UNIVERSITY OF PASSAU
Faculty of Computer Science and Mathematics

Unlocking Flexibility Potentials of Data Centers and Multi-Use Battery Storages

Prof. Hermann de Meer (demeer@uni-Passau.de), **Alexander Kilian**, and **Michael Lechl**
Chair of Computer Networking and Computer Communications
University of Passau

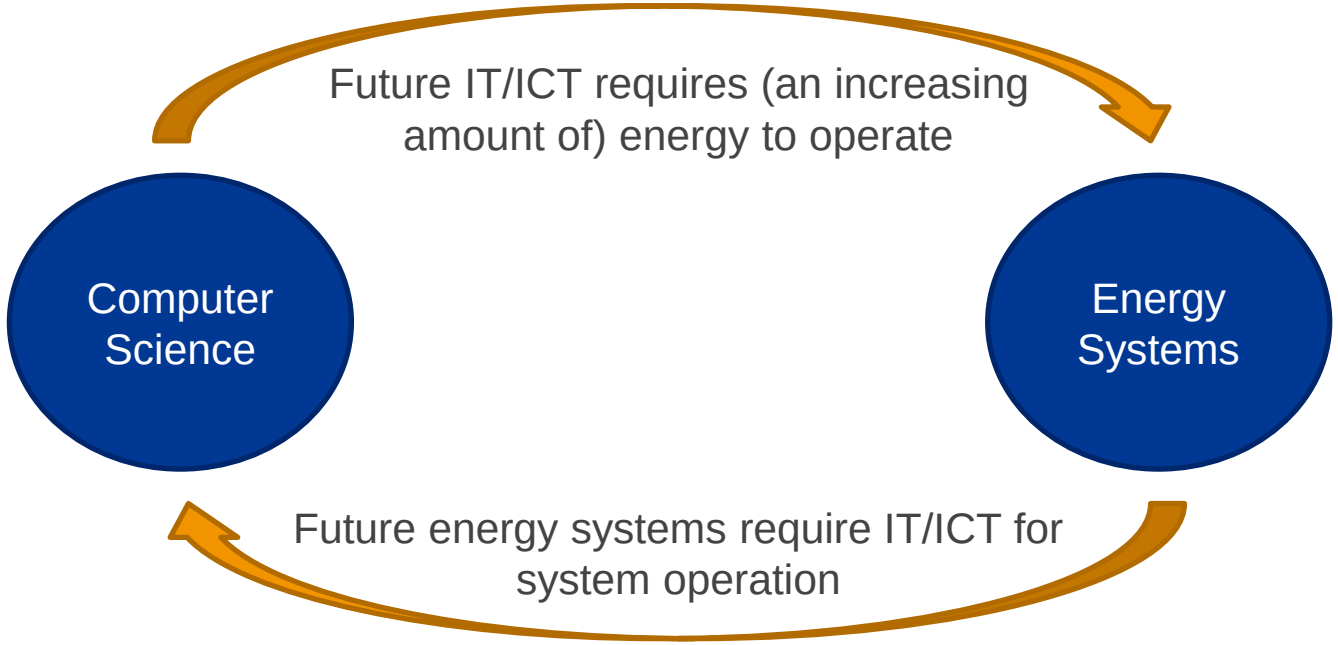
Computer Networks & Communications
Prof. Hermann de Meer

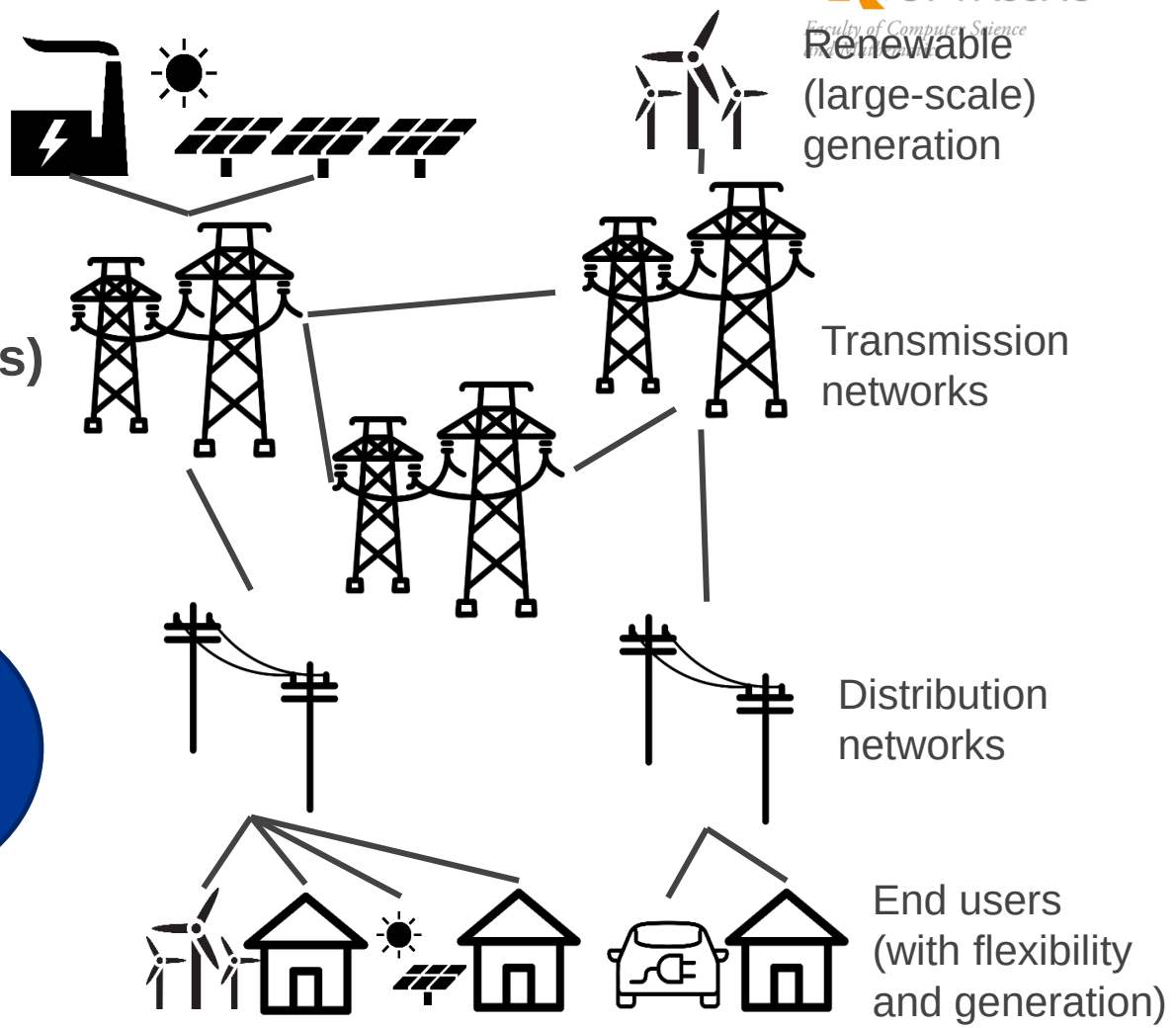
24.07.2025

Motivation: Impact of IT Systems on Energy Systems

Mutual Dependency of Power Systems and Data Networks

- **Then:** Large-scale generation connected to transmission network
- **Now**: Decentralized energy system with high penetration of **Renewable Energy Sources (RESs)**





Motivation: Impact of IT Systems on Energy Systems

Mutual Dependency of Power Systems and Data Networks

UNIVERSITY OF PASSAU
Faculty of Computer Science and Mathematics

- Two aspects of **sustainability**
  - **Energy efficiency**
    - **Local perspective**
      - Minimize power usage of consuming entities (technical solution)
    - **Grid perspective**
      - Mitigate congestion due to local overproduction
      - Consume otherwise curtailed energy
    - **Global perspective**
      - Match demand and volatile supply (demand response)
  - **Cost effectiveness**
    - RES-based energy is **cheaper than gray electricity** (merit order)
    - RESs inherit a **lower carbon footprint**
      - Lower CO_2 emissions economically coupled through **emission certificate trading**

Flexible Energy Demand from Supercomputers

Project overview

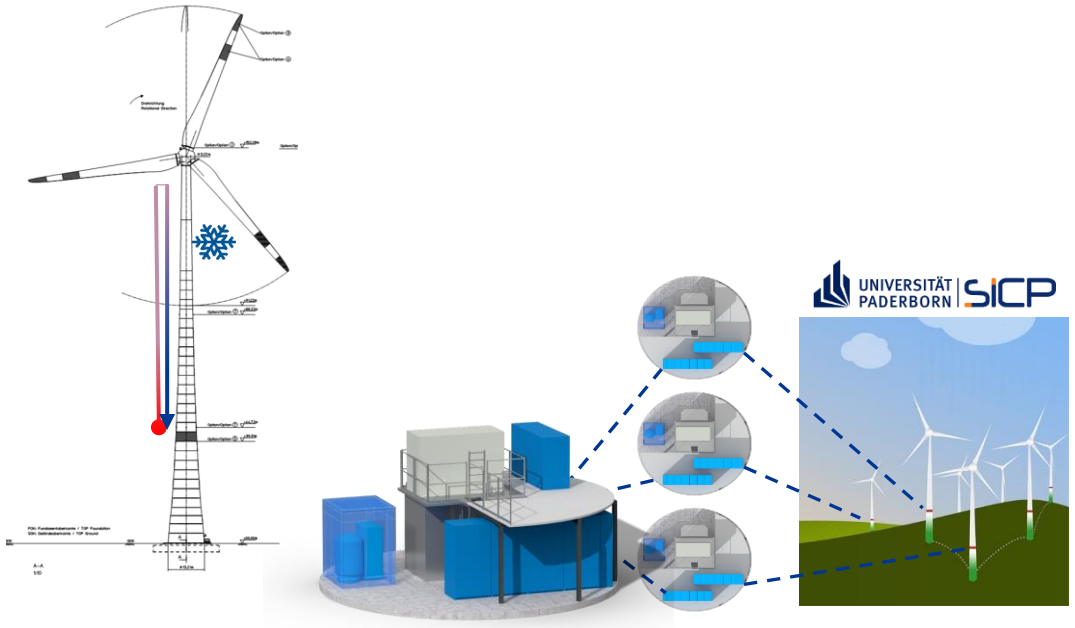
UNIVERSITY OF PASSAU
Faculty of Computer Science and Mathematics

❝ **Energy-Optimized Supercomputer Networks Using Wind Energy**

🗣 Alexander Kilian (alexander.kilian@uni-passau.de)

💰 Federal Ministry of Research, Technology and Space (BMFTR)

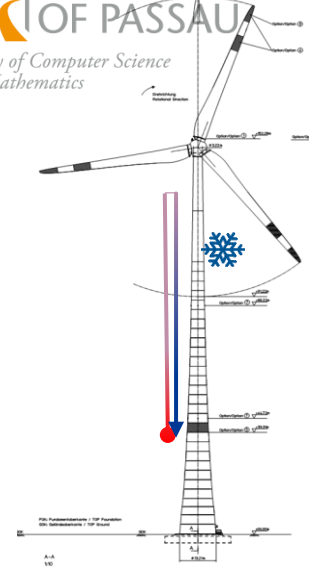
🕒 09.2022 - 3.2026



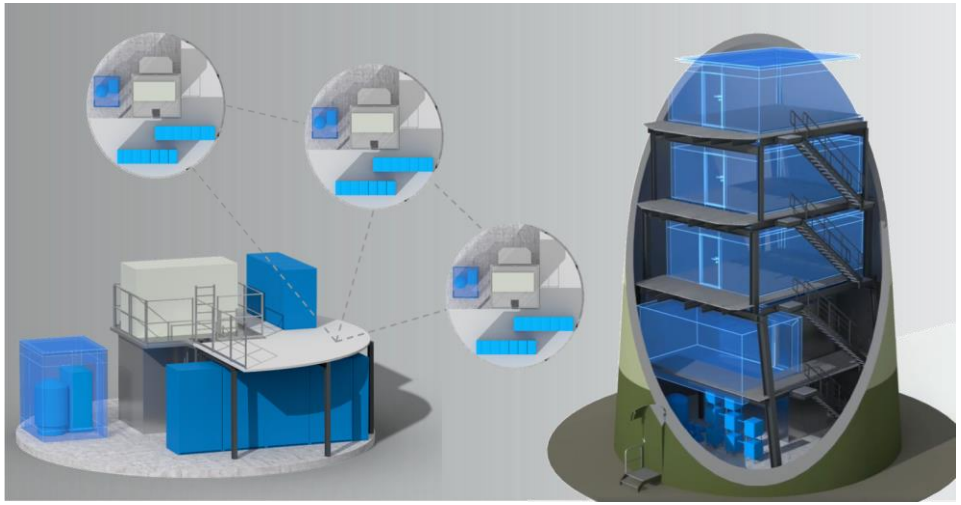
Flexible Energy Demand from Supercomputers

Energy-Optimized Supercomputer Networks Using Wind Energy

UNIVERSITY OF PASSAU
Faculty of Computer Science and Mathematics



- **Objectives**
  - **Maximize operational sustainability** of **energy-hungry** high-performance computing data centers (HPC-DCs)
  - **Increase effective power output** of RESs
- **Benefits**
  - Maximum direct and **low-loss energy supply**
    - → **Minimize power curtailment** of RESs
    - → **Congestion-awareness** of DC operation
  - **Efficient cooling** and waste heat usage
    - Wind turbine tower acts as heat sink
  - Wind turbine as an already **existing facility**
  - **Foster grid friendliness** by exploiting **flexibility potentials on demand side**



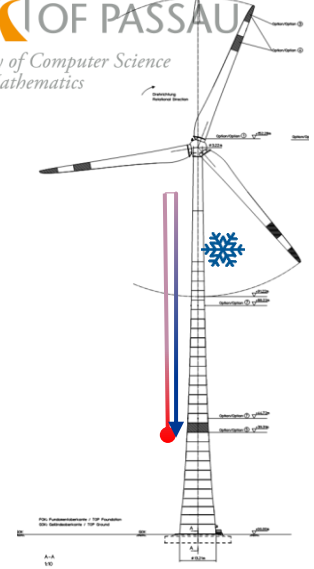
[Kilian 2025, CACM] [Berl 2009, Comput. J.]

ESN4NW@SICP.DE

Flexible Energy Demand from Supercomputers

Energy-Optimized Supercomputer Networks Using Wind Energy

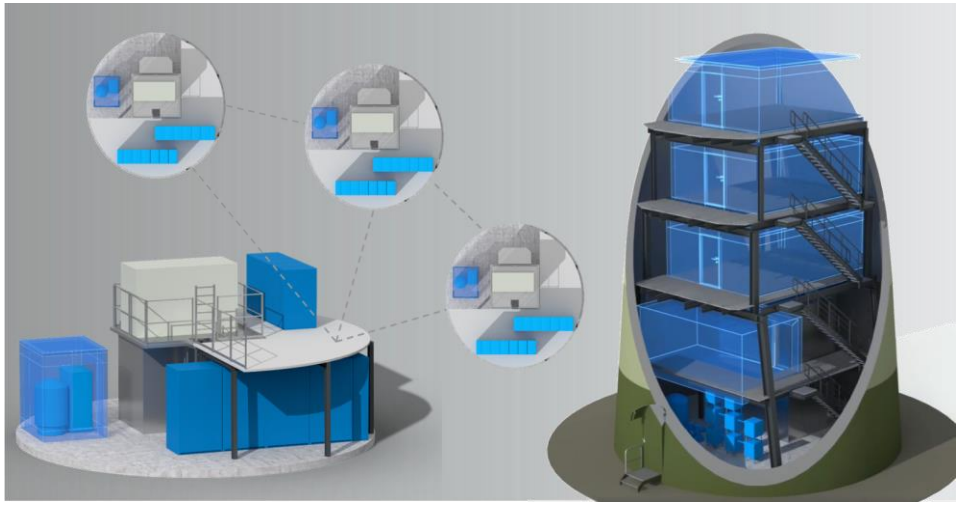
UNIVERSITY OF PASSAU
Faculty of Computer Science and Mathematics



- **Data-driven methods** and Artificial Intelligence (AI) for operational management and control of the distributed HPC cluster
  - **Reinforcement Learning** (RL) for load distribution of energy-hungry AI workloads
    - **Computational constraints** (resource availability)
    - **Environmental constraints** (thermal limits in tower, weather conditions, (wind) energy availability)
    - **User constraints** → Green Service-Level Agreements **(GreenSLAs)**
- **DC resource consolidation** (local)
- **Congestion-aware generation and consumption** (grid)
- **Spatiotemporal shifts of workloads** (global)

→ **AI for Sustainability & Sustainable AI** using **flexibility potentials**

  - See also Internet-Draft “Environmental Sustainability Terminology and Concepts” (draft-pignataro-green-enviro-sust-terminology-02)



[Kilian 2025, CACM] [Basmadjian 2018, IEEE Trans. on Smart Grid]

UNIVERSITY OF PASSAU
Faculty of Computer Science and Mathematics

FLEXIBILITY
DFG SPP 1984

❝ **Formal Modeling of Operational Flexibility in Multi-scale Multi-modal Energy Systems**

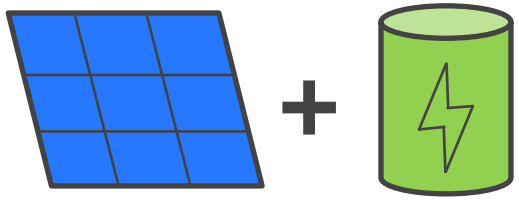
🗣 Michael Lechl (michael.lechl@uni-passau.de)

💰 German Research Foundation (DFG)

🕒 5.2021 - 6.2026

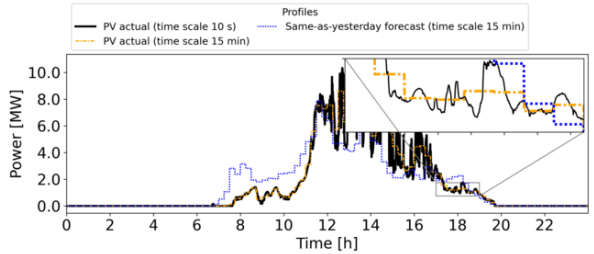
Multi-Use Battery Storage Systems

Example Use Case and Solution



Solar Farm Battery

Use Case: Schedule Battery Storage System (BSS) to **maximize economic revenues** on time scale Δ (e.g., 1 h)



PV power
- fluctuates on **multiple time scales**
- is subject to **uncertainty**

- Forecast deviations can significantly impair intraday prices
- **Alternative: Multi-Use BSS**
- Trade-off between
  - **Economic revenues**
  - **Balance uncertain deviations**

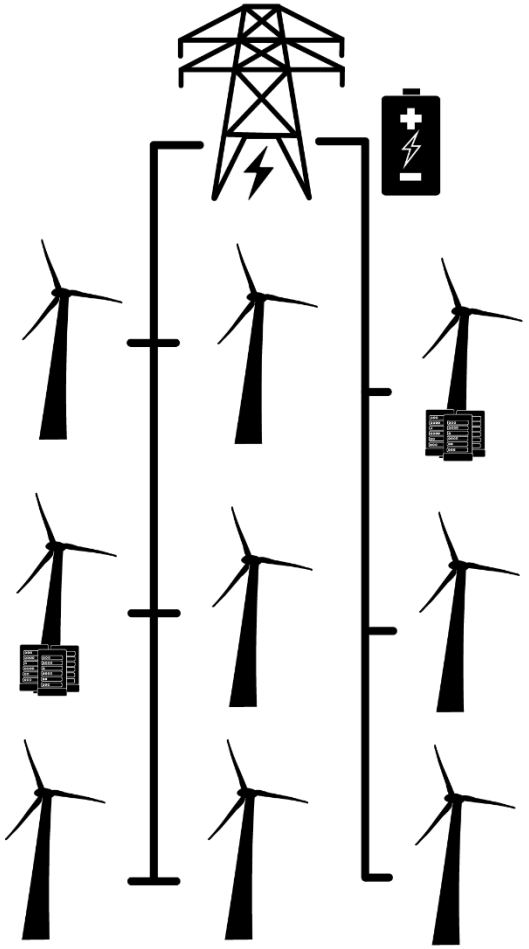
- How to model and quantify flexibility requirements (PV fluctuations) and potentials (from BSS)?
  - In general, using a metric combining **power**, **energy**, and **ramp-rate**
  - More specifically → Stochastic flexibility calculus
    - **General idea:** Time interval transformation (inspired by stochastic network calculus)
    - Allows to consider **uncertainties** and flexibility requirements on **multiple time scales**
      - **Goal:** Compute guarantees for sufficient flexibility potentials

[Lechl 2023, Elsevier RSER] [Lechl 2025, Elsevier Applied Energy] [Lechl 2025, ACM e-Energy '25]

Potential of Co-locating DCs and Battery Storage Systems

Wind turbine-housed DC architecture co-located with BSSs

- Consider the proposed architecture as a single entity called energy cell
  - **Alleviates the impact of forecast errors** (wind, volatile workloads)
  - Increases **self-sufficiency**, **operational sustainability**, and **overall efficiency** of the wind farm (less curtailment)
  - Use BSS to **foster grid-friendliness** (congestion management)



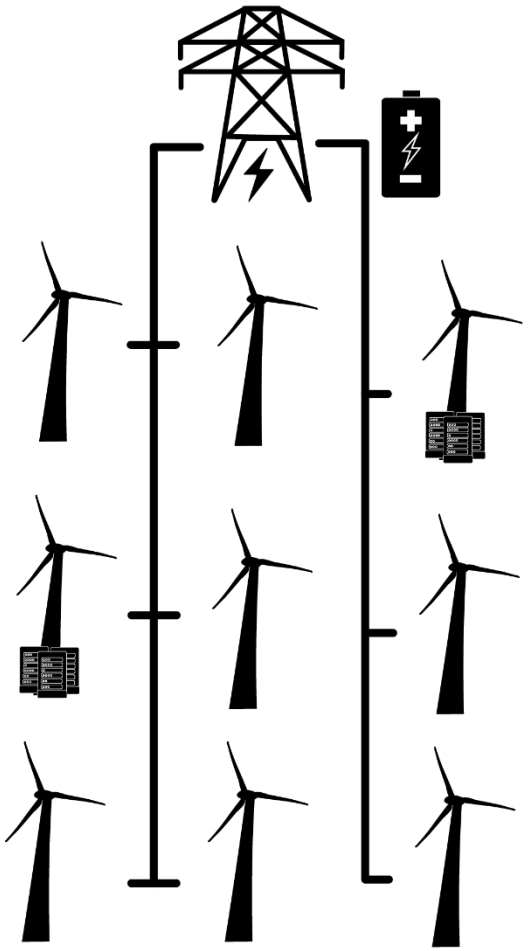
Potential of Co-locating DCs and Battery Storage Systems

Wind turbine-housed DC architecture co-located with BSSs

- Introduce
  - **GreenSLAs** between IT customers and DC operators
    - Economic incentives due to curtailment energy (no marginal costs)
    - Performance guarantees (flexible level of quality of service)
  - **Green Supply Demand Agreements (GreenSDAs)** between the energy cell, external energy suppliers, and grid operators
    - Exploit flexibility potentials of both DCs and BSSs to obey power purchase (and selling) agreements
    - E.g., exploit multi-use capability of BSSs to
      - Manage residual load (planning capability)
      - Mitigate congestion (grid operator constraints)

      → Stochastic flexibility calculus

→ Requires (extension of) **communication protocols**, e.g., OpenADR
  - Include concept of uncertain flexibility potentials and requirements explicitly



Potential of Co-locating DCs and Battery Storage Systems

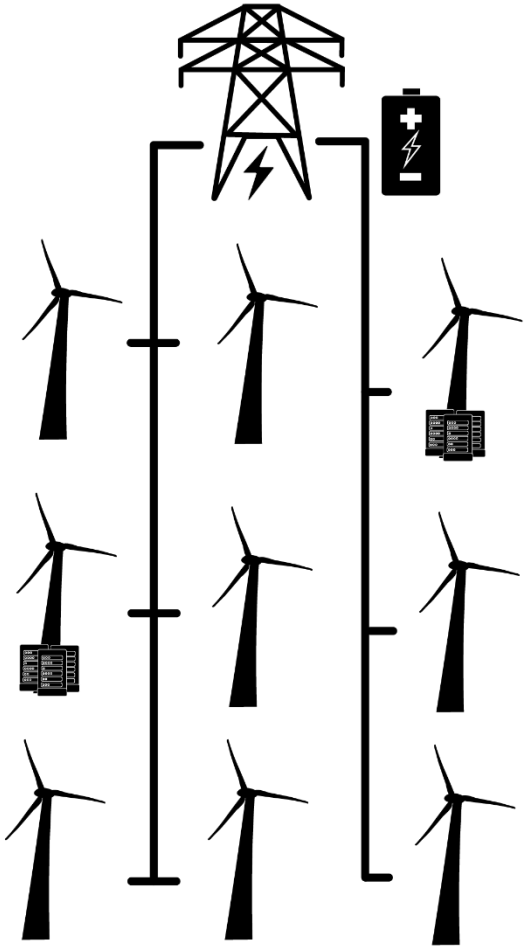
Wind turbine-housed DC architecture co-located with BSSs

- Sustainability of computing – rough estimate
  - Wind Onshore curtailment in 2024 (Germany)*: 3384 GWh
  - Assumption: 600 kW per HPC-DC

  → Max. energy consumption per year: 5.26 GWh

  → With co-location: Up to 643 HPC-DCs supplied with otherwise curtailed energy

  → ~ 13 % of Google's global energy consumption 2023**



* Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen (BNetzA)

** Google. (July 2, 2024). Energy consumption of Google from financial year 2011 to 2023 (in gigawatt hours) [Graph]. In *Statista*. Retrieved July 17, 2025, from https://www.statista.com/statistics/788540/energy-consumption-of-google/

Conclusions

- **“Energy efficiency is not energy efficiency!”**
  - Must be considered **from different perspectives (local, grid, global)** in decentralized energy systems
  - **Flexibility** is a vital tool of high intrinsic value to realize energy efficiency
- E.g., on-site placement of **(HPC-)DCs co-located with large-scale BSSs** achieve energy efficiency from **all perspectives simultaneously**
  - Resource consolidation, congestion-awareness, and spatiotemporal workload shifts
  - **GreenSLAs:** Ancillary services (global) from DCs and congestion mitigation (grid)
  - **GreenSDAs:** Manage residual load using BSSs
- **Goal:** Generalize to a broader class of decentralized energy systems and smart grids

  → Possible starting points for **standardization measures**
    - ISO 17800:2017: Facility smart grid information model
    - IEC 62746-10-1:2018: Data model and services for demand response
    - OpenADR 3.0: Information exchange model for automated demand response

References

[Basmadjian 2018, IEEE Trans. on Smart Grid]	R. Basmadjian, J. F. Botero, G. Giuliani, X. Hesselbach, S. Klingert and H. de Meer, "Making Data Centers Fit for Demand Response: Introducing GreenSDA and GreenSLA Contracts", IEEE Transactions on Smart Grid, vol. 9, no. 4, pp. 3453-3464, Nov. 2018. DOI: 10.1109/TSG.2016.2632526
[Berl 2009, Comput. J.]	A. Berl, E. Gelenbe, M. Di Girolamo, G. Giuliani, H. de Meer, M. Quan Dang and K. Pentikousis, "Energy-Efficient Cloud Computing", *The Computer Journal*, vol. 53, no. 7, pp. 1045-1051, Aug. 2009. Oxford University Press. DOI: 10.1093/comjnl/bxp080
[Kilian 2025, CACM]	A. Kilian, H. de Meer and G. Schomaker, "Energy-Optimized Supercomputer Networks Using Wind Energy", Communications of the ACM (CACM), vol. 68, no. 7, pp. 74-79, Jul. 2025. ACM. DOI: 10.1145/3725981
[Lechl 2023, Elsevier RSER]	M. Lechl, T. Fürmann, H. de Meer and A. Weidlich, "A review of models for energy system flexibility requirements and potentials using the new FLEXBLOX taxonomy", Renewable and Sustainable Energy Reviews, vol. 184, pp. 1-19, Sep. 2023. Elsevier. DOI: 10.1016/j.rser.2023.113570
[Lechl 2025, ACM e-Energy ’25]	M. Lechl, A. Kilian and H. de Meer, "Uncertainty-Aware Scheduling of Multi-Use Battery Storage Systems" in 16th ACM Int’l. Conf. on Future and Sustainable Energy Systems (e-Energy '25), June 17-20, 2025, Rotterdam, Netherlands , ACM, Jun. 2025. pp. 243-256. DOI: 10.1145/3679240.3734607
[Lechl 2025, Elsevier Applied Energy]	M. Lechl, H. de Meer and T. Fürmann, "A Stochastic Flexibility Calculus for Uncertainty-Aware Energy Flexibility Management", Applied Energy, vol. 379, pp. 1-16, Feb. 2025. Elsevier. DOI: 10.1016/j.apenergy.2024.124907

UNIVERSITY OF PASSAU
Faculty of Computer Science and Mathematics

Thank you for your attention
Questions?

Flexible Energy Demand from Data centers

UNIVERSITY OF PASSAU
Faculty of Computer Science and Mathematics

Energy Efficiency for Data Centers (2010-2012):

- Concept for increasing the energy efficiency and sustainability of data centers and supercomputers
- Energy awareness: plug-ins for data center automation frameworks
- Intelligent allocation of ICT resources, data center consolidation
- Compliance with existing SLAs and QoS metrics

Green Interplay between Data Centers and Energy Providers (2012-2014):

- Collaboration between data center operators and energy providers
- Coordination of supply and demand
- Development of new concepts and technologies such as GreenSLA and GreenSDA
- Control system: consumption adapts to fluctuating supply

Environmentally Sustainable Data Center for Smart Cities (2013-2016):

- Data centers in smart cities in the role of ICT service provider and gigantic energy consumer
- Integration of renewable energies
- Reduction of power consumption (data center consolidation)
- Compliance with QoS metrics