Delft AI Energy Lab

Topic
Dynamic Sustainable Energy Systems

Mission & objective
• combine groundbreaking ML with the reliable theory of the physical energy system
• make energy systems sustainable, reliable, effective

Education
• EE4C12 ML for Electrical Engineering
• SC42150 Statistical Signal Processing
• SC42110 Dynamic Programming and Stochastic Control
• MOOC Digitalization of Intelligent and Integrated Energy Systems
• Crash course of “Data-science”

Research
• Supervised learning for real-time grid assessment with many renewables
• Distributed learning for power system congestion management
• Data-driven grid models for electricity load and weather forecasts
• Characterizing healthy/normal trajectories of complex dynamical systems using dictionary learning
• From fast Fourier transform to fast reinforcement learning

Key innovations
• AI-based algorithms for grid operation
• Real-time security assessment and anomaly detection
• Real-time learning algorithms for control and security of complex dynamical systems

Team
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https://www.tudelft.nl/ai/delft-ai-energy-lab
Statistical Learning on Graphs for Power System State Estimation

Scope: This thesis project will investigate a statistical power flow and Graph Neural Networks to learn for various use cases within power system state estimation.

Problem definition: Estimating the state of the system involves a complex interaction of many devices and connectivity of the power system. Typically, the estimation involves numeric integration methods of the power flow equations based on weighted least square method. This process does not converge, and is limited in the accuracy making inappropriate assumptions. The problem is that the underlying algorithm for state estimation is not ready for increasingly active and flexible future distribution grids considering renewable energy integration. Hence, a more sustainable energy systems needs better state estimators.

Methodology: The power system can be represented as a meshed graph and graph theory as well as statistical learning can be applied. Recently, graph neural networks were found useful for predicting purposes where the interconnectivity is responsible for system-properties. Neural networks have the advantage to predict complex input-output relationships in real-time. In this work, we will combine graph-theoretical approaches to power systems with the latest cutting-edge methodologies. You will participate in Delft working groups on graph neural networks (Elvin Isufi) and dynamic systems (Jochen Cremer).

Research objectives:
- Literature review on state estimation, statistical learning, graph-neural networks, selected topics from graph-theory
- Investigate state estimators in PandaPower and PyPSA on a small test system in Python.
- Develop a graph-neural network training approach for state estimation
- Develop an approach to inform the graph-neural network with the power flow algorithm
- Test the approach with standard neural network-based approaches, state-of-the-art numeric integration.

Industry relevance/partner: The system stability is very important in the future as natural stabilities, such as fossil-fuel based generators will be removed from the energy mix. We will share the findings with a Distribution System Operator. Developing AI-based algorithms is in highly demand in the industry. Hence, you put yourself in an advantageous position for industrial (and academic) positions.

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- Dr. Elvin Isufi (E.Isufi-1@tudelft.nl)
Neural Ordinary Differential Equations for Power System Dynamics

Scope: This thesis project will focus on using machine learning (ML) to predict power system dynamic trajectories after system disturbances. You will use the ML method of Neural Ordinary Differential Equations (NODE) to train efficiently known power system dynamics.

Problem definition: The structure and operation of the power systems are evolving while our society must move toward a sustainable and carbon free future. Power grids become more vulnerable against large disturbances that can cause blackouts. Dynamic simulations reveal the system performance for a specific disturbance scenario but simulation of real operation is highly challenging due to the unpredictable nature of the blackouts and the large number of scenarios to consider. Alternatively, ML models can be trained in near real time by using high-resolution post fault measurements. NODE models are promising to mimic dynamical systems efficiently and accurately.

Methodology: You will develop a NODE algorithm for the prediction of power system dynamics. You will review the literature about dynamical systems, numerical integration, neural networks, and time-series models, and NODEs. Then, you will construct a dynamic model of a test system in a simulation environment (e.g., DlgSILENT PowerFactory). You will generate data by simulating a disturbance, analyze the data. Subsequently, you will develop a concept for training your own neural network architecture that utilizes NODEs. You will then test your own concept on a dynamic power system model. Finally, you will fine-tune the model and analyze the NODE architectures that captures the post fault dynamical behavior of the power system.

Research objectives:
- Literature review on dynamical systems, numerical integration, neural networks, time-series models, NODEs
- Conducting dynamical simulations of a power system to investigate blackout events.
- NODE modeling, training, and prediction of simulated power system events.

Industry relevance/partner: This MSc thesis is part of the PAIBET industrial project with TenneT (NL, DE), TNEI (UK), and Stedin (NL). There, security of the operation is an essential and challenging task for transmission system operators like RTE (France), National Grid (UK), or TenneT (NL, DE) in Europe. This thesis combines the ML and power system dynamics which is highly valuable in both academia and system operation.

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- Supervisor: Dr. Jochen Cremer (J.L.Cremer@tudelft.nl)
Reinforcement Learning for Coordinating Energy communities

**Scope:** This thesis project will focus on the coordination of energy communities with reinforcement learning.

**Problem definition:** Energy communities aim at balancing their own energy demand and generation to reduce congestion of the grid. Community participants have individual constraints and objectives, and little information are known about the other participants. However, the community balancing objective is known to the participants and minimal information can be exchanged between participants while preserving their privacy. The problem is that when each participant aims for the same objective symmetric responses can be expected resulting, if no coordination is present, in mismatches in the balance (e.g. rebounce effect). Hence, you will develop novel decentralised control methods where individual agents coordinate and focus on individual objectives at the same time.

**Methodology:** Multi-agent reinforcement learning (MARL)’s outstanding methodological advantage is learning from a dynamic environment with the objective of maximizing a local reward. You will investigate novel MARL techniques that aim at balancing cooperation and competition to the application of coordinating energy communities.

**Research objectives:**

- Learn about Deep Reinforcement Learning, Actor-Critic, cooperative Deep Reinforcement Learning, and other AI methods for coordination
- Develop a testing model environment for coordinating energy communities (e.g., based on Pecan street)
- Develop a novel cooperative Reinforcement Learning approach to coordinate energy communities (e.g., through incentive based demand response)
- Investigate the developed approach on specific use cases, e.g., sustainability impact, carbon reductions or reducing network congestions
- Communicate findings to scientific community

**Industry relevance/partner:** You will learn highly relevant technical skills on AI, neural networks, and sustainable energy systems. The developed methods can be used for distribution system operators (DSOs) and energy community managers, municipalities, and behavior analytics.

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Master's Thesis Proposal

From disease spreading to energy transition: AI in agent-based models

Scope: This thesis project will focus on combining agent-based modelling (ABM) with Artificial Intelligence (AI) for spreading human diseases and sustainable energy systems.

Problem definition: Individual investment decisions for heating devices (and networks) and policy measures (e.g., to incentivise specific heat devices) have a massive impact on the problem of energy heating transition and their costs. Also, the problem of spreading diseases over cities is highly impacted by regulatory measures and individual behaviour. For these two and other similar problems, ABM is a very powerful tool for simulating this evolution of large systems. ABM can be used to understand the input-output relationships. In the energy system problem, the wind, photovoltaic, hydrogen and energy storage are the inputs, and the outputs can be the impact on carbon emissions. In the disease problem, the individual choices, regulatory decisions are inputs, and the output can be the hospitalisations over time. An agent can model individual behaviours, and ABM aggregates many agents to study the system. However, the system is highly uncertain and complex and to discover the input-output relationships requires studying many possible input combinations which are computationally infeasible.

Methodology: Recent methods from AI however are very effective to study individual contributions (neurons) in a larger framework (neural network) and training their individual parameters toward minimizing a global loss function. You will combine these methods from AI with ABM so that the relationship from single agents to system-level global objectives can be discovered for the energy system. You will learn about neural networks, how global loss functions are minimized and develop a method for multiple agents to translate those global losses into individual losses. This will help us to understand the sensitivity of individual players (e.g., policy, markets) in the energy system. After you develop this methodology, you will apply this to two problems: (i) disease spreading, (ii) heat energy transition.

Research objectives:
- Learn about Neural Network training, ABM, sensitivity analysis, agent-based simulations
- Develop an AI-inspired method that investigates contribution from agents to final simulation outputs of ABN
- Implement two suitable use cases, (i) disease spreading and (ii) heating energy transition
- Investigate the approach on the uses cases for reducing hospitalisation in (i) and carbon emissions in (ii)
- Communicate findings to ABM communities and/or modellers of heat networks and disease spreads

Industry relevance/partner: You will learn highly relevant technical skills on AI, neural networks, and sustainable energy systems. The developed methods can be used for distribution system operators and energy community managers, municipalities, and behaviour analytics.

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Non-intrusive Load Monitoring of the Electricity Consumption

Scope: This thesis project will investigate Physics-Informed Deep Learning to non-intrusive load monitoring.

Problem definition: Often, electricity data can be observed from smart meters. Smart meters typically measure the electricity consumption over time of a household, several households or businesses. From the recorded data it is of high interest to analyse which appliance was active at what times. However, such a non-intrusive way of monitoring directly the appliances is not always feasible from the recorded smart-meter data. The data may be noisy, the system of appliances may not be known, and the appliance characteristics vary.

Methodology: Deep Learning is promising for the NLM-task, and recently substantial improvements were made on Physics-informed DL. We will investigate a novel hybrid-approach based on control theory of appliances. Subsequently, we will investigate combining such theory with AI-based approaches for the NLM-task. We will investigate a deep learning approach using latest SynD data published in Nature, 2020.

Research objectives:
- Literature analysis for NLM, Physics-Informed DL
- Investigating Physics-Informed combining control theory with Physics-informed DL.
- Utilize DL and applied control to maximize the learning outcomes.
- Test the approach against state-of-the-art NLM approaches.

Business relevance: Identifying appliances “behind the meter” opens up start-ups the chance for smart home energy management. There, we will share our findings with a Dutch startup seeking combining NLM with PV data. You will develop skills in data analytics, artificial intelligence and apply these directly to a very relevant energy application of NLM.

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AC Optimal Data Generation (ACODG) for Power System Security

Scope: This thesis project will focus on developing a novel data generation method for the dynamic security assessment (DSA) classifier. Convex restriction of the AC power flow optimization enables the generation of feasible possible operating conditions based on historical observations. Active learning framework further improves the quality of the dataset.

Problem definition: Machine learning (ML) based DSA requires a rich dataset for successive prediction. Training data must cover past observations, possible future operations, and samples around the security boundary. Sampling strategies from historical data cannot anticipate unseen possible conditions. Greedy search algorithms suffer from the nonconvex feasibility space of the power flow. ML labels require costly dynamic simulations for the predefined contingency cases. Label generation costs can be reduced extensively with an efficient, effective, and automatic data generator.

Methodology: You will develop a sequential optimization problem called AC optimal data generation (ACODG) that explores nonconvex AC optimal feasible space with convex constrained envelopes around the historical feasible operating points. The objective is to maximize dissimilarity between discovered points and control variables. You will conduct dynamic simulations with generated feasible conditions to calculate security labels against the disturbance. The database is used to train support vector classifier (SVC) and artificial neural network (ANN) models. Furthermore, you will aggregate operating conditions with the agglomerative hierarchical clustering method to identify the highest ratio of misclassified samples. These samples can be used as new initial samples for the ACODG.

Research objectives:

- Literature review on AC OPF, quadratic optimization, supervised learning algorithms, clustering algorithms, DSA.
- Development of the modified convex restricted AC OPF.
- Conducting dynamic root mean square (RMS) simulations on the test system.
- Development of the ML pipeline: Preprocessing, feature selection, model construction, training, and tuning.
- Design of high scale high dimensional unsupervised clustering algorithm.

Industry relevance/partner: This MSc thesis is part of the PAIBET industrial project with Tenet (NL, DE), TNEI (UK), and Stedin (NL). There, security of the operation is an essential and challenging task for transmission system operators like RTE (France), National Grid (UK), or Tenet (NL, DE) in Europe. This thesis combines the ML and power system dynamics which is highly valuable in both academia and system operation.

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**Data-Driven Adaptive Dynamic Equivalents of Active Distribution and Transmission Networks**

**Scope:** This thesis project will focus on utilizing Machine Learning (ML) and Artificial Intelligence (AI) to create distribution network equivalent models that help adapt the operating conditions under external signals.

**Problem definition:** The massive increase of renewables and distributed generation in power systems led to highly complex distribution networks and increase in operational uncertainty. As a result, the transmission systems operators (TSOs) do not have the information to fully model distribution systems, nor the efficacy to simulate the operation of multiple distribution systems connected to them. For this reason, distribution system equivalent models are being created to represent the distribution system as a few components, or a black box. However, such efforts typically neglect modelling changes within the distribution system, and rather focus on accurately representing the distribution system’s response to faults on the transmission system’s side. Additionally, the generated equivalent models are typically dependent on operating conditions, which requires them to frequently/online update or be fine-tuned. Therefore, creating a machine learning (ML) model which emulates the distribution system’s response to shifting requests by the TSO, can provide an adaptive equivalent model of the distribution system.

**Methodology:** Recent equivalent models represent the distribution network through recurrent neural networks (RNNs), or Long short-term memory (LSTMs). You will initially study these models. Then, you will decide which modelling techniques or approach to follow based on our problem’s focus on adaptiveness and alterations within the distribution system. Afterwards, you will perform simulations on the transmission and distribution network models to generate data, train and fine-tune the ML models based on the simulated data. Within the last month, you will finalize the report, including your findings and contributions. For an excellent thesis, to go beyond these methods, you can also consider the model’s dependency on weather conditions (eg. as additional inputs on the ML model), or test the model’s applicability to multiple points of interconnection.

**Research objectives:**
- Learn about dynamic equivalent modelling, neural network models and surrogate modelling,
- Learn about machine learning models and their capabilities for time-dependent signal representation,
- Develop and implement an adaptive distribution network equivalent model,
- Develop a training algorithm of the equivalent model in a structured Python environment,
- Communicate findings to scientific literature, energy system modellers or AI experts

**Industry relevance/partner:** This research is part of the MEGAMIND project and may be directly used by TenneT B.V.

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AI for Estimation of a Time-Variant Flexibility for Active Power – Frequency Support in the Containment Period of Imbalances

**Scope:** This thesis project develops an AI-based algorithm to estimate time-variant flexibility with minimal number of measurements for active power–frequency support in the containment period of imbalances. The scope includes testing the applicability of the flexibility estimation from both the TSO and the DSO sides.

**Problem definition:** The massive increase of renewables and distributed generation in power systems led to higher variability and unpredictability. As a result, the need is high for cooperation between the transmission system operator (TSO) and distribution system operator (DSO). This cooperation requires accurate estimation of the power grid flexibility given a forecasted operating state. The flexibility can be illustrated as a ‘region’ around the operating state, in which the system state could be quickly shifted if needed. In estimating such a region, some problems are:

- the time dependency of a flexibility area for the same connection is neglected,
- the time characteristics of flexibility sources such as ramping rates are neglected,
- the computational complexity for an accurate flexibility estimation can be high given the system constraints,
- the increasing uncertainties in loads and stochastic generation complicate the estimation.

AI is promising to predict this flexibility faster and more accurately. A long standing challenge for learning models is to consider uncertainties and identify repetitive patterns in the quantification of this flexibility.

**Methodology:** Recent flexibility predictions suffer inaccuracies caused by simplifications. You will start with a literature review will include techniques from supervised machine learning and multi-objective optimization. Then, you will design an AI-based algorithm that balances the model simplification with the improvement of its prediction accuracy of the flexibility. For an excellent thesis, to go beyond these methods, you consider the time dependencies of flexibility sources and patterns in flexibility areas from the same connection.

**Research objectives:**

- Learn about TSO-DSO connection and flexibility prediction, supervised learning, multi-objective optimization, sensitivity, and perturbation analysis.
- Develop a model for the dependency between system components, their constraints and flexibility.
- Develop an algorithm that estimates the time dependency of flexibility evolutions.
- Test your methods in an environment that models the TSO-DSO interactions.
- Communicate findings to scientific literature, energy system modellers or AI experts

**Industry relevance/partner:** This research is part of the MEGAMIND project and may be directly used by TenneT B.V.

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Reinforcement Learning for Topology Control of Power Systems

Scope: This thesis project will combine approaches from Reinforcement Learning (RL) and Artificial Intelligence (AI) to securely operate electric power systems.

Problem definition: Electric power systems are undergoing a fundamental transition to become more sustainable through intelligent operations. Uncertain renewable sources (e.g., wind and solar) with limited flexibility are replacing flexible, dispatchable conventional generators (e.g., diesel, coal, gas, etc.). Recently, many researchers demonstrated the under-exploited flexibility of transmission network topology to reduce operational cost and improve system security. Transmission network topology control refers to the switching on/off of the transmission networks elements such as branches with switching to re-direct active and reactive power flows in the network. Currently system operators rely on their experience, predetermined look-up table and heuristic methods to perform corrective switching topological actions. However, these approaches could lead to sub-optimal or power blackouts. To overcome this challenge, the French system operator has launched a series of competitions called the L2RPN challenge to use reinforcement learning (RL) for secure operation of power systems. There, agents are trained to perform topology control actions to avoid cascading failures in the system.

Methodology: You will investigate the methodology of the best performing agent(s) in the L2RPN challenge. To this end, you will investigate and implement deep reinforcement learning and tree-search algorithms to securely perform topology control of transmission networks.

Research objectives

- Review literature of topology control of power systems, deep reinforcement learning (DQN), and Monte Carlo tree search (MCTS).
- Investigate the L2RPN challenge and the developed winning agents of the competition.
- Select the best performing agent that used DQN and Beam search.
- Implement this agent in standard environment in Python (Grid2Op Python package from L2RPN).
- Develop and investigate the agent considering renewable uncertainty, outages, economics, and scalability.

Industry relevance/partner:

You will learn technical skills on AI, deep reinforcement learning, and operation of transmission systems. The developed approach could be used by transmission system operators to securely operate power networks.

Contact detail:

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Neural Network for N-k Security Constrained Optimal Power Flow

Scope: This thesis project will focus on developing a neural network that is trained for a N-k Security Constrained Optimal Power Flow. You will combine linear algebra and end-to-end learning from neural networks to train a neural network that predicts the N-k security constrained optimal power flow (SCOPF).

Problem definition: With conventional methods the N-k SCOPF can only be solved for small k. The objective of the SCOPF is to compute a secure operating condition for a grid where k equipment failures. The number of equipment's like generators will drastically increase due to decentralization of energy resources which is why the combinatorial challenge of consider N-k equipment outages increases raising an additional serious threat to systems: cascades.

Methodology: You will develop a neural network that exploits the structure of the power system using linear algebra. There, you will investigate suitable neural networks structures, and decide for one structure based on thorough analysis. Then you will invent a tailored loss function for training your Neural Network structure that predicts solutions for the N-k SCOPF by just considering N-1 failures. You will then maximize the capability to generalize to N-2, N-3,... N-k faults of this trained Neural network that you have trained with your developed structure-exploiting loss function considering only N-1 failures. You will implement your developed method in standard packages from Python using CVXPY, Numpy, Pytorch, and other packages.

Research objectives:

- Literature review on neural networks, backpropagation algorithms, linear algebra, linear, convex, and graph-based formulations of optimization problems
- Design a method that generates N-1 Secure Optimal Solutions
- Design a supervised learning workflow training to predict N-1 Secure Optimal solutions substituting SCOPFs
- Developing a neural network structure exploiting the structure of N-k SCOPFs to predict for N-k solutions
- Develop a training workflow for N-k SCOPF predictions combining concepts from linear algebra, mathematical optimisation and neural networks
- Test the method on its generalizability from N-1 to N-k faults. Test on different power system networks.
- Disseminate results to scientific article if results allow.

Additional note: This thesis topic is thought through, ambitious, challenging and may lead to scientific publication. Hence, please only apply as an outstanding individual demonstrated with high-performing grades, strong scientific interest, critical thinking and independence.

Industrial relevance: Assessing the power system for N-k faults is of utmost importance for system operators like TenneT. If you develop a novel methodology that can solve this ambitious and challenging problem you are in a very good position to enter the job market being qualified: with relevant skills (ML/AI) and important engineering skills to address key issues of energy transition.

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