RWTH AACHEN UNIVERSITY

AALBORG UNIVERSITY

# Towards Controller Hardware-in-the-Loop testing of Internet-inspired Cyber-physical Energy Systems for Store-and-forward Energy Routing


- Subham Sahoo*, Andres Acosta**, Majd Hamza**, Tobias Heins**
- *Aalborg University, **RWTH Aachen University



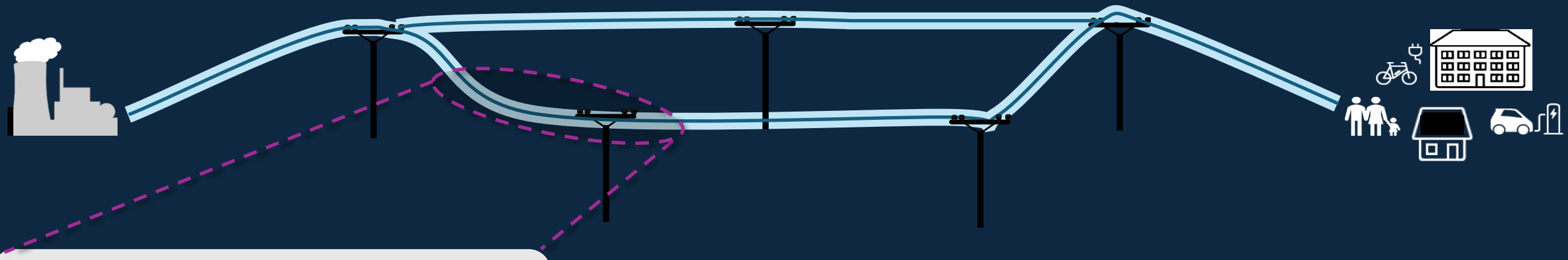



HUGM RTDS USER'S GROUP MEETING

2026 MADRID USER'S GROUP MEETING
MADRID, SPAIN

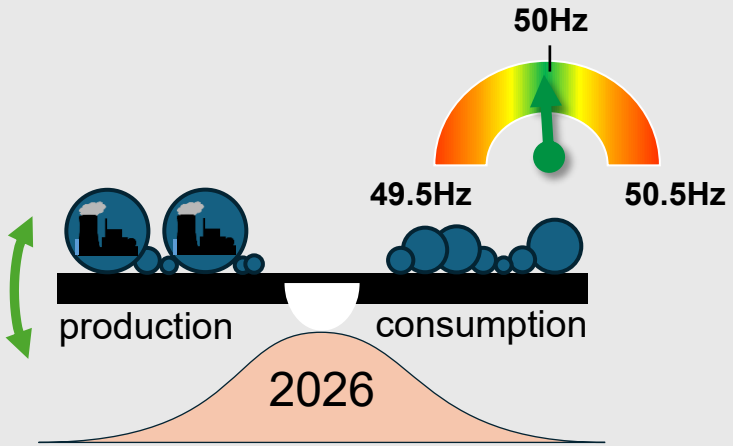
RTDS Technologies
AMETEK

# Motivation: The limits of the *power grid's synchronicity principle*



## Global Balancing of Power

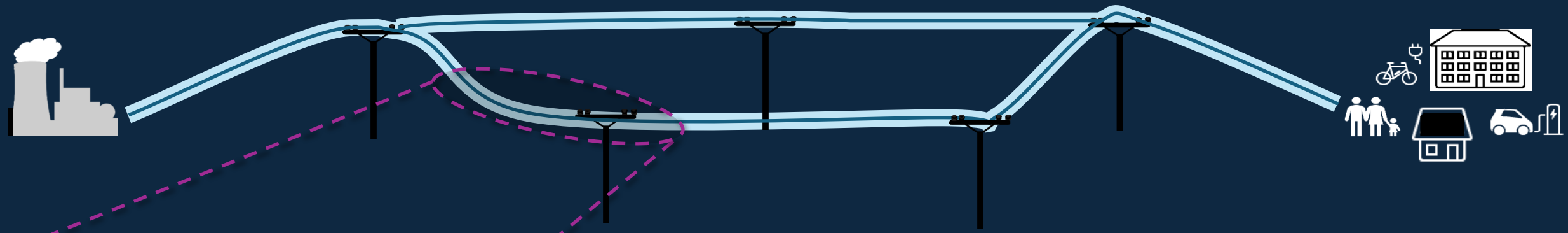
(in the traditional grid)



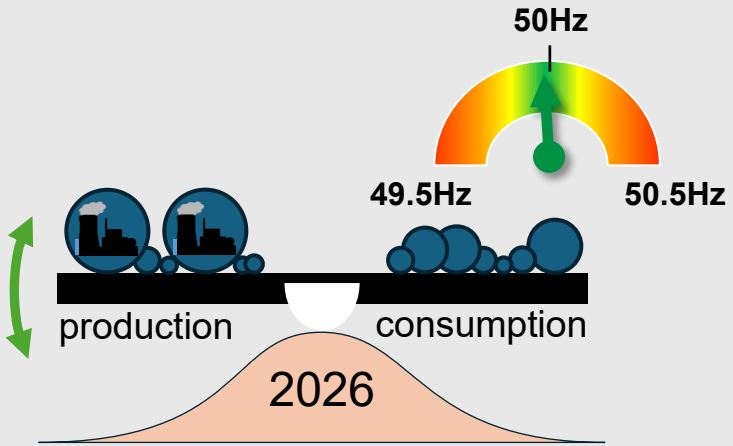

**3x more demand for electric energy**

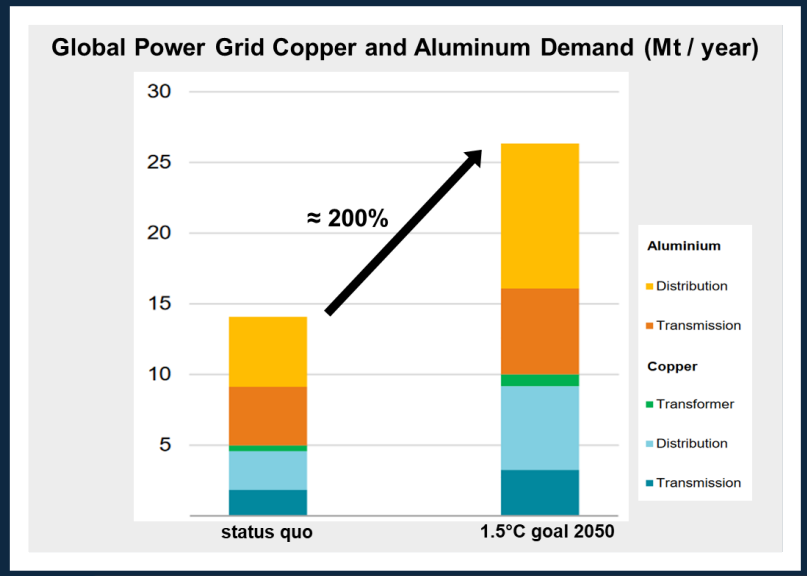
**25x more volatile energy production**

# Motivation: The limits of the *power grid's synchronicity principle*



## Global Balancing of Power
(in the traditional grid)





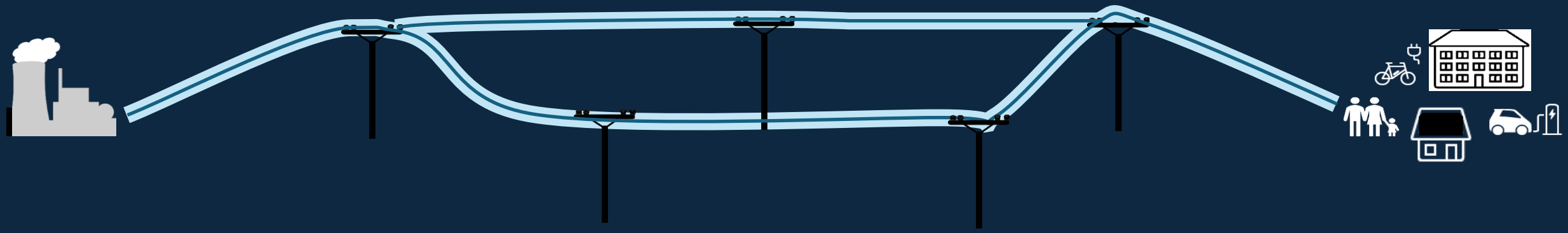


Source: IEA 2021

**insane increase in annual grid investments**

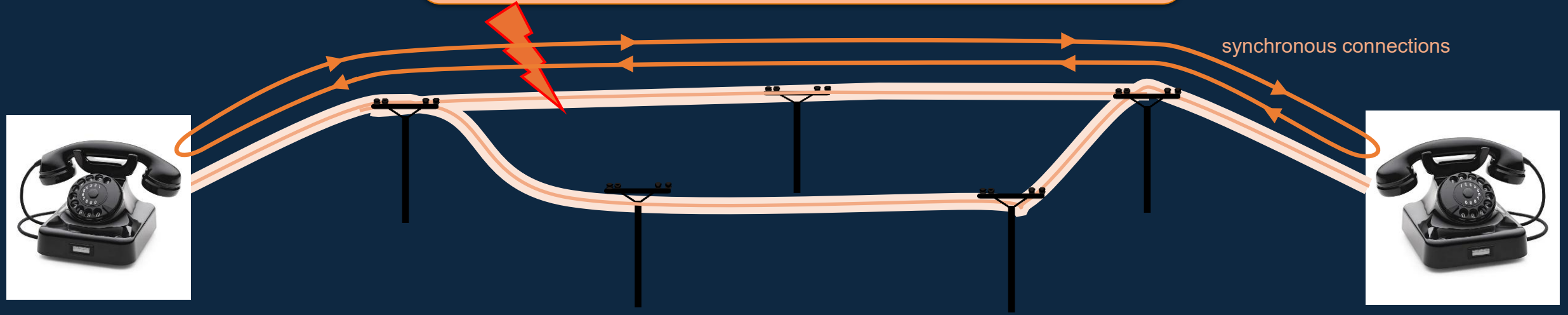
(800 USD billion/year, ≈ 4x2024 total EU budget)

# Idea and Approach: *The very obvious analogy*

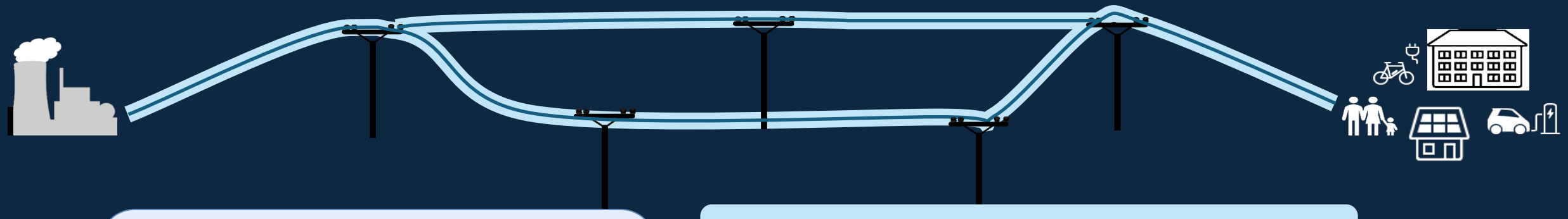


**Communication networks in the 1960s**

- not reliable, not scalable
- supported only one application (voice calls)



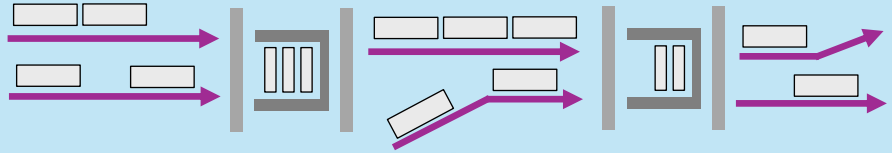
# Idea and Approach: *The very obvious analogy*

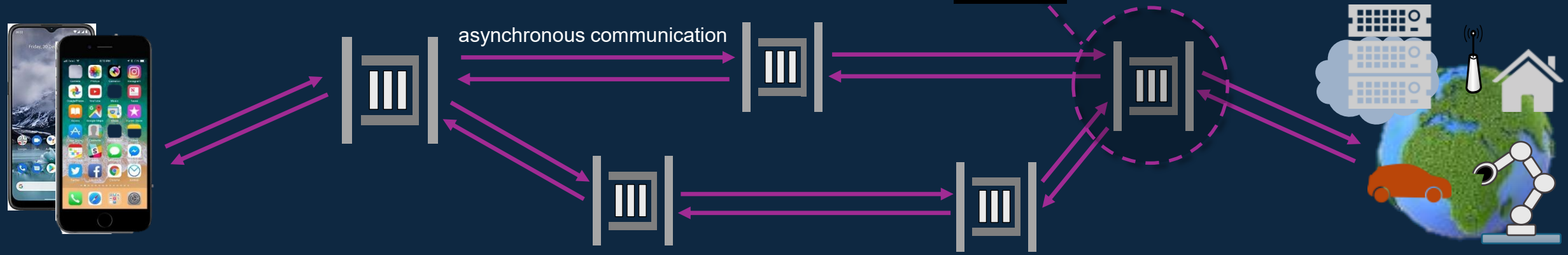


**Disruptive new approach:**

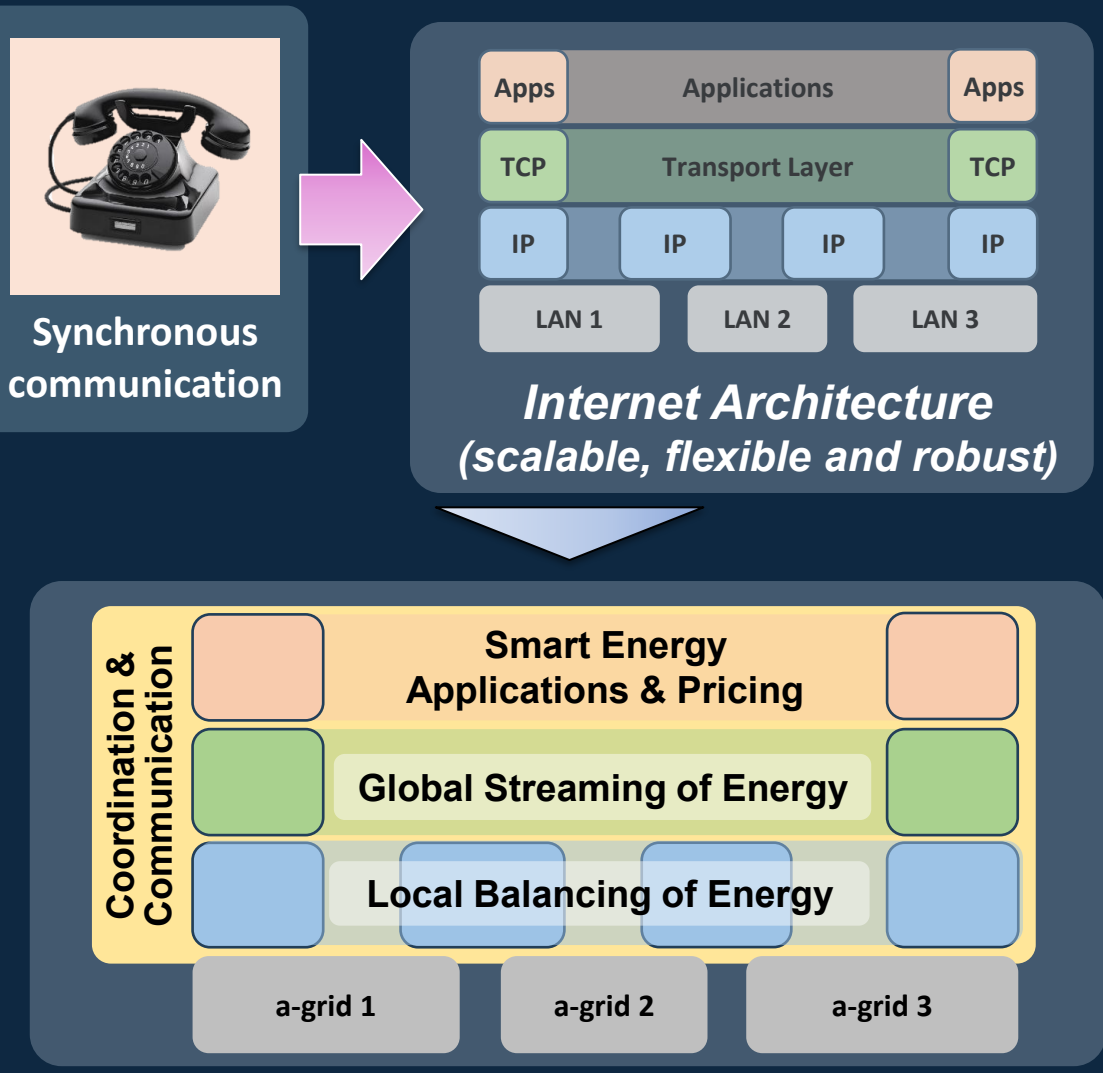
- asynchronous store-and-forward
- scalable and reliable
- stable core network – no blackout yet

## Store-and-forward Routing of Data

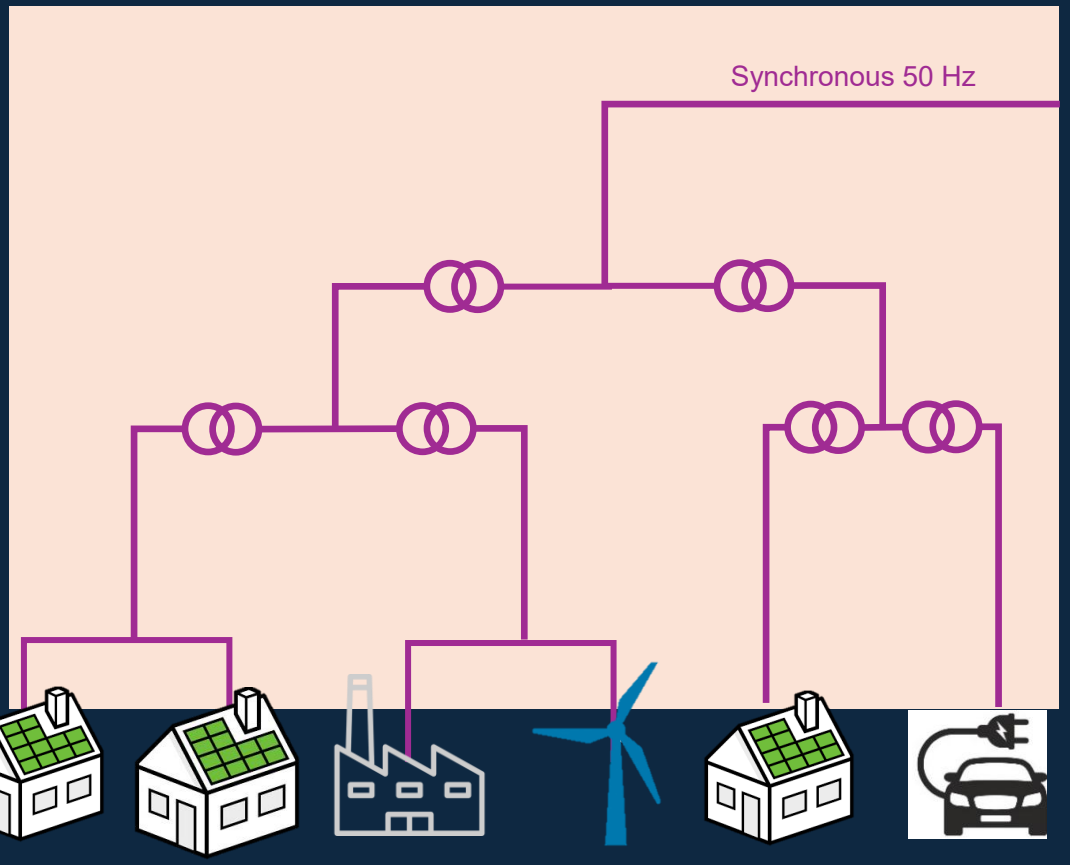




# Idea and Approach: *How SAFEr Grid will solve the problem*

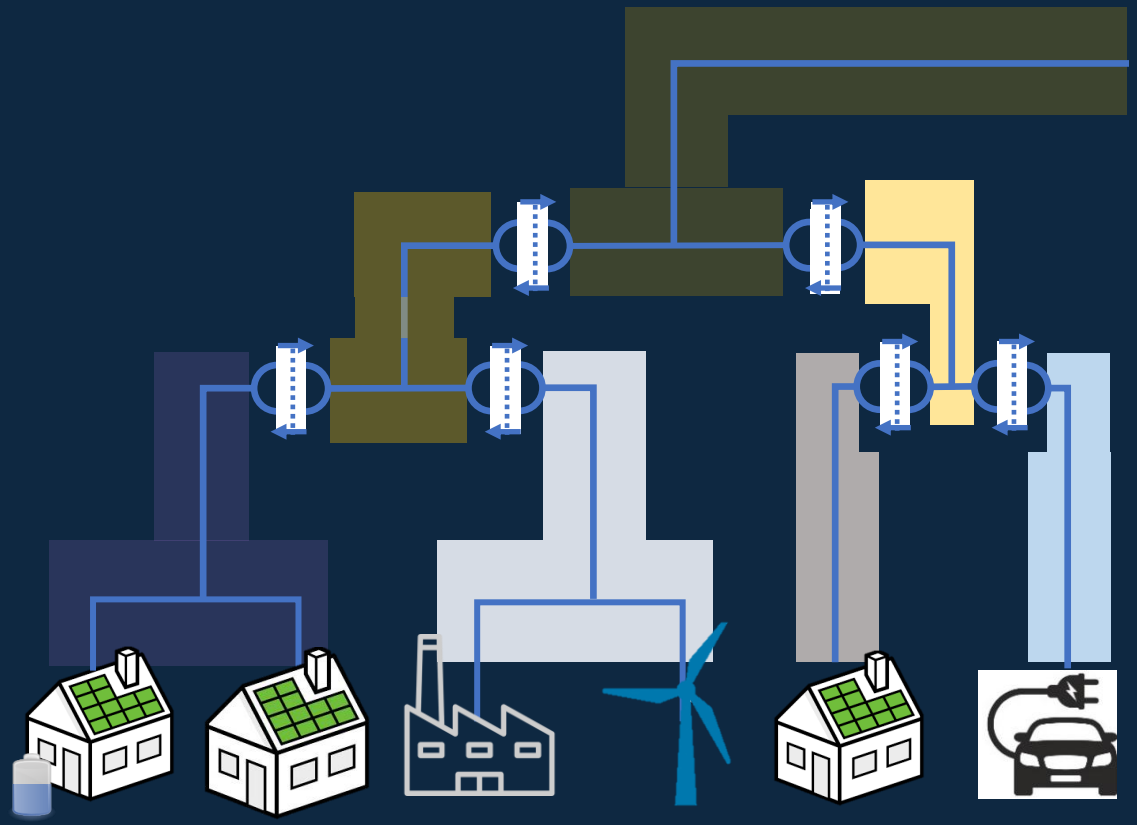



## Synchronous Global Balancing of Power

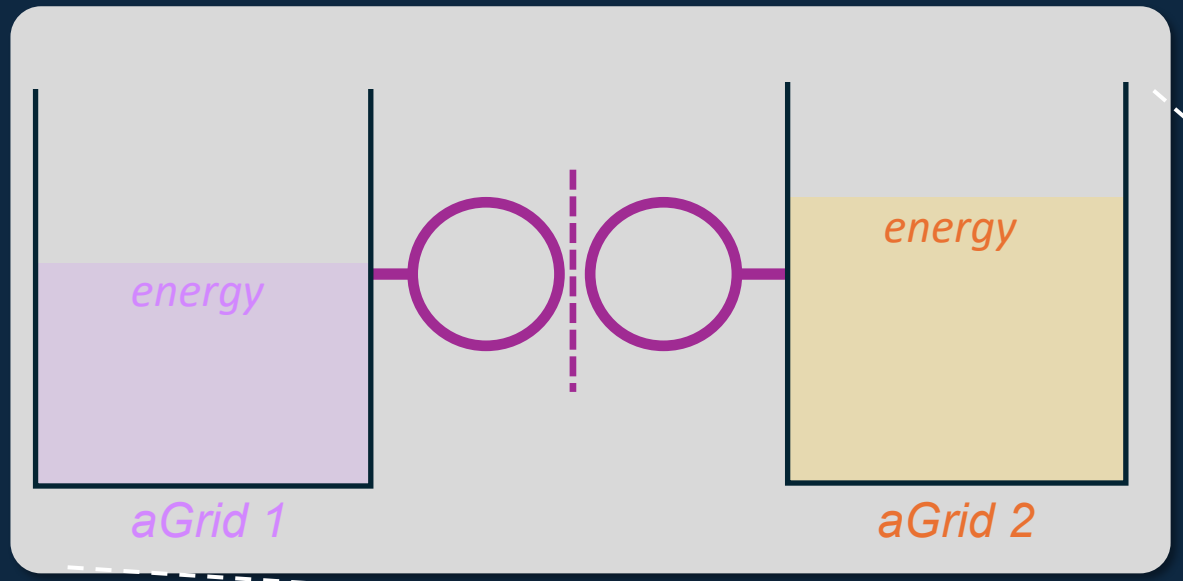


# Idea and Approach: *How SAFEr Grid will solve the problem*

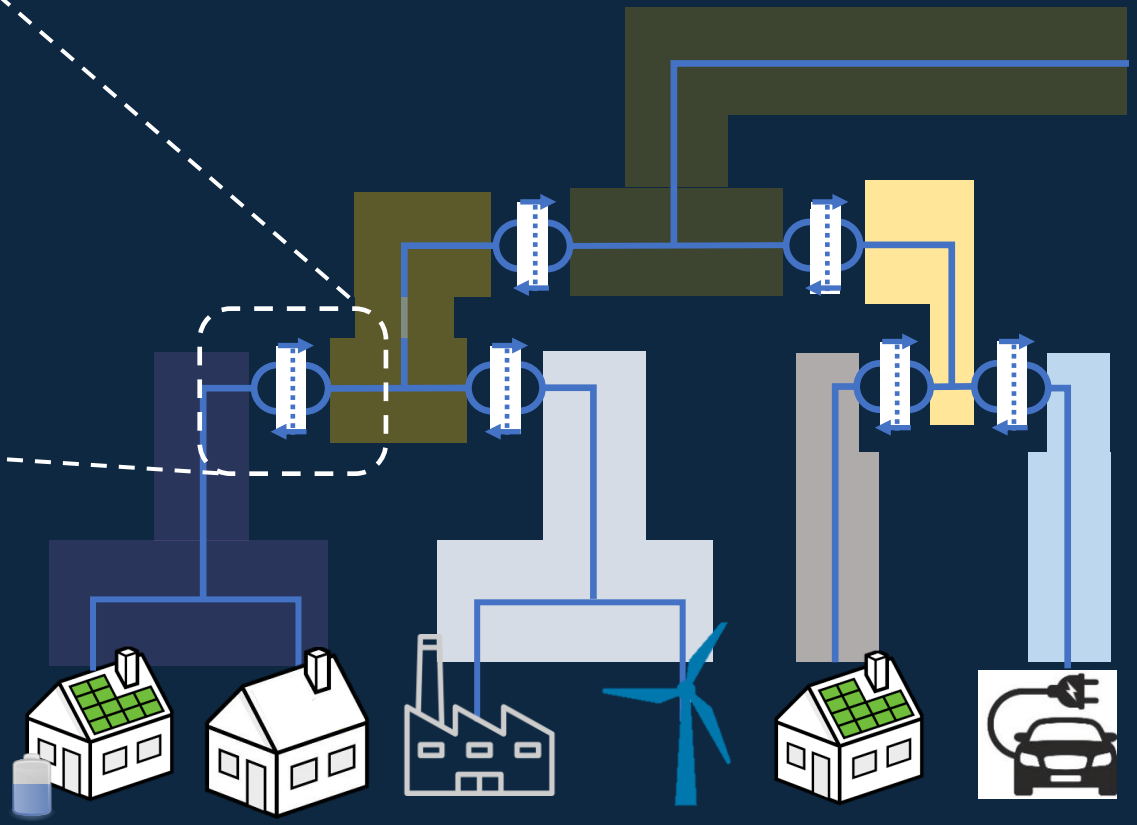
## Asynchronous Local Balancing of Energy



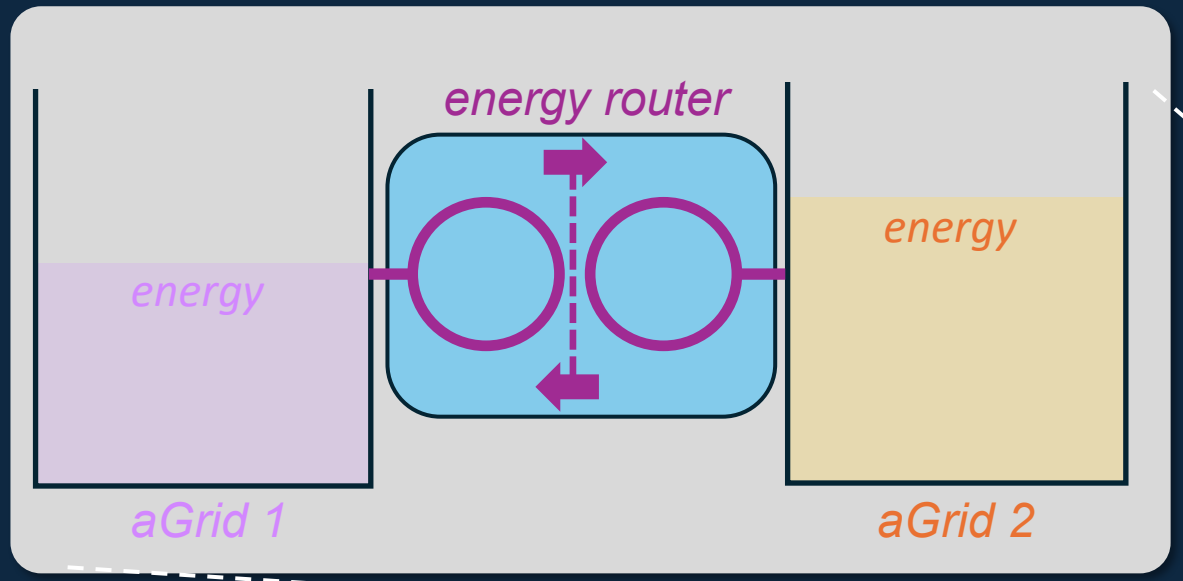
# Idea and Approach: *How SAFEr Grid will solve the problem*



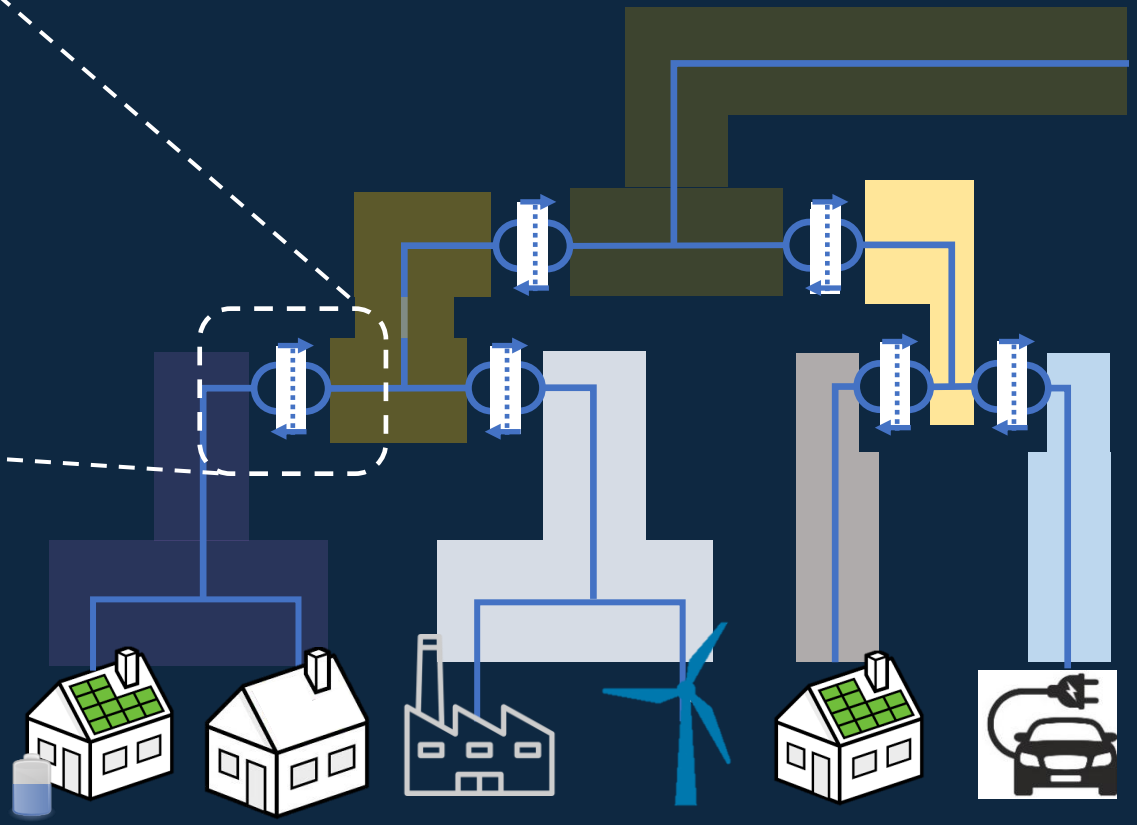

## Asynchronous Local Balancing of Energy



# Idea and Approach: *How SAFEr Grid will solve the problem*



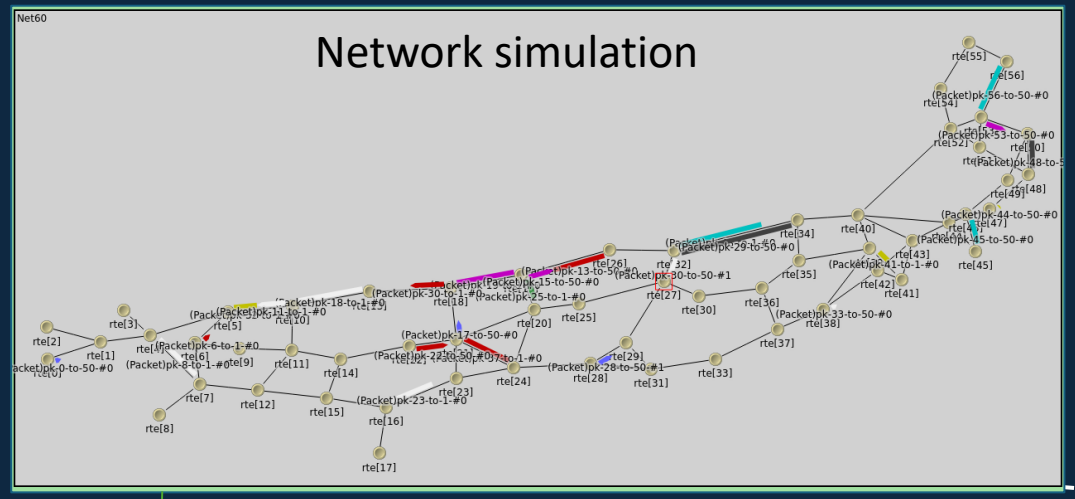

## Asynchronous Local Balancing of Energy



**Energy router**

- Multiple isolated asynchronous grids
- Protects and allows coordinated exchange

# SAFEr Grid in one Controller HiL Simulation




Coupling Interface



Coordination & Communication

Smart Energy Applications & Pricing

Global Streaming of Energy

Local Balancing of Energy

a-grid 1

a-grid 2

a-grid 3

# Network Simulation Logic

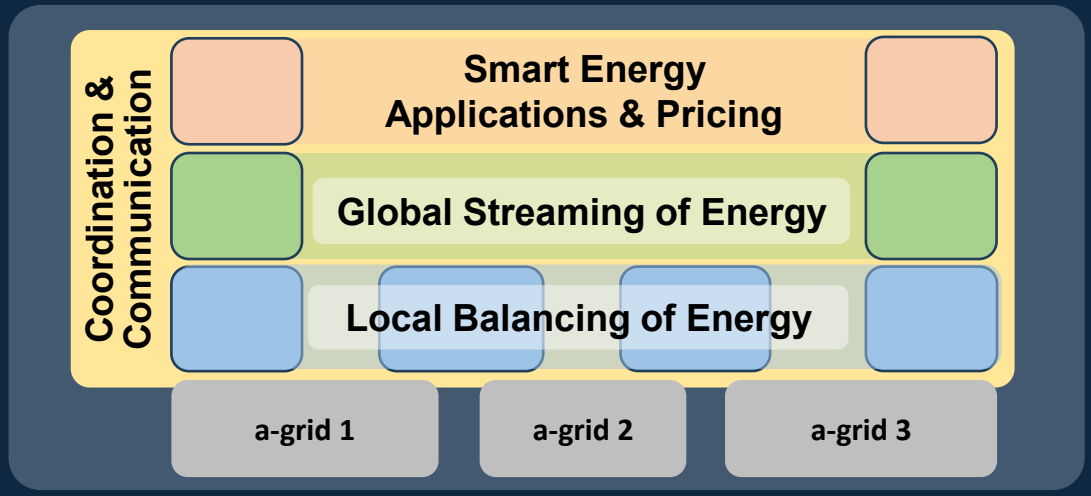
Users exchange needs over the network

Streams of energy are aggregated, and minimum cost of operation is computed

Power commands are generated per operational port

Coupling Interface

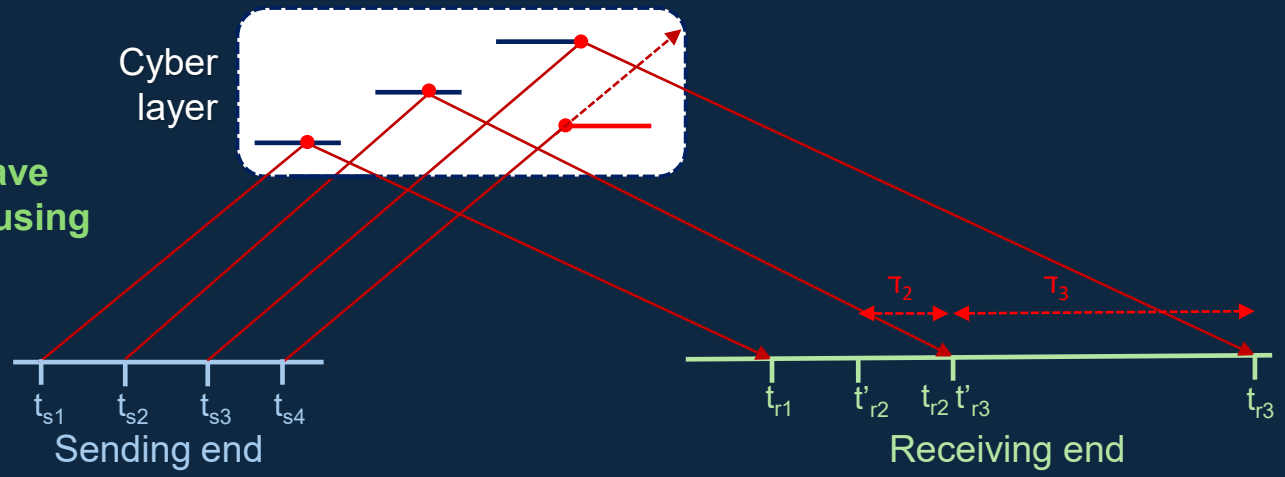




# Implementation of Cyber-layers Using OMNeT++

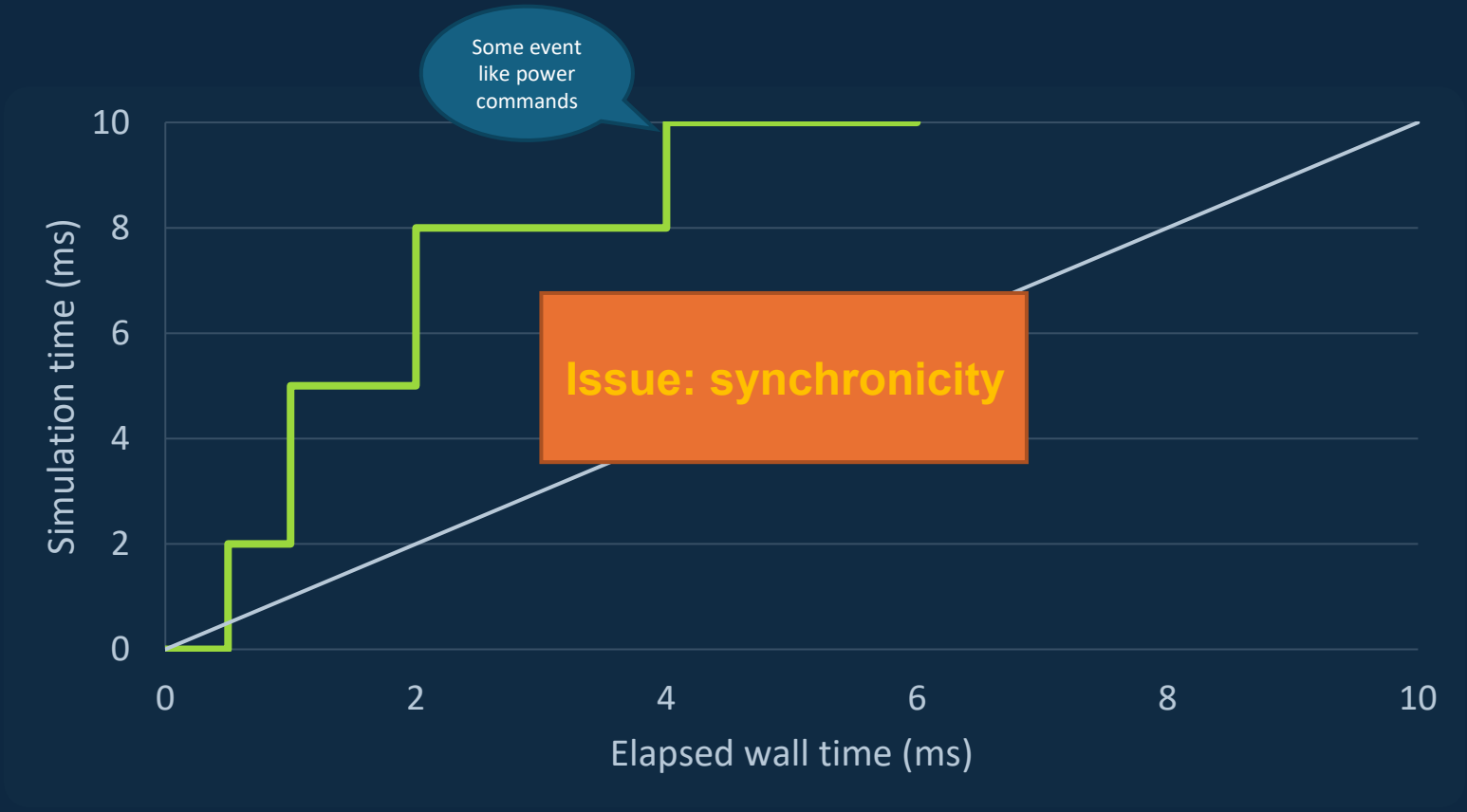
- OMNeT++ allows network simulations in discrete events
  - Cyber layers represent user communication traffic, user behavior and network operation
  - Transfer of control information need to be tested for our architecture

***Until now, experiments have modelled communication using stochastics**




*S. Sahoo and **F. Blaabjerg**, "A Model-Free Predictive Controller for Networked Microgrids with Random Communication Delays," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), Phoenix, AZ, USA, 2021.

# OMNeT++ can advance faster than wall time!




GREEN

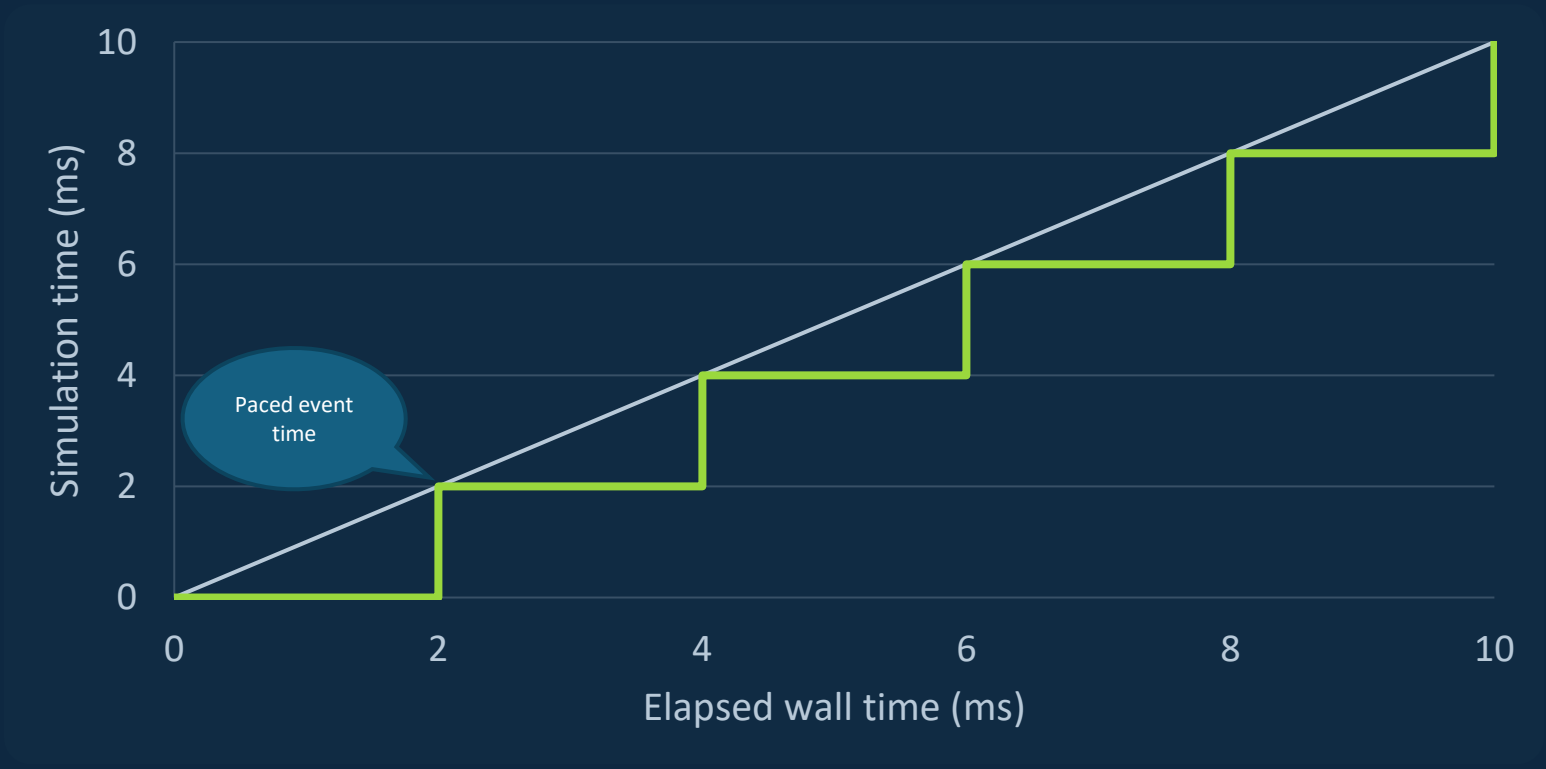
## Logical event time

An event at 10 ms can execute before 10 ms has elapsed physically.

**A simulated send event does not itself wait for hardware.**

Illustrative traces. Grey diagonal: wall-clock reference.

# OMNeT++ can advance faster than wall time!




GREEN

## Logical event time

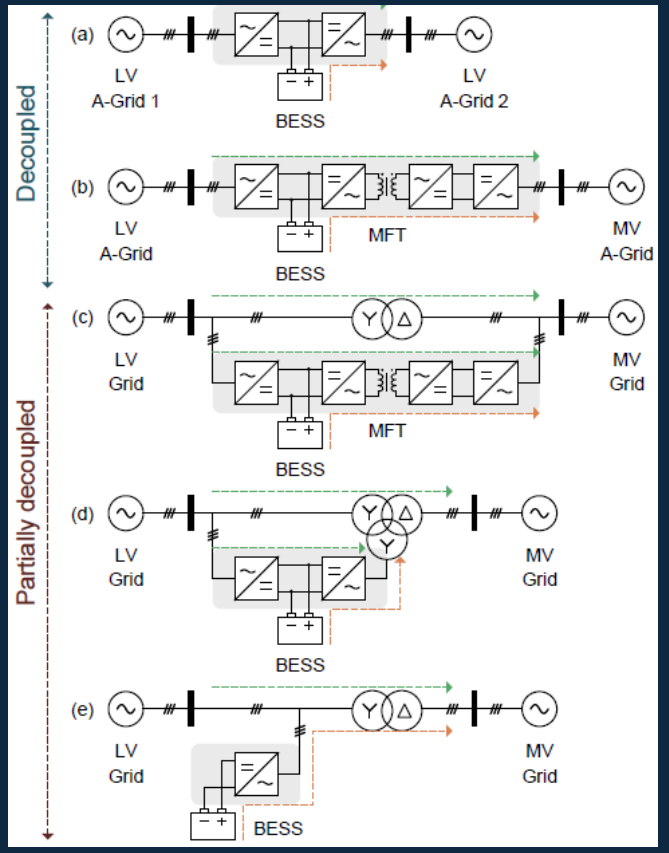
Early events wait in the scheduler

**A simulated send event does not itself wait for hardware.**

Illustrative traces. Grey diagonal: wall-clock reference.

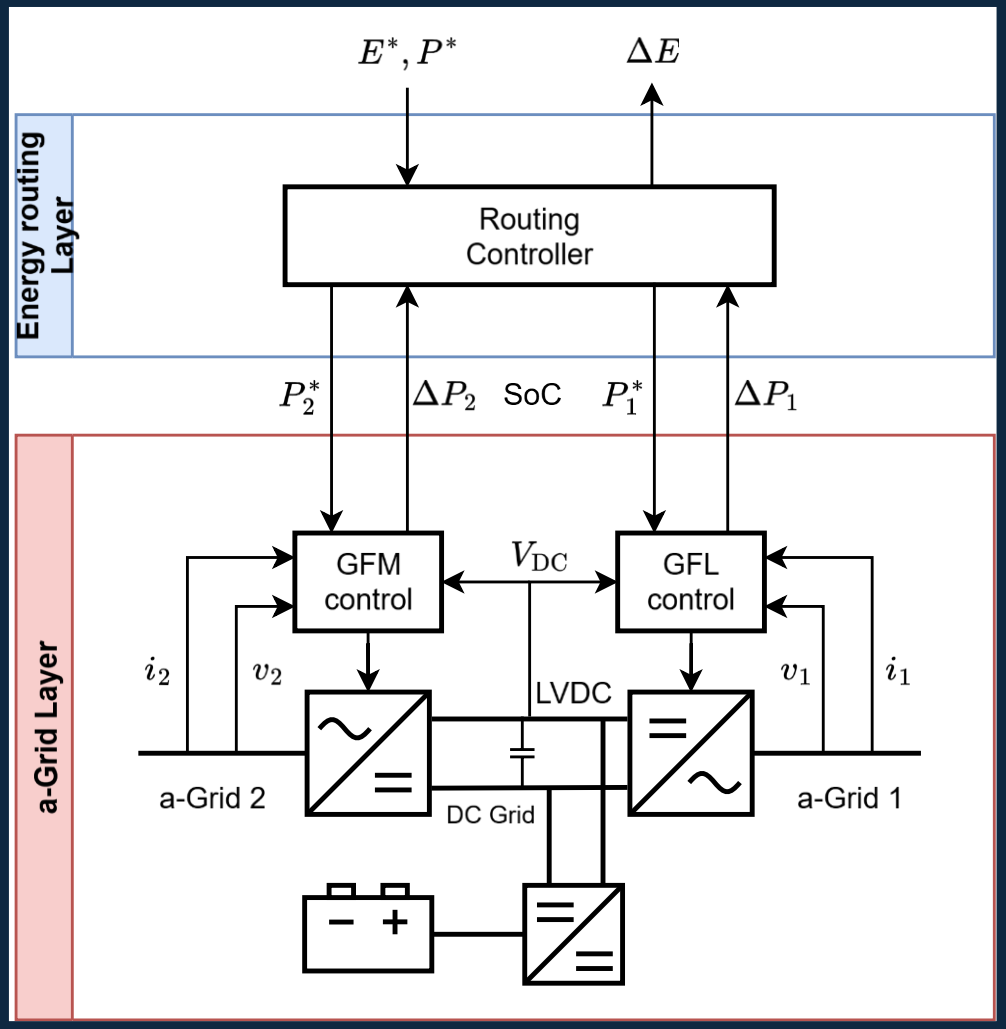
# Envisioned SAFEr Grid validation experiments

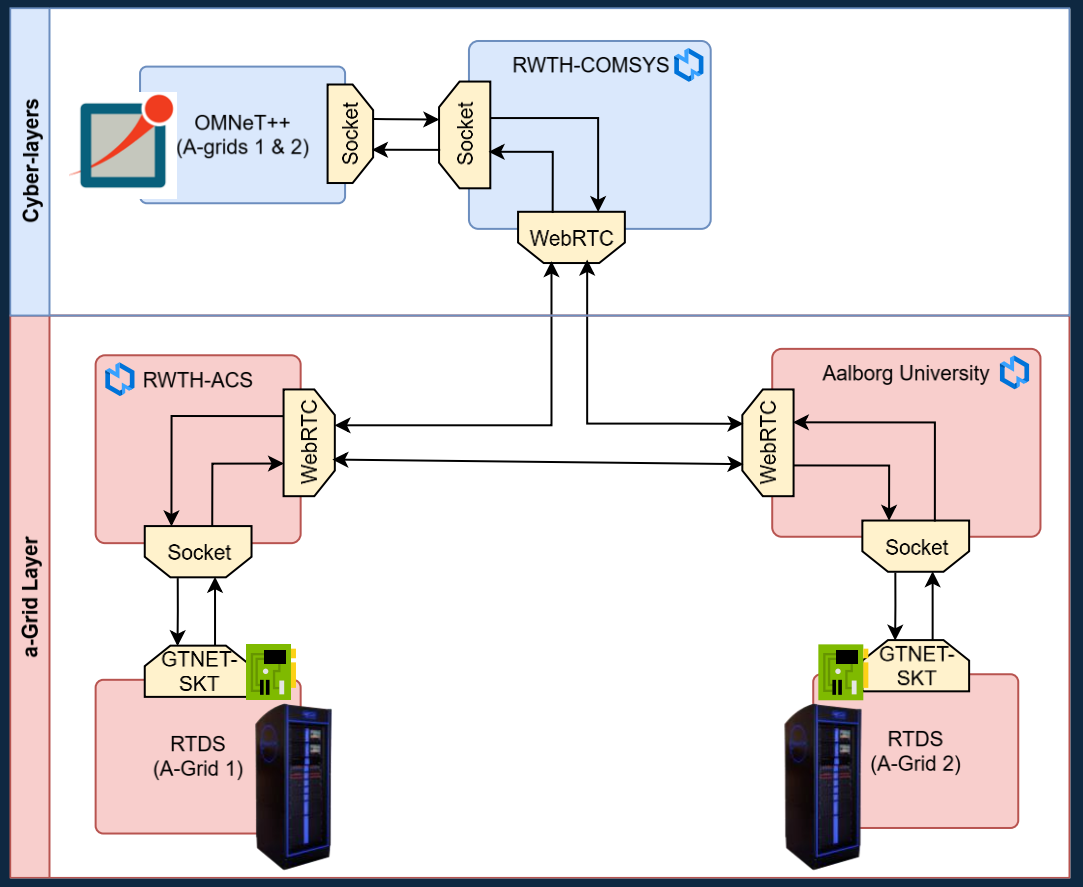
| Scenario | Configuration | Exemplary grid | Setup | Phenomenon of interest |
|---|---|---|---|---|
| 1 | (a) | Any low-voltage benchmark with a single feeder | Power system – ICT RTCS | Transient behavior in the EMT domain and energy transfer in phasor domain |
| 2 | from (b)-(e) | Modified version of the CIGRE medium-voltage benchmark | Power system – ICT RTCS | Transient behavior in the EMT domain and energy transfer in phasor domain |
| 3 | from (c)-(e) | Transmission and distribution system | Power system – ICT RTCS and GD-RTS | Global energy transfer in the phasor domain |
| 4 | (a) and (b) | Transmission and distribution system | Power system – ICT RTCS and GD-RTS | Global energy transfer in the phasor domain |
| 5 | from (a)-(e) | Any of the previous scenarios | CHIL to test the SAFEr grid protocol stack | Transient behavior in the EMT or hybrid simulation |
| 6 | (a) and (b) | Any of the previous scenarios | Local PHIL | Transient behavior in hybrid simulation |
| 7 | all | Transmission and distribution system | GD-RTS and PHIL | Transient behavior in hybrid simulation |




Alternatives to realize the energy router in partially-decoupled and fully-decoupled configurations

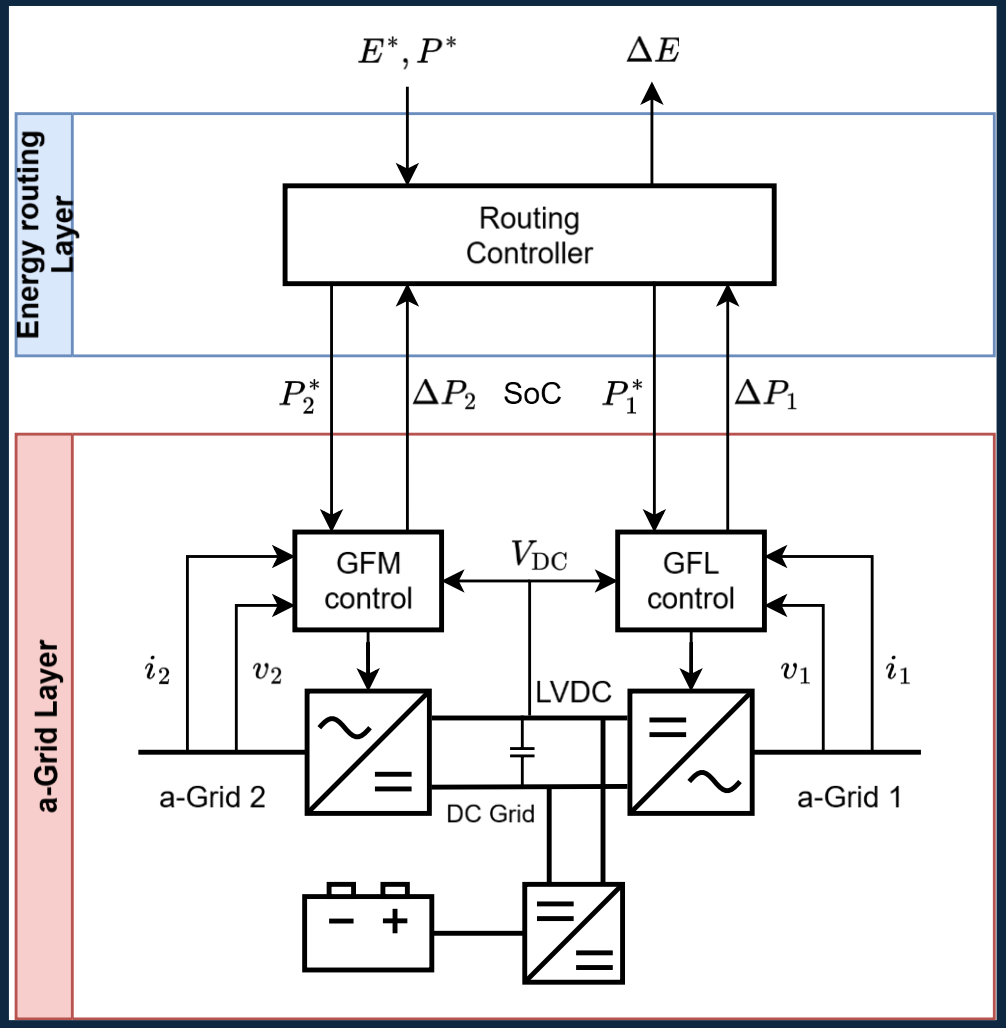
# Envisioned SAFEr Grid validation experiments

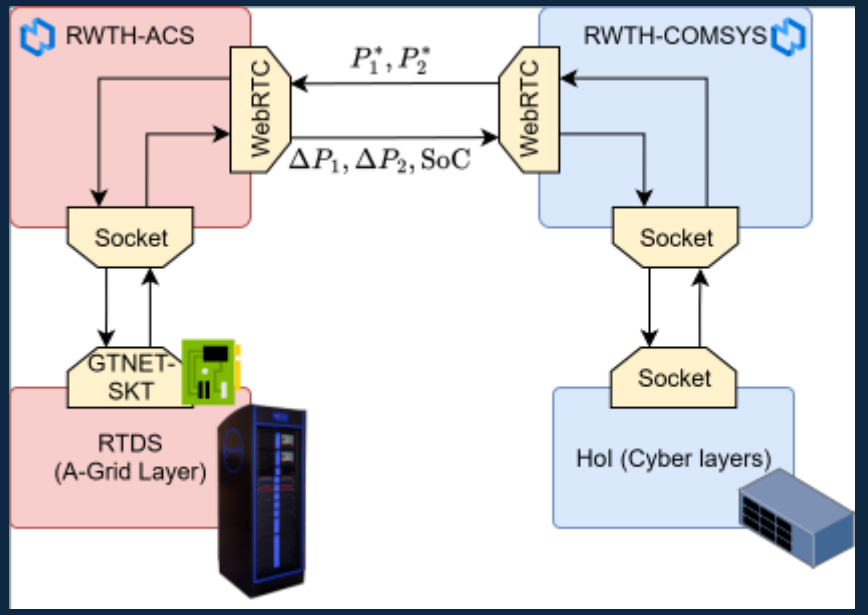



Setup 1: Multi-lab Cyber-physical co-simulation

# Envisioned SAFEr Grid validation experiments

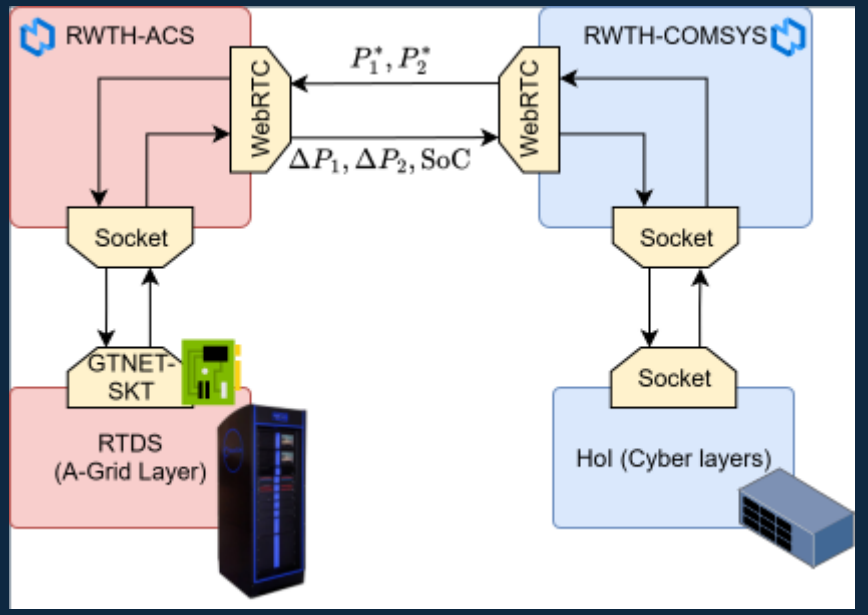



Setup 2: CHIL to test the SAFEr grid protocol stack

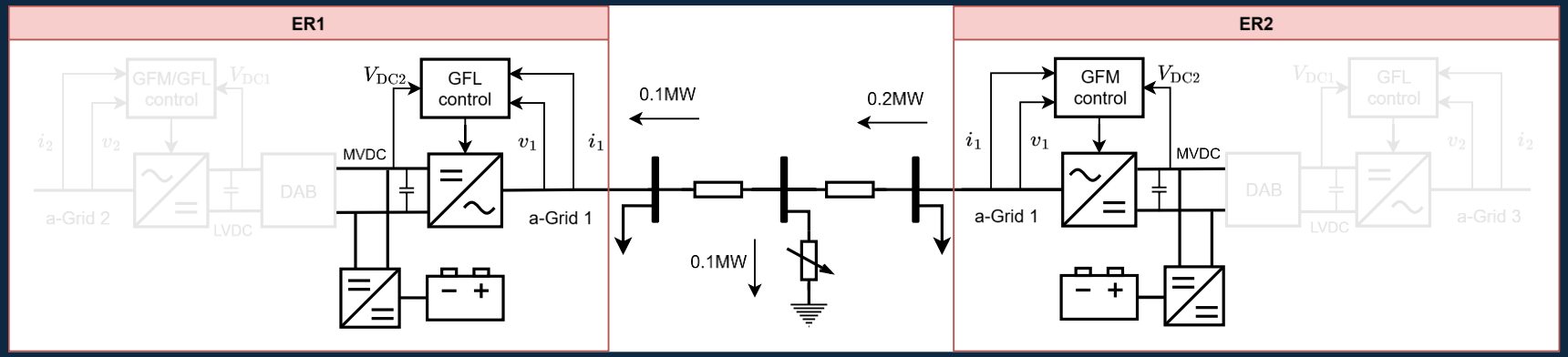
# Distributed Co-simulation and CHIL Enabler: VILLASnode

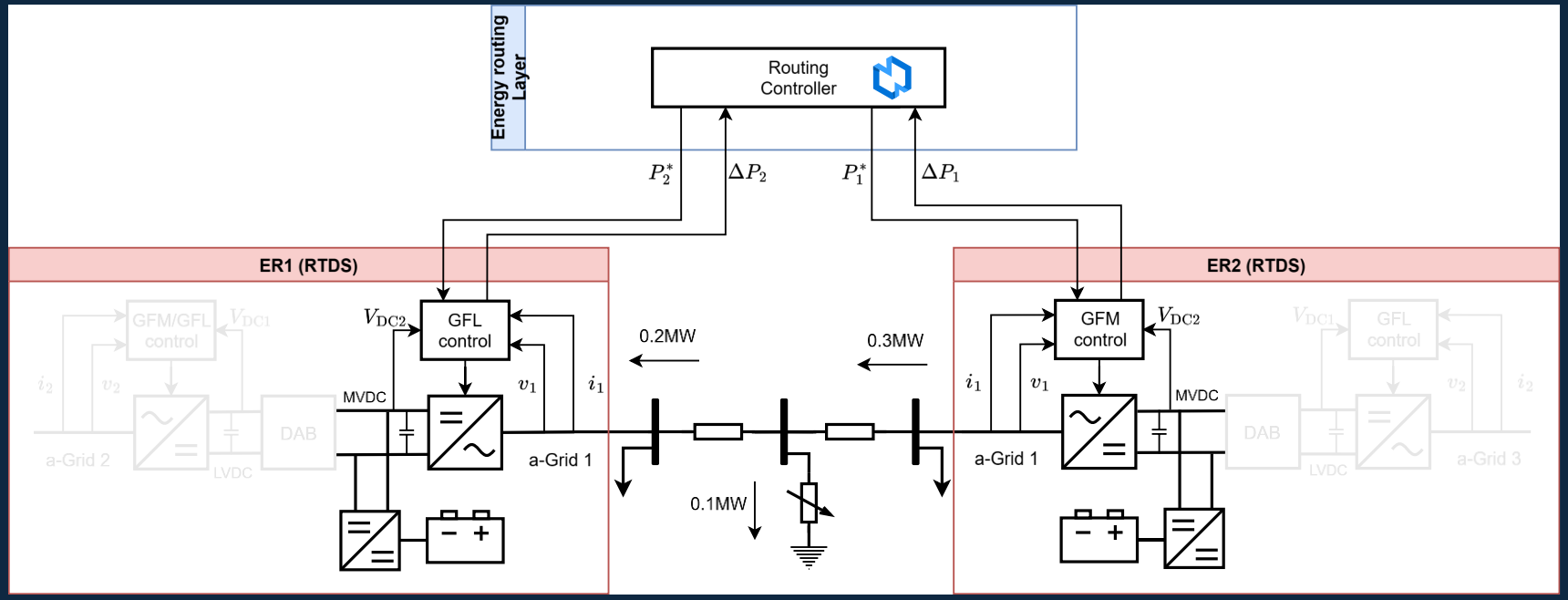
- VILLASnode is an open-source, flexible and real-time-capable gateway
- Supports multiple protocols, enabling co-simulation and HIL experiments
- Facilitates GD-RTS with WebRTC protocol support



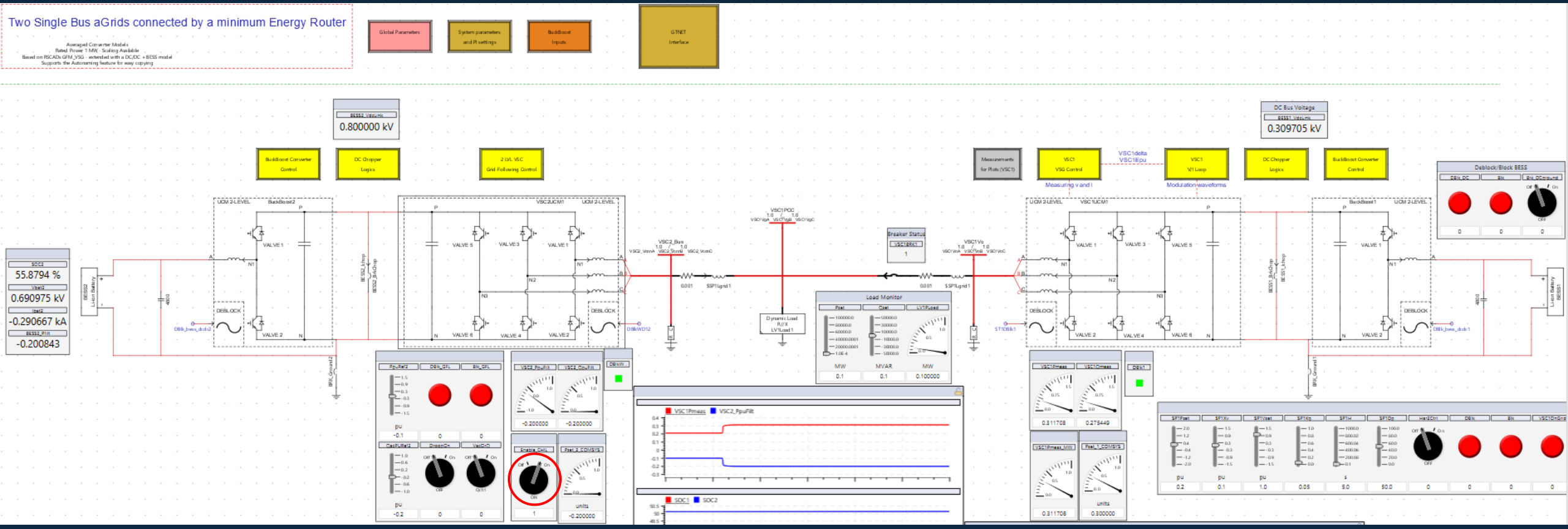

Setup 2: CHIL to test the SAFEr grid protocol stack

# Preliminary experiments I



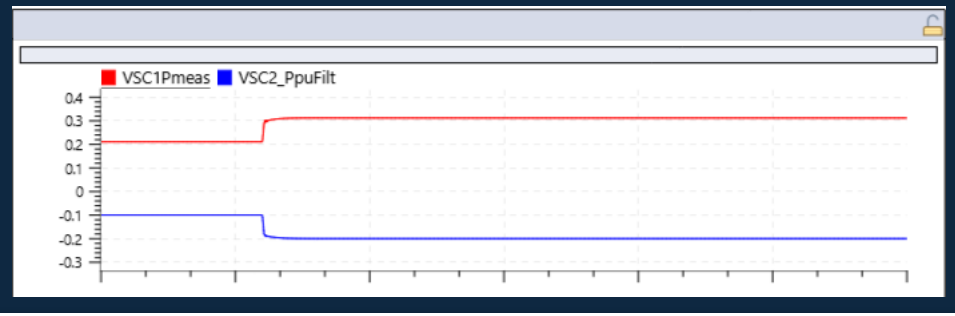



# Preliminary experiments II





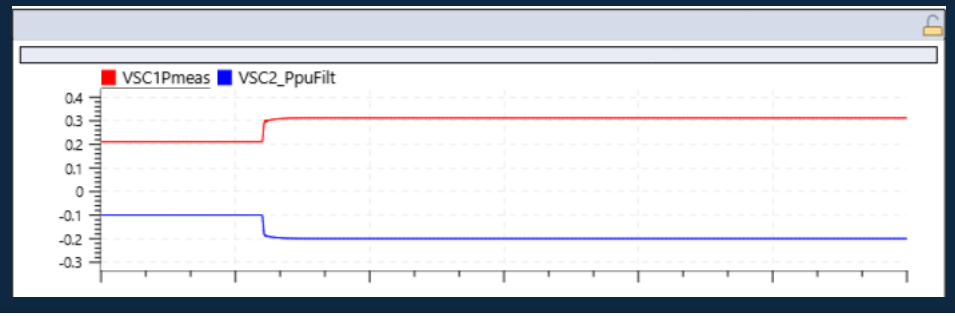




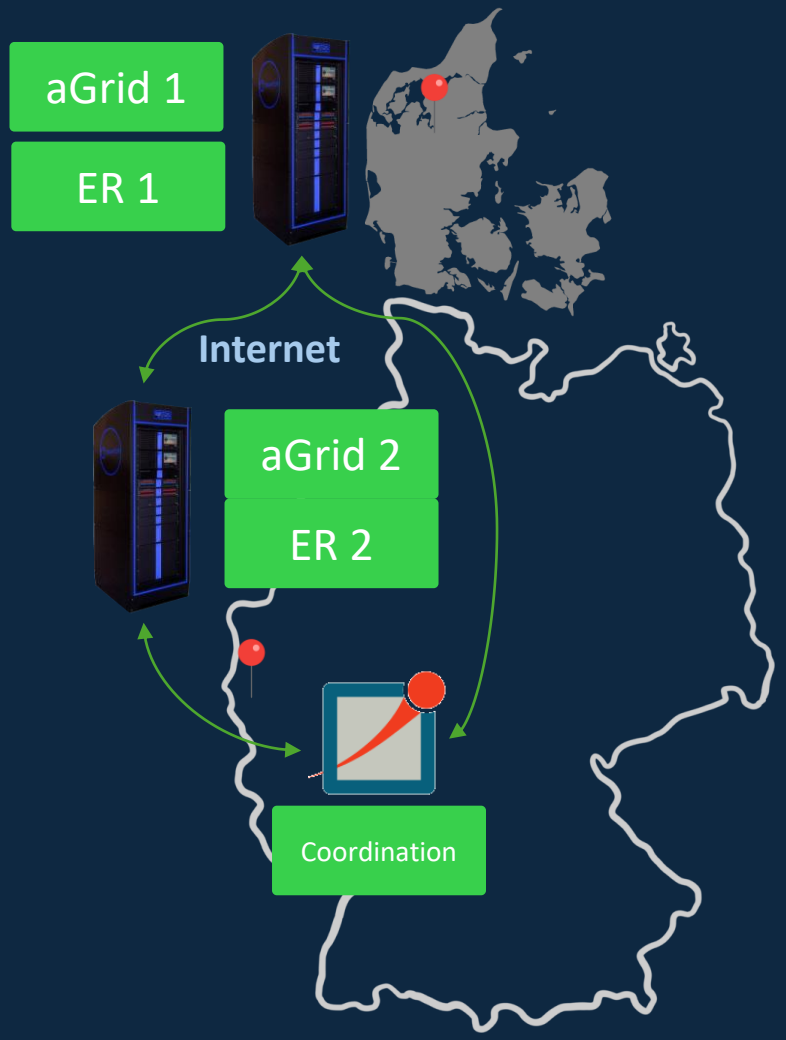
# Preliminary experiments III

| | | | P1 | SOC1 | P2 | SOC2 |
|---|---|---|---|---|---|---|
| villas_rwth | 09:44:43 info hook:print | rwth-rtds => loopback_node 1792403083.872272777+0.000000e+00(0) | 0.21061591804027557 | 49.21931457519531250 | -0.10000000149011612 | 50.04008102416992188 |
| villas_rwth | 09:44:44 info hook:print | rwth-rtds => loopback_node 1792403084.872033210+0.000000e+00(1) | 0.21061591804027557 | 49.20043563842773438 | -0.10000000149011612 | 50.04145431518554688 |
| villas_rwth | 09:44:45 info hook:print | rwth-rtds => loopback_node 1792403085.872416768+0.000000e+00(2) | 0.21061591804027557 | 49.18155670166015625 | -0.10000000149011612 | 50.04283142089843750 |
| villas_rwth | 09:44:46 info hook:print | rwth-rtds => loopback_node 1792403086.872367805+0.000000e+00(3) | 0.21061591804027557 | 49.16268157958984375 | -0.10000000149011612 | 50.04420471191406250 |
| villas_rwth | 09:44:47 info hook:print | rwth-rtds => loopback_node 1792403087.872267822+0.000000e+00(4) | 0.21061591804027557 | 49.14380645751953125 | -0.10000000149011612 | 50.04558181762695312 |
| villas_rwth | 09:44:48 info hook:print | rwth-rtds => loopback_node 1792403088.872225139+0.000000e+00(5) | 0.21061591804027557 | 49.12493133544921875 | -0.10000000149011612 | 50.04695510864257812 |
| villas_rwth | 09:44:49 info hook:print | rwth-rtds => loopback_node 1792403089.872386100+0.000000e+00(6) | 0.21061591804027557 | 49.10605621337890625 | -0.10000000149011612 | 50.04832839965820312 |
| villas_rwth | 09:44:50 info hook:print | rwth-rtds => loopback_node 1792403090.872349074+0.000000e+00(7) | 0.21061591804027557 | 49.08718490600585938 | -0.10000000149011612 | 50.04970550537109375 |
| villas_rwth | 09:44:51 info hook:print | rwth-rtds => loopback_node 1792403091.872400454+0.000000e+00(8) | 0.21061591804027557 | 49.06831741333007812 | -0.10000000149011612 | 50.05107879638671875 |
| villas_rwth | 09:44:52 info hook:print | rwth-rtds => loopback_node 1792403092.872440004+0.000000e+00(9) | 0.31175625324249268 | 49.04856872558593750 | -0.20001617074012756 | 50.05330657958984375 |
| villas_rwth | 09:44:53 info hook:print | rwth-rtds => loopback_node 1792403093.872409614+0.000000e+00(10) | 0.31170818209648132 | 49.02830505371093750 | -0.20000018179416656 | 50.05604171752929688 |
| villas_rwth | 09:44:54 info hook:print | rwth-rtds => loopback_node 1792403094.872538116+0.000000e+00(11) | 0.31170752644538879 | 49.00804138183593750 | -0.20000000298023224 | 50.05877304077148438 |
| villas_rwth | 09:44:55 info hook:print | rwth-rtds => loopback_node 1792403095.872540793+0.000000e+00(12) | 0.31170749664306641 | 48.98777770996093750 | -0.20000000298023224 | 50.06150817871093750 |
| villas_rwth | 09:44:56 info hook:print | rwth-rtds => loopback_node 1792403096.872552471+0.000000e+00(13) | 0.31170749664306641 | 48.96751785278320312 | -0.20000000298023224 | 50.06423950195312500 |
| villas_rwth | 09:44:57 info hook:print | rwth-rtds => loopback_node 1792403097.872666814+0.000000e+00(14) | 0.31170749664306641 | 48.94725799560546875 | -0.20000000298023224 | 50.06697463989257812 |
| villas_rwth | 09:44:58 info hook:print | rwth-rtds => loopback_node 1792403098.872637862+0.000000e+00(15) | 0.31170749664306641 | 48.92699813842773438 | -0.20000000298023224 | 50.06970596313476562 |
| villas_rwth | 09:44:59 info hook:print | rwth-rtds => loopback_node 1792403099.872786499+0.000000e+00(16) | 0.31170749664306641 | 48.90674209594726562 | -0.20000000298023224 | 50.07243728637695312 |
| villas_rwth | 09:45:00 info hook:print | rwth-rtds => loopback_node 1792403100.872705196+0.000000e+00(17) | 0.31170749664306641 | 48.88648605346679688 | -0.20000000298023224 | 50.07517242431640625 |
| villas_rwth | 09:45:01 info hook:print | rwth-rtds => loopback_node 1792403101.872783516+0.000000e+00(18) | 0.31170749664306641 | 48.86623001098632812 | -0.20000000298023224 | 50.07790374755859375 |
| villas_rwth | 09:45:02 info hook:print | rwth-rtds => loopback_node 1792403102.872836520+0.000000e+00(19) | 0.31170749664306641 | 48.84597778320312500 | -0.20000000298023224 | 50.08063888549804688 |
| villas_rwth | 09:45:03 info hook:print | rwth-rtds => loopback_node 1792403103.872831423+0.000000e+00(20) | 0.31170749664306641 | 48.82572555541992188 | -0.20000000298023224 | 50.08337020874023438 |



# Summary



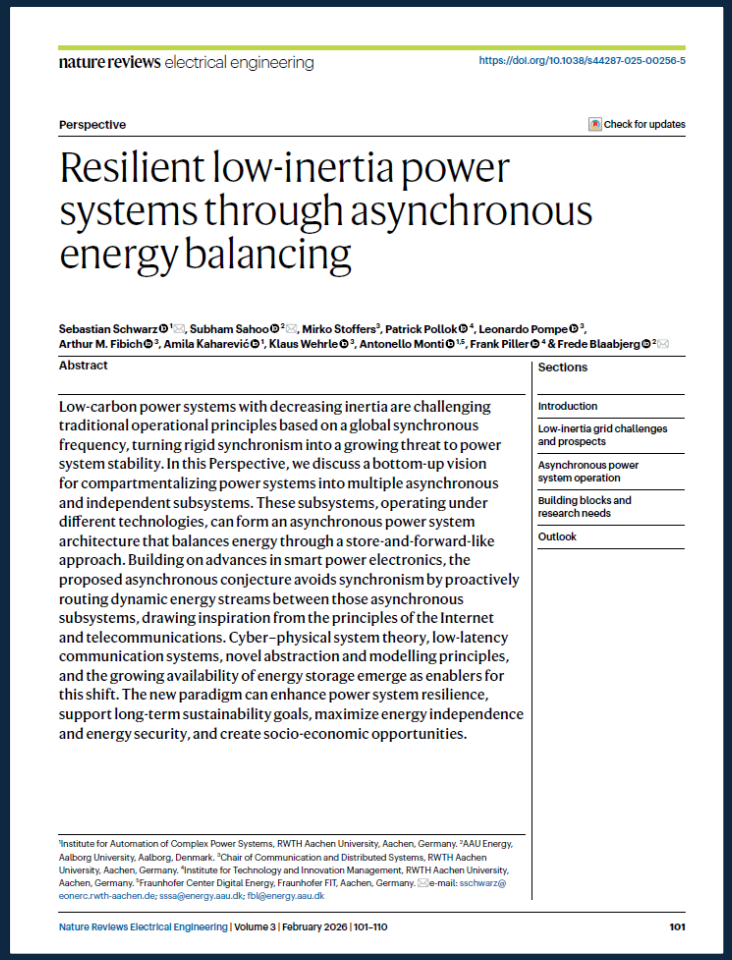

- Grid operation will be redefined with **SAFEr Grid** project
- **RTDS** for **energy router** models
  - Capacity
  - Flexibility expectation
  - Stability investigation (Compartmental grid)
- **Villas** allow **co-simulation**
  - Between different RTDS instances
  - And to the cyber physical layer
- **OMNeT++** covers the communication
  - Delays and real network scenarios
  - Solutions to operating setpoints

# Acknowledgment


**Subham Sahoo**
*Aalborg University*
sssa@energy.aau.dk

**Andres Acosta**
*RWTH Aachen University*
andres.acosta@eonerc.rwth-aachen.de

**Majd Hamza**
*RWTH Aachen University*
majd.hamza@comsys.rwth-aachen.de

nature reviews electrical engineering

https://doi.org/10.1038/s44287-025-00256-5

Perspective

Check for updates

Resilient low-inertia power systems through asynchronous energy balancing

Sebastian Schwarz, Subham Sahoo, Mirko Stoffers, Patrick Pollok, Leonardo Pompe, Arthur M. Fibich, Amila Kaharević, Klaus Wehrle, Antonello Monti, Frank Piller & Frede Blaabjerg

Abstract

Low-carbon power systems with decreasing inertia are challenging traditional operational principles based on a global synchronous frequency, turning rigid synchronism into a growing threat to power system stability. In this Perspective, we discuss a bottom-up vision for compartmentalizing power systems into multiple asynchronous and independent subsystems. These subsystems, operating under different technologies, can form an asynchronous power system architecture that balances energy through a store-and-forward-like approach. Building on advances in smart power electronics, the proposed asynchronous conjecture avoids synchronism by proactively routing dynamic energy streams between those asynchronous subsystems, drawing inspiration from the principles of the Internet and telecommunications. Cyber–physical system theory, low-latency communication systems, novel abstraction and modelling principles, and the growing availability of energy storage emerge as enablers for this shift. The new paradigm can enhance power system resilience, support long-term sustainability goals, maximize energy independence and energy security, and create socio-economic opportunities.

Sections

Introduction

Low-inertia grid challenges and prospects

Asynchronous power system operation

Building blocks and research needs

Outlook

Nature Reviews Electrical Engineering | Volume 3 | February 2026 | 101–110

101


This work was supported by an ERC Synergy Grant (Grant No. SAFEr Grid [101166783]).