APPLICATION OF MACHINE LEARNING METHODS IN POWER GRID OPERATION

Martin Braun, Alexander Scheidler

Fraunhofer IEE & University of Kassel

Outline

- Background Energiewende / Challenges in electrical grids
- Competence Center Cognitive Energy Systems
- AI Approaches in electrical grids
  - State Estimation / Monitoring
  - Power Flow
  - Optimal Power Flow
  - L2RPN Competition

German "Energiewende" (status – scenarios – megatrends)

Decarbonization

> 40% RES power supply

some regions >100%

2050: 100% RES in power, heat, mobility

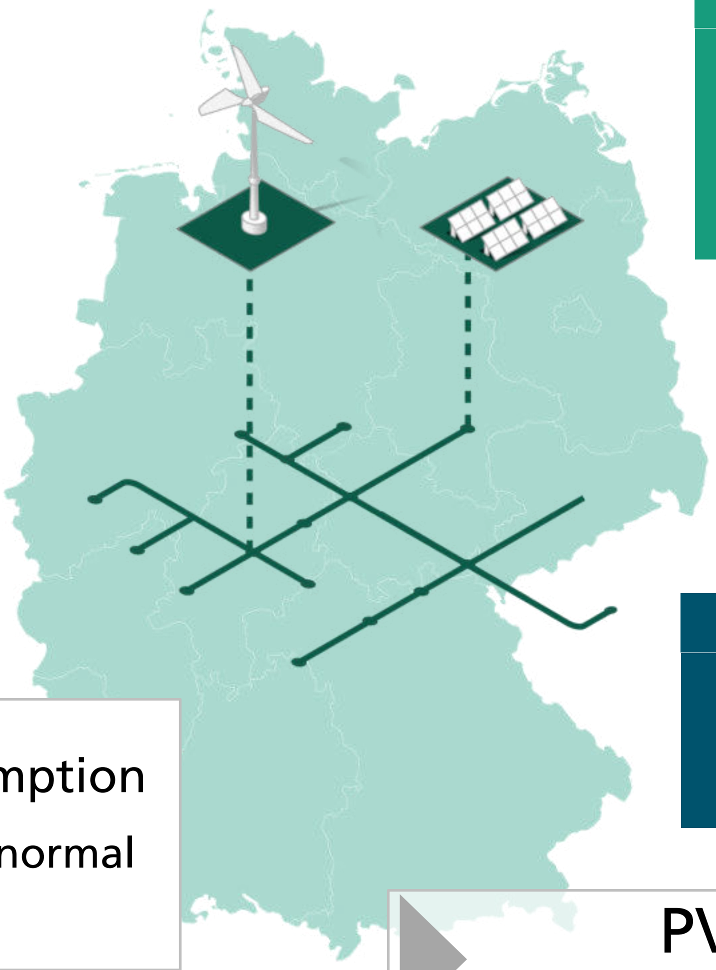
Decentralisation

~ 70 GW RES capacity

in distribution grids

Generation > consumption

Reverse power flow is normal in many grids



RES with power electronics

2% - 89% PV & wind

share of total load May 19th-21st, 2018

01010
10010
10001

Digitalization

Autarky

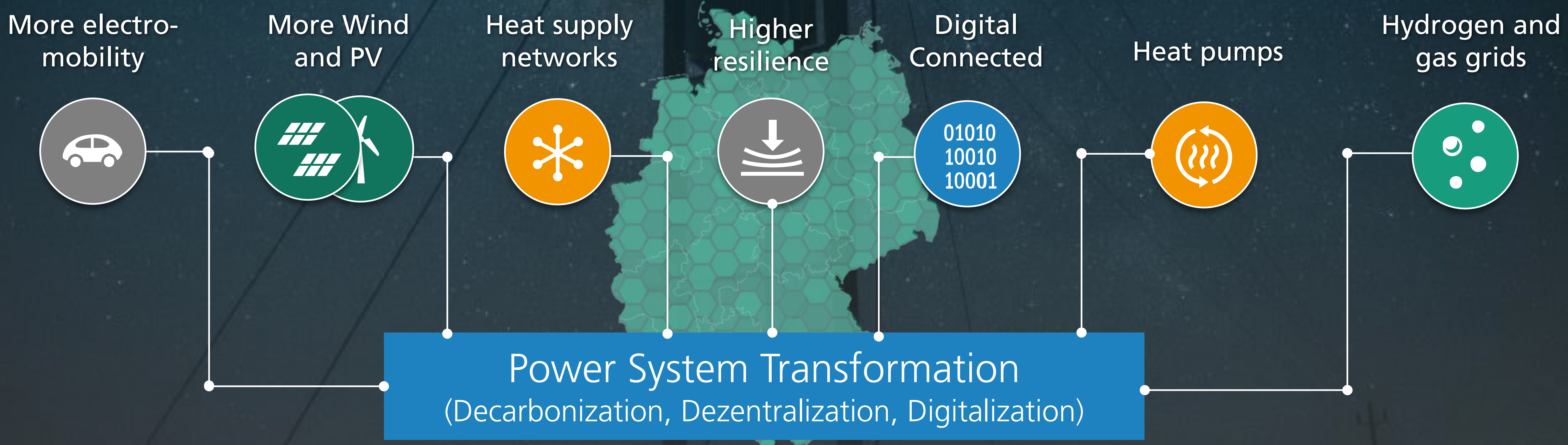
> 120.000 PV-battery-systems

PV and wind power are system-relevant

Mega Trends

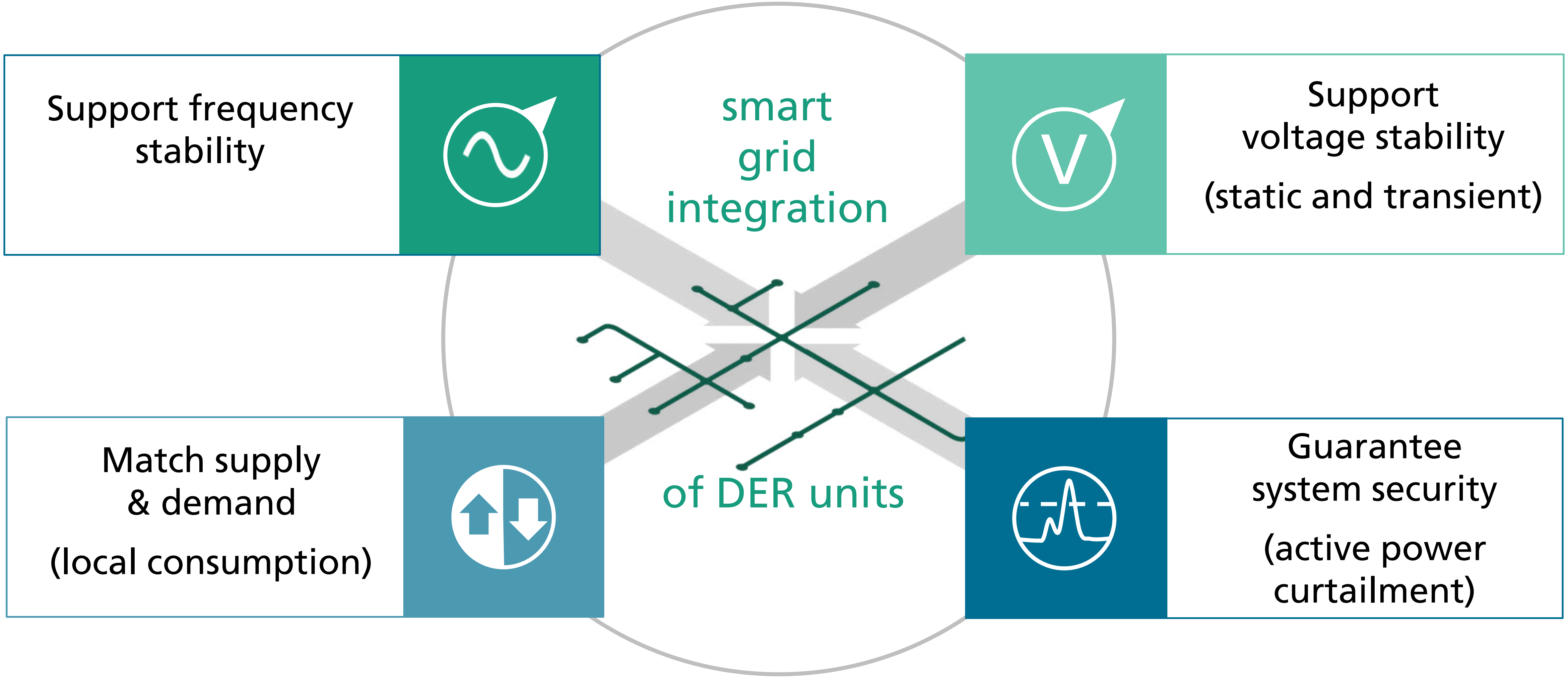
Decarbonization	Renewable Energy Sources (RES)
Decentralization	RES in distribution
01010 10010 10001 Digitalization	Data, information, communication, automation
Autarky	Cellular microgrid approach

Power Systems as Critical Infrastrucure



Quelle: https://www.netdoktor.at/anatomie/herz-7149

Smart Grid Integration of Distributed Energy Resources



Electrical Grid Characterization (Examples)

- Transmission Systems vs. Distribution systems
  - Meshed ←→ Radial
  - Interconnected European Power System ←→ Local cables in streets
  - High reliability (no blackouts) ←→ Average outage time of about 1-2 hours in residential areas
  - …
- Time domain spectrum
  - Planning (annual over decades)
  - Operational planning (hours over days)
  - Operational management (minutes)
  - Primary controls for frequency/voltage stability (seconds)
  - Transient stability / Protection (milliseconds)
  - …

Benchmark Grid Data:

www.simbench.de

SimBench

Electrical Grid Applications (Examples)

- Grid Planning (static models)
  - Grid Analysis (Data Fusion of historic data sets)
  - Optimization of future grid designs under uncertainty
- Grid Operation (quasi-stationary models with time series)
  - State Estimation / State Forecasting
  - Optimization to keep voltage range, maximum loading and n-1-security
    - With active and reactive power flows
    - By Distributed generators / grid assets
    - By reconfiguration (e.g. after faults)
- Grid Stability (dynamic/transient models with differential equations)

Why ML/AI in power grids ?

Real measurable benefit against classical methods!

- **Increase speed of grid calculations**
  (e.g. large grid models with nodal time series)
  - Results nearer to real time (operation)
  - Reduce computational efforts (desktop instead of cluster)

- **Find better solutions in optimization / estimation**
  - e.g. combinatorical grid planning $2^{(\text{number of measures})}$
  - e.g. state estimation

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Kognitive Energiesysteme

COMPETENCE CENTER COGNITIVE ENERGY SYSTEMS

We make energy intelligent!

Bild @Freepic

Powered by Fraunhofer IEE

Raw Materials	Conversion / Generation	Transport / Distribution	Trading / Sales	Customer / Services

Cognitive Energy System Technology

- Raw Materials
  - Procurement
  - Logistics
- Conversion / Generation
  - Operations
  - Maintanence
  - Aggregation

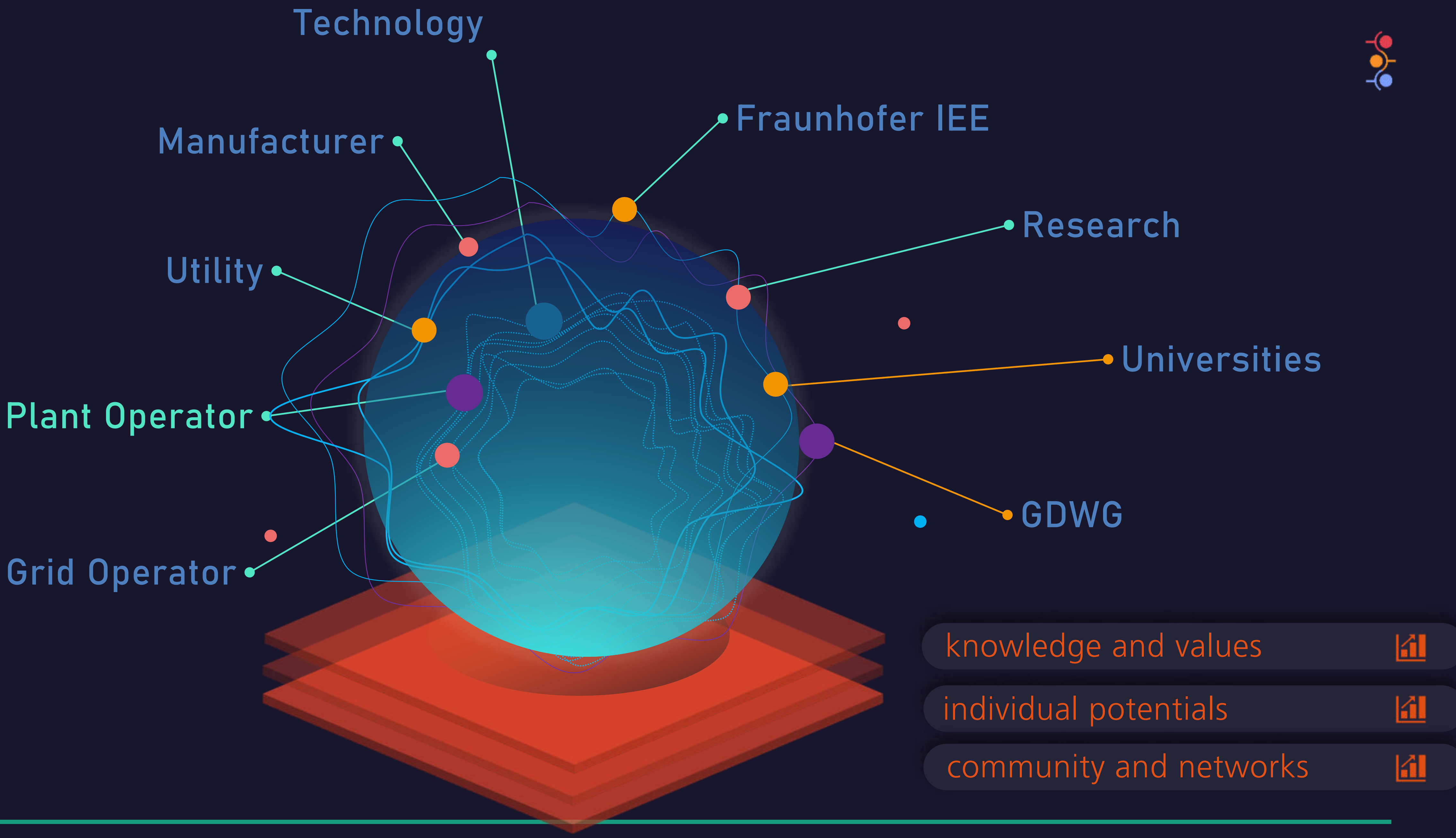
Cognitive Grids

- Transport / Distribution
  - Operations
  - Maintenance
  - Planning

Cognitive Energy Economics

- Trading / Sales
  - Trafing
  - Personalised products
  - Customer service
- Customer / Services
  - Flexibility
  - Efficiency
  - Optimization

Cognitive Energy Systems


Technology
Manufacturer
Fraunhofer IEE
Research
Utility
Universities
Plant Operator
GDWG
Grid Operator
knowledge and values
individual potentials
community and networks

IC4CES – Entwicklung eines Innovationsclusters für Kognitive Energiesysteme

- 2. Wettbewerbsrunde um die Zukunftscluster
- 15 Finalisten von 117 Wettbewerbsbeiträgen
- Förderung für Konzeptionsphase
- https://www.bmbf.de/de/karliczek-wir-foerdern-die-innovationsnetzwerke-von-morgen-14401.html
- Kassel - Göttingen

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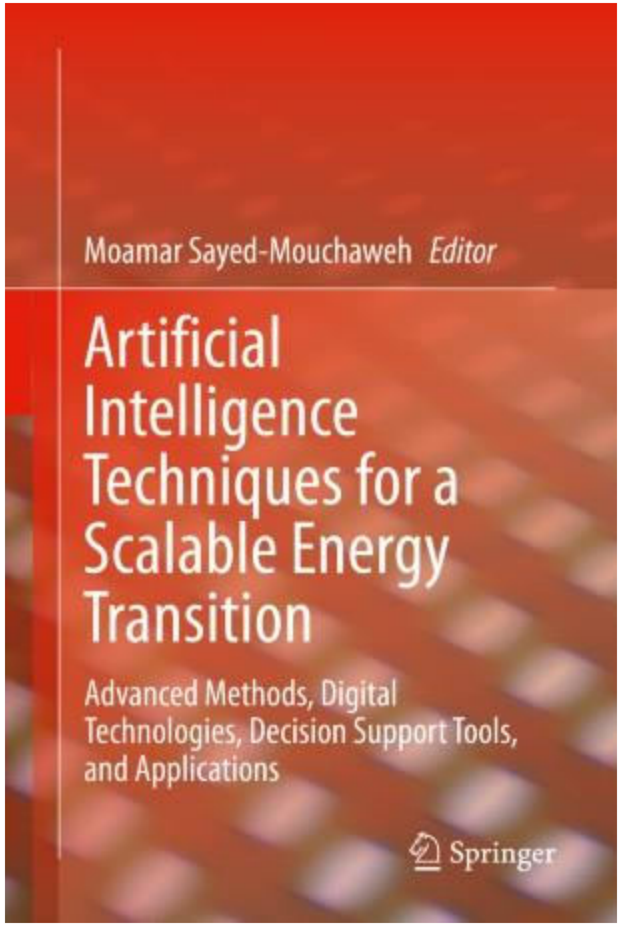


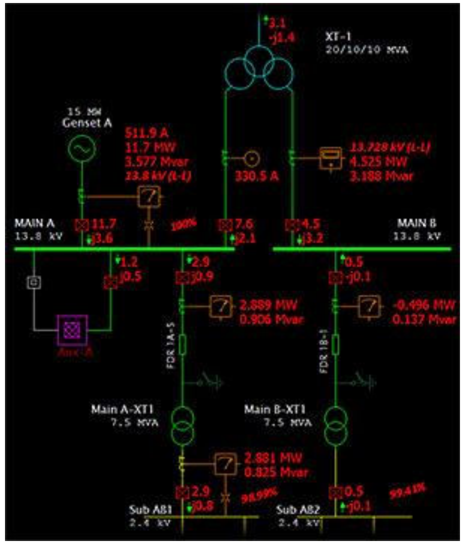
pandapower – Open Source Tool for power system calculation

pandapower

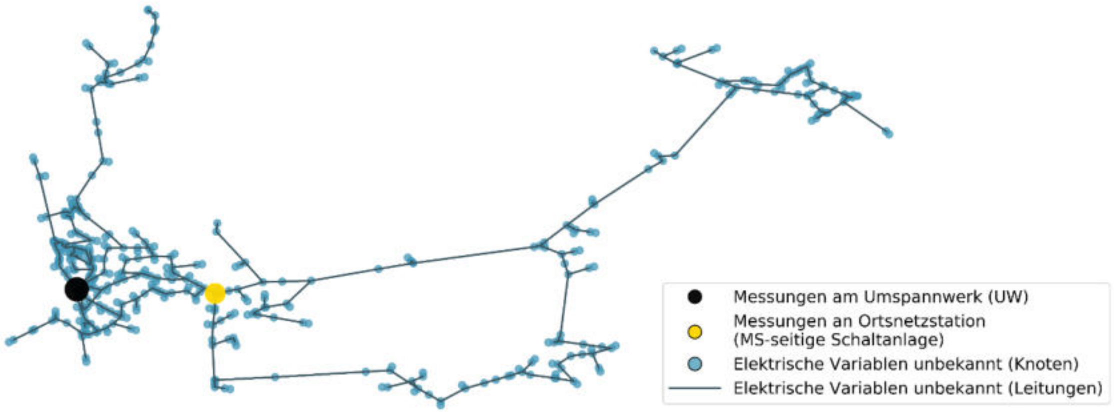
www.pandapower.org

Monitoring of distribution grids

- State of High Voltage Level grids is well known due to extensive measurements
- distribution grids have very little measurements
- In future grids are operated closer to the operational limits due to increased RES / electric vehicle charging
- But: installation of measurement devices is costly and requires reliable communication infrastructure
- **-> Demand for methods that can estimate grid state with a relatively low number of real-time measurements**
- **This problem is called State-Estimation, traditionally solved with e.g. WLS**



Source: https://scientificservices.eu/item/power-system-monitoring--simulation-software/780



Machine learning for grid state estimation

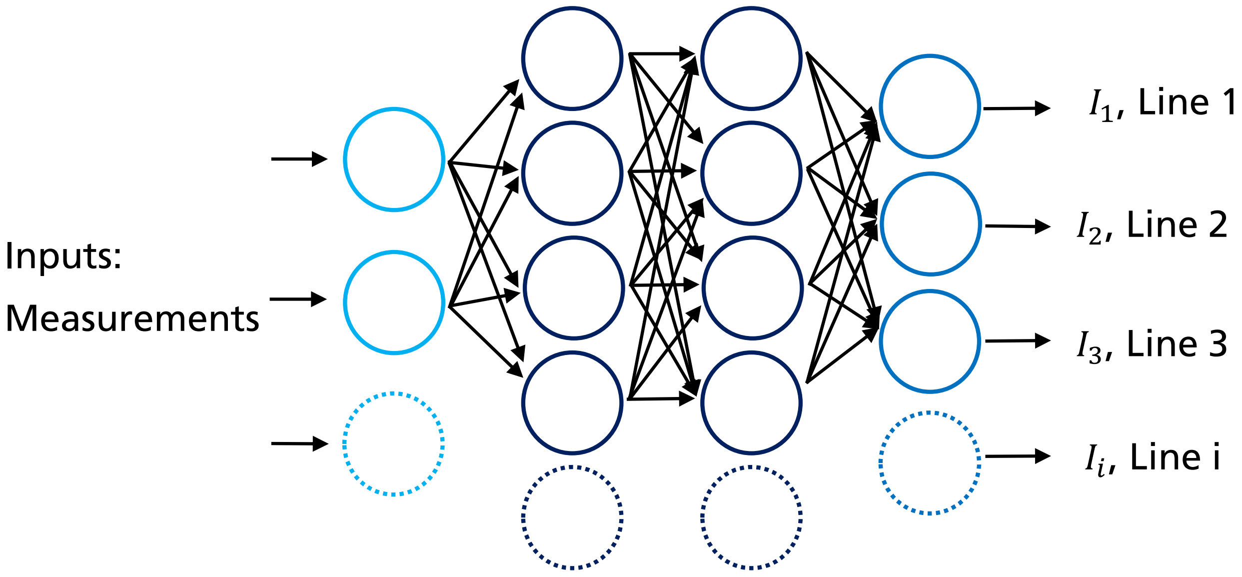
Our approach: Artificial Neural Network for State-Estimation

ANN Input: real-time measurements

ANN Output:

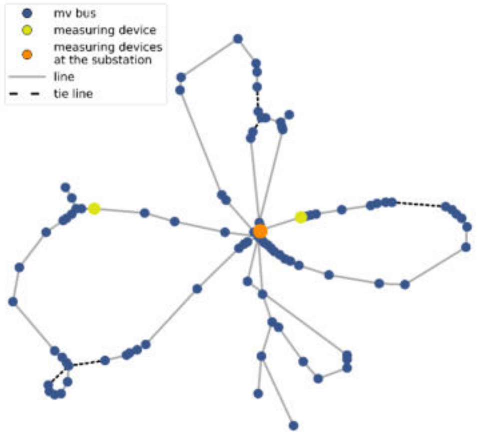
- bus voltage magnitudes V_k
- current flow through the lines I_l
- active power flows P_l
- reactive power flows Q_l

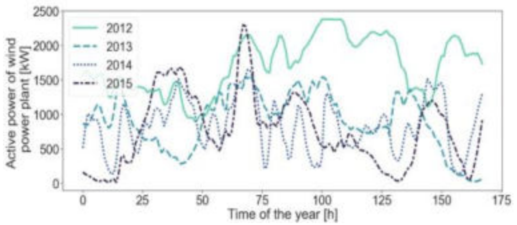
for the nodes k and lines l



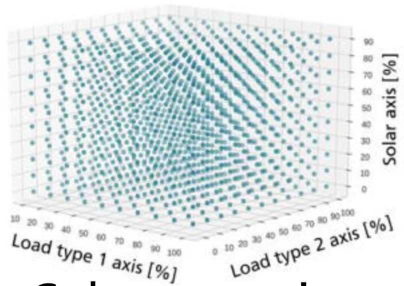
Training of the ANN

Create synthetic training samples:

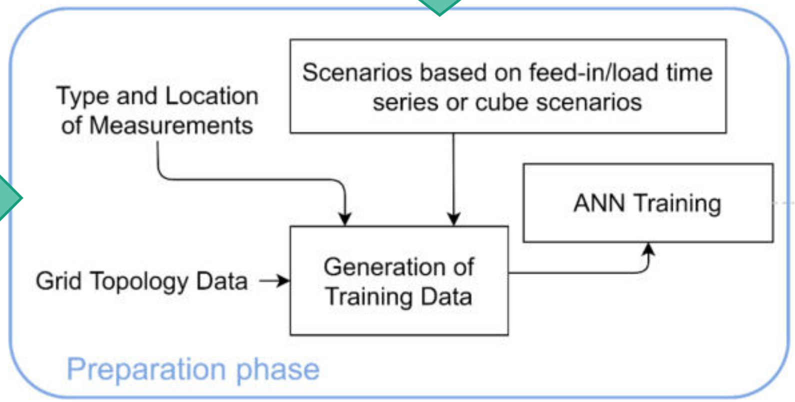




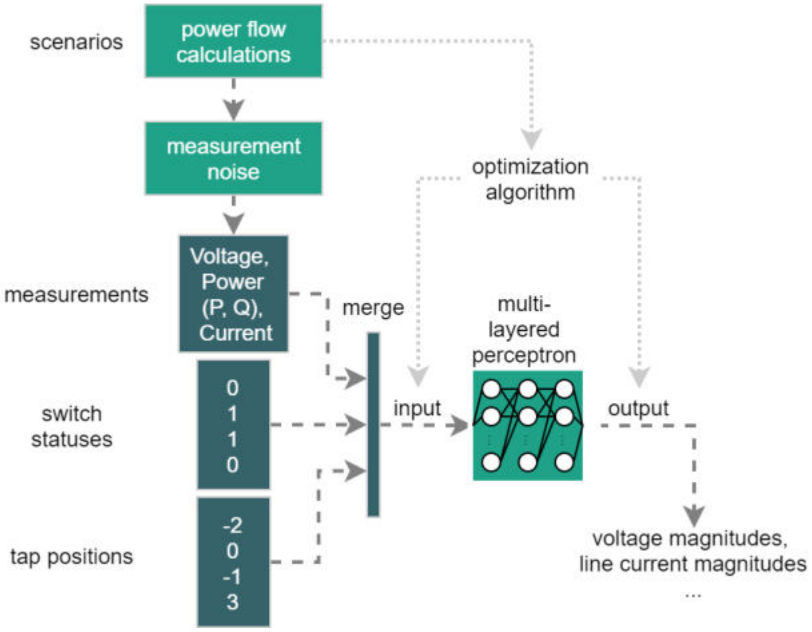
Time series data



Cube scenarios



Train with synthetic samples



Powerflow (pandapower) to calculate synthetic grid states

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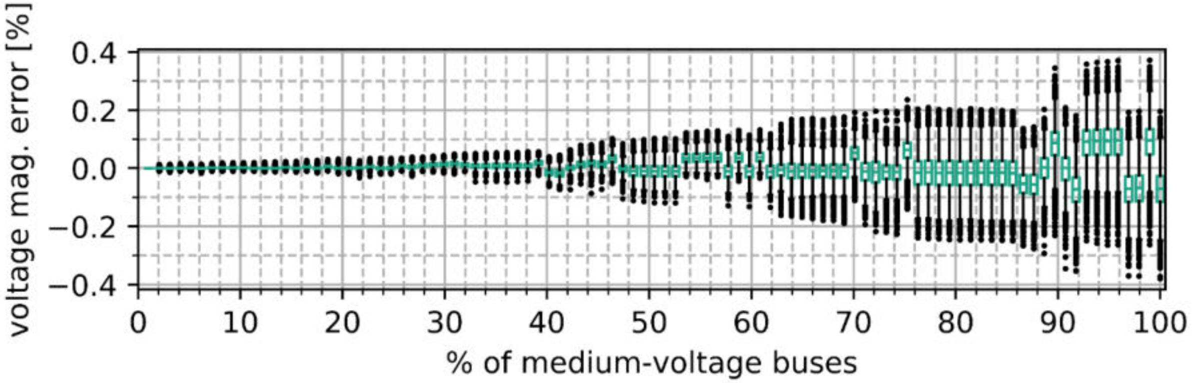
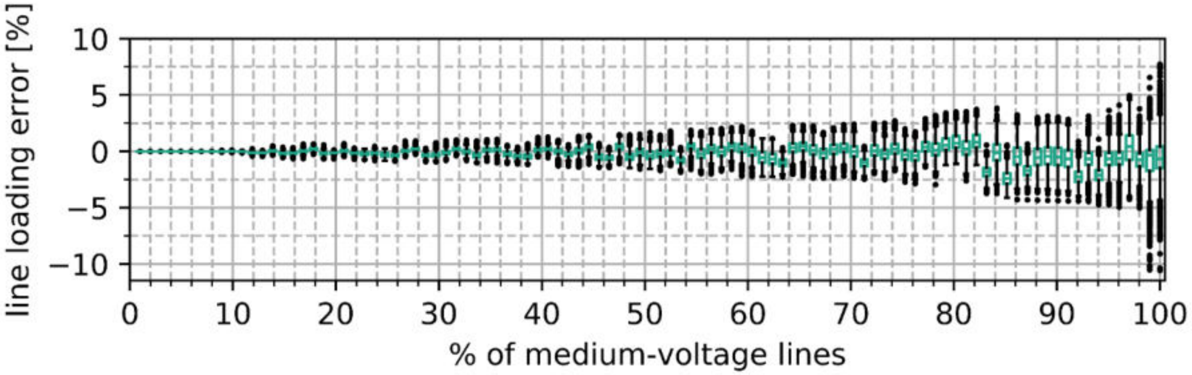
Example Estimation Results



Estimation Error of V_k:

$4 \times 10^{-5} \pm 4.9 \times 10^{-4}$ p.u.

(max.: 0.38%)



Estimation Error of I_l:

– 0.5 ± 1.8A

(max.: 10.55%)

Benchmarking Example

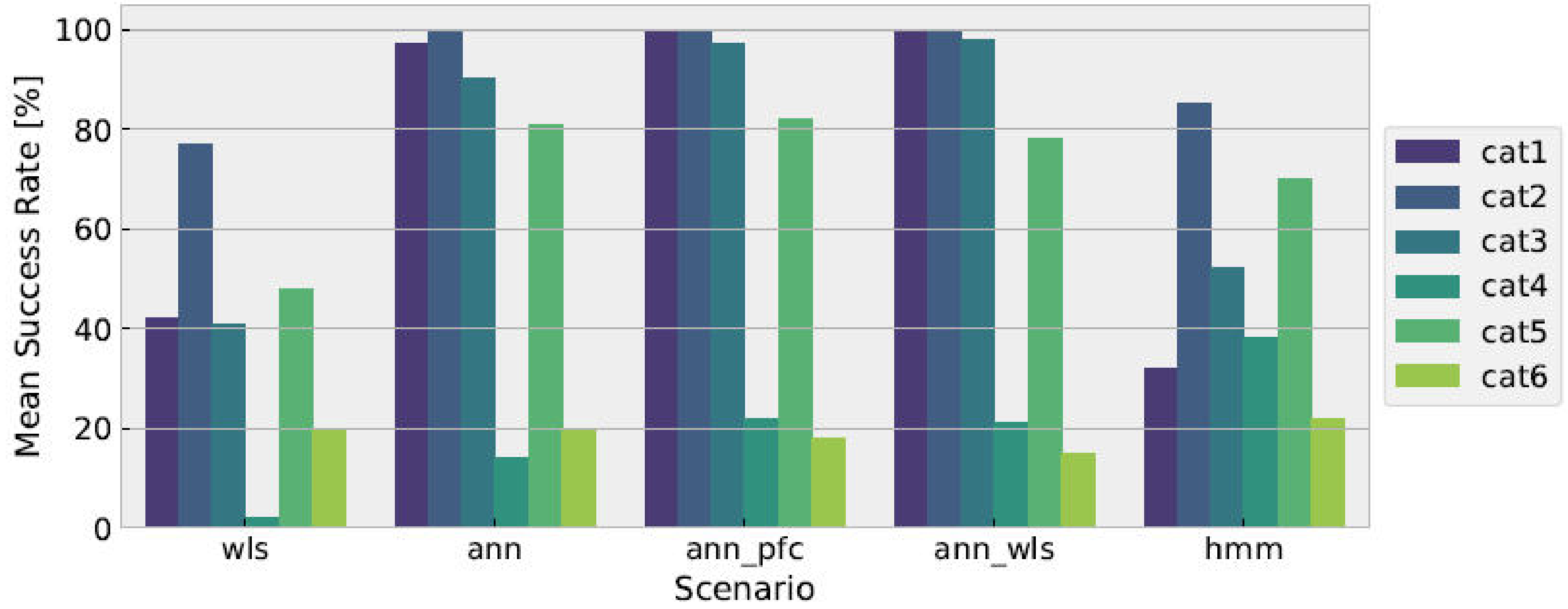
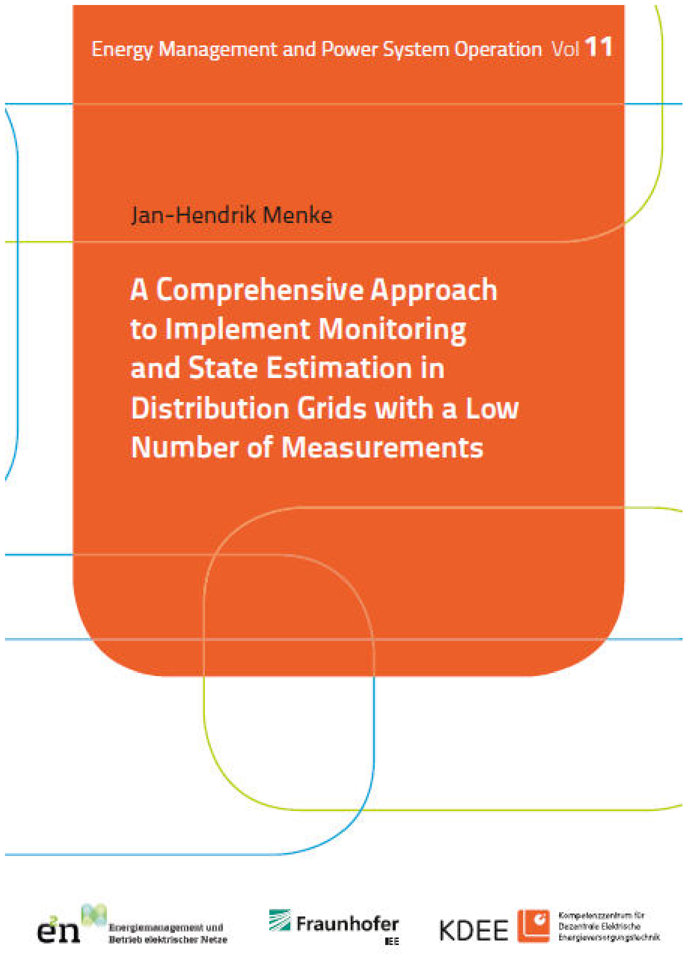


Figure 5.2: Comparison of the mean success rates of the monitoring schemes regarding different test criteria. The categories *cat1* - *cat6* are transferred from Table 5.10



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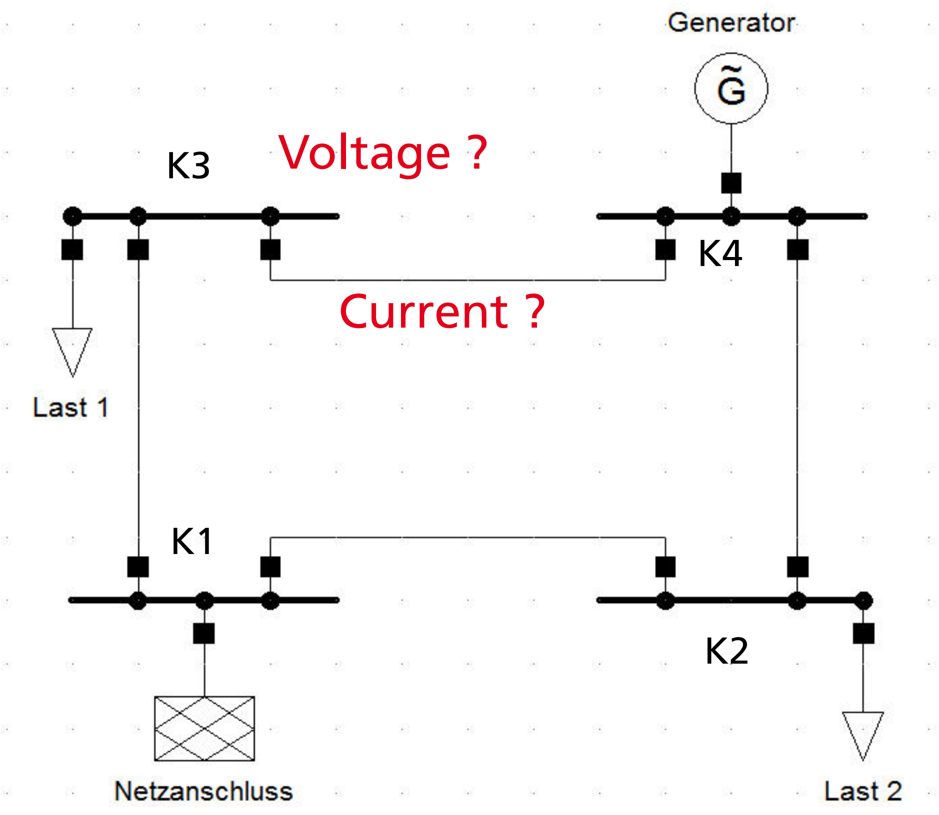
Power Flow Problem

- Widely used analysis method to study power grids
- Given: properties of Equipment (Lines, Transformers, Grid-Topology, …), Loads, Generation
- Goal: Calculate the resulting Steady-State Voltages and Powerflow
- Different formulations: AC/DC, balanced/unbalanced
- Mostly used calculation method: Newton-Rhapson Method
- GNN based Approaches:
  - **Graph neural solver for power systems.** B. Donon, B. Donnot, I. Guyon, and A. Marot. International Joint Conference on Neural Networks (IJCNN), 2019.
  - **Deep Statistical Solvers;** Donon · Zhengying Liu · Wenzhuo LIU · Isabelle Guyon · Antoine Marot · Marc Schoenauer, NeurIPS2020



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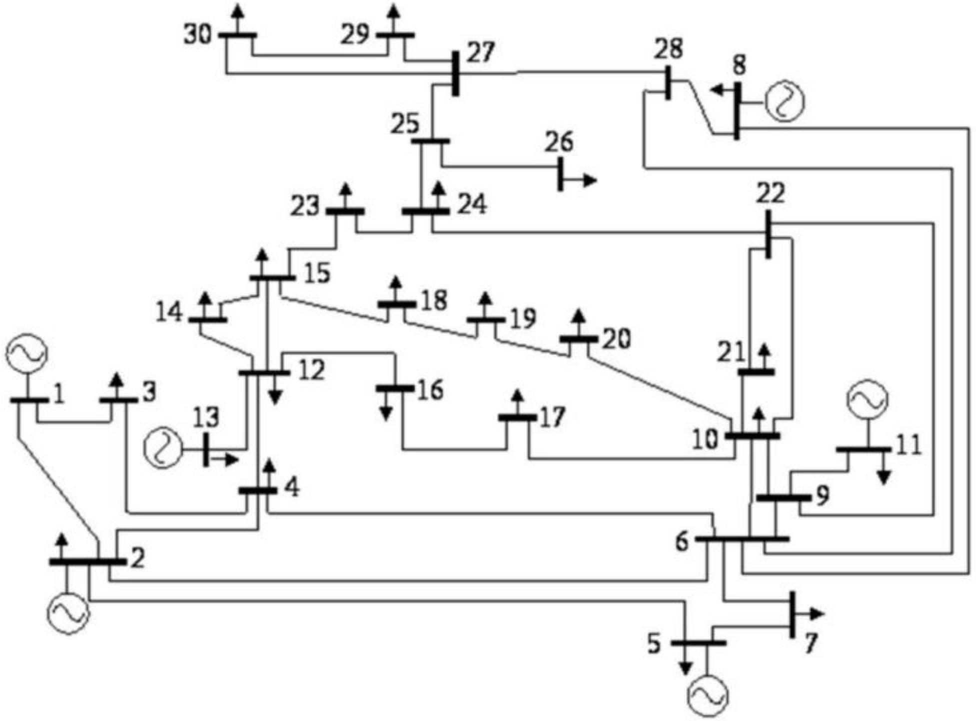
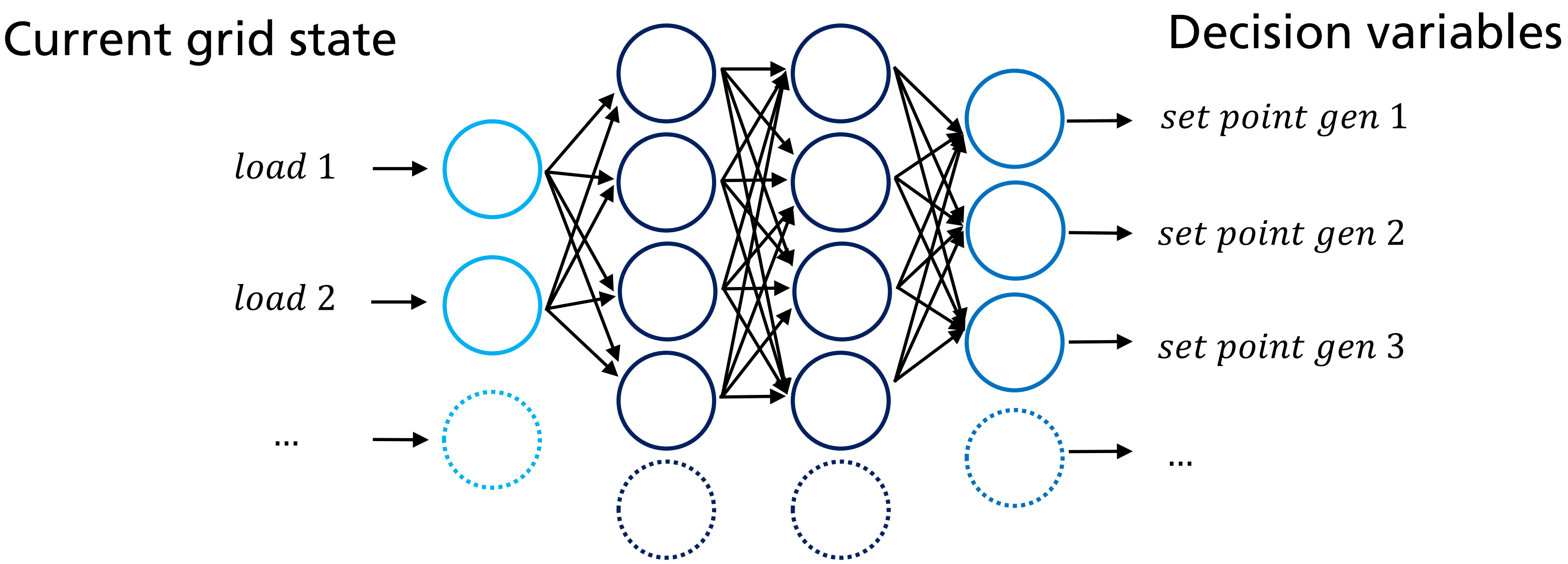
Optimal Power Flow (OPF)

OPF is a mathematical process, which is essential in the grid operation to fulfil the goal of e.g., ***minimization of operational costs (losses)*** under the operational constraints e.g., ***branch loading percent*** and ***allowed voltage range*** by adapting the working state of grid assets e.g., ***generators (P, Q, V)***.

- Solution Methods
  - Standard: mathematical Optimization
    - Long computation time
    - Mathm. modell of the problem necessary
    - Convergence difficulty due to non-convexity
  - Recently raising interest in ML-methods to solve OPF (50+ Papers 2019/20)



ANN for Optimal Power Flow



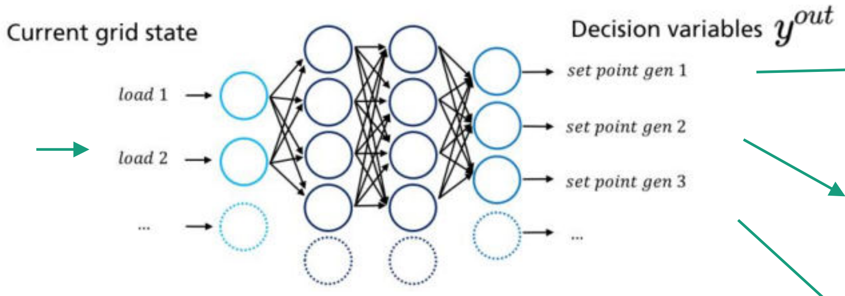
How to train such a model ?

Create (random) grid states → Use "classic" OPF to find set points → Train model to generalize the grid state -> set point function

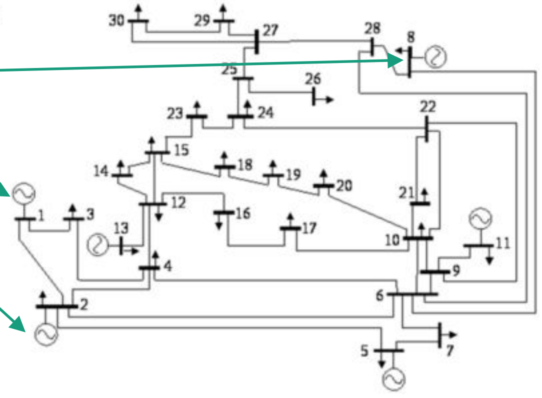
Disadvantage:
Still needs OPF

Our new Approach in the Lighthouse-Project “KI-OPF” based on Differential Programming

(random) grid states



Power flow



Custom Loss

(Grid power loss + Penalty term for constraint violation)

$$l = l_{loss} + l_{constrains}$$

Numerical gradient

$$\frac{\partial l}{\partial y_i^{out}} \approx \frac{l(y^{out} + \epsilon e_i) - l(y^{out})}{\epsilon}$$

Backpropagation

- Good computational performance in running phase (e.g. Ki-OPF 0.9 ms vs Math. OPF: 654 ms)
- Optimization model free in running phase
- No numerical solver/extra tools required
- Suitable for probabilistic simulation

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REINFORCEMENT LEARNING FOR GRID OPERATION

- 2016 AlphaGo beats 18-time world GO champion Lee Sedol
- 2019 MuZero masters Chess, Shogi, Go and 57 Atari games to superhuman performance without knowing rules in advance
- Reinforcement Learning
  - Agent learns to act within an environment based on rewards he gets for his actions
- Main Drivers for Development:
  - New Algorithms (Combining Artificial Neural Networks and Reinforcement Learning)
  - Massive Increase in Computing Power
  - Open AI-Gyms

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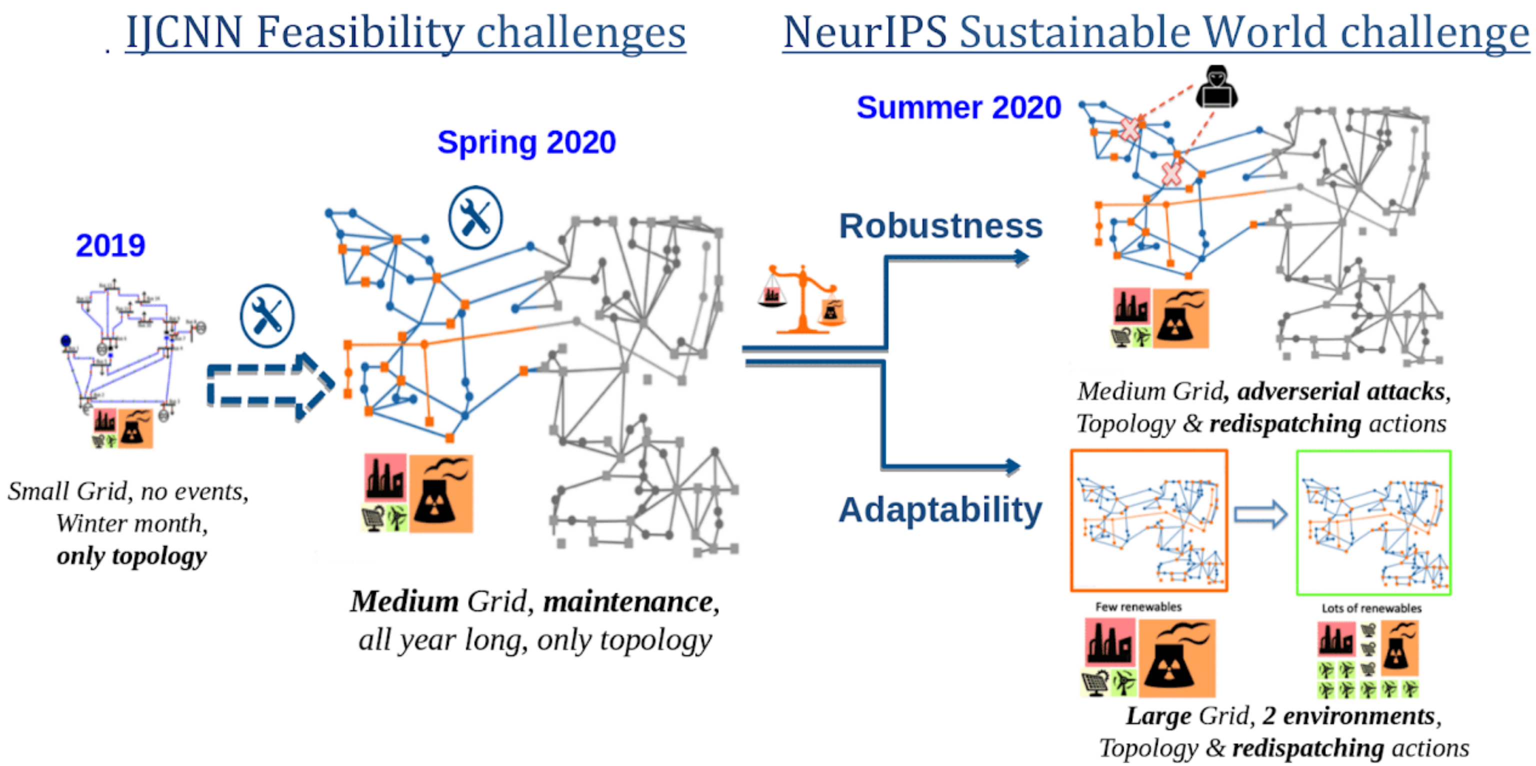
L2RPN CHALLENGES – LEARN TO RUN A POWER NETWORK

- Organized by French TSO RTE
- Goal: Develop Agent that can operate a power grid
  - Possible Actions: Topology, Redispatch
  - Prevent congestion at low cost
  - Deal with outages, attacks and strongly fluctuation sources
- Winners of NeurIPS Challenge:
  1st BAIDU, 2nd HUAWEI, 3rd NARI (largest power system vendor in China), 5th Fraunhofer IEE
- 6 Actions Depth (superhuman)



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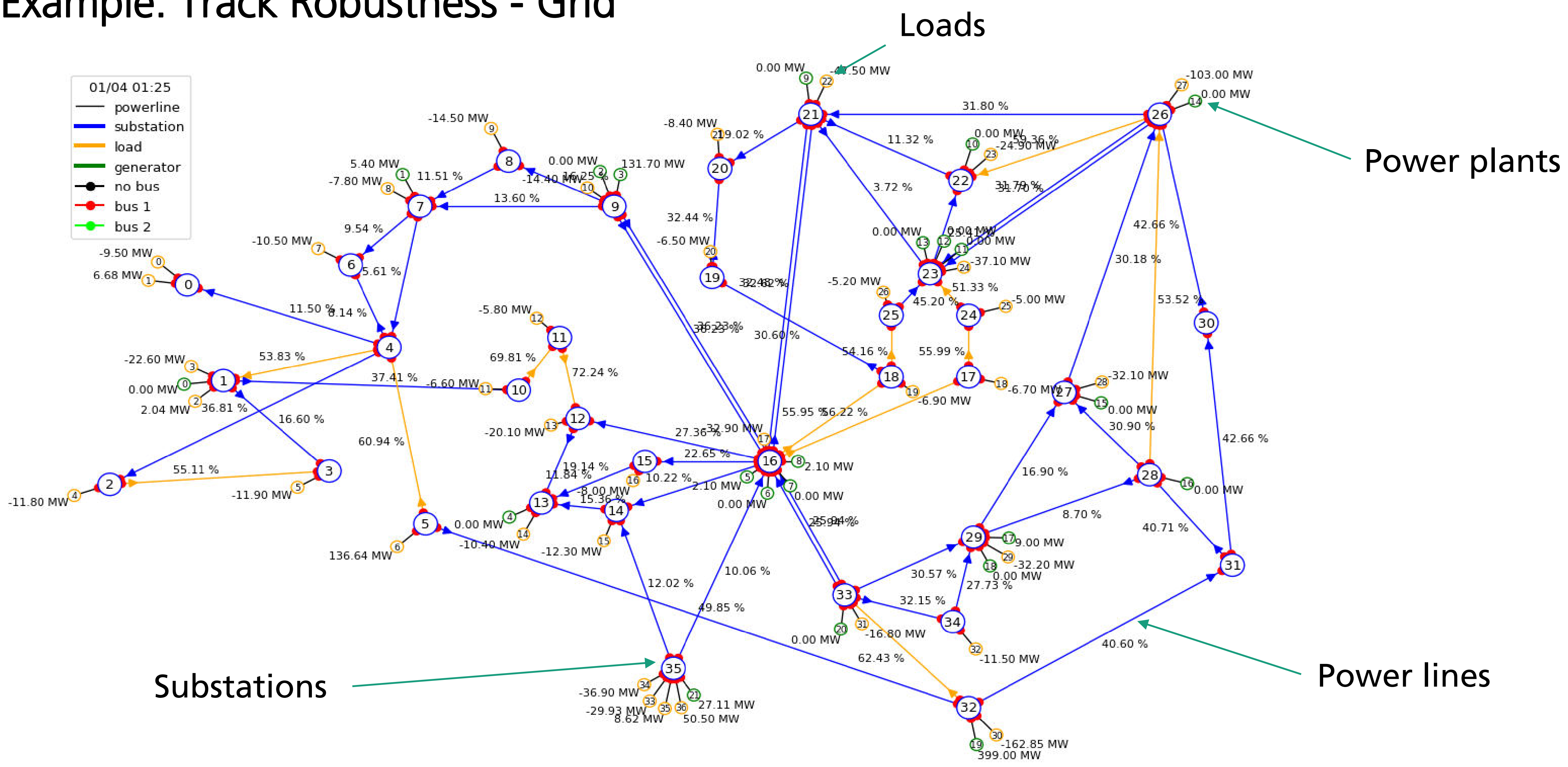
Example: Track Robustness - Grid



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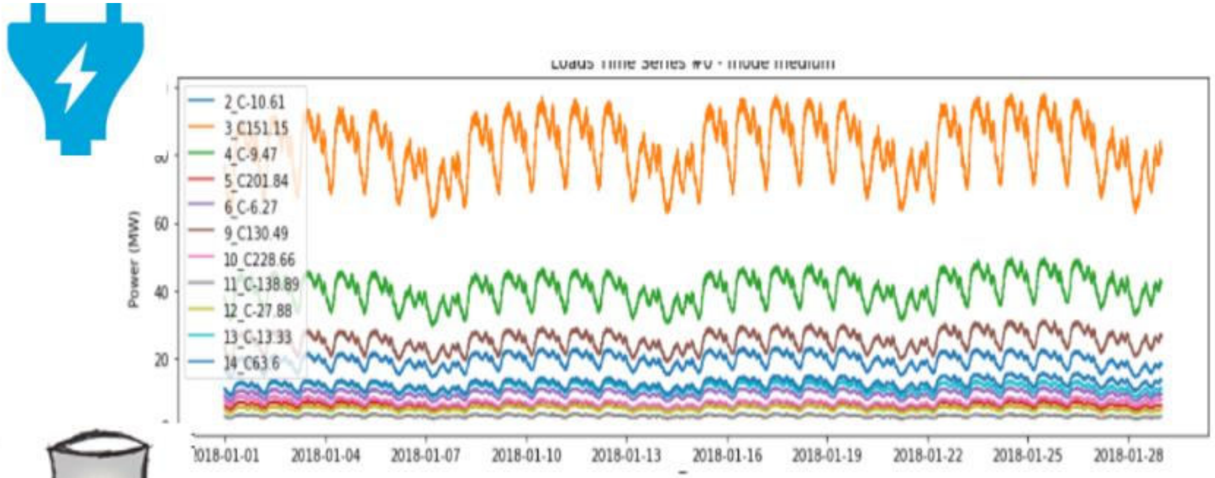
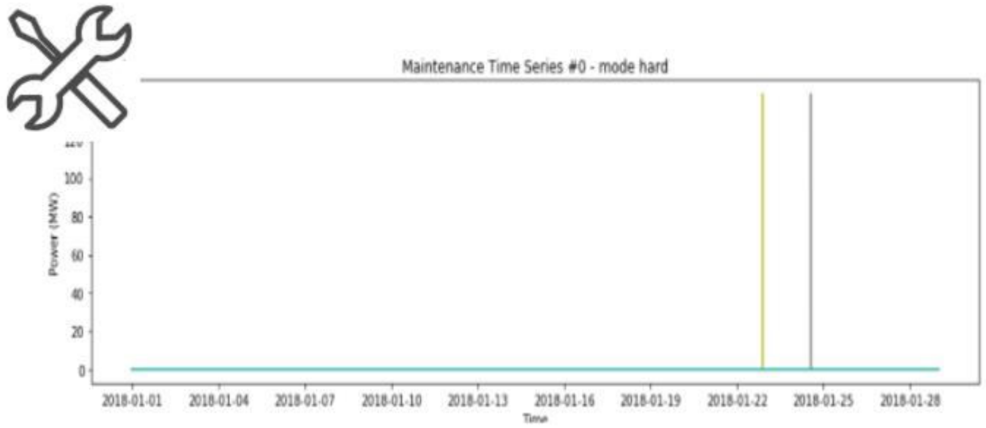
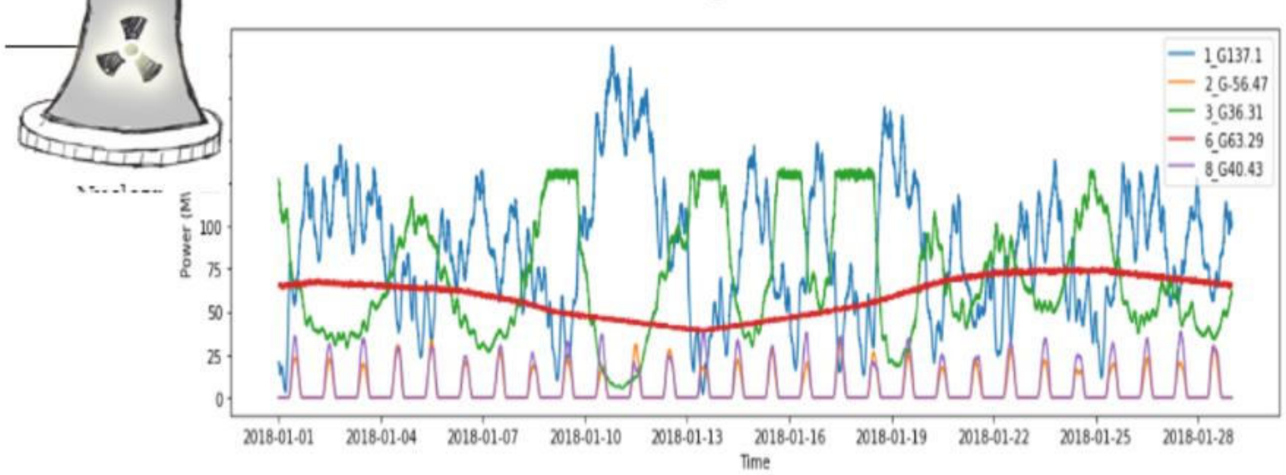
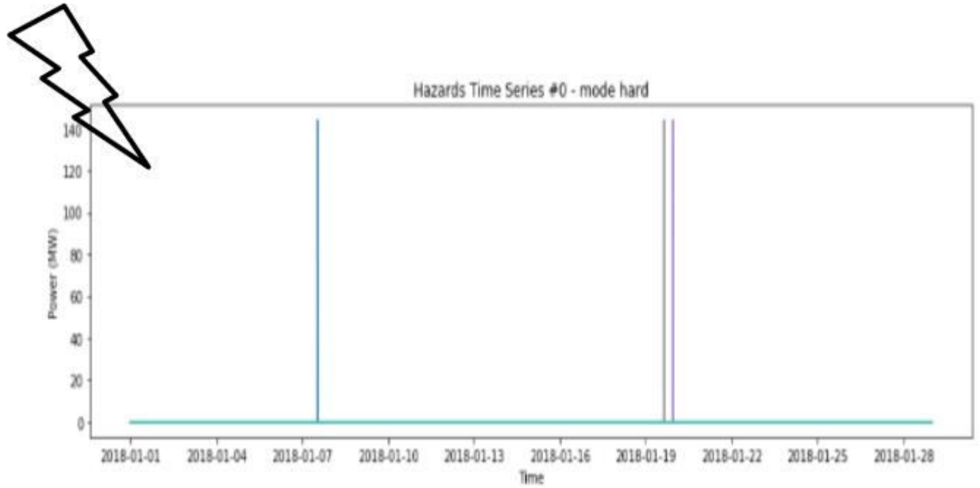
Example: Track Robustness – Time Series Data



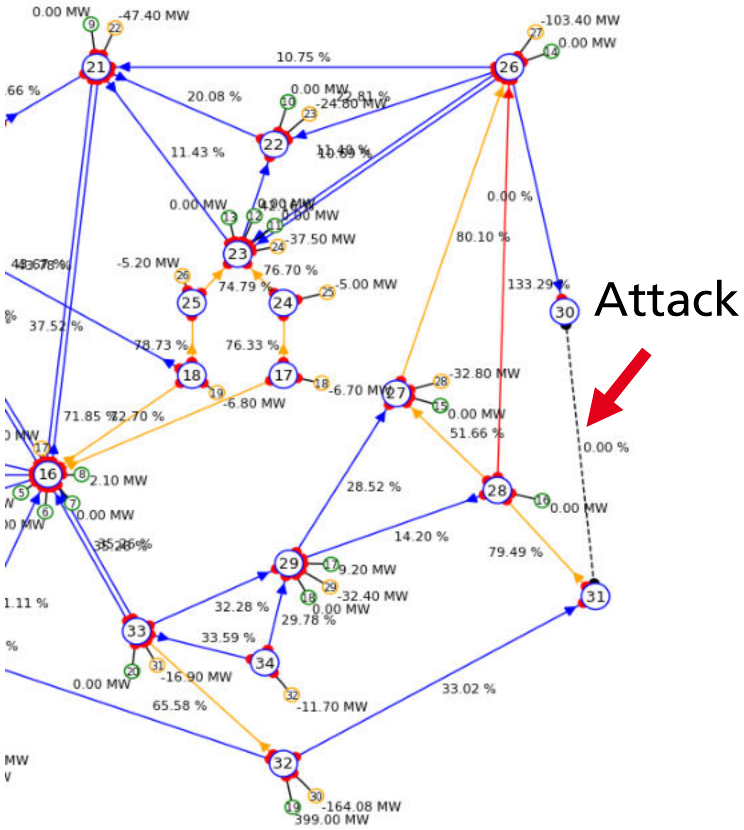




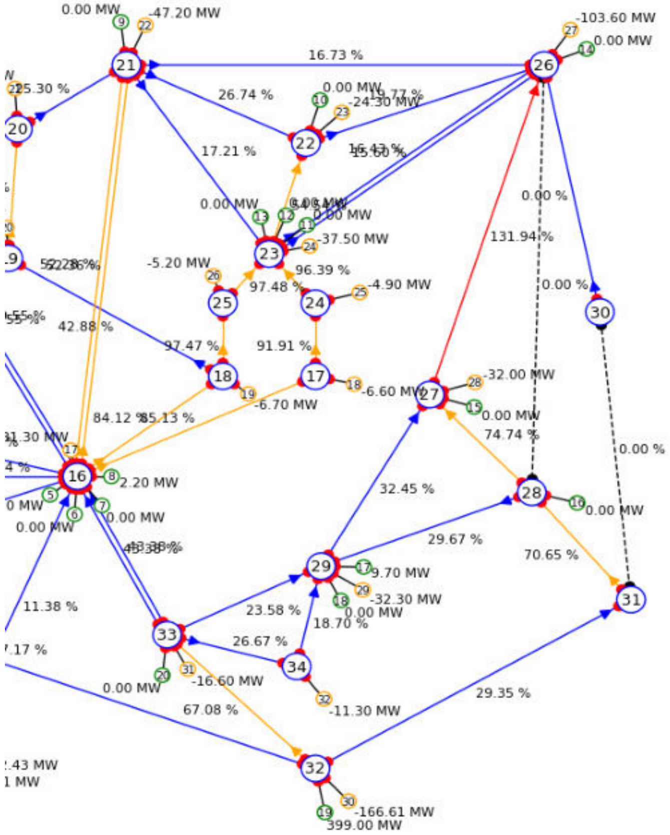


Example: Track Robustness - Attack

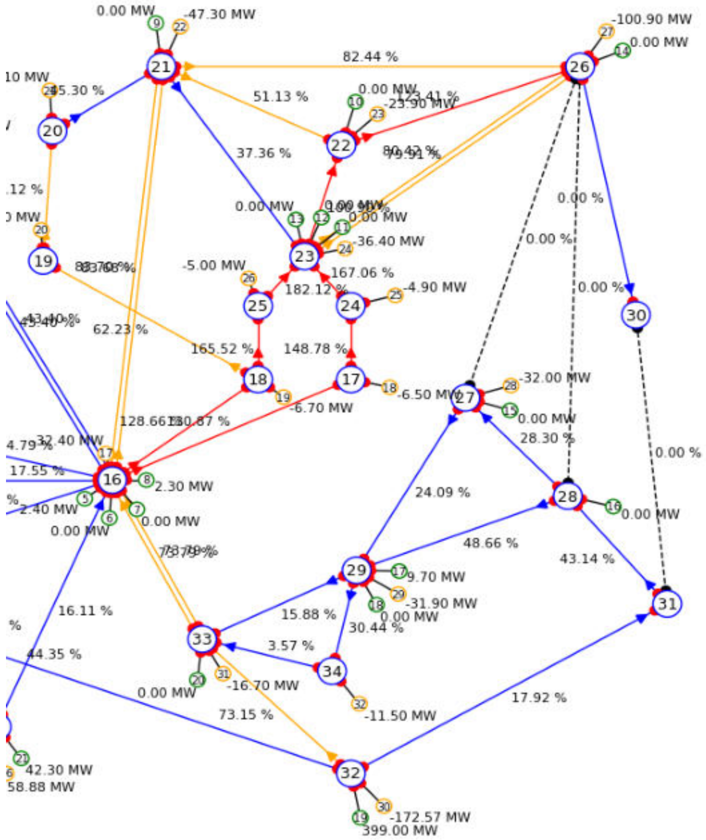
Time step 17



Time step 21

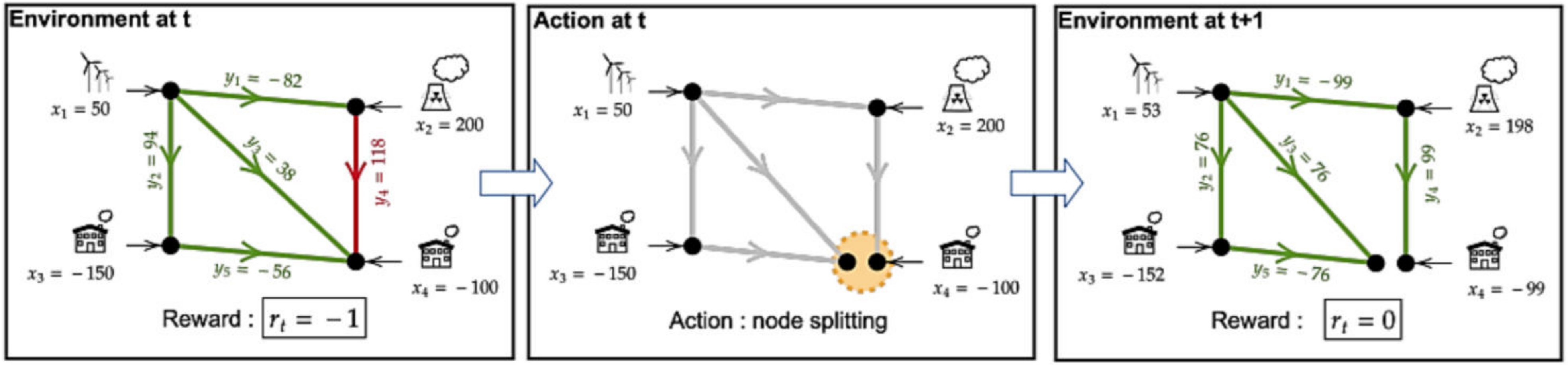


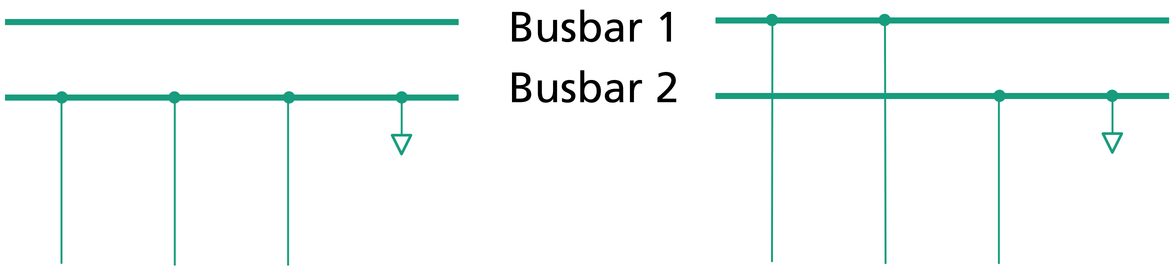
Time step 24 – GAME OVER



Possible Actions

- „Traditional“ Actions: Redispatch (expensiv), switch off lines
- Topology Actions



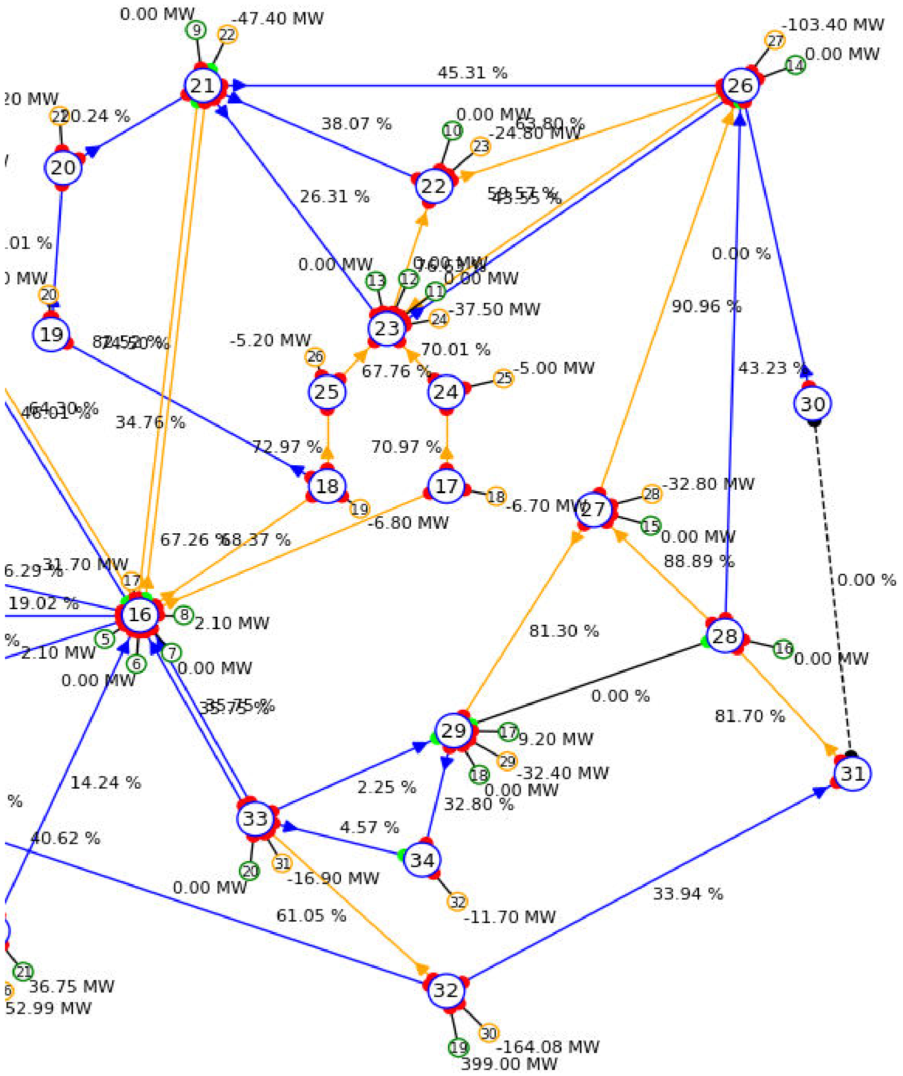


Example: Track Robustness - Our Agent

Agent changes Topology of the grid

-> mitigates overloading

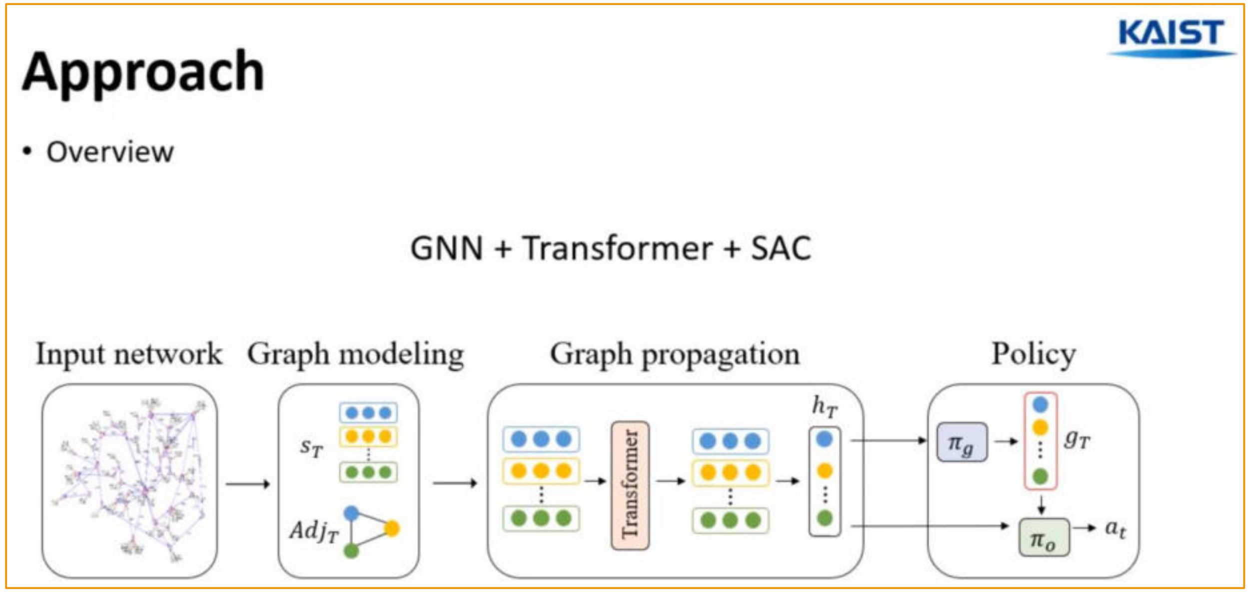
Problem has Extremely large Action Space!



Solution Approaches

- 1st NeurIPS (BAIDU): FeedForward-NN for policy - training based on gradients and evolutionary black-box optimization
- 2nd NeurIPS (Huawei): Actor-Critic model with PPO + imitation learning
- 3rd NeurIPS: DDQN
- 1st WCCI 2020: **GNN**

- Next Challenge July 2021:
  Form a Team IEE + GAIN to participate ?



Conclusions

- Power system models = networks / graphs
- Complex challenges in planning and operation of power systems
- Machine learning can bring in benefits
  - Increase speed of calculation
    - Results nearer to real time (operation)
    - Reduce computational efforts (desktop instead of cluster)
  - Finding better solutions in optimization / estimation
- We are open for collaboration ☺
  - We bring in application problems
  - GAIN provides GNN-based methods for solutions

Contact

Prof. Dr.-Ing. Martin Braun
Director Grid Planning and Grid Operation Division
martin.braun@iee.fraunhofer.de
Phone: +49 561 7294 118
www.iee.fraunhofer.de/grids

Dr. Alexander Scheidler
alexander.scheidler@iee.fraunhofer.de

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- Automated planning tools www.pandapower.pro
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- (Co-simulation) test platforms for operational solutions www.opsim.net/en
- Multi-energy system planning and operation (power, heat, gas) www.pandapipes.org
- Microgrid/ hybrid system test bench and PHiL tests

Contact

Prof. Dr. Martin Braun
Chair of Energy Management and
Power System Operation

- Mail: martin.braun@uni-kassel.de
- Phone: +49 561 804 6202
- http://www.e2n.uni-kassel.de

Department e²n

Energy Management and Power System Operation

- Development of models, methods, algorithms and tools for analysis, operation and control, and design of the future decentralized power system with high share of renewable energies. e.g. www.pandapower.org
- Multi-Objective/Perspective/Level Optimisation of the power system
- Simulation of the power system over time scales and system levels.
- Resilient Control Design incl. power system stability, network restoration, microgrid structures