Hochschule Konstanz
University of Applied Sciences

Optimized Operation of Active Distribution Grids with a Control System based on Graph Neural Networks

Manuela Linke[a], Marcel Arpogaus[a], Lea Anat Brass[a], Julian Maier[a], Christof Wittwer[b], Gunnar Schubert[a]

[a]University of Applied Sciences Konstanz HTWG, Konstanz, Germany
[b]Fraunhofer Institut for Solar Energy Systems ISE, Freiburg, Germany

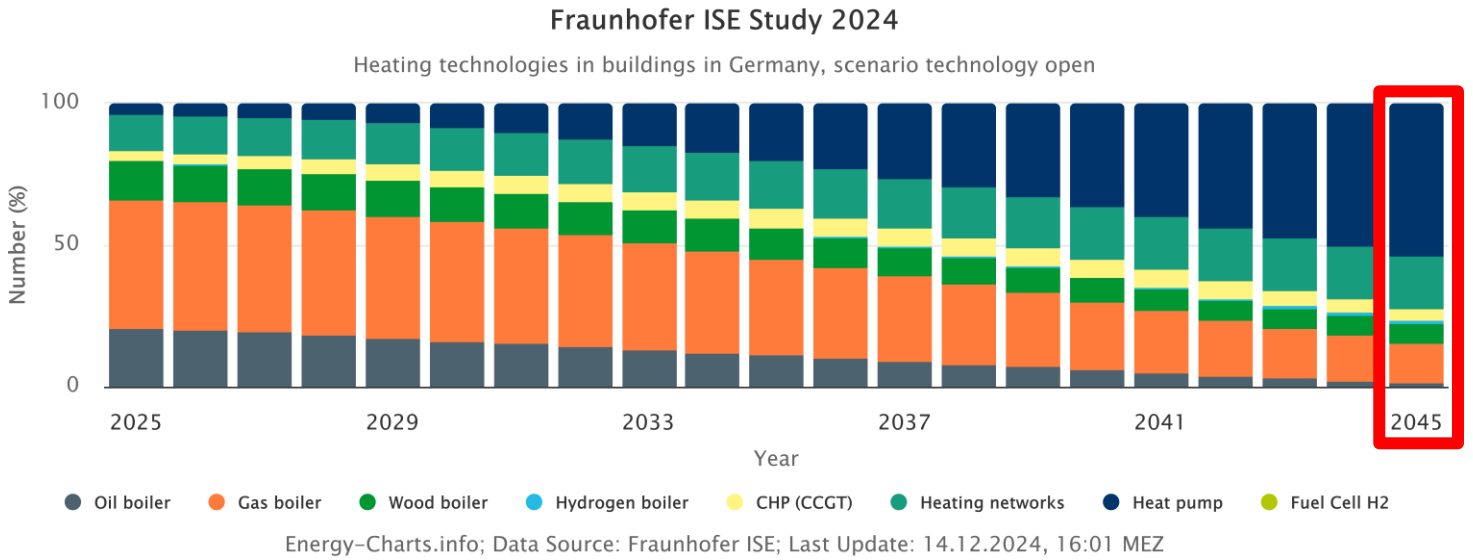
ABM4Energy, 31.03.2025

Motivation

Challenges of the energy transition in Germany

Electrification of the consumer sector by 2045

- Share of heat pumps > 50%
- Up to 35 million electric vehicles



- Increasing amount of volatile generators in the grid
- Distribution grids are the least monitored and controlled parts of the grid
- Conventional methods (e.g. state estimation) are not suitable

Image source: www.energy–charts.info - last update: 14.12.2024, 16:01 MEZ
Data source: Thelen, C. et al. „Wege zu einem klimaneutralen Energiesystem: Bundesländer im Transformationsprozess“, 2024, Fraunhofer ISE

Grid operation management

Goal

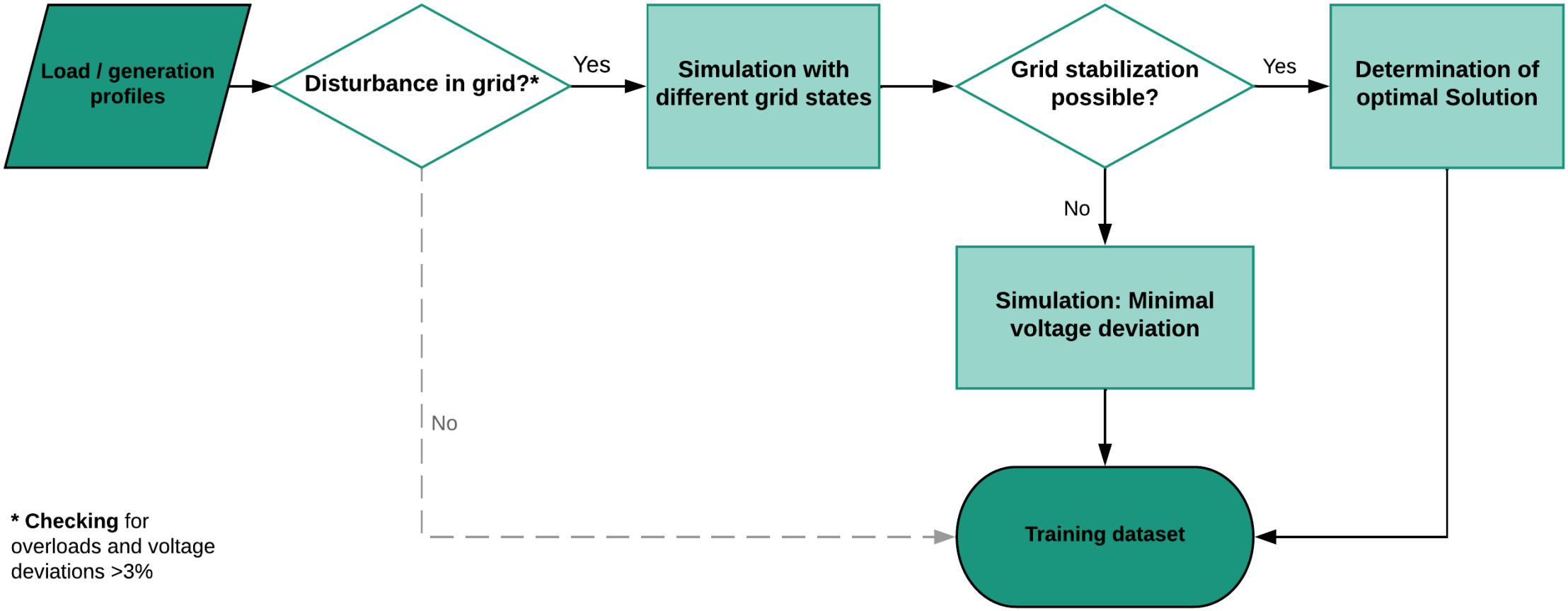
- Intelligent use of the existing grid infrastructure
- Reduction on grid expansion
- Avoidance of supply bottlenecks

Solution measures

- **Transformer tap changers**
- Congestion measures of controllable loads an generators
- Remote controlled switches

Problem: Data availability and quality!

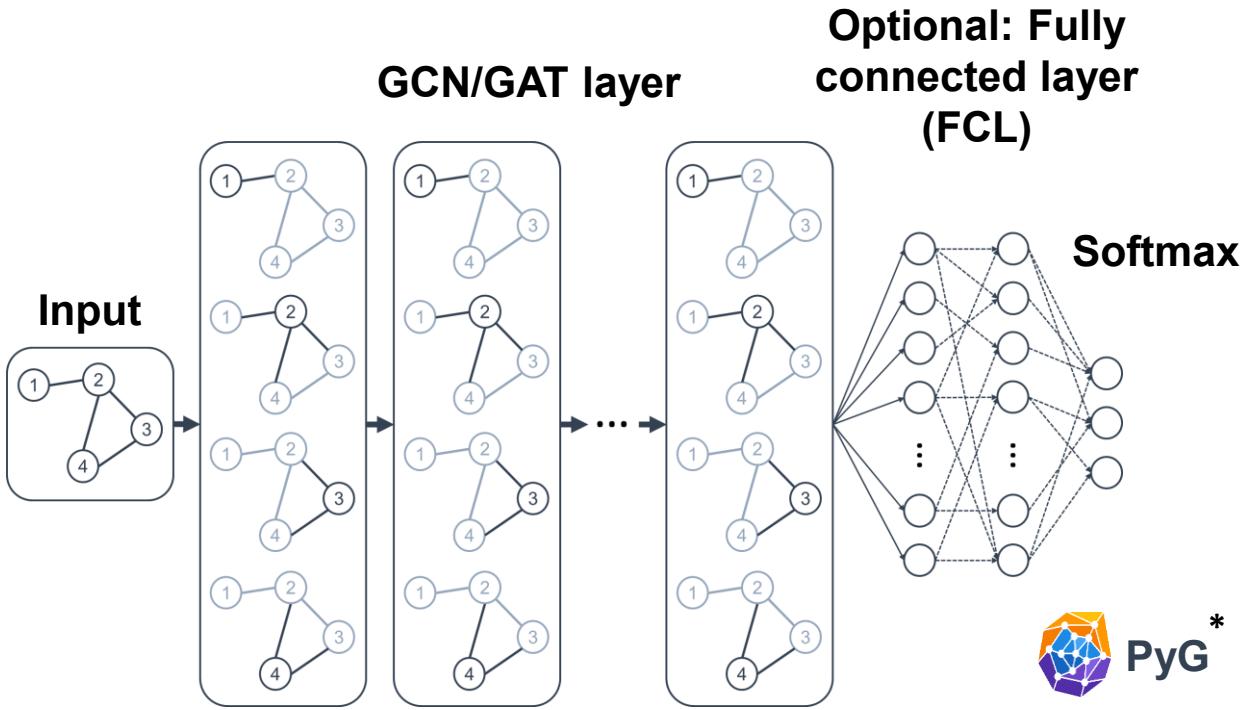
Training data generation



Graph Neural Network

Graph Convolutional Network (GCN) / Graph Attention Network (GAT)

- Topology of the network is used for training (neighborhood relationships)
- Independent of the size of the input and permutation invariant
- Generalizability: Trained GNN can also be applied to new topologies

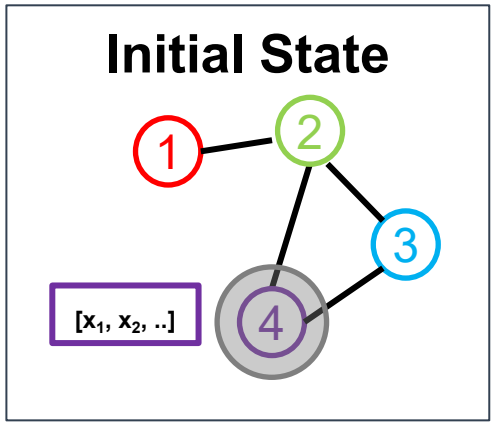


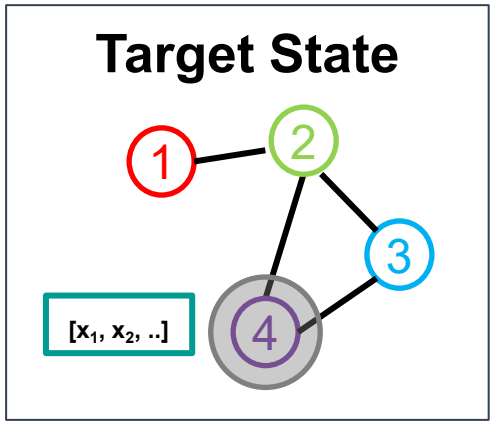
M. Linke et al., „Distribution Grid Management with Graph Neural Networks", https://www.zee-uni-freiburg.de/wp-content/uploads/2023/11/Poster-12-Distribution-grid-management-with-graph-neural-networks.pdf

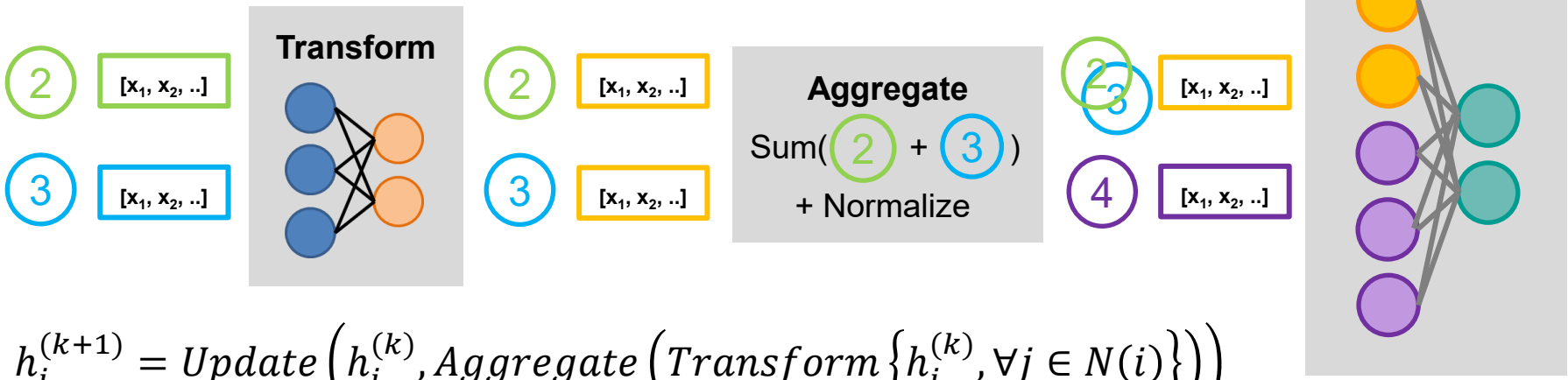
* M. Fey, J. E. Lenssen, Fast Graph Representation Learning with PyTorch Geometric, 2019, ICLR 2019 (RLGM Workshop), https://doi.org/10.48550/arXiv.1903.02428

Graph Neural Networks

Message Passing Mechanism



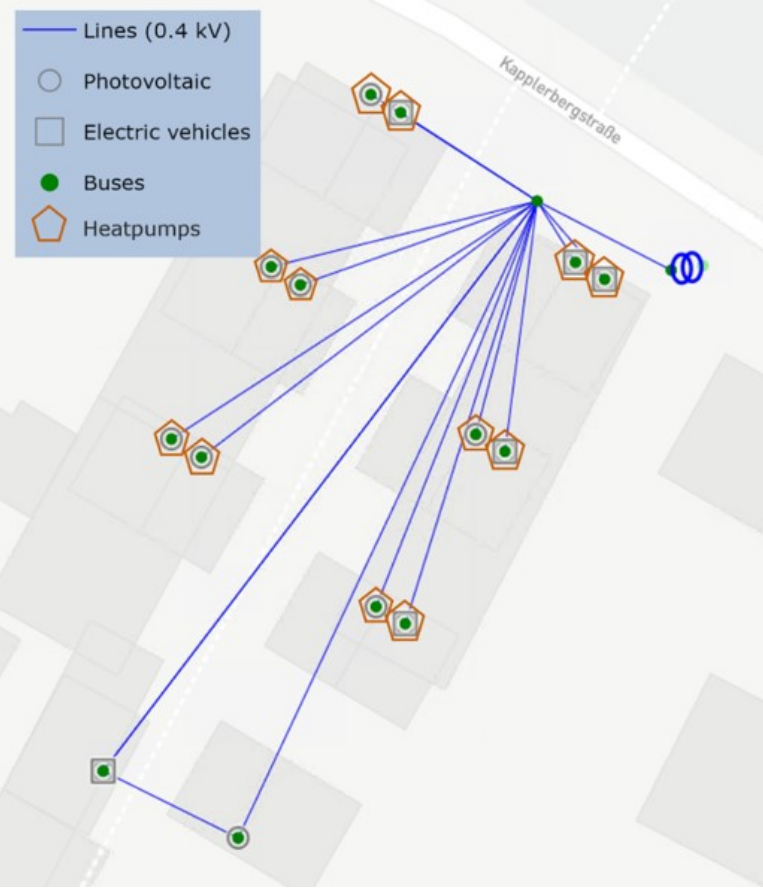




$$h_i^{(k+1)} = Update\left(h_i^{(k)}, Aggregate\left(Transform\left\{h_j^{(k)}, \forall j \in N(i)\right\}\right)\right)$$

Test

LV grid with 19 nodes



Grid parameters	
Node features	Loads [MW]
	Generations [MW]
Edge features	Line length [km]
	Primary line constants (x, r, g, b)
	Tap ratio of transormer station
Edge index	Adjacency matrix

0	1	…	1
1	0	…	0
…	…	…	…
1	0	…	0

Results

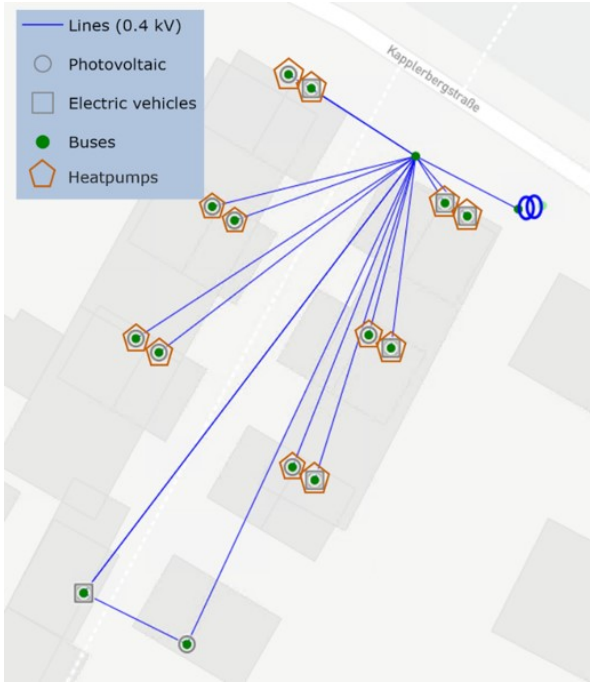
Graph Convolutional Network (GCN) / Graph Attention Network (GAT)

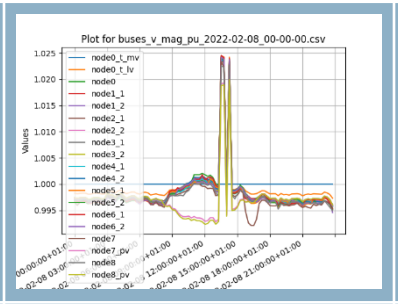
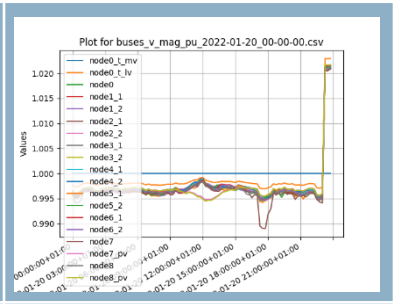
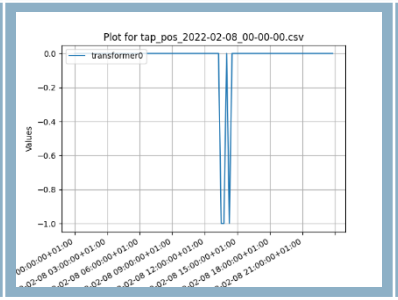
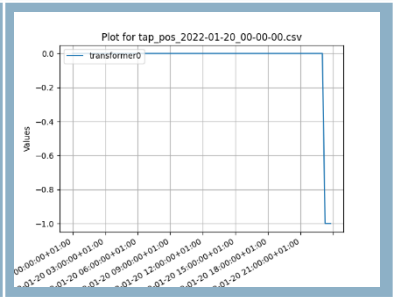
Model	Training Loss	Validation Loss	Training Accuracy	Validation Accuracy	Test Accuracy
GCN	0.191	0.152	0.945	0.944	0.922
GAT	**0.099**	**0.079**	**0.964**	**0.976**	**0.944**
GCN-FCL	0.238	0.164	0.949	0.933	0.930
GAT-FCL	0.097	0.108	0.968	0.981	0.936

FCL: Fully Connected Layer

Tested at the Digital Grid Lab @ Fraunhofer ISE*

- Electricity grid: Digital twin of the Allensbach electricity grid
- Time series of 3 months (January to March 2022)
- 4 voltage band violations detected



	08.02.2022	20.01.2022
Voltage values		
Tap position		

* http://www.digital-grid-lab.de/

Conclusion & Outlook

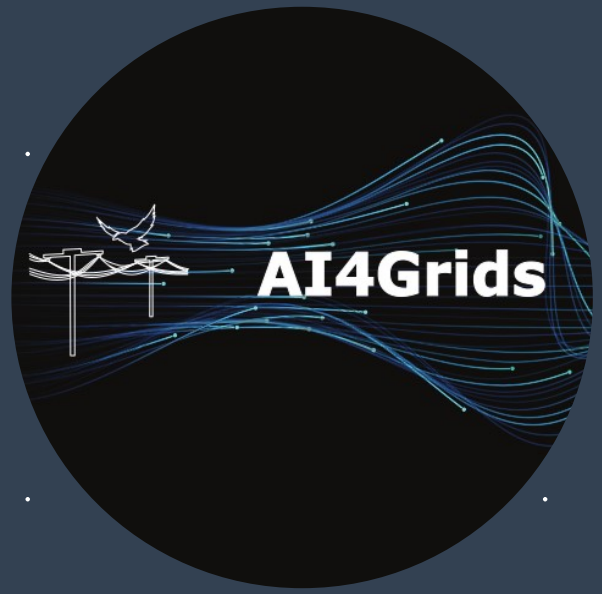
- GNNs are well-suited for controlling a distribution grid and enable optimal use of existing grid infrastructure
- Data distribution of the classes affects accuracy of the prediction
- Tested in lab environment

Outlook

- Congestion measures of controllable loads and generators
- Explainability to meet the requirements of the EU AI Act*
- Scalability: Combination with agent-based system to realize in large grid areas
- Application to the dynamic and complex energy-relevant processes for process optimization in the energy-intensive industry

*European Parliament and Council of the European Union, Regulation (eu) 2024/1689 of the european parliament and of the council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending regulations (ec) no 300/2008, (eu) no 167/2013, (eu) no 168/2013, (eu) 2018/858, (eu) 2018/1139 and (eu) 2019/2144 and directives 2014/90/eu, (eu) 2016/797 and (eu) 2020/1828 (artificial intelligence act) (2024). URL http://data.europa.eu/eli/reg/2024/1689/oj

HTWG



Hochschule Konstanz
University of Applied Sciences

Thank you for your attention!

manuela.linke@htwg-konstanz.de

Carl Zeiss Stiftung

Supported by:

Federal Ministry
for the Environment, Nature Conservation,
Nuclear Safety and Consumer Protection

based on a decision of
the German Bundestag