On the Mutual Dependency of Power Systems vs Information and Networking Technology

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Agenda

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1. **Introduction**
2. Interdependencies and Dependability
3. Power-ICT System Interdependencies by the Example of Flexibility
4. Conclusions

1. Introduction

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 Information and Communication Technology (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

[Basmadjian 2012, SustainIT 2012] [Basmadjian 2018, IEEE Trans. on Smart Grid]

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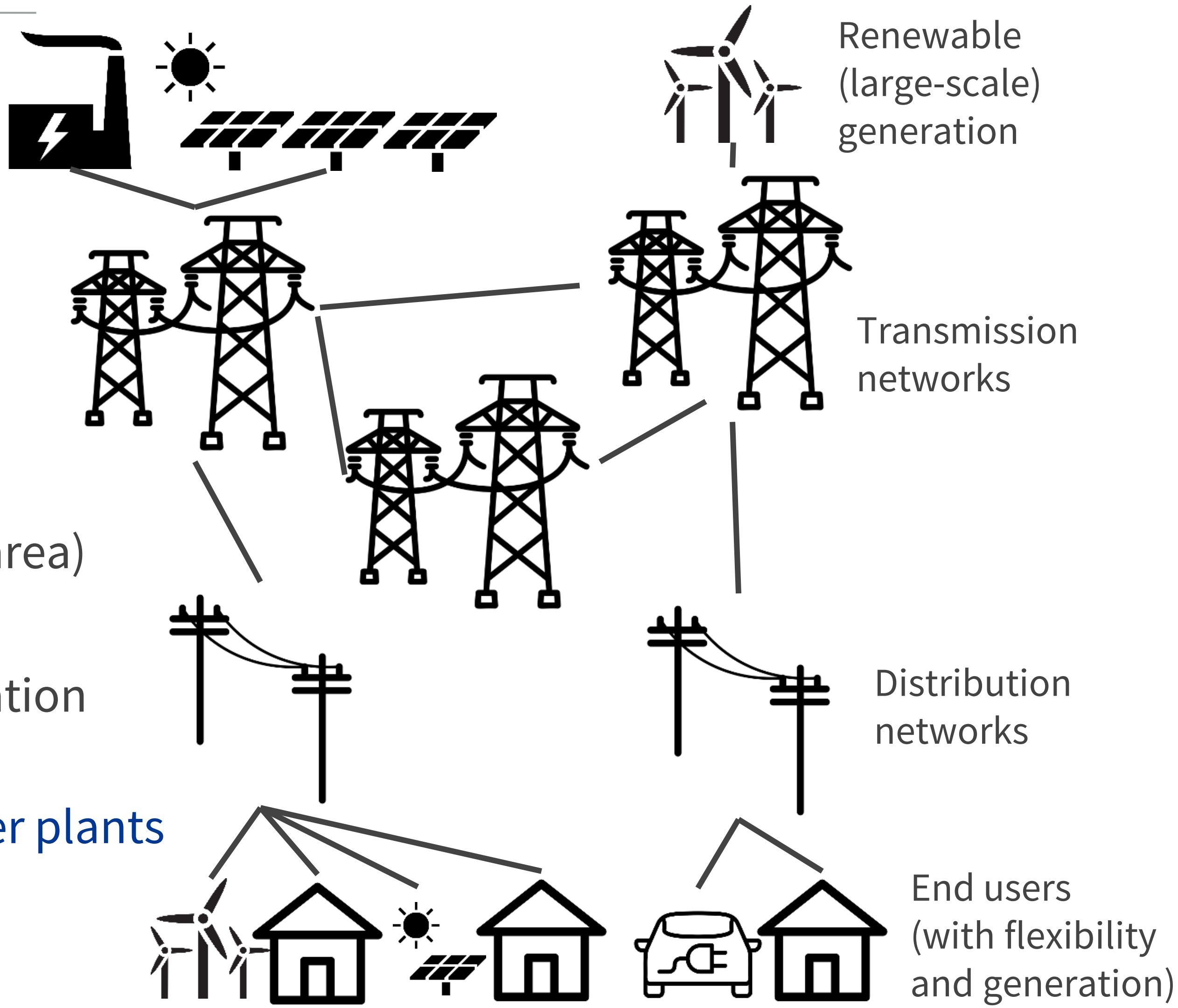
The power system

- Large-scale generation connected to transmission network
- Transmission network with high voltage for long-distance transport of energy
- Distribution network at a lower voltage for short distance transport (e.g., within a municipal area)
- End users that consume energy
- **Renewable energy transition:** Renewable generation is volatile and increasing in magnitude
  - E.g., weather effects on large-scale wind power plants
- ICT required to forecast and control renewable generation (and demand)



1. Introduction

On resilience: Degraded dependability <u>due to (structural) changes</u>

- As critical infrastructures, power grids must be dependable
- Power grids currently face major (structural) changes:
  - Inclusion of more renewable generation
  - Decommissioning of (expensive) fossil-fuel-based / nuclear generation
- (Structural) changes can reduce a system's dependability
  - **Resilience is the gradient** of the measures defined in the context **of dependability**

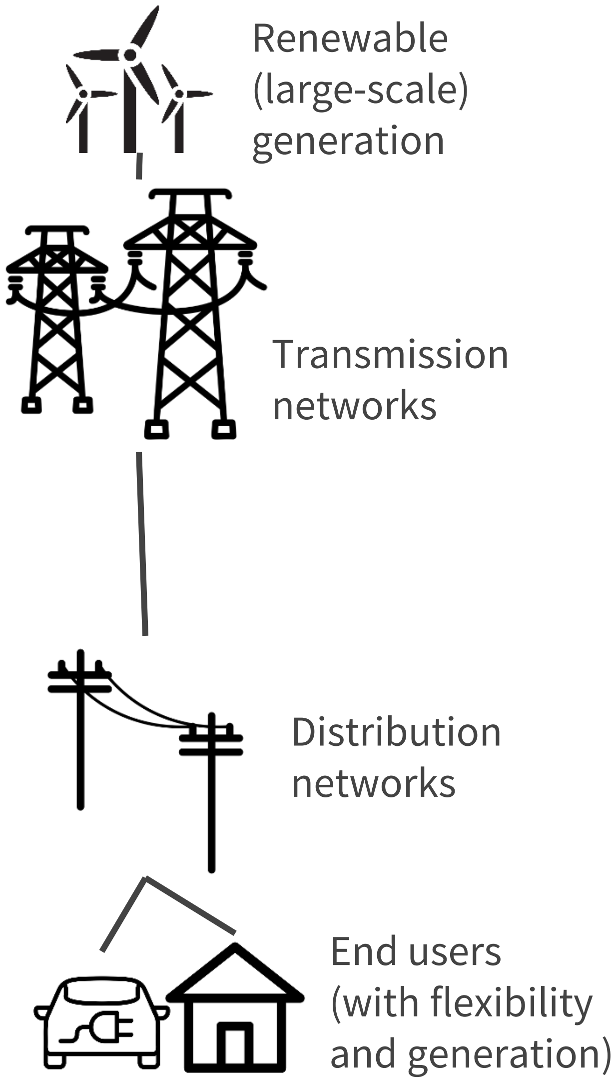
  → E.g., increasing forecast errors due to volatile renewables

    → Forecast errors can decrease a system's resilience

    → Due to excessive deviation between generation and demand

  → Decreasing reliability of supply

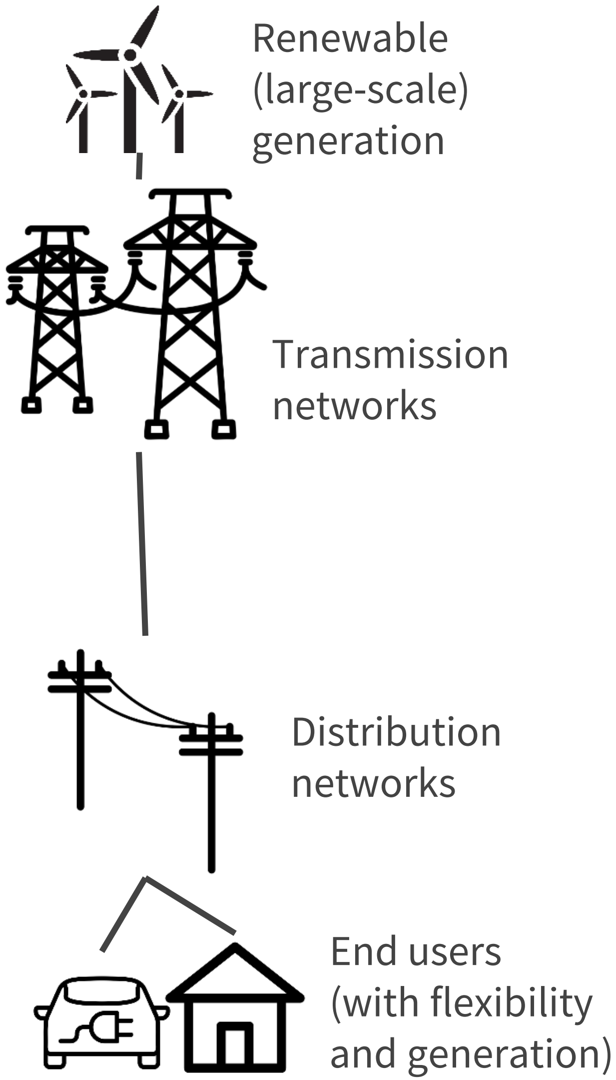
  → Degradation of power quality and, thus, dependability



[de Meer 2025, RNDM 2024]

Role of ICT: Power forecast requirements

- On system level: Balance supply and demand at all times
  - Requires forecasting and control of power generation and demand
  - Forecasts can be imprecise, e.g., due to volatility of renewable generation
    - Requires **flexible generators and consumers**
      - In particular, optimizing the energy efficiency of, e.g., data centers is not sufficient
- On a large-scale generator level: Market operation
  - Energy is sold on markets in various time-scales
    - E.g., day-ahead or minutes ahead
  - Plan / forecast demand of consumers accordingly
    - Energy efficiency vs. CO_2 efficiency



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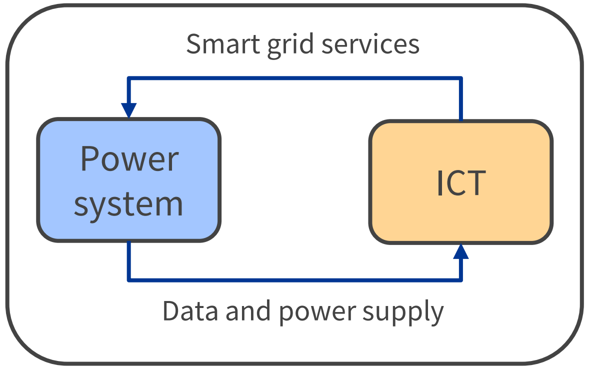
- Forecasting the generation of Distributed Renewable Energy Sources (DRESs) can be tackled using ICT
  - ICT-based power grid services to maintain power grid stability
    - Also called smart grid services
  - Proactive measures
    - Using generation and demand forecasts for planning
  - Reactive measures
    - Activating flexible reserves to maintain balance between generation and demand
- Forecast errors can lead to incorrect planning, potentially resulting in power outages or power quality issues
  - Voltage drops (e.g., brownouts) can lead to a failure of the supporting ICT infrastructure
  - This impact can propagate into the power system, as less information is available for reactive measures

→ **Mutual dependency** between power systems and ICT systems

[de Meer 2025, RNDM 2024]

ICT-based power grid services

- ICT-based power grid services are one of two types according to the European Network of Transmission System Operators for Electricity (ENTSO-e)
  - High-level services
    - These services assist in maintaining the “normal” operation state
  - Remedial actions
    - These services assist in taking corrective or preventive actions against contingencies
- The power system relies on the ICT system for data collection, transfer, and decision making
  - Incorrect or delayed data transfer or decision making can lead to catastrophic consequences!
- The ICT system relies on the power system for power supply
  - ICT component outage implies a lack of sufficient information for control decisions
    - Decreased dependability

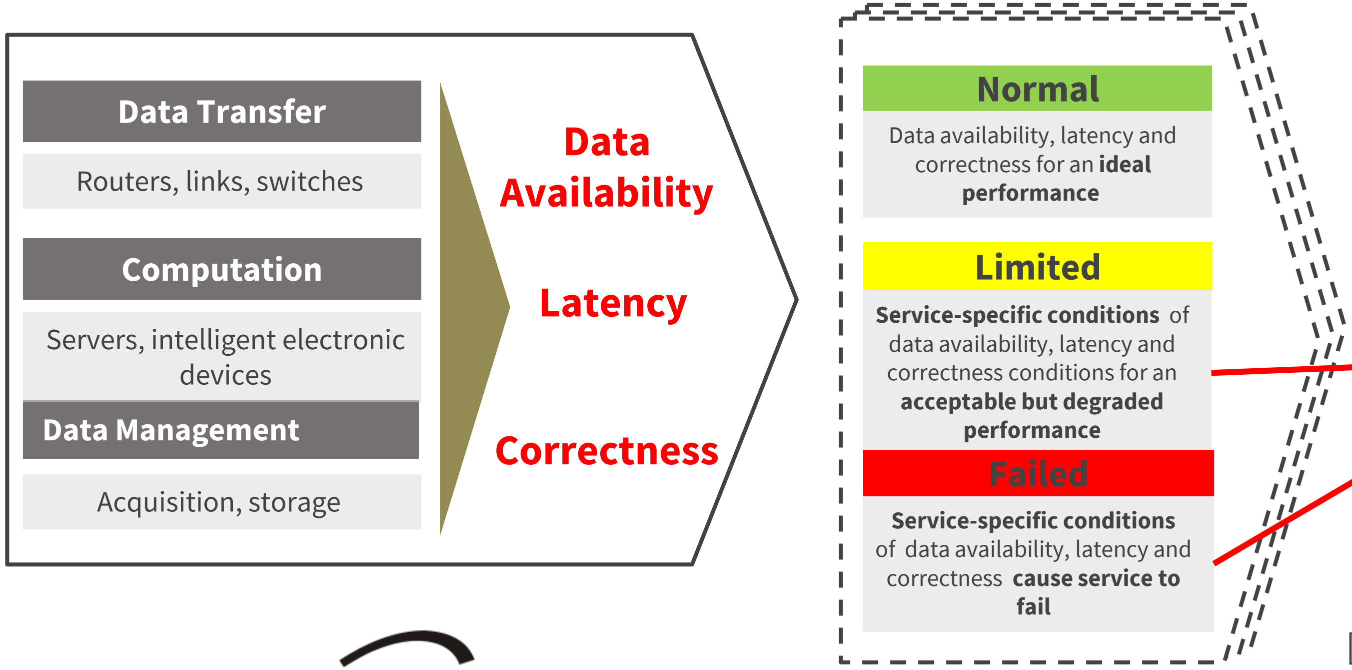


[Klaes 2020, DACH+ Energy Informatics Conf.]

ICT-based power grid services

- These services encapsulate the power-ICT interdependencies
  - High-level services rely on forecasts to maintain stable operation proactively
  - Remedial actions such as protection rely on real-time data collection
  - Each service can exist in one state at a point in time
    - The state indicates the expected performance of the service

ICT-based smart grid service states



Degraded ICT performance impacts the **dependability** of the smart grid service

[Klaes 2020, DACH+ Energy Informatics Conf.]

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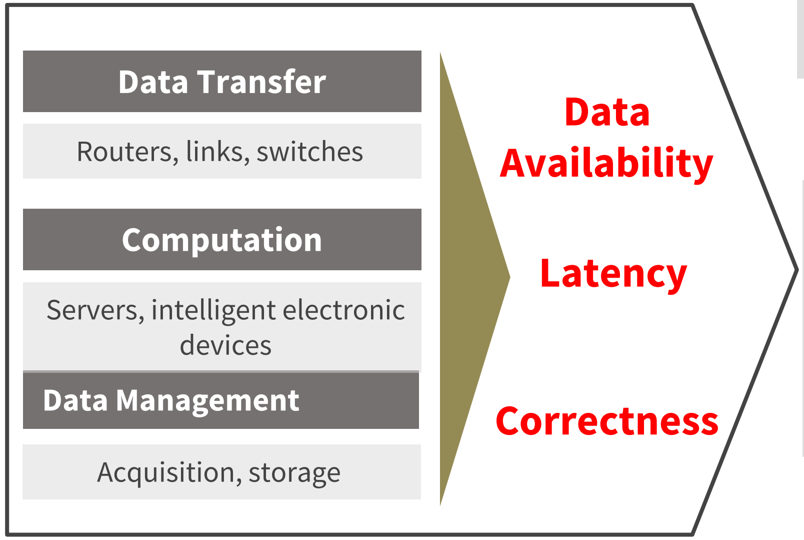
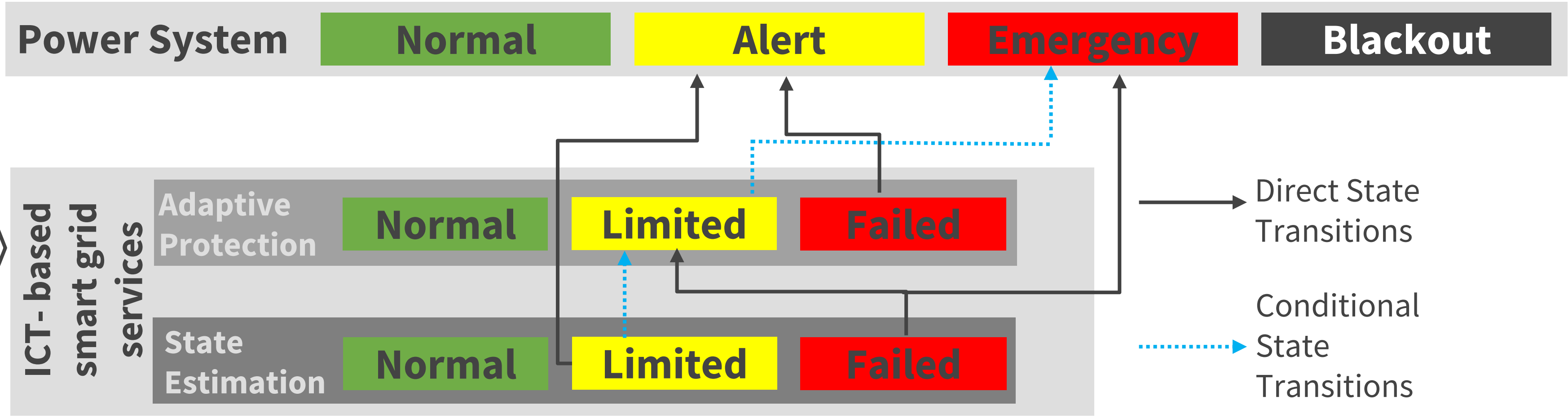
ICT-based power grid services

- These services encapsulate the power-ICT interdependencies
- The state of a service, e.g., state estimation, can impact the state of other services, e.g., protection
  - **Limited state** of services introduced
    - In addition to only operational (Normal) and non-operational (Failed) states
  - **Direct state transitions** occur by definition of the state description ***or*** service interdependency
  - **Conditional state transitions** occur due to service interdependency ***and*** scenario-specific external events





Warning: State transitions depicted in the figure above are non-exhaustive.

[Klaes 2020, DACH+ Energy Informatics Conf.]

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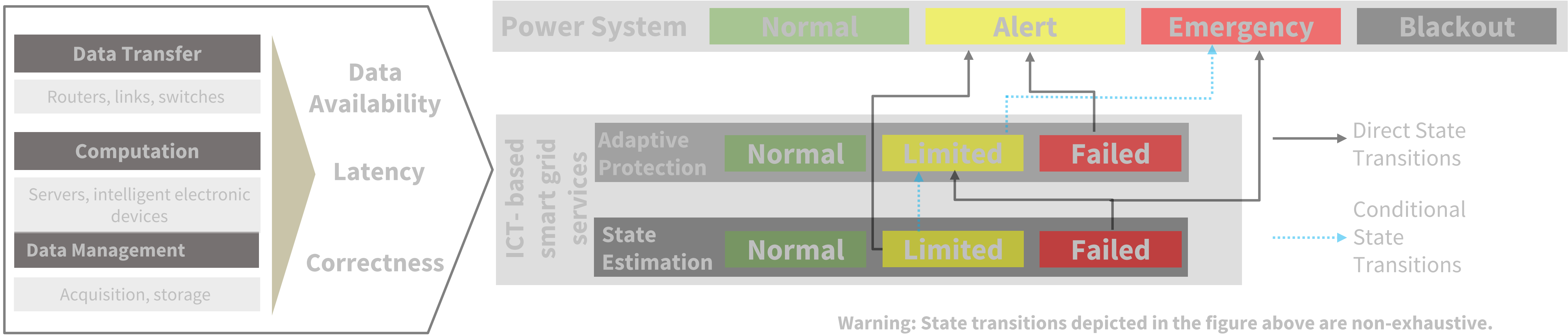
ICT-based power grid services

- These services encapsulate the power-ICT interdependencies
- The state of a service, e.g., state estimation, can impact the state of other services, e.g., protection
  - Limited state estimation service state implies that the output may be incorrect or delayed due to loss of certain measurement data
  - Based on Limited state estimation service state, protection operates based on incorrect information or only local information
    - This could lead to a potential fault not being cleared and the power system in Emergency state



[Klaes 2020, DACH+ Energy Informatics Conf.]

ICT-based power grid services

- **Interdependencies** between power systems and ICT systems are susceptible to **cascading failures**
  - E.g., cascading failures can be caused by exploiting IT security gaps
  - A coupling coefficient reflects the degree to which the power system is reliant on ICT
  - More information on this topic: [Ghasemi 2023, IEEE TNSE]

[Ghasemi 2023, IEEE TNSE]

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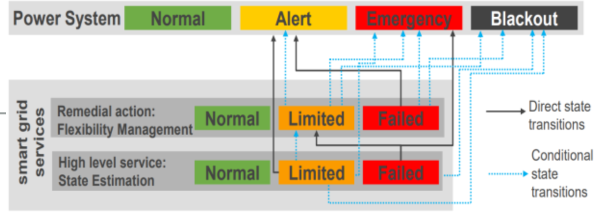
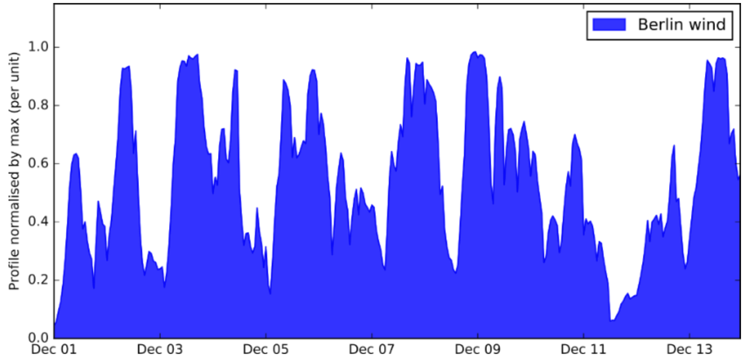
3. Power-ICT System Interdependencies: Flexibility

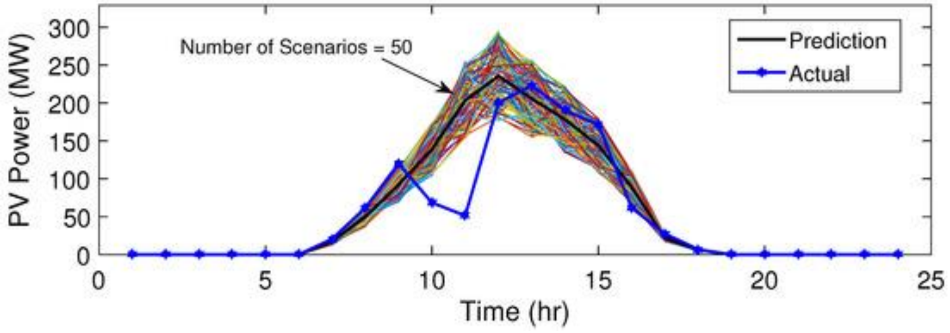


Power and ICT interdependencies in flexibility services

- **Flexibility requirements**
  - Deviations from planned or expected power/energy/ramp-rate values
  - *Example:* Volatility and uncertainty of renewable energy resources
  - Quantification requires **forecasts/measurement data** provided by an ICT system
- **Flexibility potentials**
  - Controlled feasible deviations of a flexibility resource, e.g., Battery Storage System (BSS), data center
  - Required to **balance flexibility requirements**
  - Procurement process relies on **real-time data of flexibility resources** (e.g., current setpoint)
    - Provided by ICT system
  - Basis of **flexibility services**, e.g., redispatch, ancillary services



[Volatility of wind generation; Figure by Tom Brown, CC BY-SA 4.0]



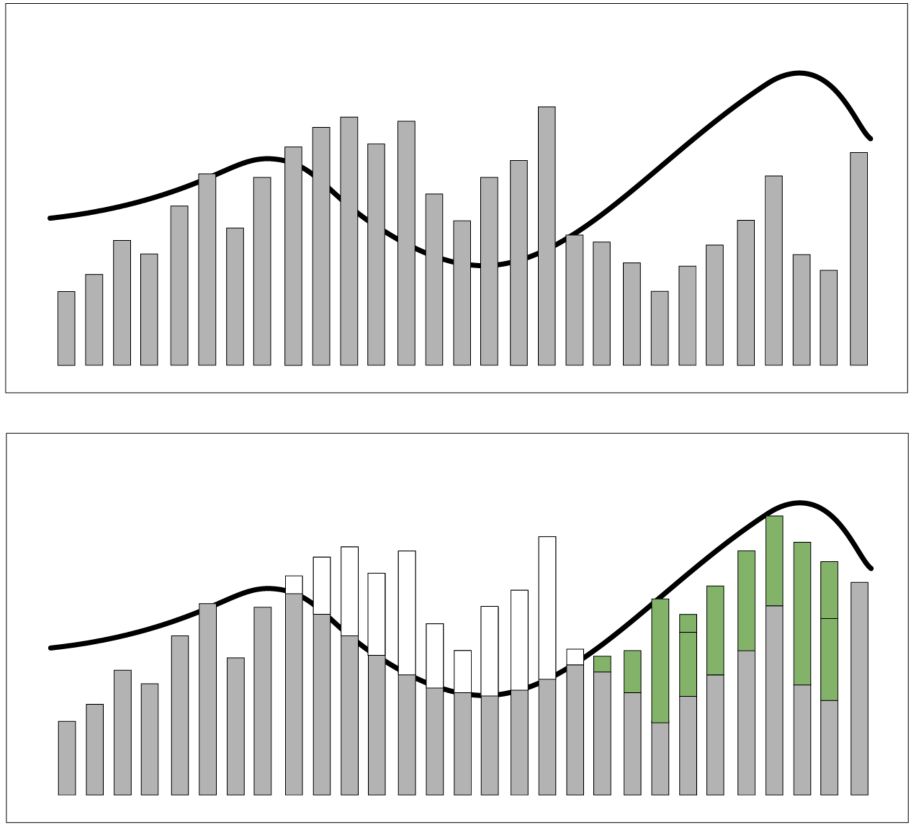
[Uncertainty in PV generation; Figure by Sediqi, CC BY 4.0]

[Lechl 2023, Elsevier RSER] [de Meer 2025, RNDM 2024]

3. Power-ICT System Interdependencies: Flexibility

Demand response

- **Exploit controllable loads as a flexibility resource**
  - Adapt load profiles to match availability of volatile renewable energy (requires forecasts)
    → Consider CO_2 efficiency besides energy efficiency
  - Example: Data centers
    - Provide forecasts **and** power system flexibility potentials
    - **Spatiotemporal shifts of workloads** from periods with low penetration of renewable energy sources to periods with (forecasted) high availability of electric power generated by renewables
    → Particularly: **Energy-hungry applications (AI)**
    - Improves both the operational carbon footprint of data centers and dependability of the power system
    → Green Supply Demand Agreement (**GreenSDA**)
  - ICT is indispensable for realizing such demand response schemes



Temporal shift of data center workloads to cover energy consumption by available renewable energy

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

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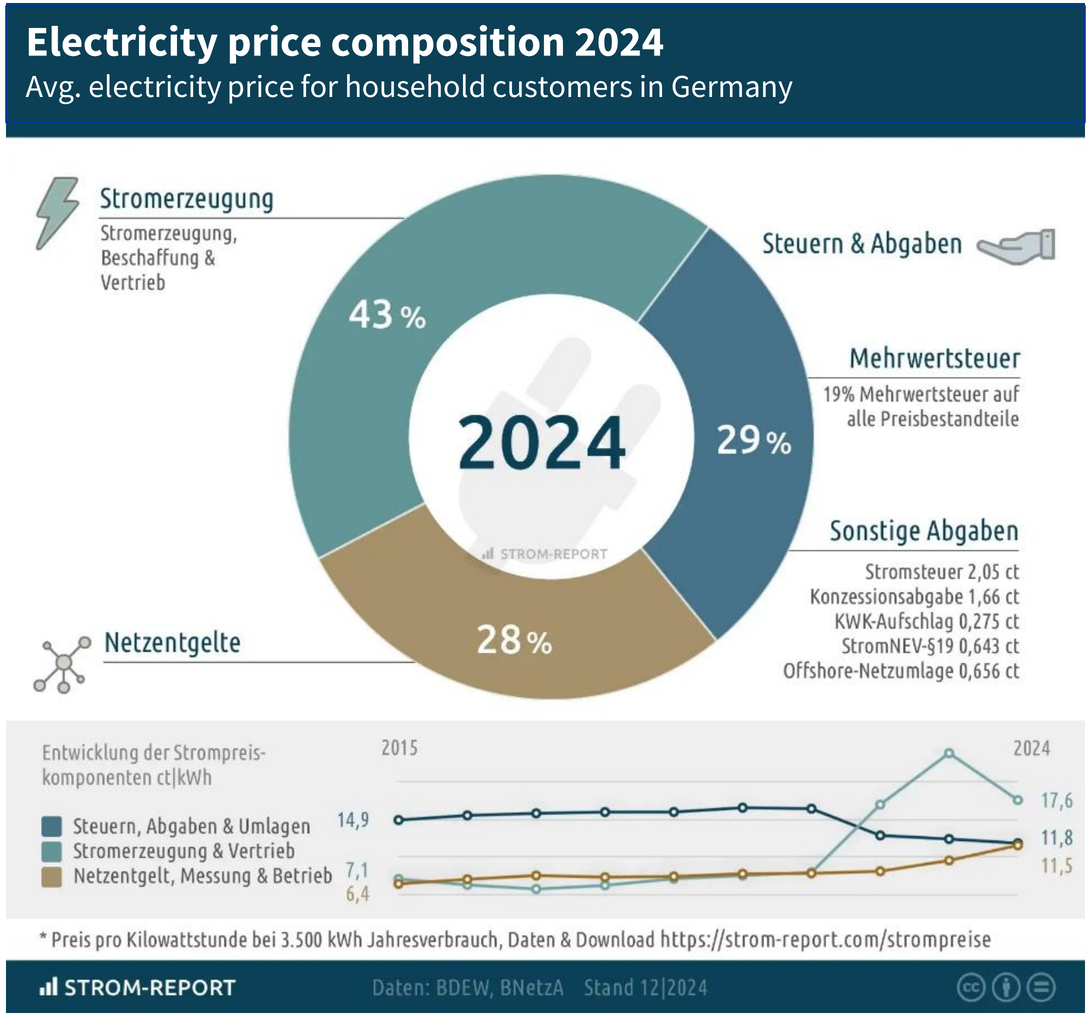
- Better planning/forecasting of power system operation using ICT means that
  - Less (carbon-intensive) flexibility resources are needed → more sustainable
  - Electricity price decreases
    - Main cost factor is flexibility in systems with large share of renewables



[Lechl 2023, Elsevier RSER]

Source: https://strom-report.com/strompreise/#strompreiszusammensetzung-2024

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Energy efficiency revisited

- Power and ICT systems are increasingly interdependent
  - Power systems rely on ICT for critical services, e.g., forecasting renewable generation and demand
  - ICT relies on power systems for (renewable) power supply
- Flexibility is essential to maintain stable, carbon-aware power system operation
  - Improving only energy efficiency of data centers not sufficient to reduce carbon footprint
    - Shifting data center workloads to periods with high availability of renewables required to improve CO_2 efficiency and reduce costs
  - Data centers are flexibility resources, but also provide input for flexibility services (e.g., forecasts)
  - Outlook: AI methods in combination with batteries can be crucial to realize flexibility services in renewables-based systems

    → AI for Sustainability & Sustainability of AI

    → More information in SUSTAIN RG meeting (Thursday, 17:00 – 19:00)

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Thank you for your attention
Questions?