Karlsruher Institut für Technologie

The Energy Packet Grid

Transferring Internet ideas to the Power Grid

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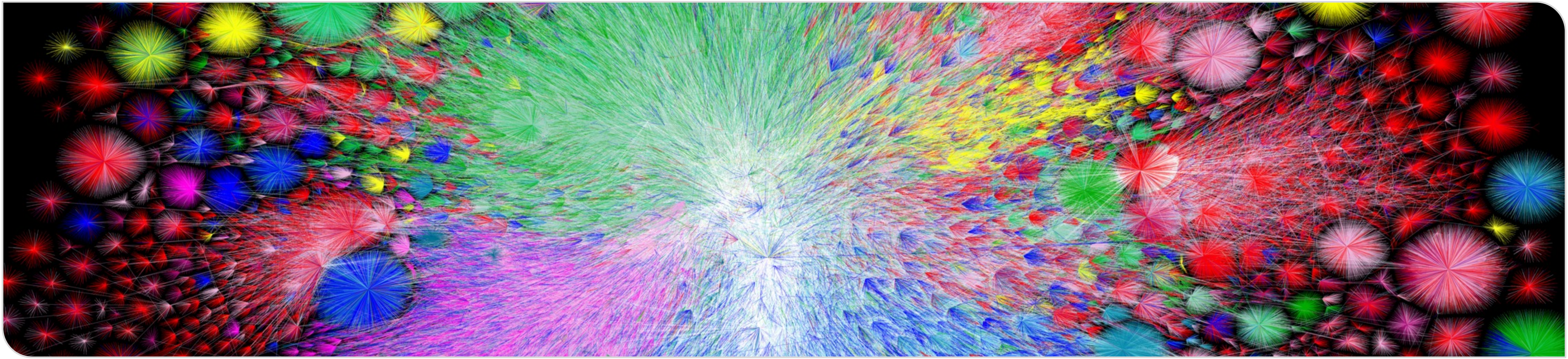
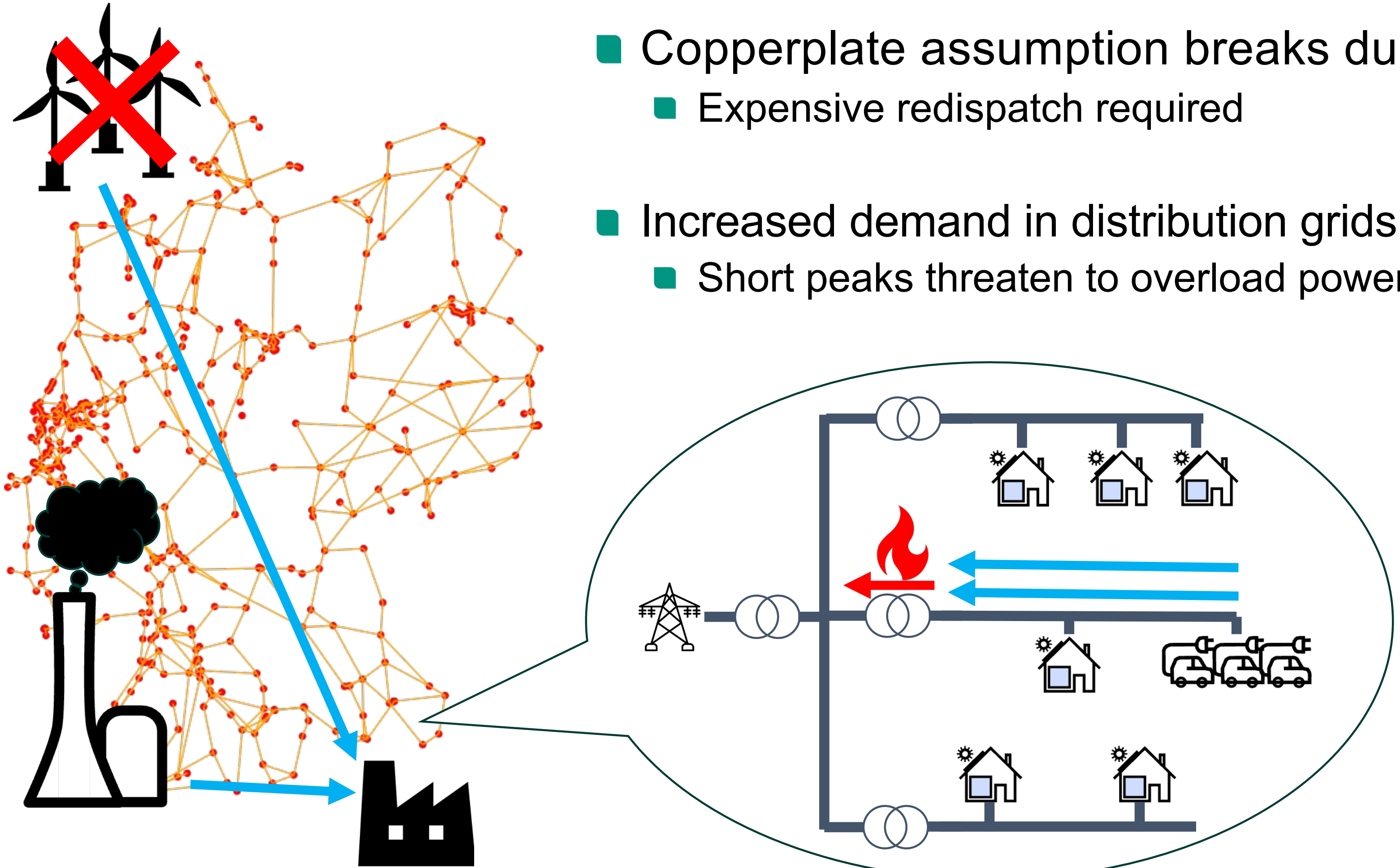


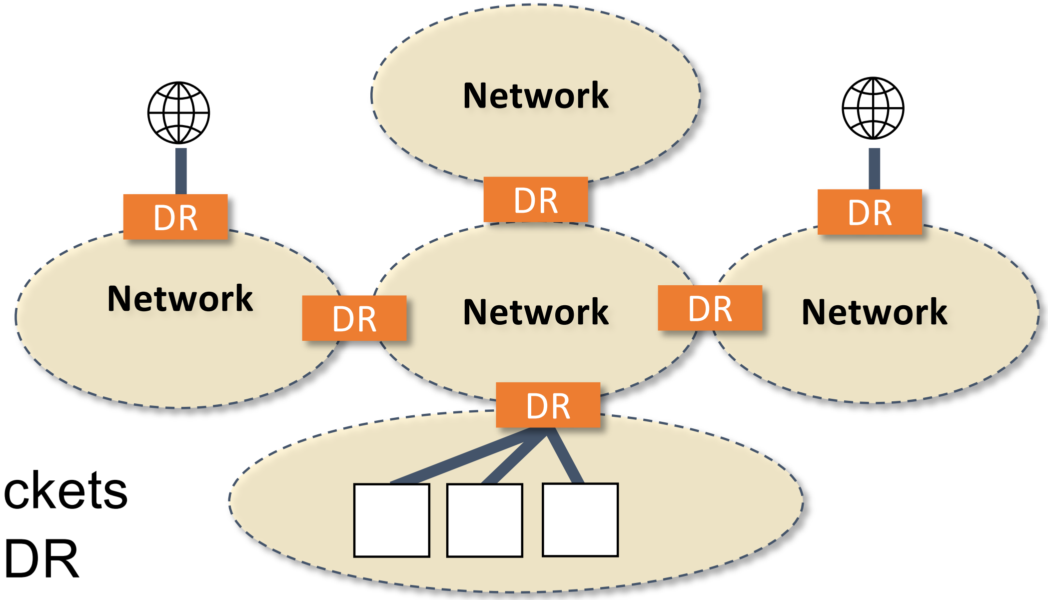
Current Power Grid Challenges

- Copperplate assumption breaks during peaks
  - Expensive redispatch required
- Increased demand in distribution grids
  - Short peaks threaten to overload power lines/transformers

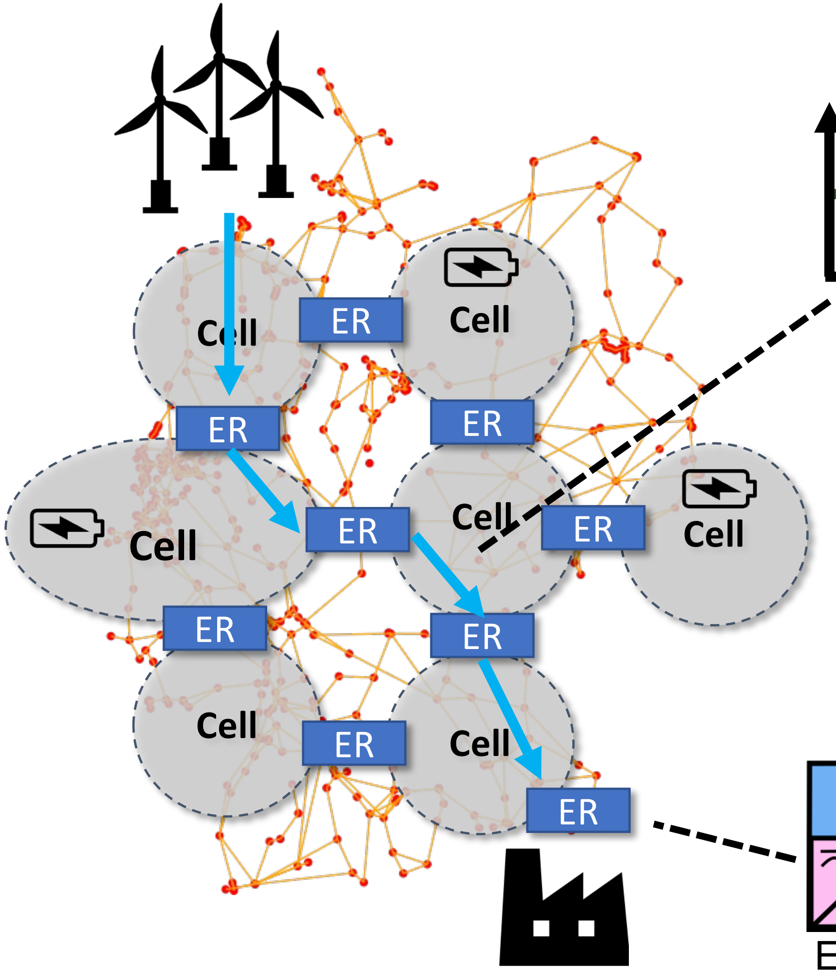


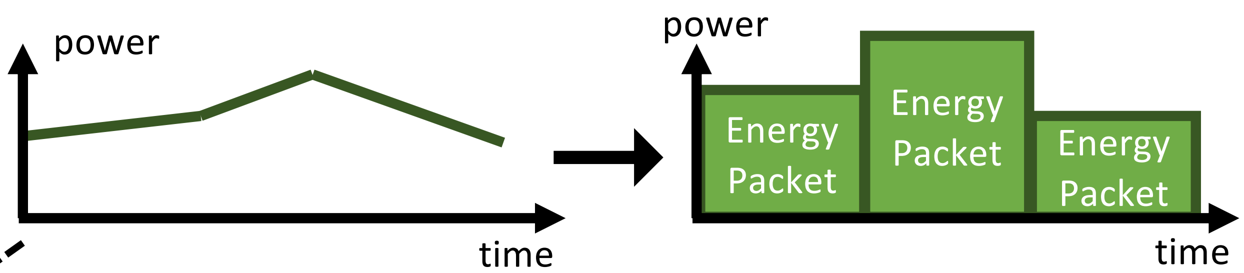
Taking inspiration from the Internet

- The Network of Networks
  - Division into independent subnets
  - Data Routers (DR) connect subnets
  - Divide and conquer principle
- Discretization approach
  - Data streams discretized into data packets
  - Packets routed trough network using DR

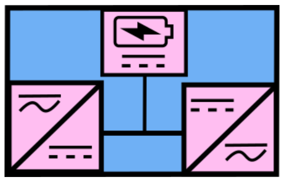


The Energy Packet Grid: A future Power Grid Architecture



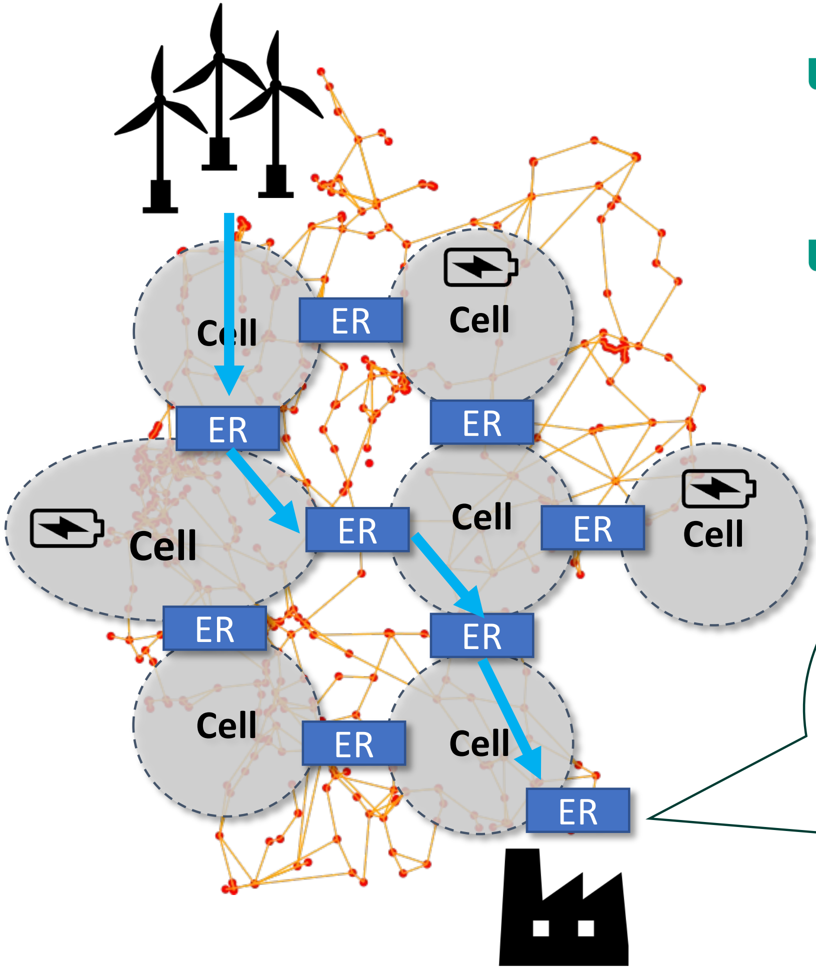


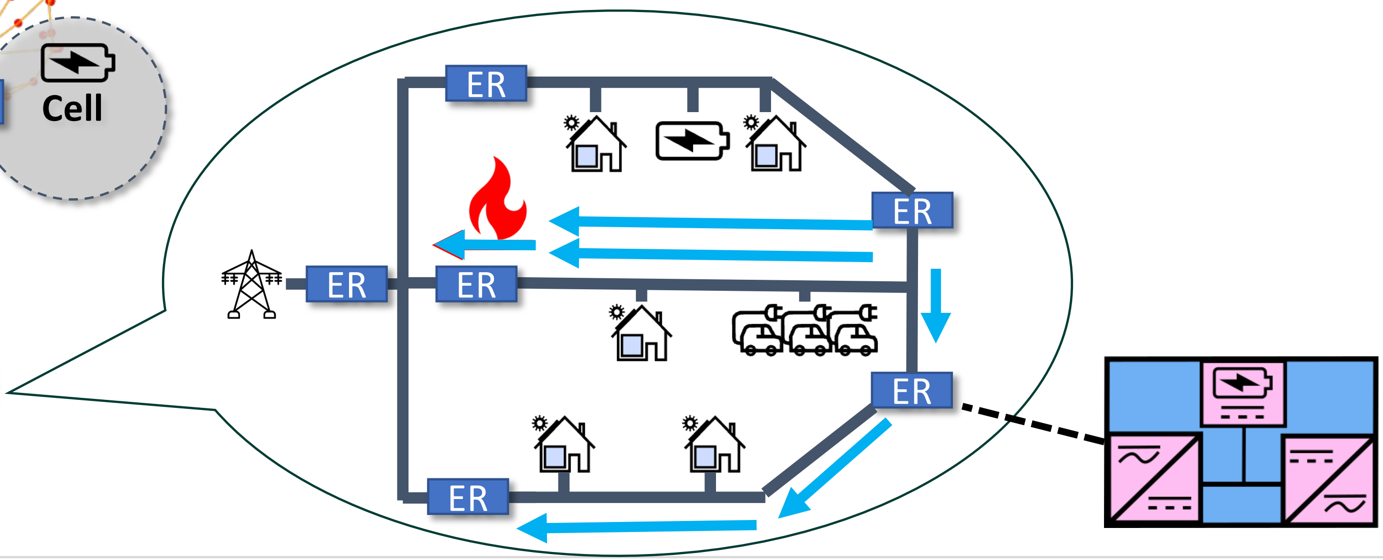
- Power grid separated into cells
  - Electrically independent
  - Connected using Energy Routers (ER)
- Power flows discretized into Energy Packets (EP)
  - Scheduling between consecutive EPs


Energy Router

The Energy Packet Grid: A future Power Grid Architecture

- Distribution grids transformed into mesh-topology
  - ERs connect previously unconnected power line segments
- Enables balancing of local feeders

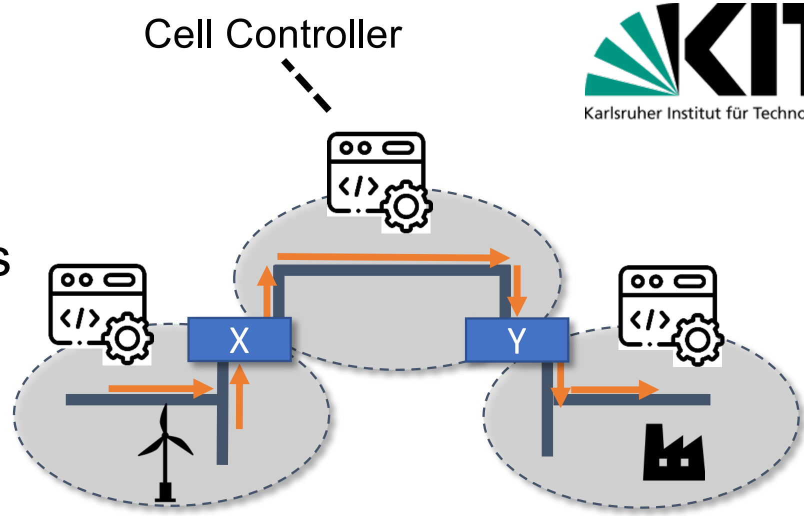


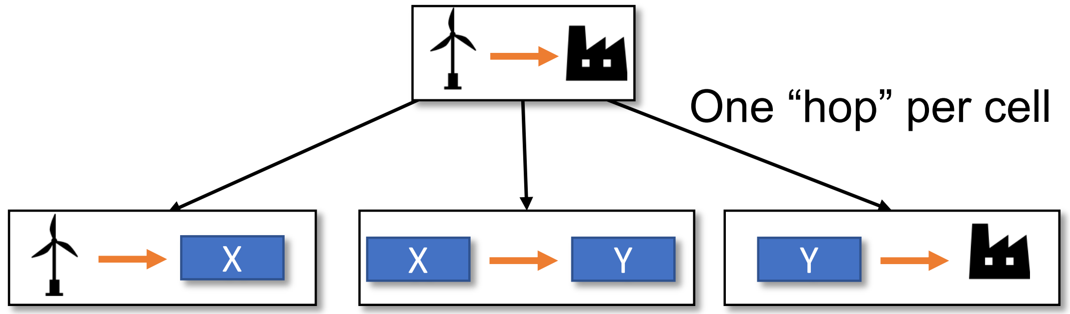


Distributed control architecture

- Idea: Media Access Layer for the Smart Grid
- EP Transfers performed between participants
  - Transfer a predefined energy and power
  - Self-Healing

- Cell Controllers placed in each cell
  - Approve and schedule EP Transfers
  - Operate independently
  - Ensures safe operation, i.e., infrastructure limits





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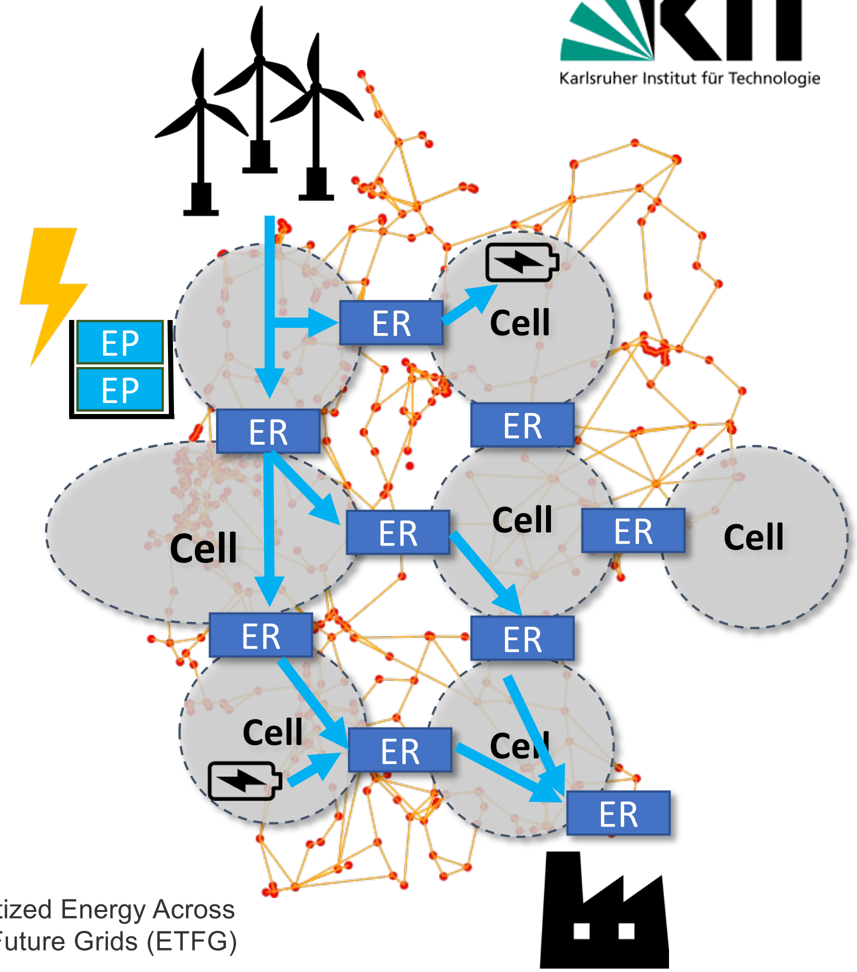
Schneider, K; Schulz, D; Helmig, D.; Wiegel, F.; Hagenmeyer, V; Hiller, M; Zitterbart, M. (2025). Scheduling Electric Currents in Converter-Dominated Power Grids with Time-Slotted Energy Packets. In: Energy Informatics. EI.A 2024

Active steering of power flows

- Steer power flows on alternate paths
  - Distributes load evenly across the grid
- Key Mechanism: Congestion Control
  - Throttles power flows to prevent overloads
  - Causes Back-Pressure at generators
- Back-Pressure reported to scheduling
  → Creates feedback loop



Hildenbrand, C.; Schneider, K.; Schulz, D.; Hiller, M.; Hagenmeyer, V.; Zitterbart, M. "Transferring Packetized Energy Across Cells with Asynchronous Forwarding", 2025 IEEE International Conference on Energy Technologies for Future Grids (ETFG)

Hildenbrand, C.; Schneider, K.; Schulz, D.; Hiller, M.; Hagenmeyer, V.; Zitterbart, M. "Controlling power flows in a meshed power grid using congestion aware Asynchronous Forwarding", In: Energy Informatics. EI.A 2026, In Submission

Internet Concepts for the Smart Grid !?

- Topic is not that new
- Various approaches in research
  - The Energy Internet, 2011 [1]
  - Digital Grid, 2011 [2]
  - TCP-like EV charging controller, 2019 [3]
  - Cellular transformation of the Grid, 2015 [4]
- … but what about evaluations, real implementations, and experience ?

- Earlier discussions among various attendees here





[1] Huang, A.Q., Crow, M.L., Heydt, G.T., Zheng, J.P., Dale, S.J.: The future renewable electric energy delivery and management (freedm) system: The energy internet. Proceedings of the IEEE 99

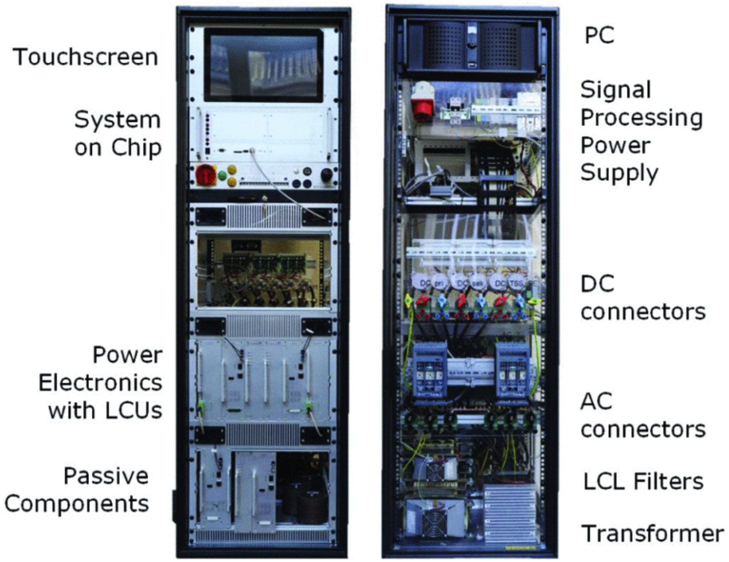
[2] Abe, R., Taoka, H., McQuilkin, D.: Digital grid: Communicative electrical grids of the future. IEEE Transactions on Smart Grid 2

[3] Alyousef, Ammar & Meer, Hermann. (2019). Design of a TCP-like Smart Charging Controller for Power Quality in Electrical Distribution Systems.

[4] VDE-ETG Task Force: The Cellular Approach – The Basis of Successful, Cross-regional Energy Transition, 2015, VDE Study. Available online: www.vde.com/resource/blob/2316160/9e7075474d567a1a30e9459b6ca467b5/ vde-study-the-cellular-approach-data.pdf (accessed July 3, 2026).

Hardware Prototypes and Experiments

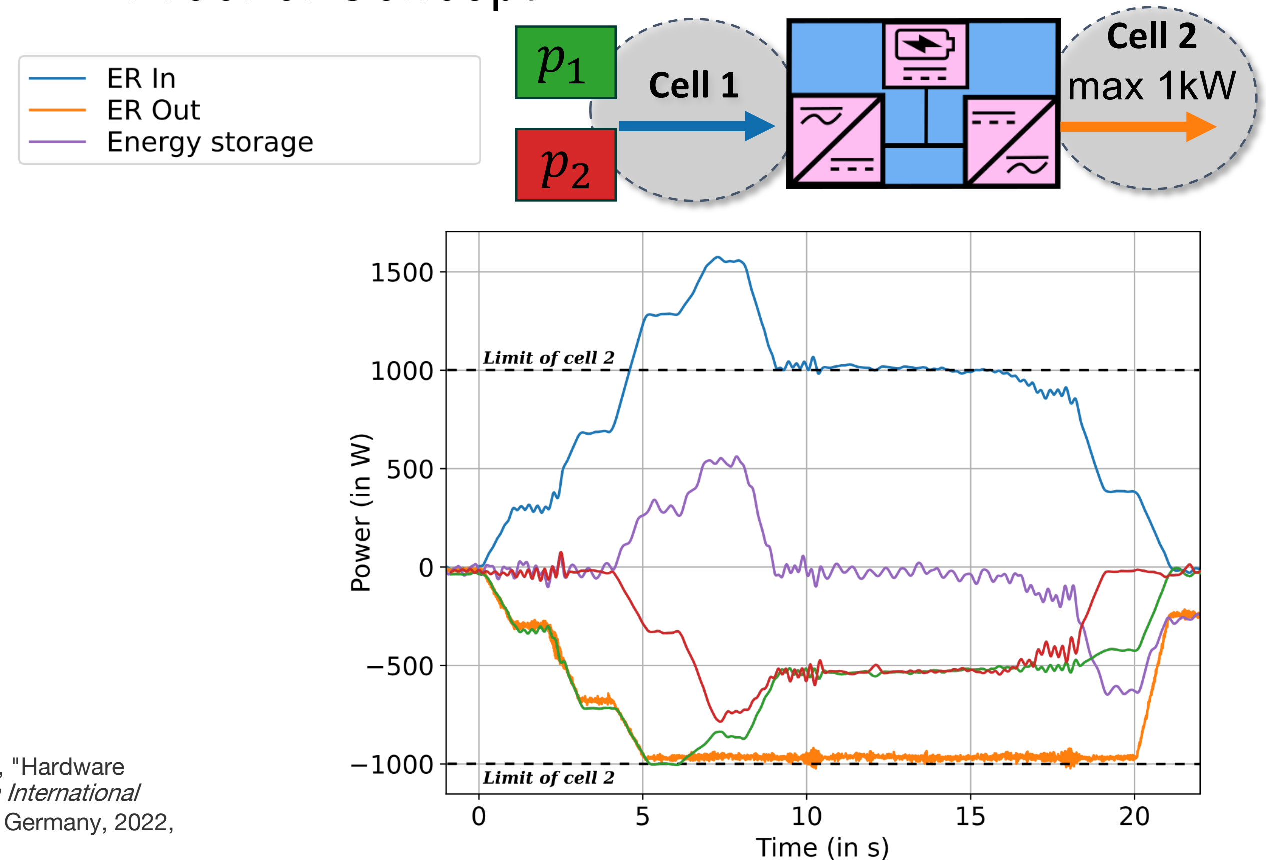
Prototype ER



KIT Future Fields Project
Hagenmeyer, Hiller, Zitterbart

D. Schulz, K. Schneider, M. Weßbecher, V. Hagenmeyer, M. Zitterbart and M. Hiller, "Hardware Realization of Participants in an Energy Packet-based Power Grid," *2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Kiel, Germany, 2022, pp. 1-6, doi: 10.1109/PEDG54999.2022.9923290.

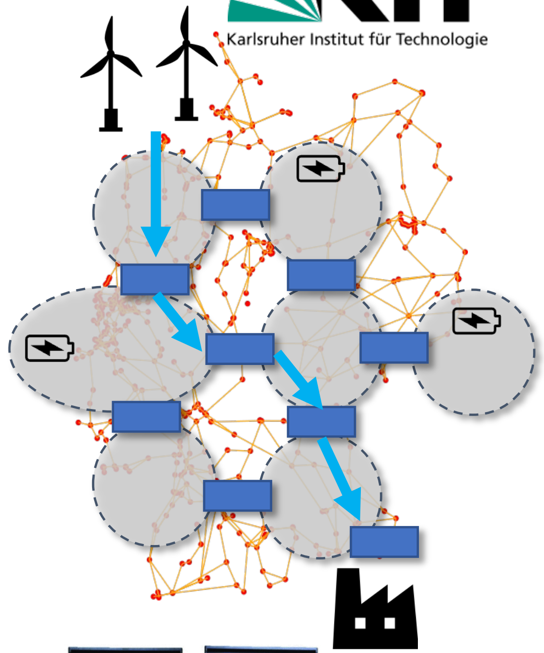
Proof of Concept

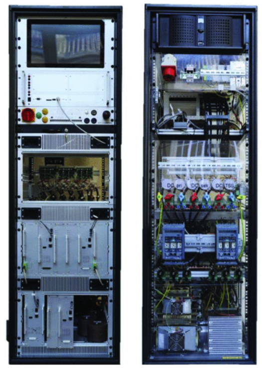


Conclusion

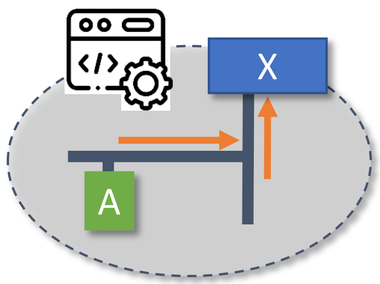
- New power grid architecture: The EP Grid
  - Inspired from the Internet
  - Based on Energy Packet Transfers
- Design and evaluation of first EP Grid protocols
  - Work on prototypical Energy Routers
- High complexity
  - Electrical engineering, Optimization, Communication, etc.

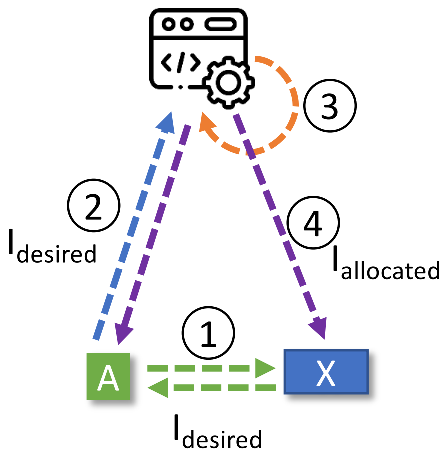
→ Interdisciplinary group of researchers required



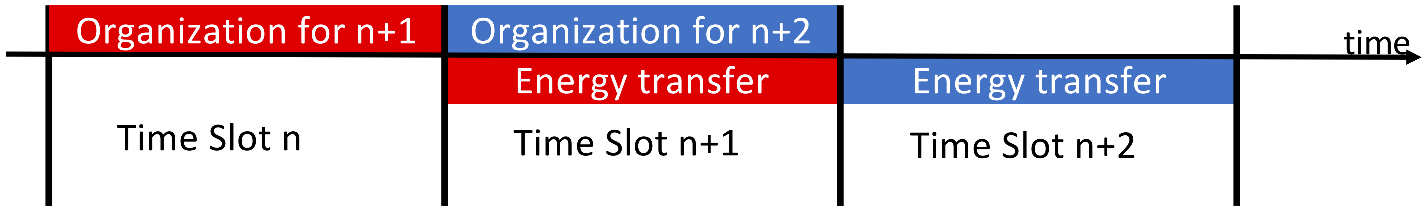


Intra-Cell: Time-slotted EP Transfer (TEPT) Protocol

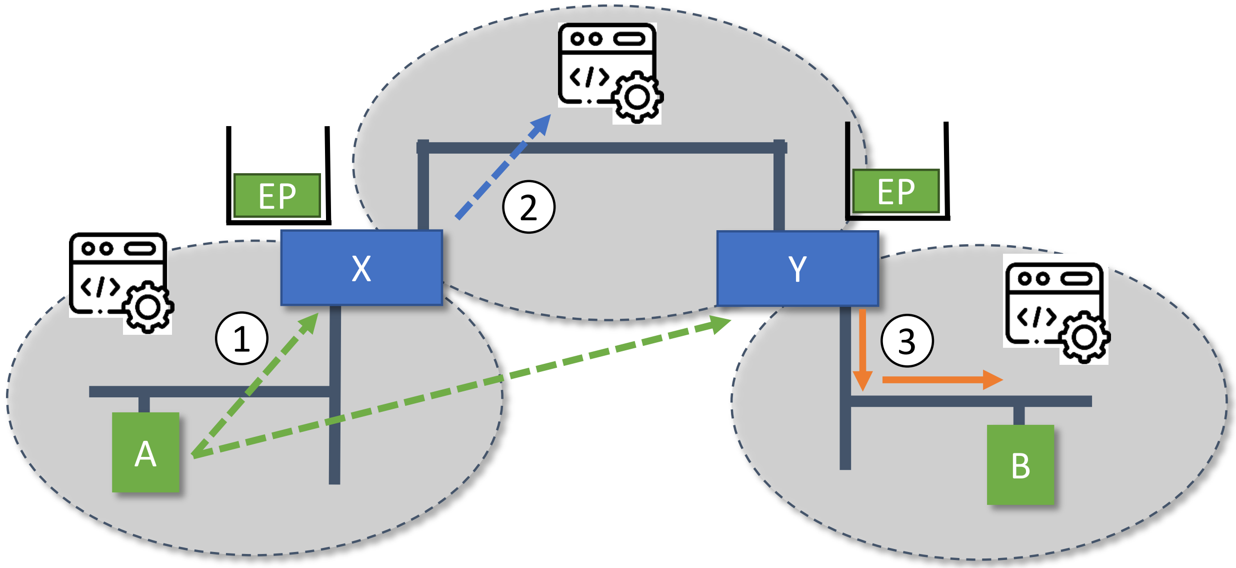




- ① Devices agree on parameters
  - Desired electric current: $I_{desired}$
- ② Register EP transfer at the Cell controller
- ③ Calculation of schedule
  - Goal: no power line overloading
- ④ Distribute results
  - Allocated electric current: $I_{allocated} \leq I_{desired}$



Intra-Cell: Asynchronous Forwarding



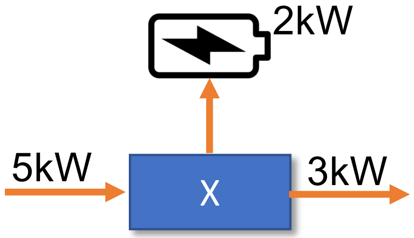
→ 1 Device A requests Inter-Cell transfer at ERs X & Y

- Energy Packet is put into queue, desired power P_{wish}

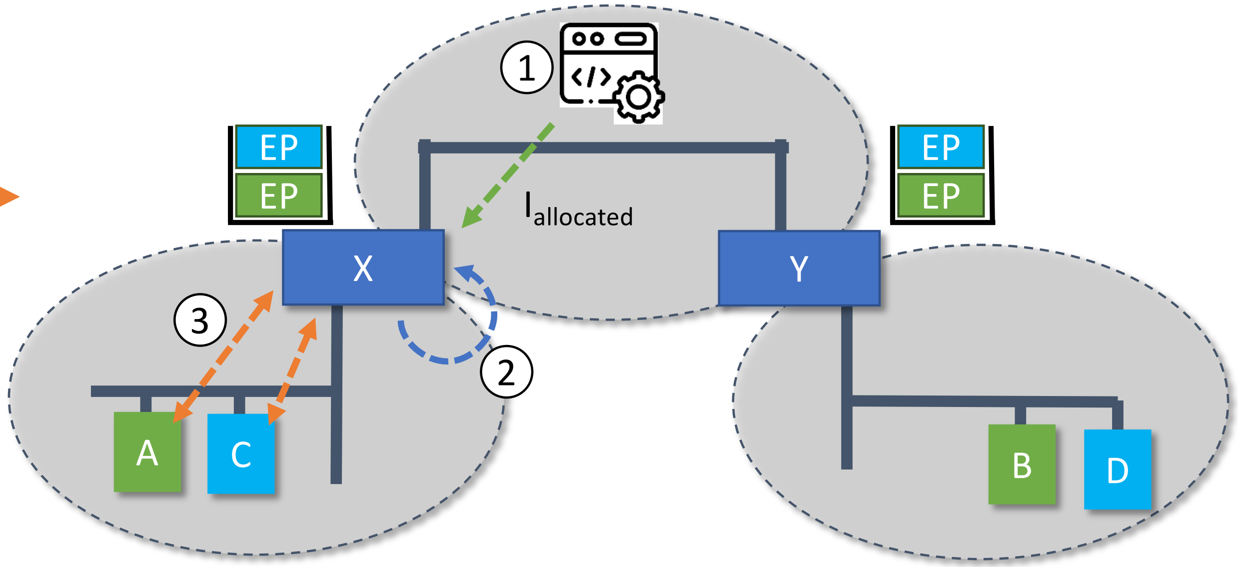
→ 2 Each ER negotiates Intra-Cell transfer to next hop

→ 3 Each ER is allocated line capacity to next hop

Congestion Control



Congested ER



- ① Estimate available line capacity
  - Based on recent allocated electric current: $I_{allocated}$
- ② Distribute available line capacity
- ③ A and X update their desired power P_{wish}