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Optimization and Machine Learning for Integrated Climate and Energy System Modeling – iKlimEt

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Integrated Climate and Energy System Modeling – Motivation

The energy sector increasingly faces **weather- and climate-related uncertainty** affecting both the generation and demand sides. This challenge stems from the rapid expansion of **weather-dependent renewable energy sources** and **changing consumption patterns**, further amplified by the **electrification** of industry, transport, heating and cooling, and the production of **renewable gases**. These developments are expected to substantially increase electricity demand and drive stronger **integration between the power and gas sectors**.

Energy system planning under this growing uncertainty requires coherent time series of future weather realizations and energy demand, as well as detailed infrastructure data, all of which must be integrated within **energy system optimization models (ESOMs)** that serve as **key decision-support tools**. Crucially, ESOMs must be designed to be **modular and flexible** to handle the high complexity arising from the spatial, temporal, technical, and uncertainty dimensions of **large-scale, sector-coupled energy systems** while remaining computationally tractable.

Preview – Converting Weather to Energy System Data

Climate models generate ensembles of **coherent, spatially resolved time series of future weather realizations**, providing variables such as temperature, irradiation, wind speed and precipitation. For integration with ESOMs, these data require statistical downscaling, interpolation, and conversion into capacity factors or energy quantities.

To this end, we develop a **climate-energy translator tool** that produces such time series for **solar, wind,** and **hydropower generation**. A particular focus lies on deriving **inflows to run-of-river and (pumped-)storage hydropower plants** using a **run-off model** calibrated on historic data [2], thereby extending beyond the capabilities of existing tools.

iKlimEt at a Glance

iKlimEt, funded by the Austrian Research Promotion Agency (FFG), explores **the integration of climate and energy system modeling**. To overcome the disconnect between these disciplines, the project develops a **climate-energy translator** and a **machine learning-driven demand scenario tool** that generate coherent time series of future weather realizations and energy demands for integration into **sector-coupled energy system optimization models** for **large-scale energy system planning**. The resulting tools and models are applied to **planning the decarbonized Styrian energy system for 2040** in the European context. Figure 1 shows the project structure and the consortium, led by IEE.

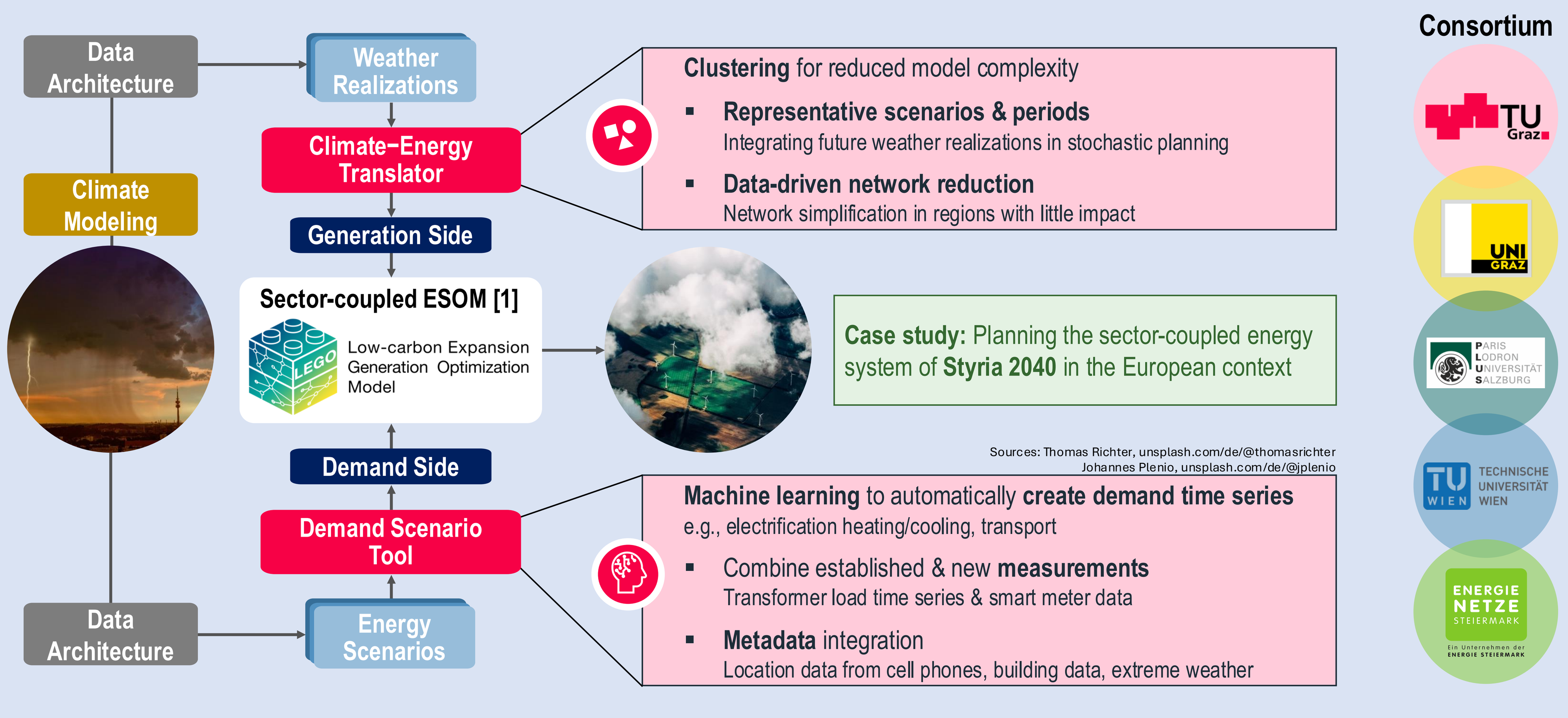

Figure 1: Project structure and consortium partners of iKlimEt.

Selected publications

[1] S. Wogrin, D. A. Tejada-Arango, R. Gaugl, T. Klatzer, U. Bachhiesl, *"LEGO: The open-source Low-carbon Expansion Generation Optimization model"*, SoftwareX, vol. 19, p. 101141, 2022.

[2] L. Kloiber, *"Hydropower time series modelling for climate-resilient energy system optimization"*, Master's thesis, Graz University of Technology, Graz, Austria, 2025.

[3] F. C. A. Auer, D. A. Tejada-Arango, S. Wogrin, *"Connecting representative periods in energy system optimization models using Markov-matrices"*, under review (IEEE Power Engineering Letters), 2025.

[4] M. Quantschnig, *"Open-source gas infrastructure data for integrated energy system optimization models"*, Master's thesis, Graz University of Technology, Graz, Austria, 2025.

[5] T. Klatzer, S. Wogrin, D. A. Tejada-Arango, G. Morales-España, *"Tight MILP formulation for pipeline gas flow with linepack"*, International Journal of Electrical Power & Energy Systems, vol. 169, p. 110734, 2025.

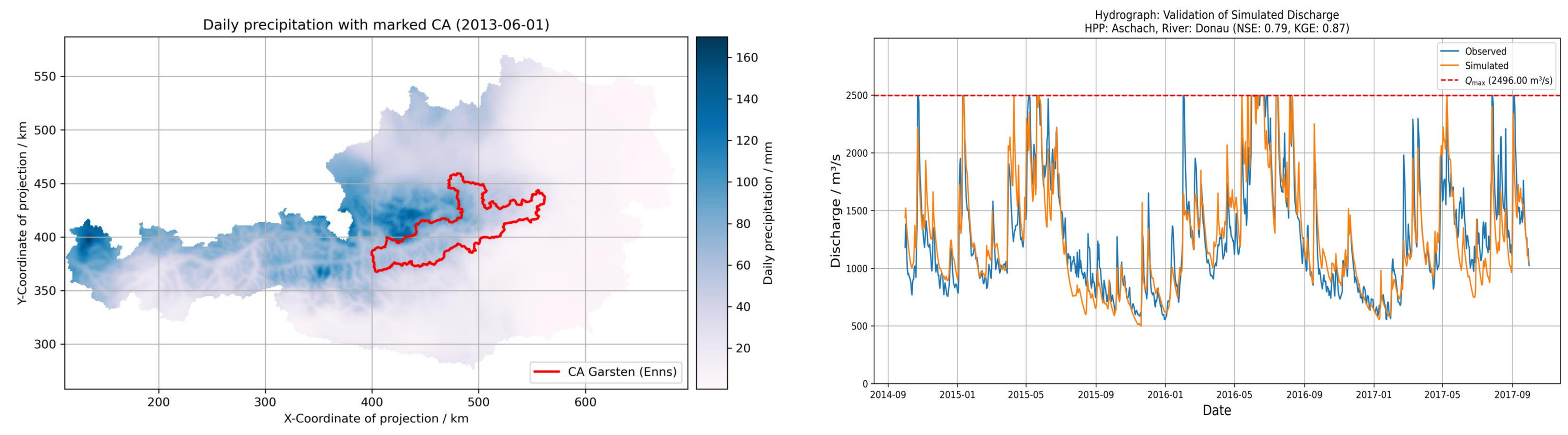

Figure 2: Precipitation data for Austria (left) and calibrated daily run-of-river discharge of a plant (right) [2].

Preview – Markov-Transitions for Representative Periods [3]

When using **time series aggregation** to **reduce the computational complexity** of **large-scale ESOMs**, **transitions between representative periods (RPs)** are **typically lost**. This leads to **inaccuracies** in storage behavior, unit commitment, and other **time-linked aspects** of the model. We propose a novel method that uses **Markov-Matrices** to **link RPs via probabilistic transitions** and expected values. The approach is also suitable for constraints that **connect multiple time steps**, and can be adjusted to work with **binary variables**. Validated using the NREL-118 bus system, our approach **reduces the error** to **one fifth of the current state-of-the-art** while retaining low computational complexity.

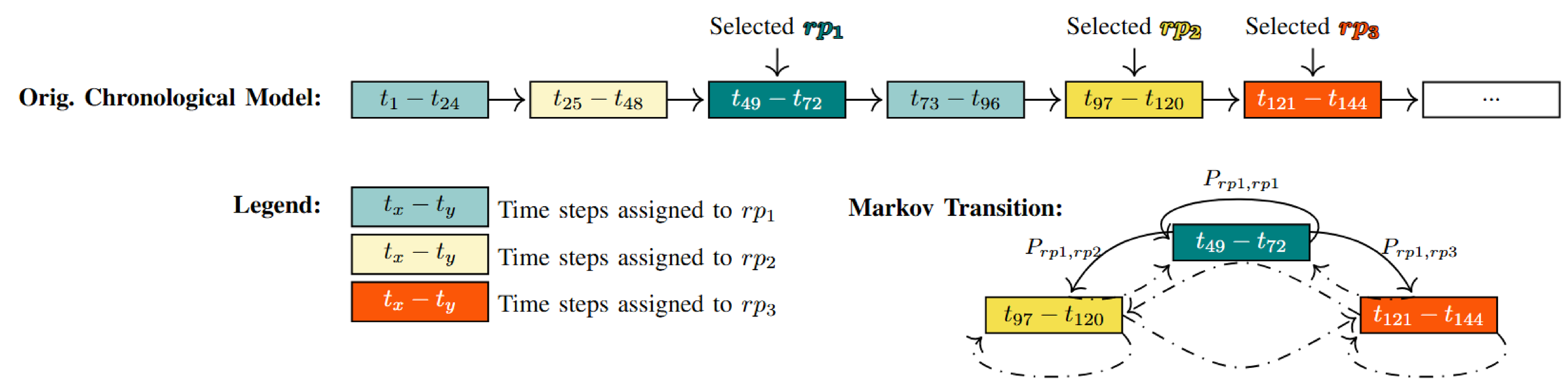

Figure 3: **Chronological Model** and **Markov-Transitions** (P_{rp_1,rp_2}: Probability of rp_2 following rp_1) [3].

Preview – Mapping Europe's Gas Infrastructure [4]

Energy system planning relies on georeferenced, topological, and techno-economic data on existing infrastructures. While such information is publicly available for the power system, comparable **high-quality datasets for the gas system are lacking**. We close this gap by collecting and harmonizing data from public sources and mapping them onto the georeferenced European gas network topology derived from the ENTSOG Transparency Map. Furthermore, we develop **QGas**, an **interactive toolkit** that enables users to **add and modify infrastructure elements via a graphical user interface** − such as pipelines, compressors, gas-fired power plants, and LNG terminals − along with their associated data.

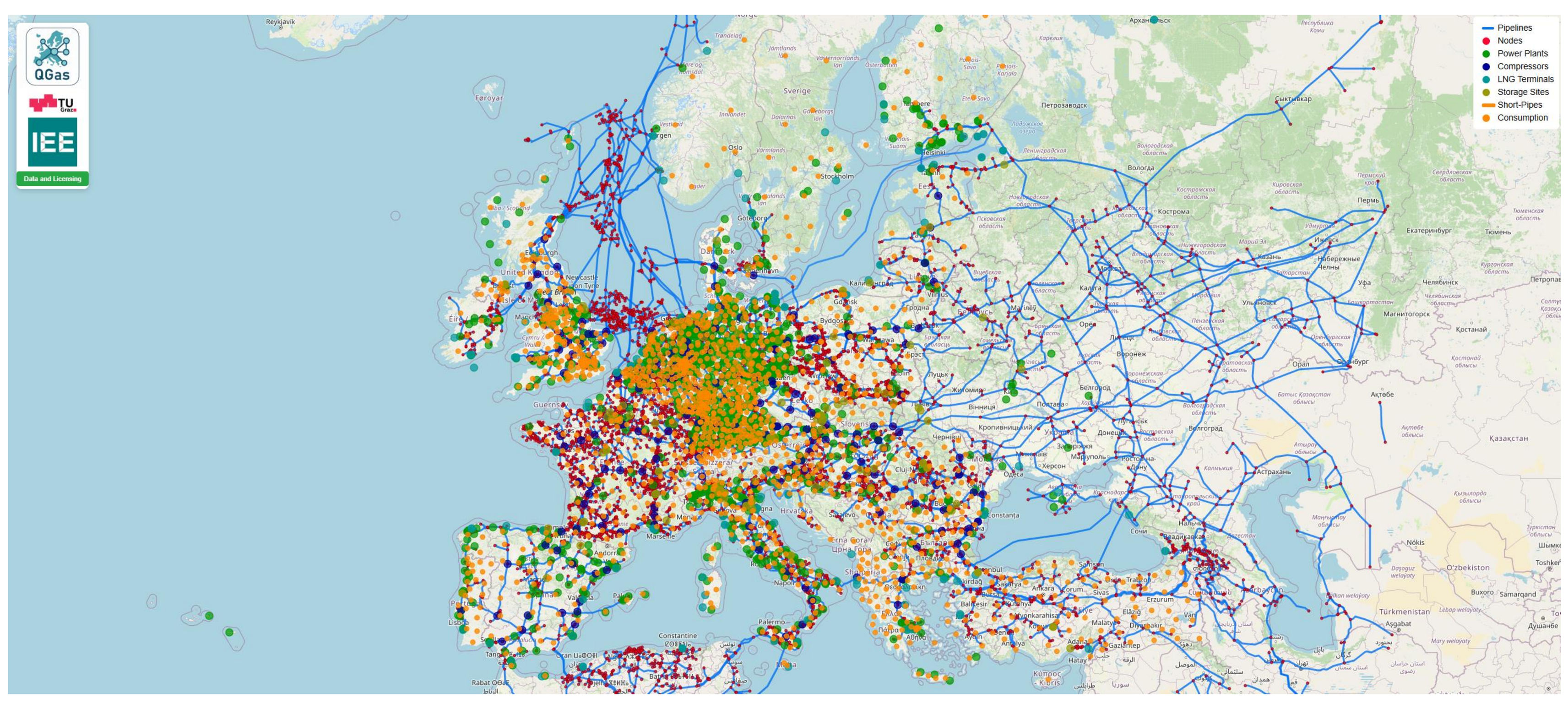

Figure 4: Visualization of the compiled European gas infrastructure data in the **interactive QGas tool** [4].

IEE Project Team

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