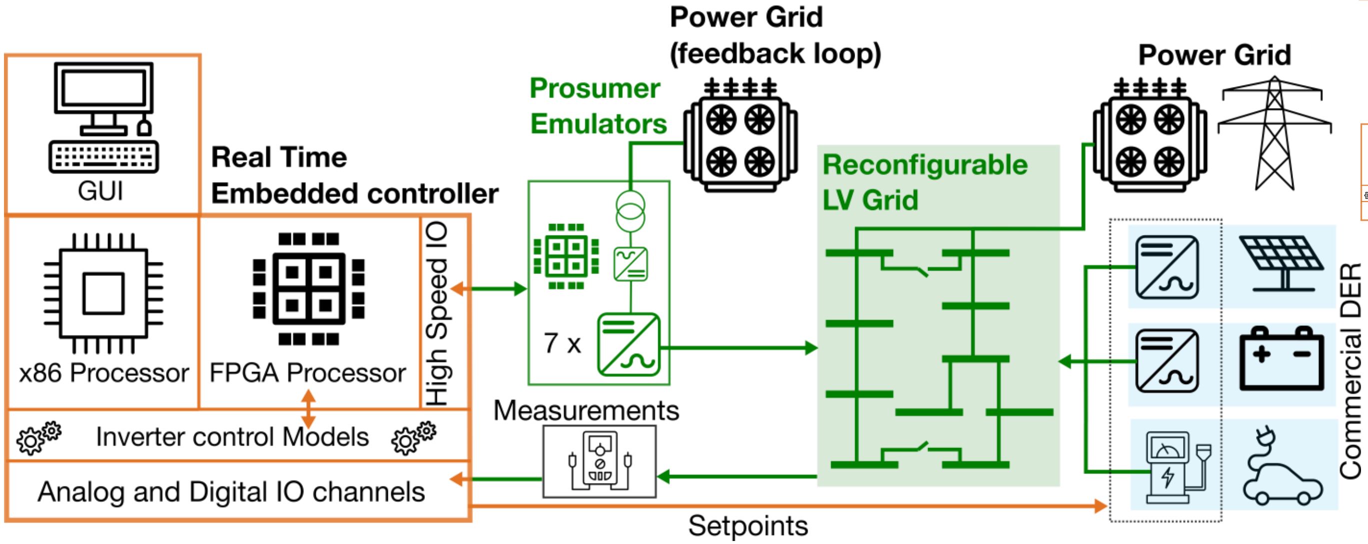


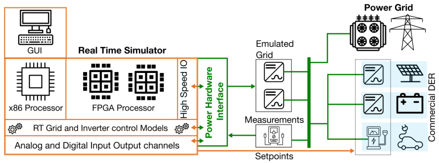
Standard Power System Lab



Electrical link, Communication link

CoSES, TUM





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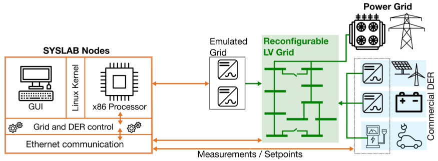


SYSLAB

Electrical link, **Communication link**

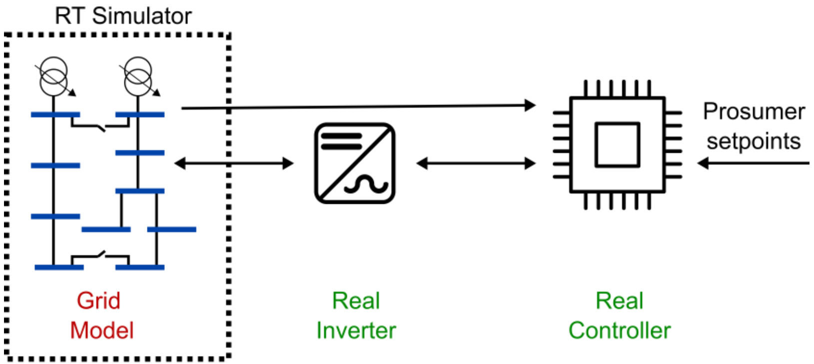
In Comparison

	Standard Lab	SYSLAB	CoSES
DER	Real DERs	Real DERs ■	Real DERs
Grid	Simulated	Real Feeders ■	Real & Reconfigurable ■ Grid
Emulation	Grid	Grid	Grid & Prosumer ■
Control	Real-time & RMS; Centralized	RMS ■; Distributed ■	Real-time ■ & RMS; Decentralized ■
Access	Proprietary	Open-source API ■	Proprietary ■ & API
Application	Device Testbeds	System Integration ■	Emulated Testbeds ■ & System Integration

■ - Strength / Unique features

What is the purpose of PHIL?

- Power hardware or device testing.
- Device or power circuit emulation.
- Stability analysis.
- Demonstrators.

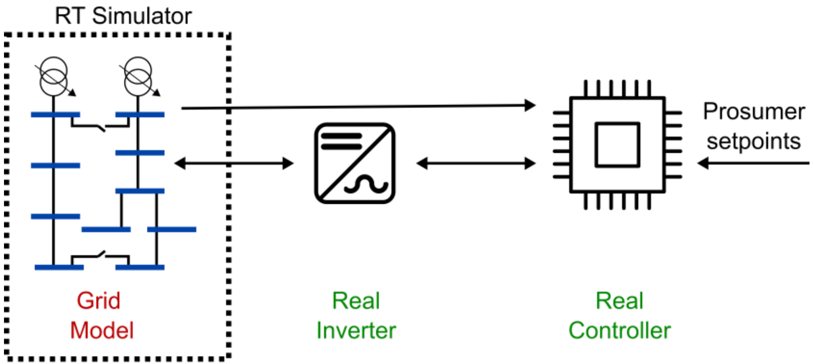


Power Hardware-in-the-loop (PHIL)

What is the purpose of PHIL?

- Power hardware or device testing.
- Device or power circuit emulation.
- Stability analysis.
- Demonstrators.

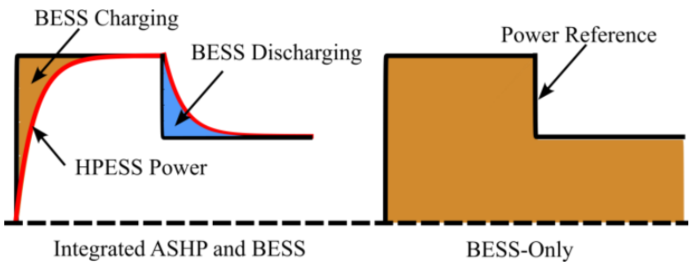
1. Sector coupling testbeds.
2. Reduced-scale emulation.
3. PHIL for heating systems.



Power Hardware-in-the-loop (PHIL)

Virtual DERs for sector coupling

- Heat pumps can be used for frequency response services
- Heat pumps are a control nightmare in the field



https://doi.org/10.1109/TSTE.2024.3456068

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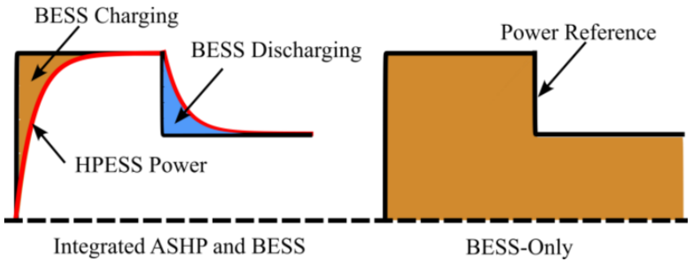


- How exactly should power system laboratories „research“ sector-coupling through heat-pumps?
  - Lack of expertise in heat-pump modelling
  - Lack of access to requisite real hardware
  - Unable to bypass any device safety features for fast control

SPIEGEL Business

Why heat pumps often consume too much electricity

They are intended to make residential buildings more climate-friendly and less dependent on gas. But many heat pumps are planned incorrectly, and customers are often left with high costs. What consumers should pay attention to.

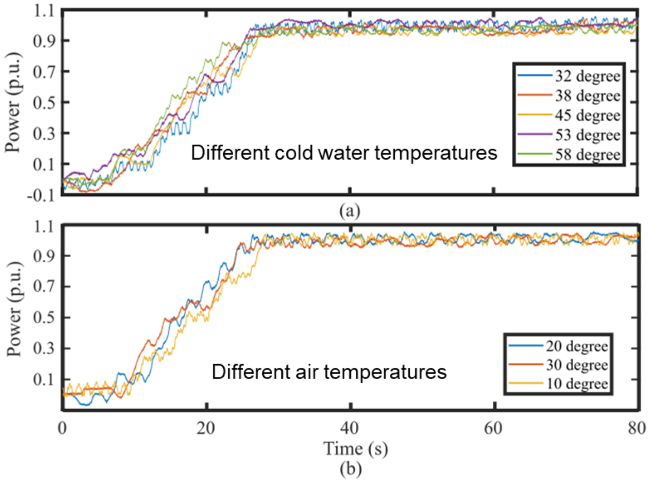
By Henning Jauernig
18.03.2022, 13:00 • from DER SPIEGEL 12/2022

https://doi.org/10.1109/TSTE.2024.3456068

Virtual DERs for sector coupling

Wolf Air Source Heat Pump
($19\ kW_{heat}$, $9\ kW_{cold}$)
+
HVAC climate generator

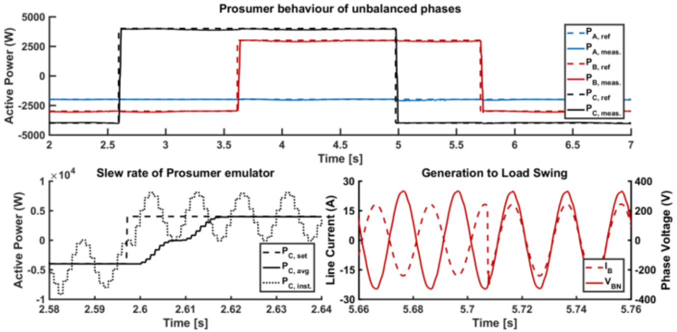
Speed-power response of the CoSES ASHP (normalized):



https://doi.org/10.1016/j.epsr.2024.110754

Virtual DERs for sector coupling

- High bandwidth PHIL emulation.

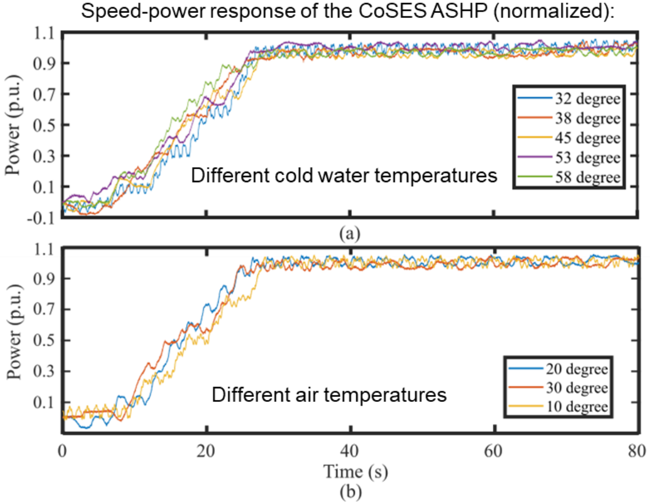


Wolf Air Source Heat Pump

(19 kW_{heat}, 9 kW_{cold})

+

HVAC climate generator



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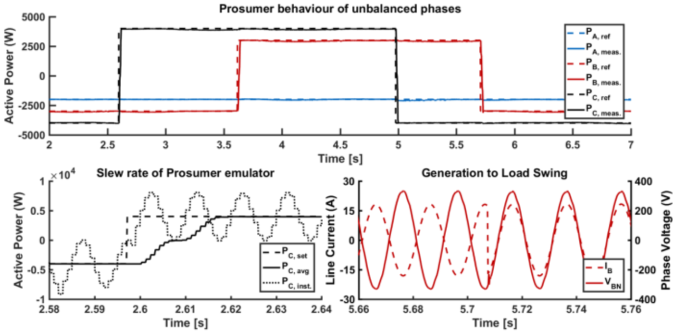
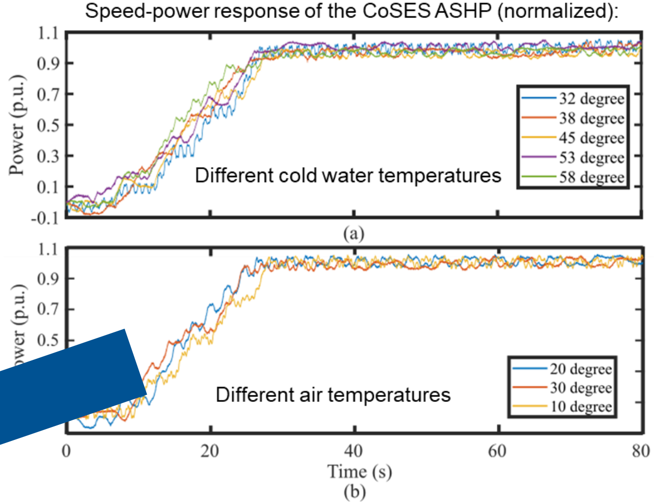


Wolf Air Source He...
(19 kW...
+
...AC climate generator



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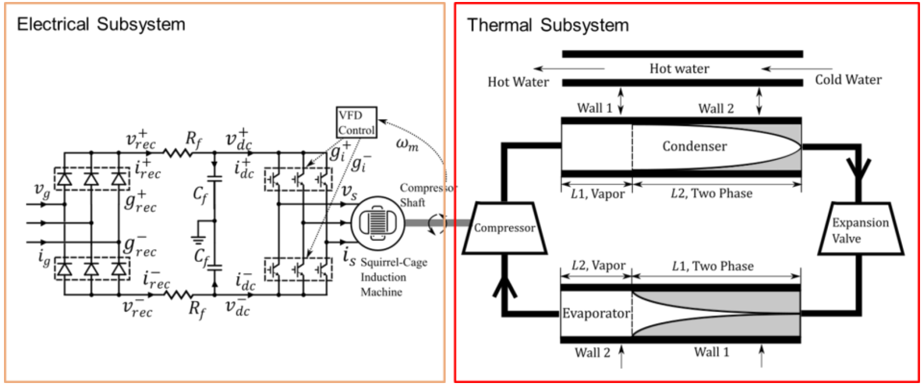
Virtual DERs for sector coupling

- Remove all the internal safety control gains and delays.
- Reflect important non-linear dynamics based on physics principles (for rapid control validation).
- Establish our "virtual PHIL Heat Pump" in a real grid environment.



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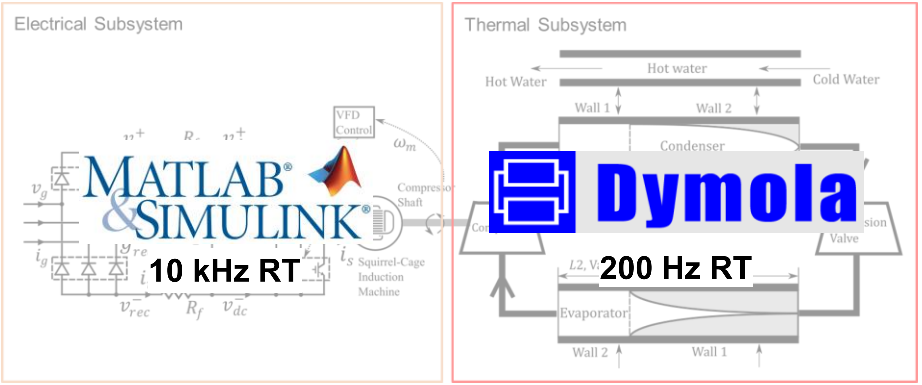

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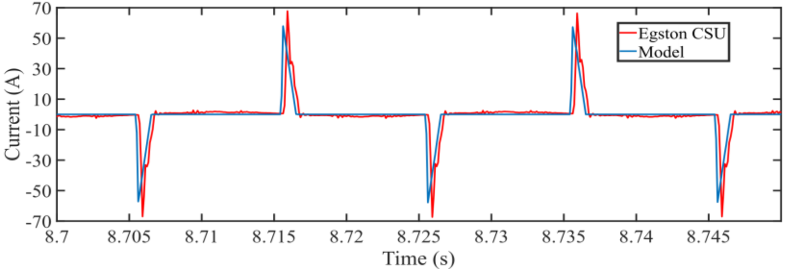

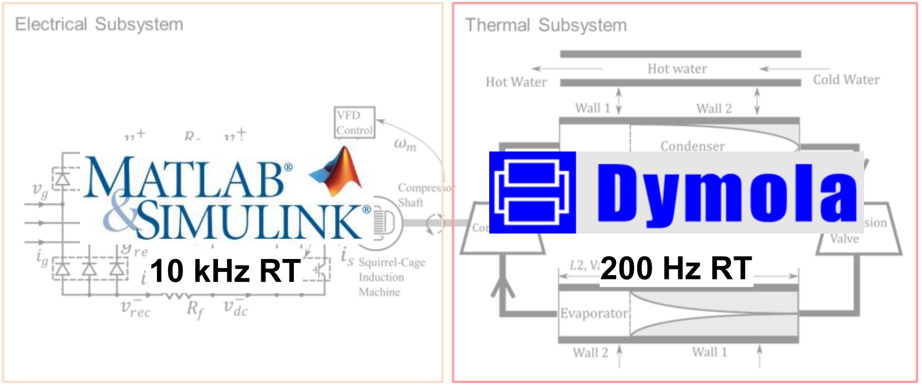

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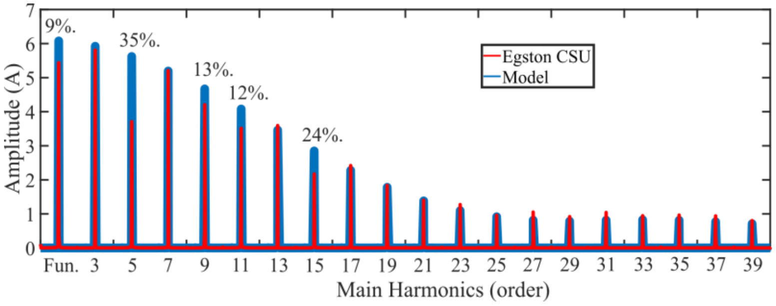

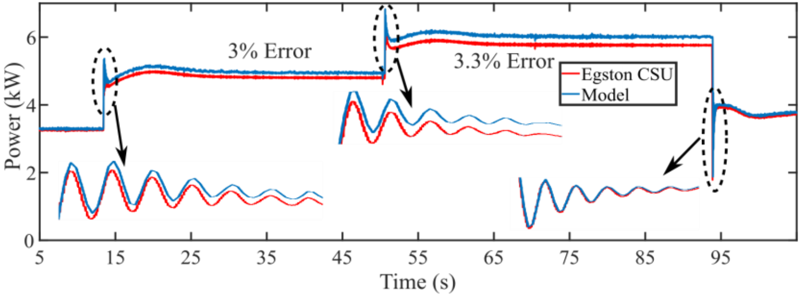

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MEP TUM

PHIL emulation for sector coupling

- PHIL research limited to emulating stand alone PV inverters, battery inverters and small microgrids.
- So far, research focus from the PHIL community has not adequately covered sector-coupling.
- A few notable mentions -

ELSEVIER Applied Energy
Volume 294, 15 July 2021, 116974

Test and optimization of a control algorithm for demand-oriented operation of CHP units using hardware-in-the-loop

Patrick Haase, Bernd Thomas

https://doi.org/10.1016/j.apenergy.2021.116974

ELSEVIER Renewable Energy
Volume 119, April 2018, Pages 106-115

Design and implementation of a power-hardware-in-loop simulator for water electrolysis emulation

Vesa Ruuskanen, Joonas Koponen, Teemu Sillanpää, Kimmo Huoman, Antti Kosonen, Markku Niemelä, Jero Ahola

https://doi.org/10.1016/j.renene.2017.11.088

ELSEVIER Journal of Cleaner Production
Volume 331, 10 January 2022, 129807

Hardware-in-the-loop real-time validation of fuel cell electric vehicle power system based on multi-stack fuel cell construction

Bingcong Jian [b c], Hanqing Wang [a b c d]

https://doi.org/10.1016/j.jclepro.2021.129807

ELSEVIER Electric Power Systems Research
Volume 235, October 2024, 110754

Power-hardware-in-the-loop validation of air-source heat pump for fast frequency response applications

Ruihao Song, Anurag Mohapatra, Thomas Hamacher, Vedran S. Perić

https://doi.org/10.1016/j.epsr.2024.110754

Our idea in SHINE Project

- Setup a PHIL Electrolyser at the Center for Combined Smart Energy Systems (CoSES) in TUM.
- CoSES – active distribution grid laboratory and research group in TUM.
- Use standard Real time simulators from OPAL-RT.
- Use standard PHIL emulators from Egston.
- Validate PHIL model with data from a real PEM-electrolyser.
- Off-nominal operation and aging effect on stack efficiency.
- *A Digital Twin of a grid connected Electrolyser*!

10 kW PEM stack at TUM Chair of Plant and Process Technology

Houston We Have a Problem…

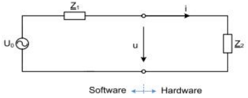
- PHIL state-of-the-art has 1:1 scale between device and emulator.

406 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 63, NO. 1, JANUARY 2016

Characteristics and Design of Power Hardware-in-the-Loop Simulations for Electrical Power Systems

Georg F. Lauss, *Member, IEEE*, M. Omar Faruque, *Senior Member, IEEE*, Karl Schoder, *Member, IEEE*, Christian Dufour, *Member, IEEE*, Alexander Viehweider, *Member, IEEE*, and James Langston, *Senior Member, IEEE*

***Abstract*—This paper presents a compendious summary of power hardware-in-the-loop (PHIL) simulations that are used for designing, analyzing, and testing of electrical power system components. PHIL simulations are an advanced application of real-time simulations that represent novel methods, which conjoin software and hardware testing. This contribution outlines necessary requirements for the implementation of PHIL simulations, which are defined by the nature of the digital real-time simulator, the power**



https://doi.org/10.1109/TIE.2015.2464308

MEP TUM

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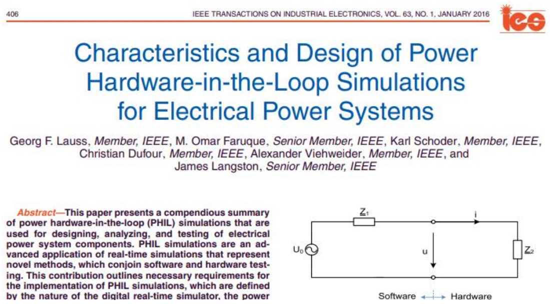
- PHIL state-of-the-art has 1:1 scale between device and emulator.
- Here a 10MW electrolyser is squeezed on a 100KVA emulator.
- Simulation must ensure credibility.



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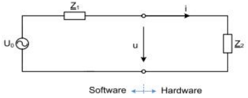

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NASA/TP—2016–219422

JANNAF/GL—2016–0001
JDOC Abstract Number: 2016-0002

NASA

JANNAF INTERAGENCY PROPULSION COMMITEE

Simulation Credibility

Advances in Verification, Validation, and Uncertainty Quantification

Unmeel B. Mehta, Editor
NASA Ames Research Center, Moffett Field, California

Dean R. Eklund
United States Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio

Vicente J. Romero
Sandia National Laboratories, Albuquerque, New Mexico

Jeffrey A. Pearce
Universal Technology Corporation, Dayton, Ohio

Nicholas S. Keim
The Johns Hopkins University, Columbia, Maryland

https://ntrs.nasa.gov/api/citations/20160013550/downloads/20160013550.pdf

MEP TUM

Three Pillars of Simulation Credibility

Uncertainty Quantification

Uncertainty Types

Aleatory – Can't be eliminated by better data	**Epistemic** – Can be eliminated by better data
Wind speed, solar irradiation	Device parameter uncertainty

Uncertainty Propagation

Transformations and sampling techniques

Verification

Code Verification

Mathematical **model** correctly implemented in the computer

Are we building the model correctly?

Solution Verification

Solver correctly implemented. Numerical error of the discretization

Are we solving the equations correctly?

Validation

Simulation Error Components

$$\delta_{Sval} = \delta_{mod} + \delta_{num} + \delta_{input}$$

Model, Numerical and Input uncertainties

Comparison to a Reference

$$E = \delta_{Sval} - \delta_R$$

Comparison against a reference system; e.g. – experiment data.

MEP

TUM

Extending Simulation Credibility to PHIL

Simulation Credibility Term	PHIL Practice
Epistemic Uncertainty δ_{mod}	Unavailability of HUT Model, Plant parameters.
Epistemic Uncertainty δ_{input}	Non-ideal Power Amplifier
Aleatory Uncertainty *(Intrinsic)*	HUT Non-Linearity/Variability. Time varying systems.
Numerical and System Error	Inaccuracies in Interface Algorithms. Solver precision. Discretization error.

Reduced Scale PHIL

- Practically non-existent literature…

IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 68, NO. 5, MAY 2021 3973

Reduced Scale PHIL Emulation Concepts Applied to Power Conversion Systems With Battery Storage

Andy Varais, Xavier Roboam, Fabien Lacressonnière, Eric Bru, and Nicolas Roux

https://doi.org/10.1109/TIE.2020.2988220

IEEE Open Journal of Industry Applications

Received 6 September 2023; revised 20 November 2023; accepted 28 December 2023. Date of publication 5 January 2024; date of current version 16 January 2024. The review of this article was arranged by Associate Editor M. Di Benedetto.

Digital Object Identifier 10.1109/OJIA.2024.3349480

A Physics-Informed Scaling Method for Power Electronic Converters in Power Hardware-in-the-Loop Test Beds

JOSEPH KIRAN BANDA [1] (Student Member, IEEE), DANIEL DOS SANTOS MOTA [2] (Member, IEEE), AND ELISABETTA TEDESCHI [1,3] (Senior Member, IEEE)

https://doi.org/10.1109/OJIA.2024.3349480

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Harmonic-Invariant Scaling Method for Power Electronic Converters in Power Hardware-in-the-Loop Test Beds

DANIEL DOS SANTOS MOTA [1] (Member, IEEE), JOSEPH KIRAN BANDA [1] (Student Member, IEEE), AYOTUNDE ADEKUNLE ADEYEMO [1] (Student Member, IEEE), AND ELISABETTA TEDESCHI [1,2] (Senior Member. IEEE)

https://doi.org/10.1109/OJIA.2023.3266882

MEP TUM

Reduced Scale PHIL

- Practically non-existent literature…
- Similitude Theory → Common in structural engineering and fluid dynamics for scale down models
- Implemented through Invariance Theorem or Buckingham π Theorem

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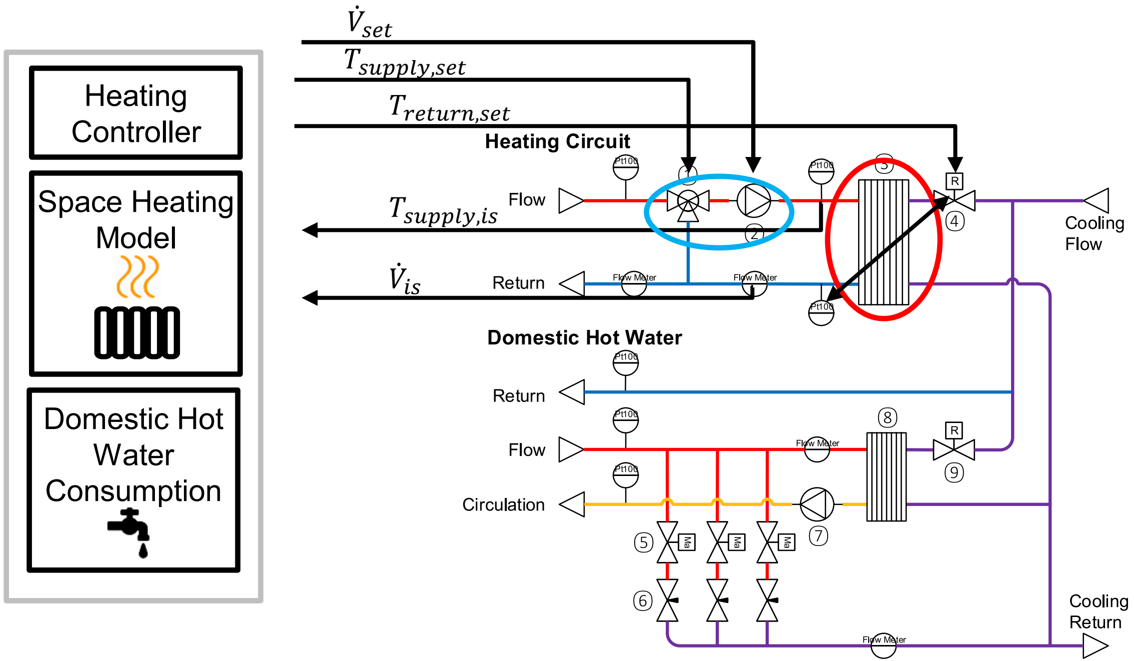
Extending Simulation Credibility to Reduced-PHIL

Simulation Credibility Term	PHIL Practice	Reduced-PHIL Practice
Epistemic Uncertainty δ_{mod}	Unavailability of HUT Model, Plant parameters.	Similitude Reduction errors. Wrong π-Groups.
Epistemic Uncertainty δ_{input}	Non-ideal Power Amplifier	Scaling factors are incorrect for complicated systems.
Aleatory Uncertainty *(Intrinsic)*	HUT Non-Linearity/Variability. Time varying systems.	Multi-system (electrical, mechanical, thermal, fluid, chemical) difference at scale.
Numerical and System Error	Inaccuracies in Interface Algorithms. Solver precision. Discretization error.	Time Compression errors.

And that‘s only where the fun begins…

Emulated Plant with HIL for Heating Systems



Validate 4th and 5th gen. heating grid control

Components and functions

- Passive balancing unit:
  - Hydraulic decoupling
  - Energy balancing
- Booster heat pump transfer station:
  - Temperature boosting
  - Pumping power

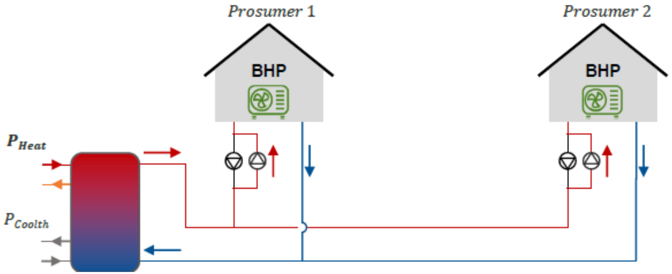
Control philosophies under test:

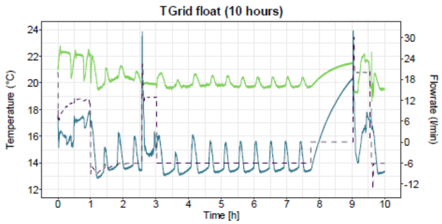
- Controlling the flow rate going through the prosumer
- Controlling the Temperature Difference (ΔT) across the prosumer

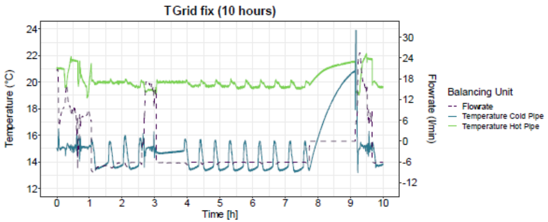
Results of concept study:

- Total 20h of experiment; Heating and cooling demand

- Passive balancing unit simplifies prosumer integration
- Control strategy with fixed grid temperature achieves more stable control



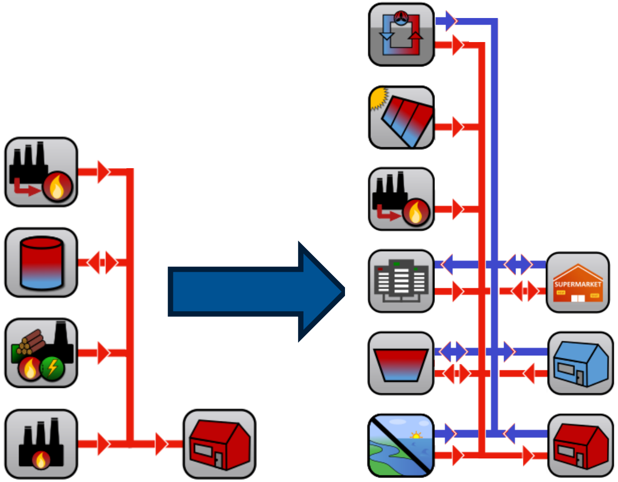




https://doi.org/10.1016/j.energy.2024.132835

Heat substation control for smart thermal grids

- From centralized, unidirectional networks to decentralized, bidirectional networks
- Need for appropriate control methods:
  – Managing the complex heat exchange between prosumers and the grid



https://doi.org/10.1016/j.apenergy.2023.122239

Heat substation control for smart thermal grids

- From centralized, unidirectional networks to decentralized, bidirectional networks
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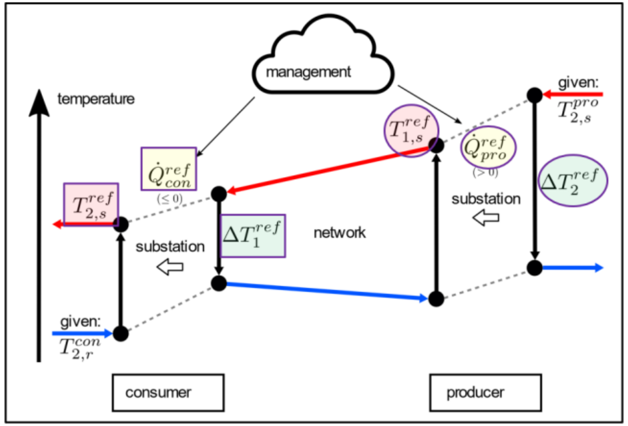

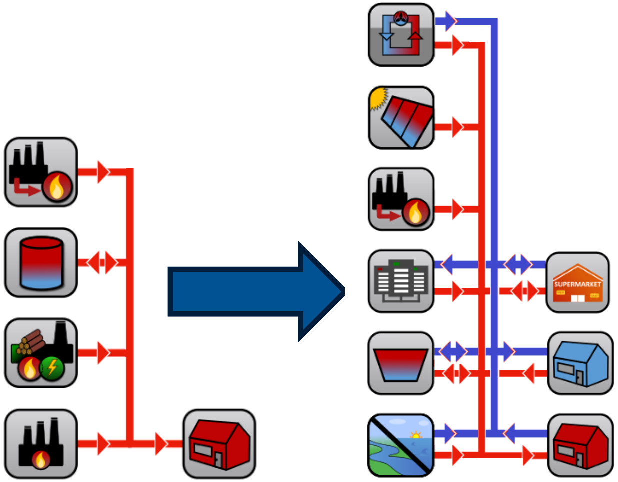

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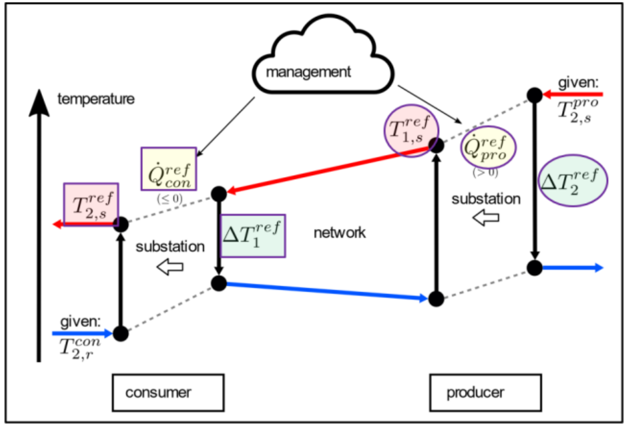

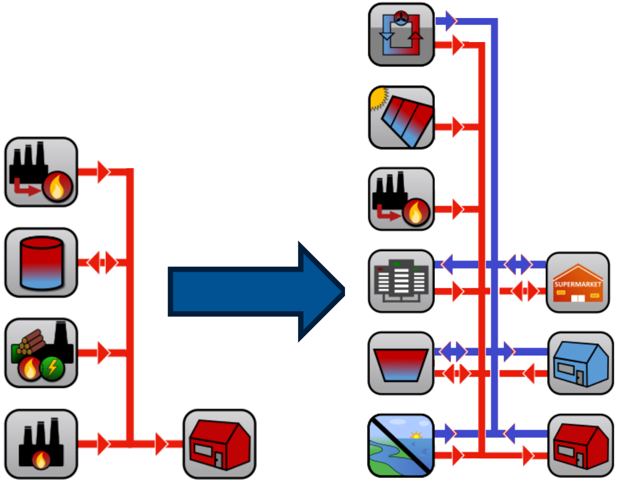

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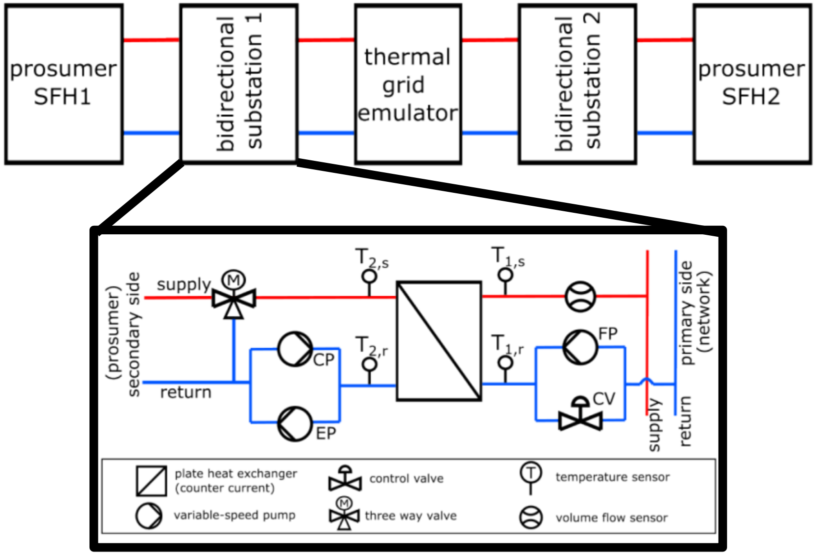
Heat substation control for smart thermal grids



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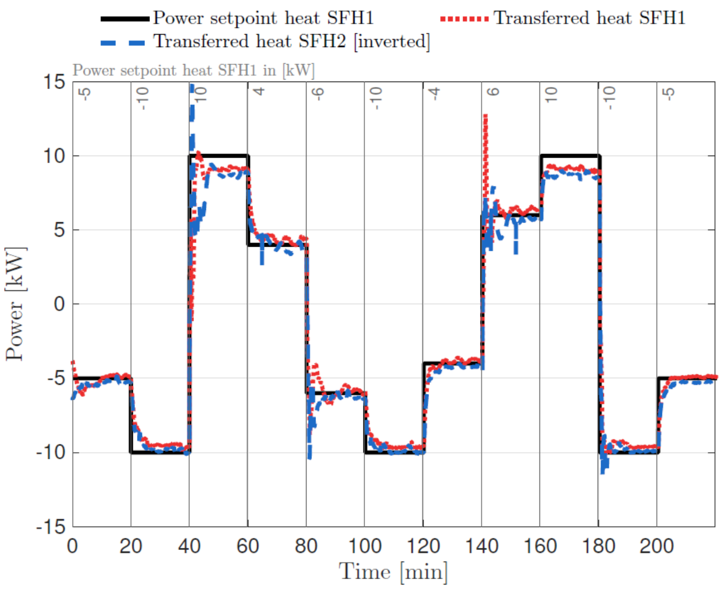
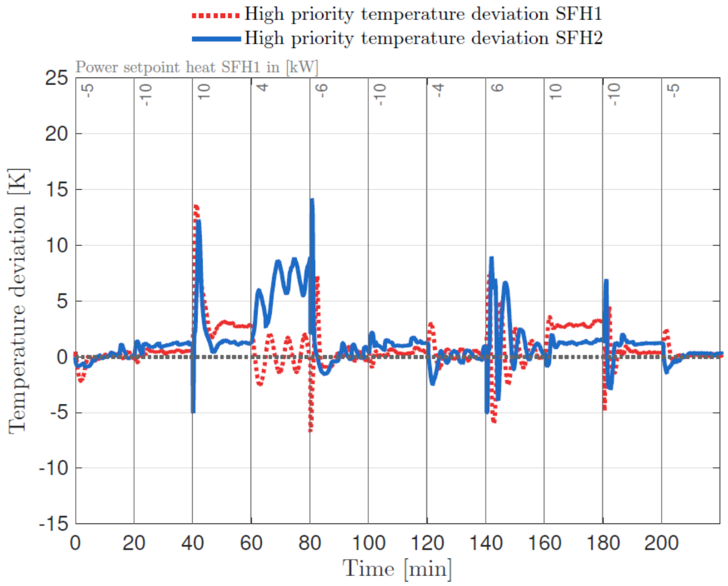
Heat substation control for smart thermal grids

Power Setpoint & Power Actually Transmitted



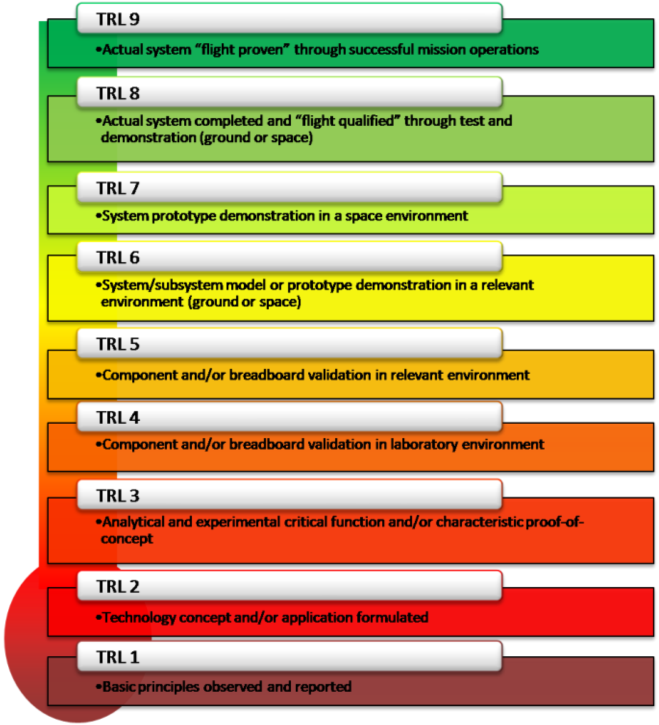
High Priority Temperature Objective



https://doi.org/10.1109/ISGTEUROPE62998.2024.10863543

Conclusion

- PHIL remains the gold standard for lab validation in power systems.
- Must be adapted to the demands of sector coupling research.
- Prosumer emulation while maintaining simulation credibility is key.
- Heating systems can be emulated through PHIL-adjacent concepts.



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Appendix – Electrical Equipment

Transformers	2 x MV/LV OLTC, 250 KVA; 1 x MV/LV 630KVA for feedback loop
LV Grid	12 x Power cables, 10 Lv Busbars, 2 x LV circuit breaker (to change the network topology)
Prosumers	Egston Compiso, 7 x bidirectional 4 leg inverters, SFP interface for control, 250KVA (total), 100KVA (single cabinet)
DERs	18KWp PV divided into 3 inverters, 2 x 13KWh battery storage, 2 x 22KW car chargers.

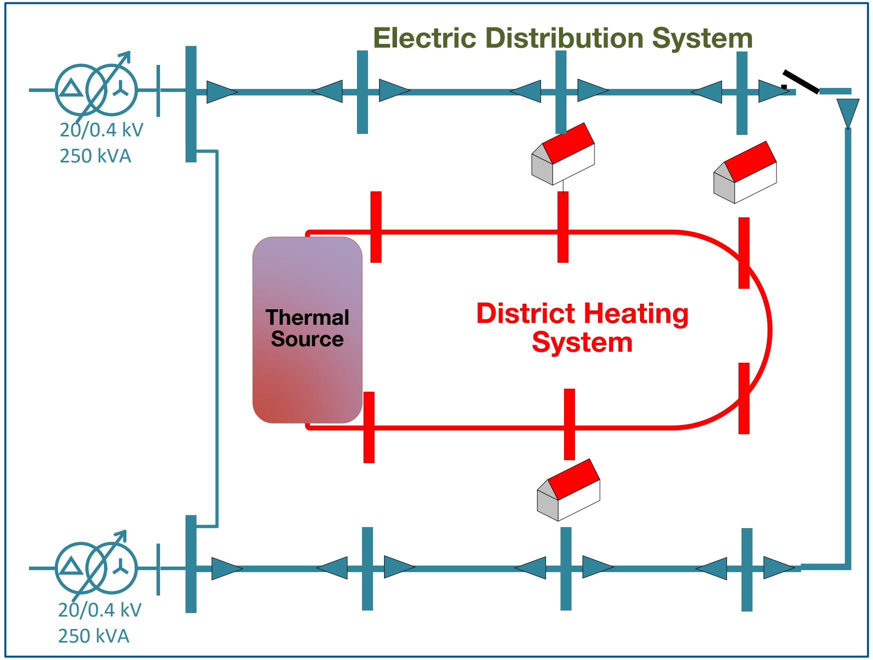


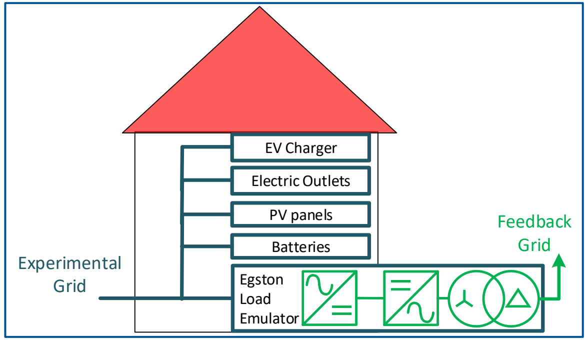
anurag.mohapatra@tum.de | https://www.mep.tum.de/mep/coses/

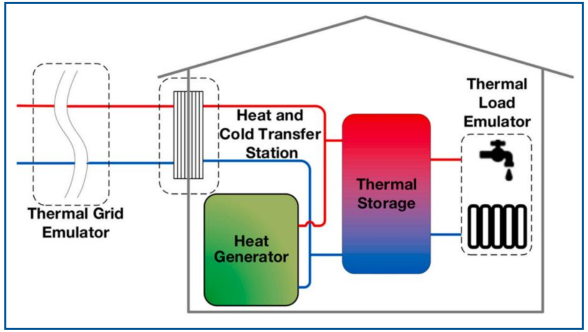
Appendix – Thermal Equipment

	Haus 1	Haus 2	Haus 3	Haus 4	Haus 5
Thermal generators	CHP (2 kW_{el}, 5,2 kW_{th}) Boiler (20 kW_{th}) Solar thermal (9 kW_{th})	Boiler (20 kW_{th}) Heat pump (19 kW_{heat}, 9 kW_{cold}) Solar thermal (9 kW_{th})	Ground source heat pump (19 kW_{heat}) Solar thermal (9 kW_{th})	Stirling Engine (1 kW_{el}, 6 kW_{th}) Boiler (20 kW_{th})	CHP (5 kW_{el}, 11,9 kW_{th}) CHP (18 kW_{el}, 34 kW_{th}) Boiler (50 kW_{th})
Thermal storage	800 l	785 l	1000 l	1000 l	2000 l
Domestic hot water	Fresh water storage (500 l)	Fresh water storage	Fresh water storage	Internal heat exchanger	Fresh water storage
Transfer stations	Bidirectional transfer station (30 kW_{th}) Booster heat pump (19 kW_{heat}, 14 kW_{cold})	Bidirectional transfer station (30 kW_{th})	Bidirectional transfer station (30 kW_{th})	Bidirectional transfer station (30 kW_{th})	Bidirectional transfer station (60 kW_{th})
Thermal loads	30 kW_{heat}, 9 kW_{cold}	30 kW_{heat}, 9 kW_{cold}	30 kW_{heat}, 9 kW_{cold}	30 kW_{heat}	60 kW_{heat}

CoSES Lab - Overview







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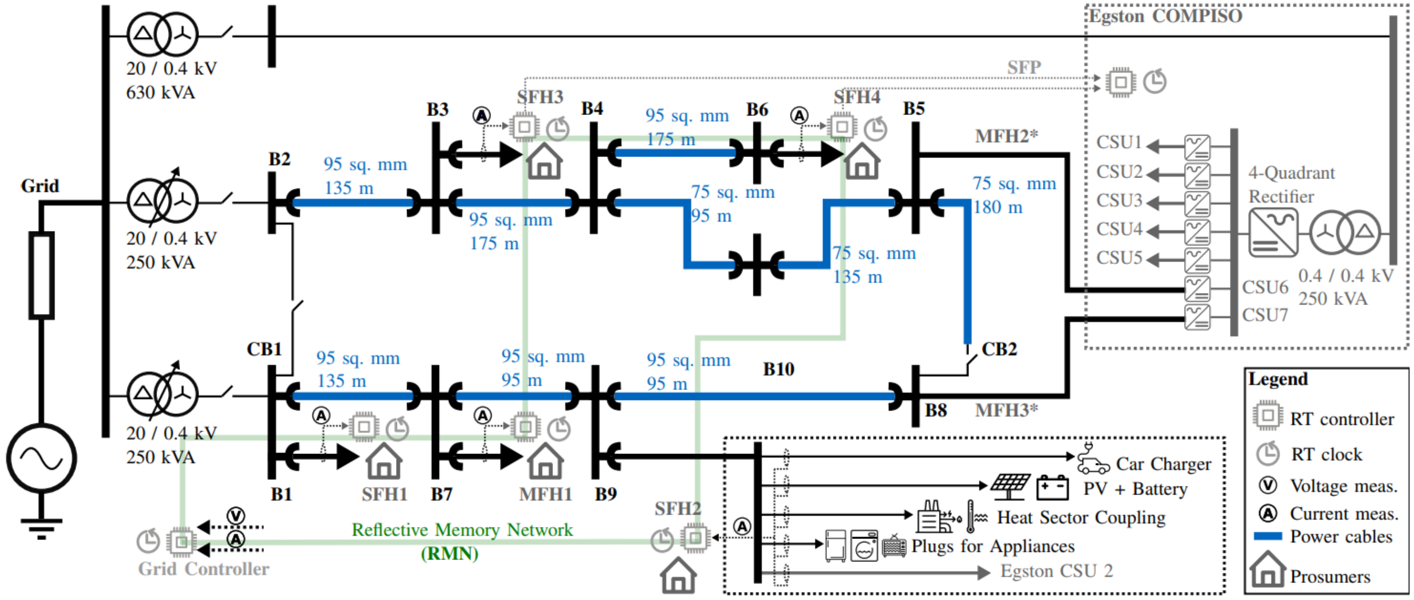
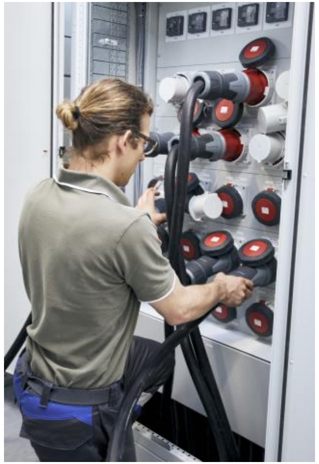
Electric Grid





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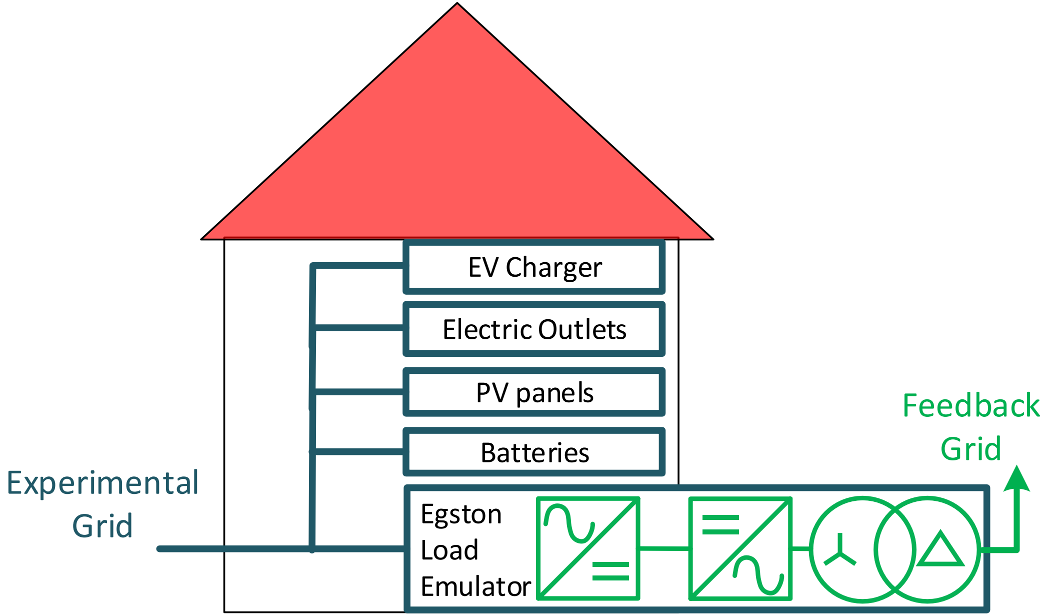
Electric Building Emulator



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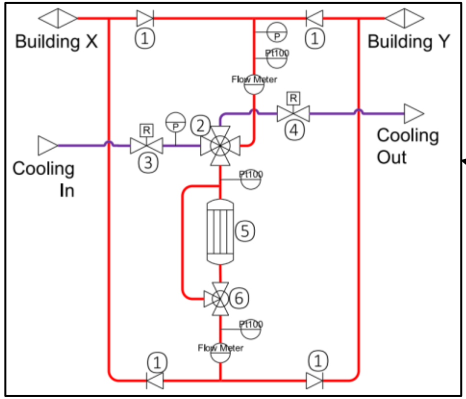
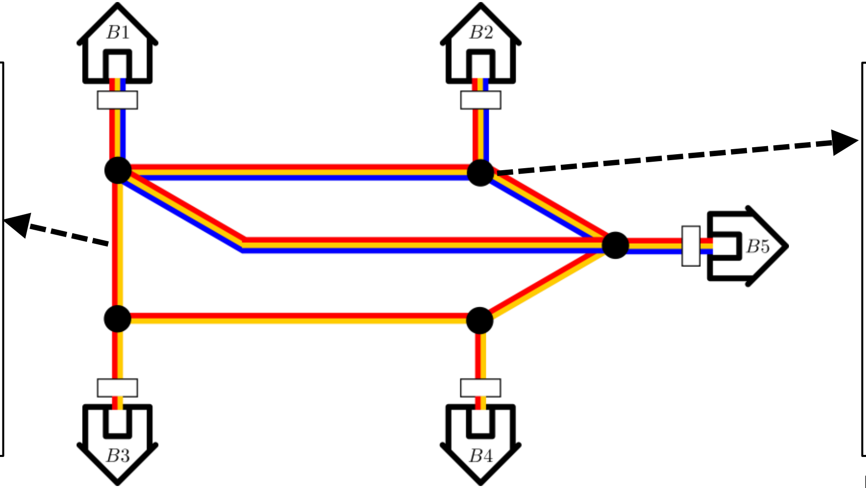
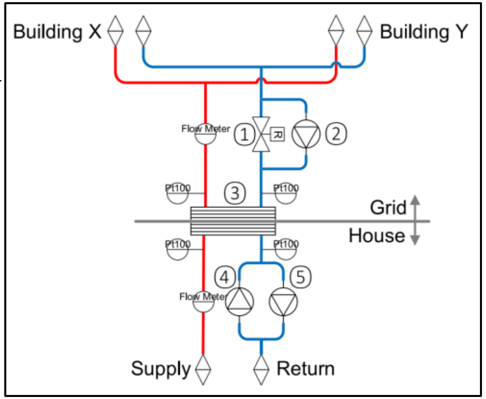
Thermal Grid



thermal network emulator /
pipe emulator

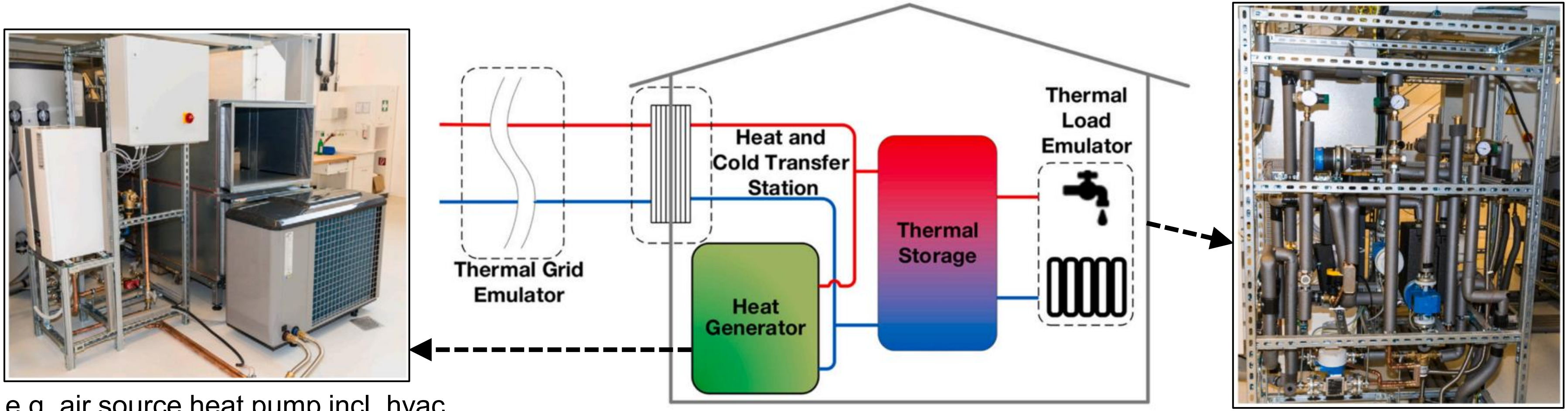


bidirectional thermal network with prosumers



bidirectional heat transfer station

Thermal Building Emulator



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

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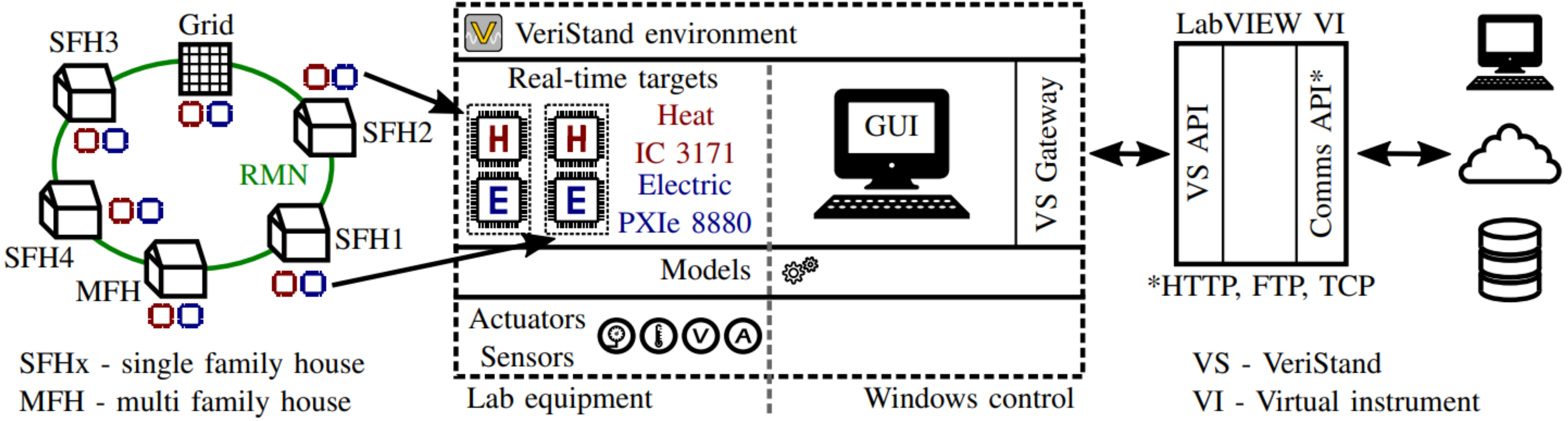
Computation and Communication



Contact

Dr. –Ing Anurag Mohapatra
CoSES Research Group
Technical University of Munich (TUM)
Lichtenbergstraße 4a
85748 Garching

Email - anurag.mohapatra@tum.de
Website - https://anuragmohapatra90.github.io/
Group - https://www.mep.tum.de/en/mep/coses/