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Energy Meteorology and Hydrology
Topics for MSc theses

The following pages contain a list of topic suggestions for MSc theses at the intersection of meteorology, hydrology energy, and data science. In each project, the Master students will have the opportunity to interact with groups from at least two of these domains, and with their work will contribute to making a weather-driven energy system more efficient.

Topic List

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Renewable energy systems in a changing climate

Supervising groups: Klose (Institute of Meteorology and Climate Research), Sandmeier / Fichtner (Institute for Industrial Production), Hagenmeyer (Institute for Automation and Applied Informatics)

Problem / state of knowledge: The availability of solar irradiation, wind, and water is a key prerequisite for an energy system of renewable resources. This availability may, however, change in space, time, and frequency in a changing climate. For example, extended drought conditions may not only lead to water shortages, but also to changes in land use, e.g. reduced vegetation coverage, and hence increased dust aerosol emissions. These in turn can increase the atmospheric extinction of solar radiation and lead to soiling of solar power plants, both reducing solar power output. The changes and impacts need to be quantified to aid the design of a future energy system relying on renewable energy. In addition, energy storage and transport need to be optimized to maximize the efficiency at which renewable energy can be utilized.

Research questions:

1. How does the expected solar and wind energy output change in a changing climate both in space and time?
2. What impact will the expected change in solar and wind energy have on the energy system?
3. Do changes in solar and wind energy output impose any new requirements on energy systems?

Data and methods: We will use ICON(-ART) simulations of the atmosphere and its composition, for the latter with a focus on aerosols from natural systems, especially mineral dust. We plan to use different scenarios of, e.g. land use, based on shared socioeconomic pathways (SSP) as the basis for our simulations. Simulations will be conducted for a few ten years at a relatively coarse resolution (e.g. 80 or 120 km). For selected time frames and regions of interest, we will conduct additional nested simulations at considerably higher resolutions of up to, e.g. 5 km.

We will use a simulation model for the European electricity market to analyse the impact of changes in solar and wind energy output on electricity prices, the security of supply and the need for e.g. additional storage units. Additionally, an optimal power flow model can be used to analyse potential congestions in the electrical transmission grid.

Relevant course programmes:

- M.Sc. Meteorology and Climate Physics / Faculty of Physics
- M.Sc. Wirtschaftsingenieurwesen (Energy Economics)

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Exploring the impact of weather effects on electricity prices with causal modelling

Supervising groups: Fichtner (Institute for Industrial Production), Schäfer (Institute for Automation and Applied Informatics)

Problem / state of knowledge: Large volumes of power are traded on the day-ahead market. This includes generation forecasts as well as resulting prices based on biddings. Accurate forecasts and understanding of day-ahead prices is necessary to enable efficient demand-side management and an optimized operation of energy storage devices. Higher availability of power lead to lower prices but this availability is coupled to weather: solar and wind power depend on sun and wind conditions. In addition, thermal power plants can only operate with limited capabilities when river levels are low or river temperatures are too high. These important causal relationships are often ignored.

Research questions:

1. How do we construct causal models of day-ahead electricity prices incorporating weather information?

Data and methods: The starting point is the day-ahead price data from the ENTSO-E transparency platform. Later, this can be expanded to other regions, e.g. North America. To obtain forecasts, bottom-up models or machine learning models (e.g. gradient boosted trees or transformers) are considered. Causal attribution can start with ShapleyFlows.

Relevant course programmes:

- M.Sc. Informatics
- M.Sc. Wirtschaftsinformatik

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Data analysis and machine learning models to predict wind power data from an on-shore wind park

Supervising groups: Schäfer (Institute for Automation and Applied Informatics), Götz (Scientific Computing Center)

Problem / state of knowledge: Power generation and demand need to be balanced at all times. Hence, forecasts of wind power generation are extremely important to have sufficient dispatchable generation available guaranteeing the balance. So far, most wind power forecast models for wind parks are limited to simulations and few investigate empirical data. Turbulence and shading effects are very important for the operation of a wind park and need to be better understood.

Research questions:

1. How correlated are the power generators across a wind park and how much does the turbulent nature of wind persist after passing through the first turbines?
2. Can we forecast the output of individual turbines and the whole wind park based by leveraging additional information?

Data and methods: Using wind velocities, wind directions and wind power generation data from the Bürgerwindpark Reußenköge, we will investigate different forecasting and analysis options. Based on the spatial distribution, we will utilize graph neural networks and compare them to aggregated forecast of the whole wind park.

Relevant course programmes:

- M.Sc. Informatics
- (M.Sc. Meteorological and Climate Physics / Faculty of Physics?)

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Physics-Informed Neural Networks for PV forecasts

Supervising groups: Schäfer (Institute for Automation and Applied Informatics), Debus (Scientific Computing Center), Cermak (Institute of Photogrammetry and Remote Sensing, Institute of Meteorology and Climate Research)

Problem / state of knowledge: Power generation and demand need to be balanced at all times. Hence, forecasts of Photovoltaics (PV) power generation are extremely important to have sufficient dispatchable generation available guaranteeing the balance. Pure data-based models have limits as they often require large amounts of training data and are poor in extrapolating.

Research questions:

1. Can we incorporate physical knowledge about PV systems and cloud movements into PV generation forecasts?
2. What are the climatological patterns of solar radiation (in space and time) in specific weather type situations?

Data and methods: Satellite information from above the clouds, Physics-Informed Neural Networks (PINNs): Include constraints or potentially full equations into the neural net as an inductive bias.

- Thesis 1: High-resolution climatologies of morning cloud disappearance by linking geostationary satellites (high temporal resolution, low spatial resolution) and low-earth orbiting satellites (low temporal resolution, high spatial resolution)
- Thesis 2: Very-high resolution spatial patterns of radiation obtained by linking balcony PV output with satellite maps.

Relevant course programmes:

- M.Sc. Informatics
- (M.Sc. Meteorology and Climate Physics / Faculty of Physics?)
- M.Sc. Remote Sensing and Geoinformatics

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Coupled models for better PV-Generation forecasts?

Supervising groups: Debus (Scientific Computing Center), Götz (Scientific Computing Center), Hagenmeyer (Institute for Automation and Applied Informatics)

Problem / state of knowledge: Prediction of PV electricity generation, especially in small local installations, is important for optimal planning of consumption and storage management. Data-driven machine learning methods are currently heavily researched in that regard. Forecasting PV generation can be performed in two ways: as a direct time-series forecasting problem from historical values or through a mapping based on weather predictions.

It is yet to be determined which strategy yields better results: Forecasting weather is an established method that accounts for regional changes and interactions. It might be easier to first make a weather forecast (data-driven or via numerical simulations) and then predict PV generation from the weather forecast. On the other hand, coupling prediction models is prone to error propagation. Furthermore, weather forecasts are often available only on a regional scale that is coarser than the PV installation. Direct forecasting might be able to account for local effects more precisely, however, the approach means learning weather by proxy, as this is ultimately the generation driving factor.

In this two-part project, we aim to address this question and the corresponding challenges: For one, we will develop a point-based weather data forecasting model (based on local weather station data) and a weather-to-PV-generation model, and couple these two models, to compare prediction quality to direct generation time series forecasting. We will conduct input sensitivity analysis, to determine which input parameters to the weather-to-PV-generation model are most relevant for accurate generation prediction, and link this to their prediction quality in the weather model.

In the second part, we will investigate the possibility of a virtual weather station, by learning local point-based weather data (based on local weather station data) from regional weather forecasts on a coarser grid, as produced by numerical weather models. Particularly the scaling behavior of this extrapolation task is of interest: How high an accuracy is needed in the regional weather forecast (and which quantities) to achieve sufficient forecasts in the virtual weather station?

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Research questions:

1. Can we predict PV electricity generation from forecasting weather parameters at a local (point-based) weather station in a coupled-model setting?
2. Which weather variables are relevant to predict PV electricity generation?
3. Can we build a data-driven extrapolation model for a virtual weather station, to predict relevant weather parameters at a local point from regional coarse-grid weather forecasts?

Data and models: Local weather station data and PV generation data from IAIs PV installation; ICON reanalysis data for regional weather forecasts; ML Models: Neural networks for time series forecasting

Relevant course programmes:

- M.Sc. (Energy) Informatics
- M.Sc. Data Science

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Spatial statistics to predict clear skies

Supervising groups: Schienle (Statistical Methods and Econometrics), Cermak (Institute of Photogrammetry and Remote Sensing, Institute of Meteorology and Climate Research)

Problem / state of knowledge: The dissipation of persistent fog in the Upper Rhine Valley is hard to predict, making it hard to plan the photovoltaics potential even a few hours ahead of time. Satellite data with a high temporal resolution are available for the analysis of such situations, but no technique exists to date for the short-term prediction of their development.

Research qestions:

1. Can GNNs be used to predict the clearance of persistent fog in the Upper Rhine Valley?
2. What distinct spatio-temporal patterns can be identified in fog dissipation?

Data and methods: Time series of satellite data of low cloud distribution in the upper Rhine valley, graph neural networks

Relevant course programmes:

- M.Sc. Wirtschaftsingenieurwesen
- M.Sc.Wi-Wirtschaftsinformatik
- M.Sc.Digital Economics
- M.Sc. Remote Sensing and Geoinformatics
- M.Sc. Meteorology and Climate Physics
- M.Sc. Geoökologie

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Quantifying radiation below clouds from satellite data

Supervising groups: Hagenmeyer (Institute for Automation and Applied Informatics), Cermak (Institute of Photogrammetry and Remote Sensing, Institute of Meteorology and Climate Research)

Problem / state of knowledge: Cloudiness reduces the radiation available for PV. Short-term forecasting and long-term planning will benefit from knowledge regarding the amount of radiation transmitted by clouds. While satellite-based products on the optical thickness of clouds exist, there is large potential to improve this data basis by explicitly linking raw satellite-derived measurements with ground-based measurements of radiation at PV installations.

Research questions:

1. How are satellite-based measurements of cloudy areas related to radiation obtained at the ground?

Data and methods: PV and radiation data from Campus North will be statistically linked to Sentinel 2 LEO satellite observations in a machine-learning approach making use of the full spectral potential of the satellite sensor.

Relevant course programmes:

- M.Sc. Remote Sensing and Geoinformatics
- M.Sc. Meteorology and Climate Physics
- M.Sc. Geoökologie

Can also be scaled to a B.Sc. thesis.

A short-term heatwave and its impact on the European electricity markets and the security of electricity supply

This idea was developed for a joint publication that is currently in development.

Supervising groups: Fichtner (Institute for Industrial Production), Ehret (Institute for Water and Environment)

Problem / state of knowledge: Heatwaves like those in 2003, 2018 and 2019 have highlighted the significant challenges that extreme weather events pose for electricity supply systems. These events disrupt power generation, especially in thermal power plants that rely on sufficient cooling water. The resulting interruptions can compromise supply reliability, lead to demand shortages, and drive electricity prices higher. Despite the diversification of Europe's generation mix, extreme weather events increasingly test the resilience and adaptability of the interconnected grid. These challenges, along with downstream effects on electricity markets and retail prices, underline the need to analyse the impact of such scenarios in more detail.

Research questions:

1. How do heatwaves impact the availability and reliability of thermal and hydropower plants in Europe?
2. What are the implications of heat-induced constraints on electricity prices and supply security?

Data and methods:

- Data
  - ENTSO-E Transparency Platform for generation, outages, and storage data
  - Power Plant Data for technical and location-specific details of power plants
  - Historical water flow and temperature data to assess cooling constraints from various sources
  - Weather data for modelling the heatwave and the future climate scenarios from various sources

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- Methods:
  - European electricity market simulation to evaluate system and market responses under heatwave conditions
  - Machine learning models to predict future water temperature data
  - Statistical methods to analyse the relationship between environmental constraints and electricity market outcomes

Relevant course programmes:

- M.Sc. Industrial Engineering
- M.Sc. Information Systems
- M.Sc. Informatics
- M.Sc. Mathematics

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Soiling Forecast of Parabolic Trough Solar Energy Collectors

Supervising groups: Götz (Scientific Computing Center), Klose (Institute of Meteorology and Climate Research)

Problem / state of knowledge: Concentrating solar power plants (CSPs) are a clean energy source capable of competitive electricity generation even at night. In CSPs, mirrors redirect sunlight onto a receiver, generating thermal energy which can be directly used for industrial processes or to power a steam turbine. A parabolic trough collector (PTC) is a type of concentrating solar power plant that is straight in one dimension and curved as a parabola in the other two. PTCs are often located in regions with arid climates and a high dust load potential. This dust loads may lead to deposition on the CSP mirrors. This effect, known as soiling, is a major source of performance loss in CSP solar fields, and therefore solar energy production, causing annual revenue losses of several billion euros. While regular cleaning is possible, it is extremely costly, due to large staff requirements and high water consumption. More so, soiling removal speeds up the degradation of the mirror materials and thus should be reduced to a minimum. Yet, an efficient cleaning strategy can only be executed if the soiling level of each mirror is accurately known in advance.

Research questions:

1. Can PCT soiling be forecast given prior soiling and weather data
   (a) as continuous soiling quantity,
   (b) b. as a binary decision when to maintain the mirrors?
2. Is it possible to enhance this forecast by
   (a) including traditional aerosol forecasts of NWP models
   (b) adapting an AI-based weather model?
3. Which quantities of the input are most relevant for making a forecast?

Data and methods: We will leverage operational data from the Andasol-3 solar through collectors in Granada, Spain covering the year 2015 to 2017. It contains the geolocations of the PTCs, local weather information with a temporal resolution of up to 1s and glossiness measurements for 40 spots every other day (as a proxy for soiling levels).
We phrase this problem as a data-driven time-series forecasting problem. Hence, we want to leverage auto-regressive neural networks to make predictions, low-rank adapation methods (LoRA) for AI weather model adaptation and post-hoc gradient based explanation methods to derive feature importances.

Relevant course programmes:

- M.Sc. Industrial Engineering
- M.Sc. Information Systems
- M.Sc. Informatics
- M.Sc. Mathematic
- M.Sc. Remote Sensing and Geoinformatics
- M.Sc. Meteorology and Climate Physics