PUMPED STORAGE HYDROPOWER GRAPH MODEL FOR CLIMATE-RESILIENT ENERGY SYSTEM OPTIMIZATION

***Kasonde Eustace Mitchell[1,2,3], Felix Clemens Alexander Auer[2,3], Thomas Klatzer[2,3], Wolfgang Richter[1,3]**

Abstract

Climate change is altering weather patterns and increasing uncertainty of renewable energy availability. Energy system modelling therefore requires coherent future time series of renewables derived from weather variables such as irradiation, wind speed, and precipitation [1]. Deriving inflows for pumped-storage hydropower schemes is particularly challenging due to the relational complexity of collection works, reservoirs, discharge pathways, turbines, and pumps [2]. Although several studies have considered relational complexities [3], modelling tools that support robust and independent scenario analysis remain limited. This work addresses this gap by developing a graph-based database of Austria's pumped-storage schemes using open-source datasets. The graph-based approach ensures the preservation of hydraulic and operational plant constraints. Coupled with a precipitation–runoff routing hydrological model, the framework generates inflow time series from spatially-temporally resolved climate data, which serves as input for energy system optimization models, such as the LEGO [4] model used in the iKlimEt project [5]. The framework is tested and calibrated in numerous case studies of Austrian pumped-storage schemes [6], demonstrating its applicability.

Methodology and Results

The developed framework comprises targeted data research [7], the development of a graph database model representing the relational structure of pumped-storage schemes. Coupled with an integration of a climate-driven GR6J [8] runoff routing tool. It incorporates hydrological inputs to simulate inflows and energy generation across pumped-storage schemes. Figure 1 illustrates the topographical map and the corresponding graph representation of the Limberg I pumped-storage scheme with its catchments, while Figure 2 shows the simulated inflows.

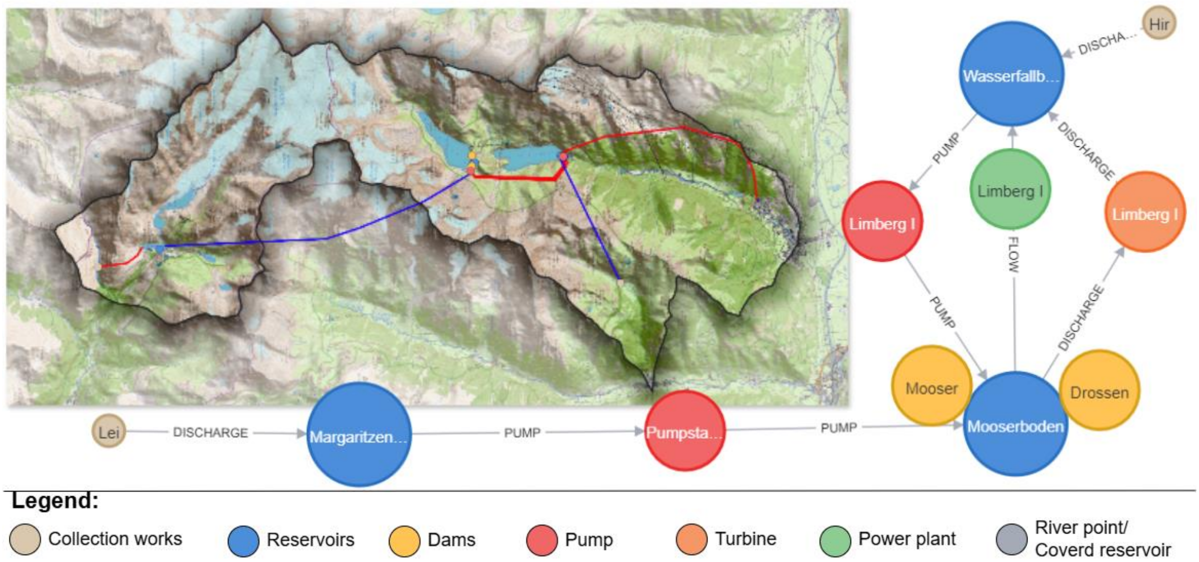

Figure 1: Topographical map (left) and graph representation (right) of the Limberg I scheme.

[1] Institute of Hydraulic Engineering and Water Resources Management, Stremayrgasse 10/II, 8010 Graz, +43 316 873-8361, hydro@tugraz.at, www.tugraz.at/en/institutes/iwb
[2] Institute of Electricity Economics and Energy Innovation, Inffeldgasse 18, 8010 Graz, +43 316 873 7901, IEE@TUGraz.at, www.IEE.TUGraz.at
[3] Research Center ENERGETIC, Rechbauerstraße 12, 8010 Graz, www.energetic.tugraz.at

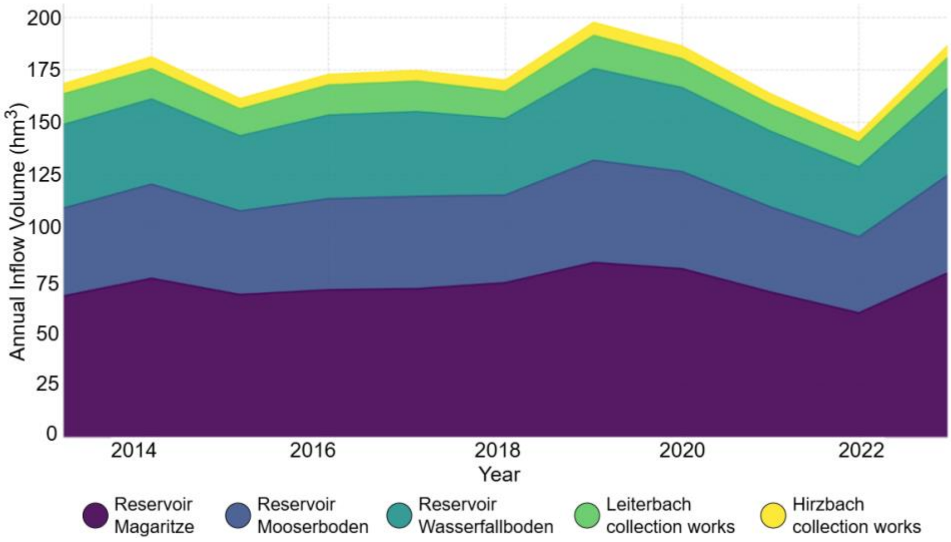

Figure 2: Simulated annual inflows of the Limberg I scheme.

Conclusion and future advancements

This work demonstrates the potential of graph-based approaches to strengthen hydropower modelling and energy forecasting under climate variability. By structuring hydropower systems as interconnected networks, the work opens new possibilities for integrating diverse data sources, exploring indirect dependencies, and supporting decision-making in complex energy systems. The outputs provide a foundation for linking hydrological processes with energy optimisation frameworks, contributing to the resilience of pumped-storage schemes in a carbon-neutral future.

Looking forward, several advancements could extend the framework's scope and impact:

- Automation of graph generation to streamline model construction from open-source data.
- Enhancement of models using detailed operational data from scheme operators for calibration.
- Application of remote sensing to estimate reservoir levels in ungauged systems.

Together, these directions highlight how graph-based modelling can evolve into a versatile toolset for hydropower research, bridging climate science, system optimisation, and sustainable energy planning.

References

[1] J. Karjalainen, M. Käkönen, J. Luukkanen, "Energy models and scenarios in the era of climate change," University of Turku, 2019. https://urn.fi/URN:NBN:fi-fe2019052116332

[2] A. S. Gragne, A. Sharma, R. Mehrotra, K. Alfredsen, "Improving real-time inflow forecasting into hydropower reservoirs through a complementary modelling framework," *Hydrology and Earth System Sciences*, vol. 19, no. 8, pp. 3695–3714, 2015.

[3] J. Qiao, K. Shen, W. Xiao, J. Tang, Y Chen, J. Xu., "Integrating graph data models in advanced water resource management: A new paradigm for complex hydraulic systems," *Water*, vol. 17, no. 1, p. 3, 2025.

[4] 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.

[5] "iKlimET - Optimization and machine learning for integrated climate and energy system models," Graz University of Technology, 10 November 2025. [Online]. Available: https://www.tugraz.at/institute/iee/forschung/aktuelle-projekte/iklimet

[6] G. Zenz, F. G. Pikl, E. J. Staudacher, W. Richter, "Pumped storage hydropower in Austria," *Verlag der Technischen Universität Graz*, 2018.

[7] European Commission, Joint Research Centre (JCR), "JRC Hydro-power database," 10. November 2025. [Online]. Available: http://data.europa.eu/89h/52b00441-d3e0-44e0-8281-fda86a63546d

[8] R. Pushpalatha, C. Perrin, N. Le Moine, T. Mathevet, V. Andréassian, "A downward structural sensitivity analysis of hydrological models to improve low-flow simulation," *Journal of Hydrology*, vol. 411, no. 1, pp. 66–76, 2011.