

Pumped Storage Hydropower Graph Model for Climate-Resilient Energy System Optimisation

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Introduction

This thesis addresses energy optimisation in pumped storage hydropower systems under climate variability, with a regional focus on Austria and the broader European context.

- **iKlimEt** research project: develop cutting-edge open-source simulation tools for integrated energy system planning that consider climate change impacts and extreme events [1].
- LEGO: The open-source Low-carbon Expansion Generation Optimization model [2].
- Hydropower Time Series Modelling for Climate-Resilient Energy System Optimization [3].
- Pumped Storage Hydropower in Austria [4].

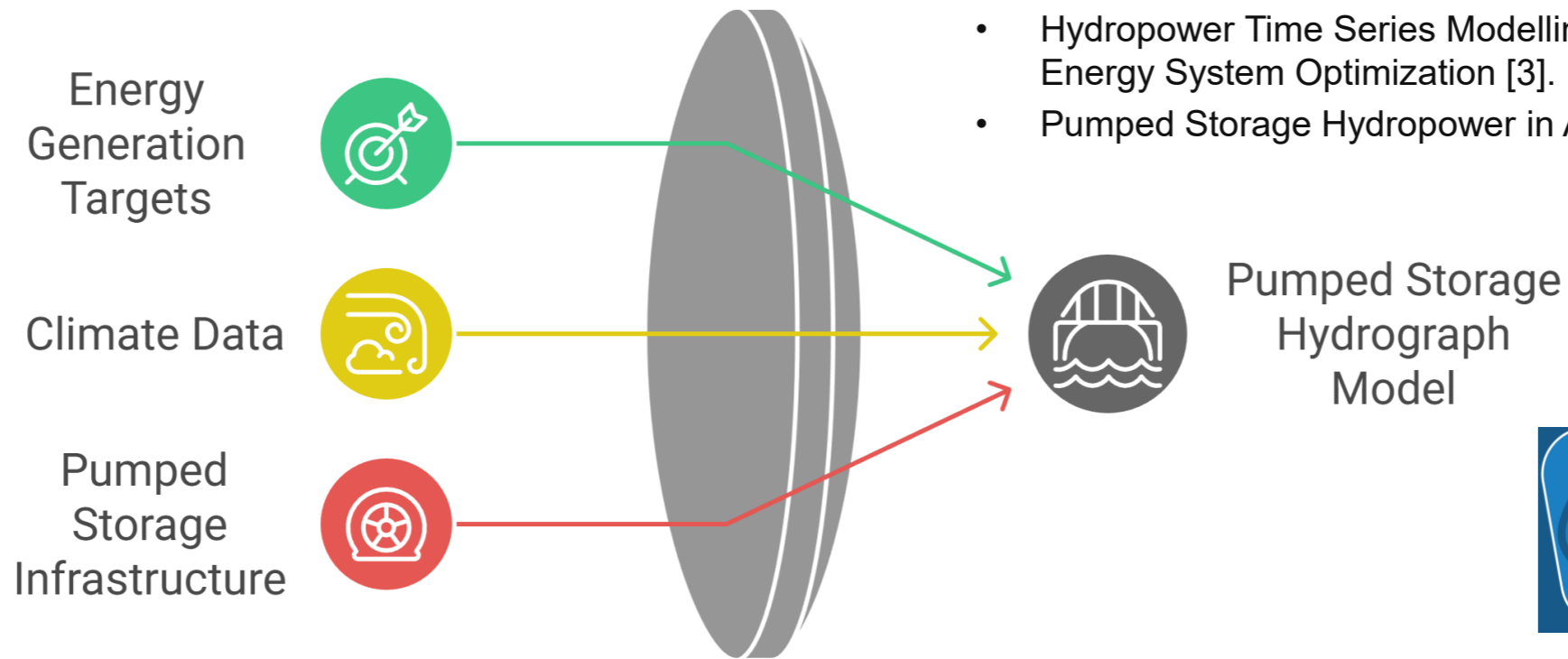


Figure 1: Key inputs to the model: infrastructure, climate data, and strategic targets.

What is Pumped Storage Hydropower?

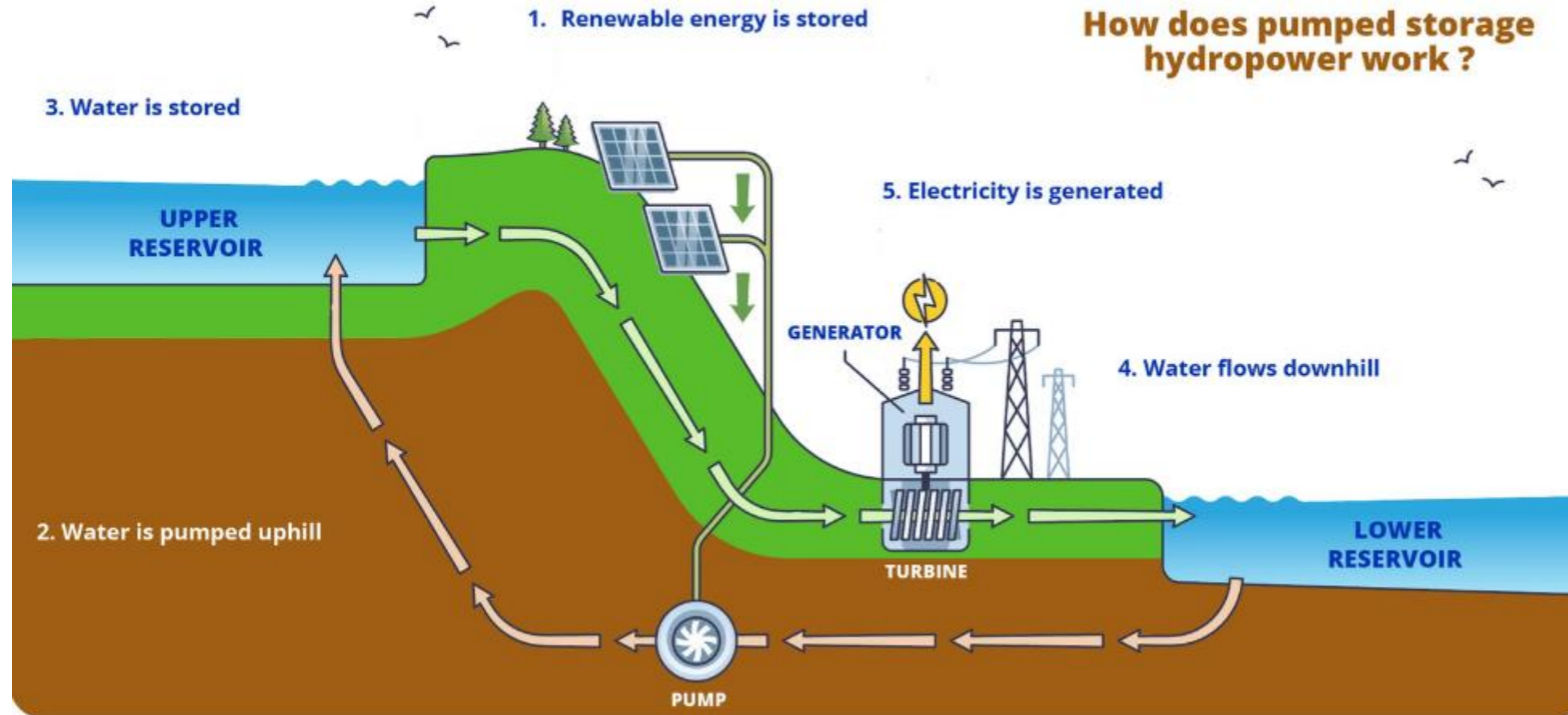


Figure 2: Pumped storage hydropower design [5].

Why focus of Pumped storage?

- Austria's hydropower installed capacity **two thirds are storage and pumped-storage plants** [4][6].

Workflow Overview

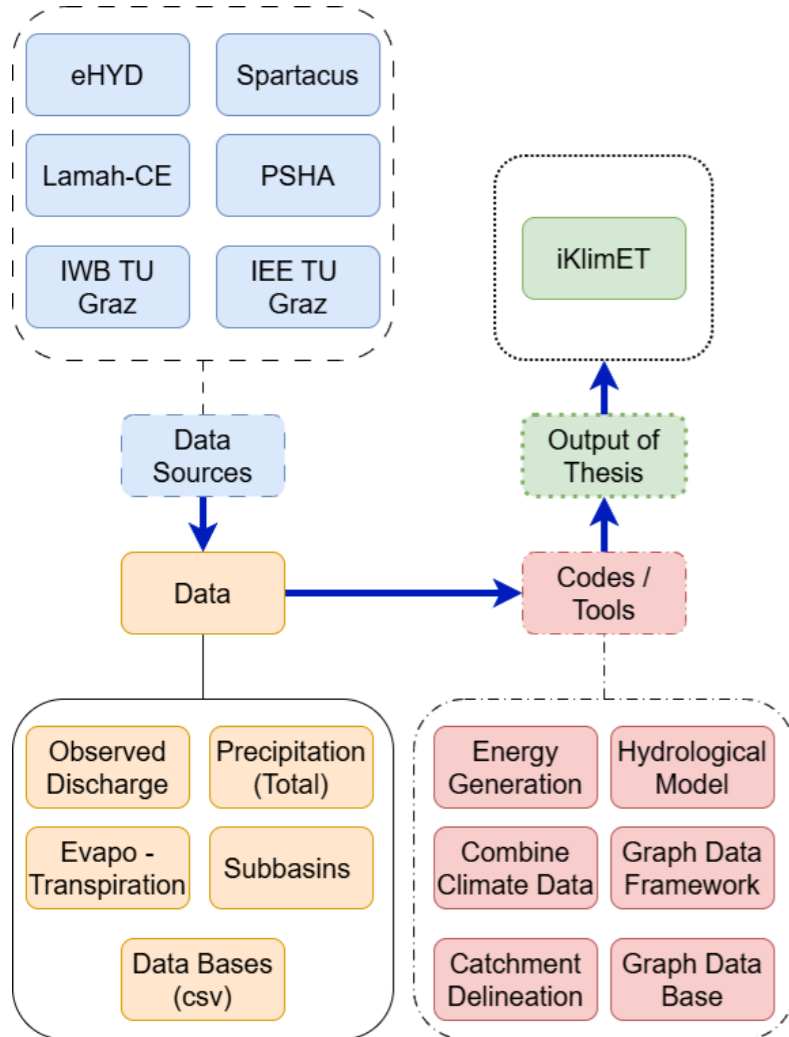


Figure 3: Overview of the entire workflow [7].

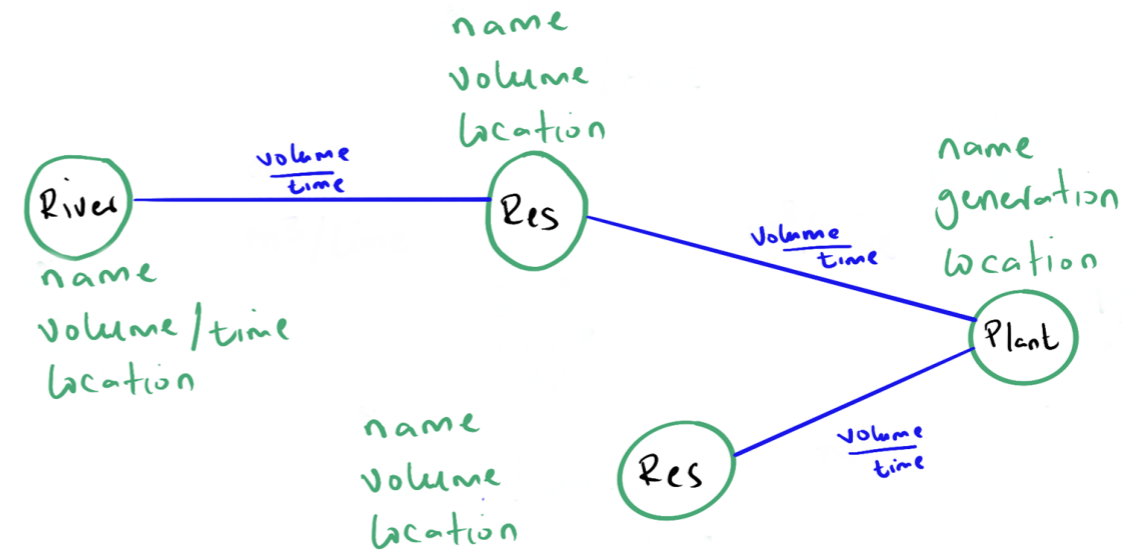


Figure 4: Sketch and overview of the entire workflow [7].

- A graph model was developed.
- Inflows estimated per basin.
- Routed in scheme using the constraints.
- Matching energy targets and/or gauge volumes.

Graph Model Database: Austrian hydropower Infrastructure

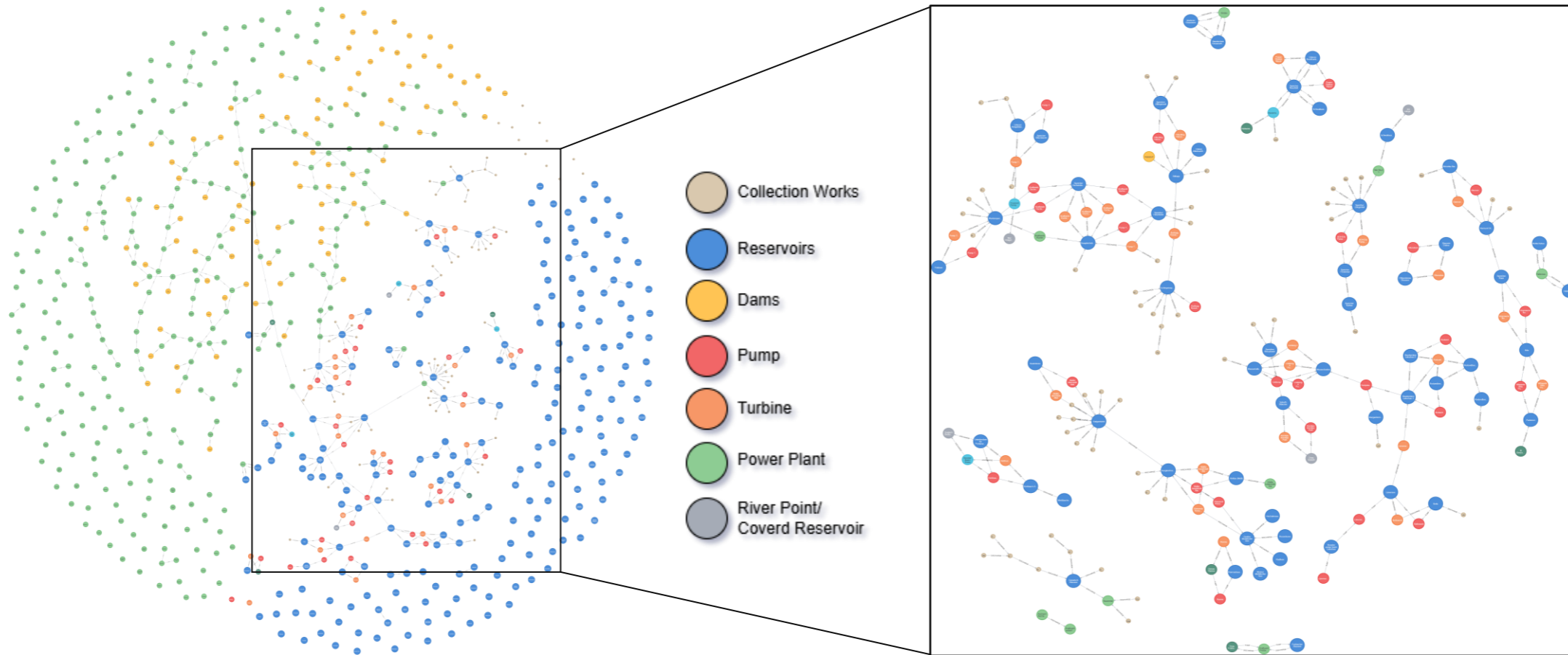


Figure 5: Graph model of Austrian hydropower infrastructure [7].

Figure 6: Graph model of 26 No. Austrian pumped storage hydropower infrastructure [7].

711 nodes and **424 connections** with 3 relationship types (natural flow, discharge and pumping).

Simulations Cases

1. ● Hintermuhr – Dual reservoir scheme.
2. ● Koralpe – Single reservoir scheme.
3. ● Nassfeld – Multiple reservoir scheme.
4. ● Feldsee – Multiple reservoir scheme.
5. ● Limberg I – Multiple reservoir scheme.

Simulation Parameters and Constraints:

- Simulation period 2013-2023. Due to reported values [4] from 2018 (± 5 years).
- Discharge volume matching for gauge where applicable (hm^3).
- Storage volumes (hm^3) and discharge capacities (m^3/s).

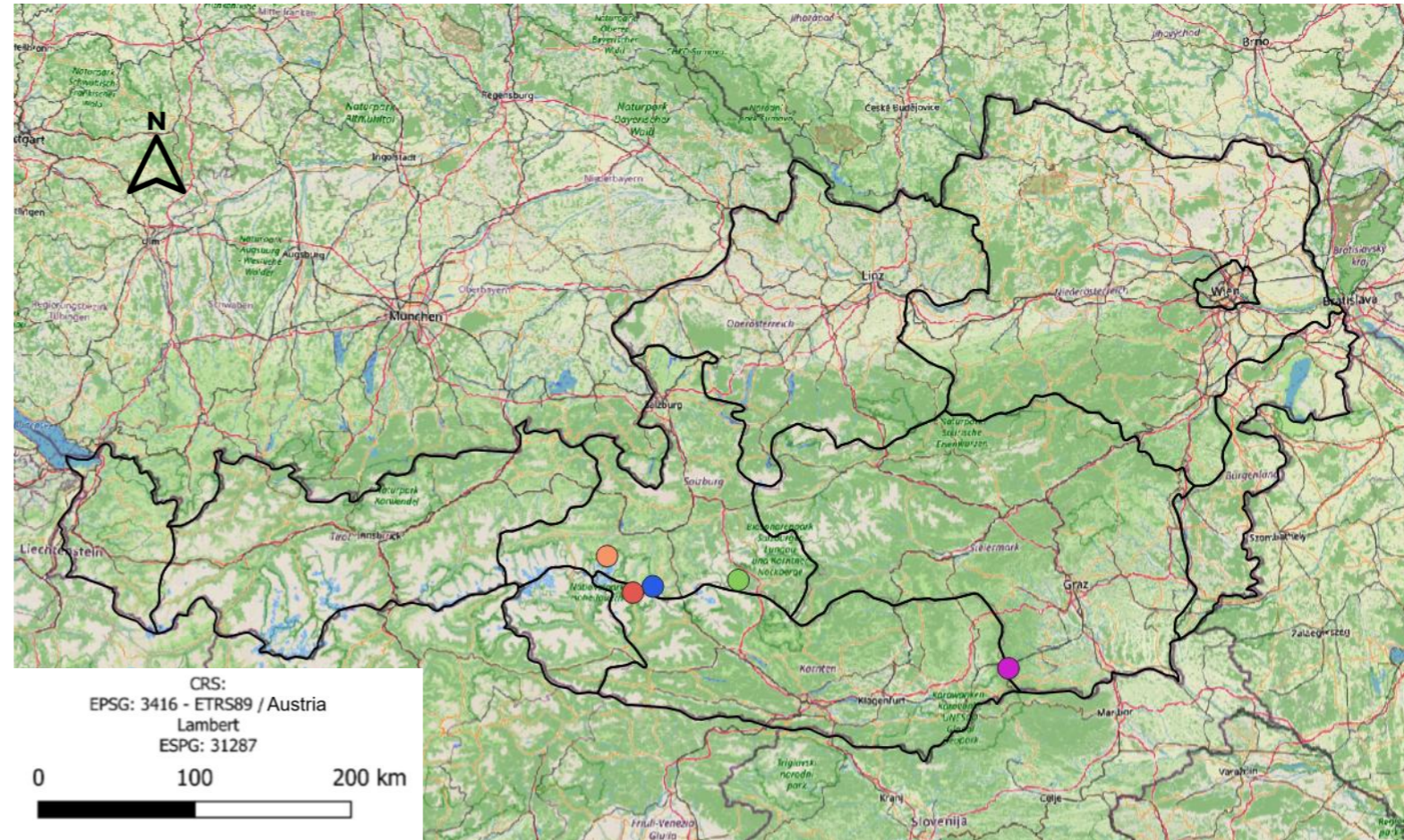


Figure 7: Overview of the entire workflow – QGIS image from created hydropower database [7].

Simulations Case Example: Hintermuhr Scheme

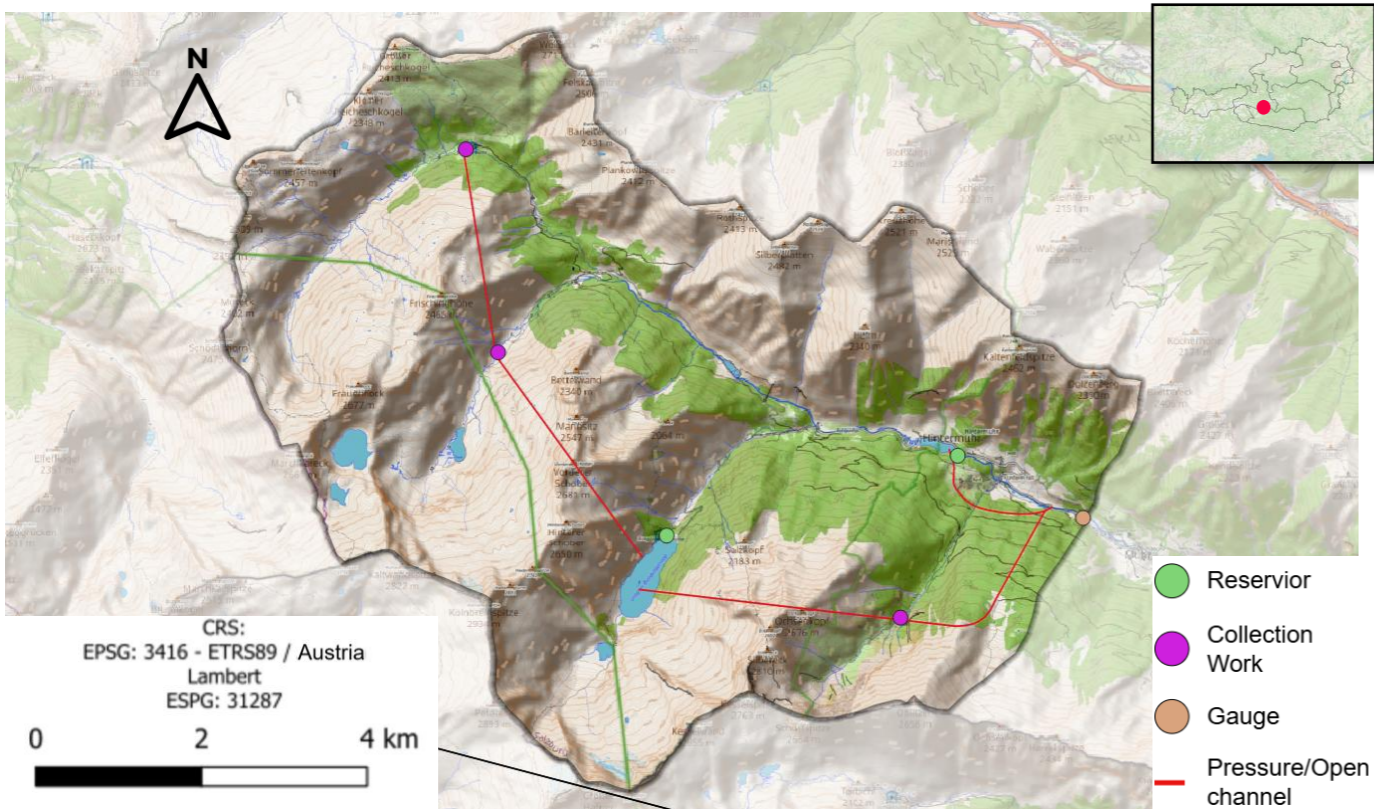


Figure 8: Hintermuhr scheme topography map – QGIS model [7].

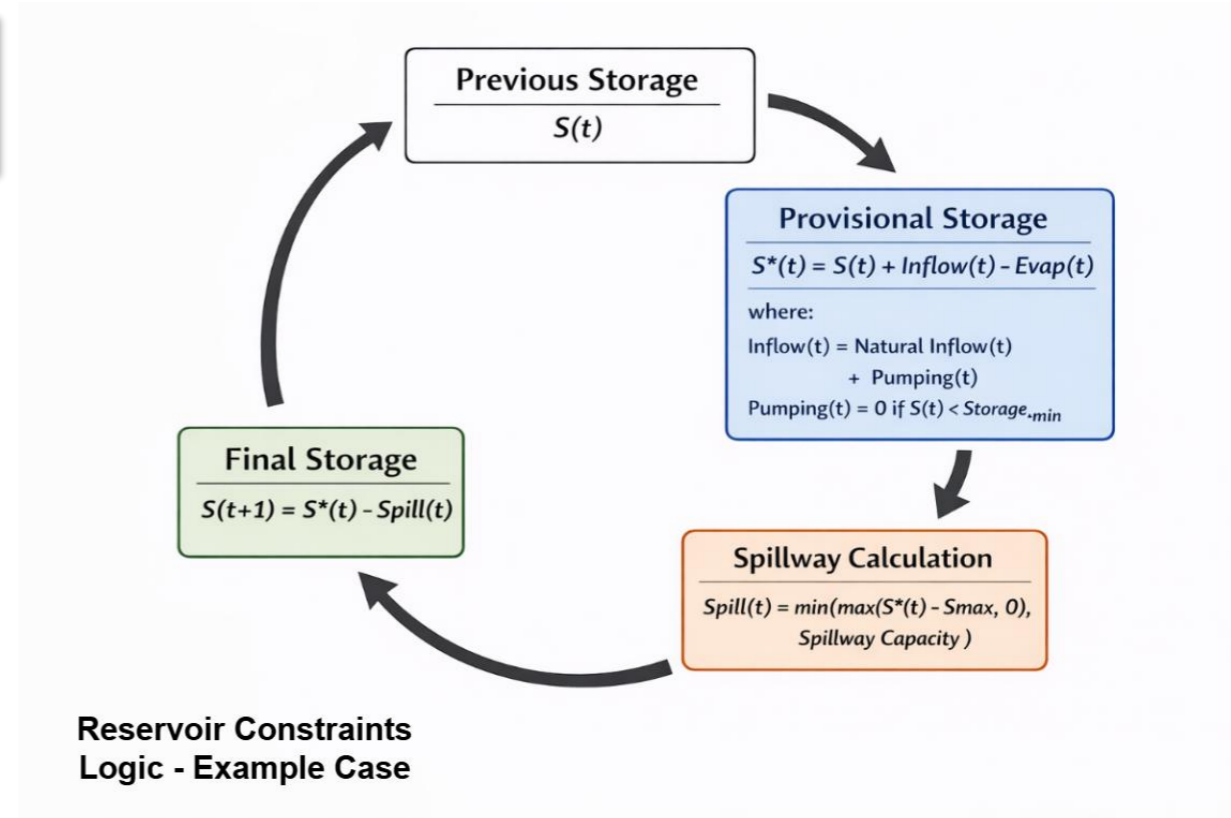


Figure 9: Hintermuhr scheme diagram – graph model from neo4j interface [7].

The benchmark scheme includes energy targets and gauge data, enabled by the presence of a gauge within the catchment area.

Simulations Performance Evaluation Metrics

1. **Root Mean Square Error (RMSE)** for annual energy generation and gauge inflow volume.
2. **Scaled inflow:**
 - Reported annual inflows and the catchment area sizes for the schemes as of 2018 [4].
3. **GR6J rainfall runoff model parameters:**
 - **X1 – X6**

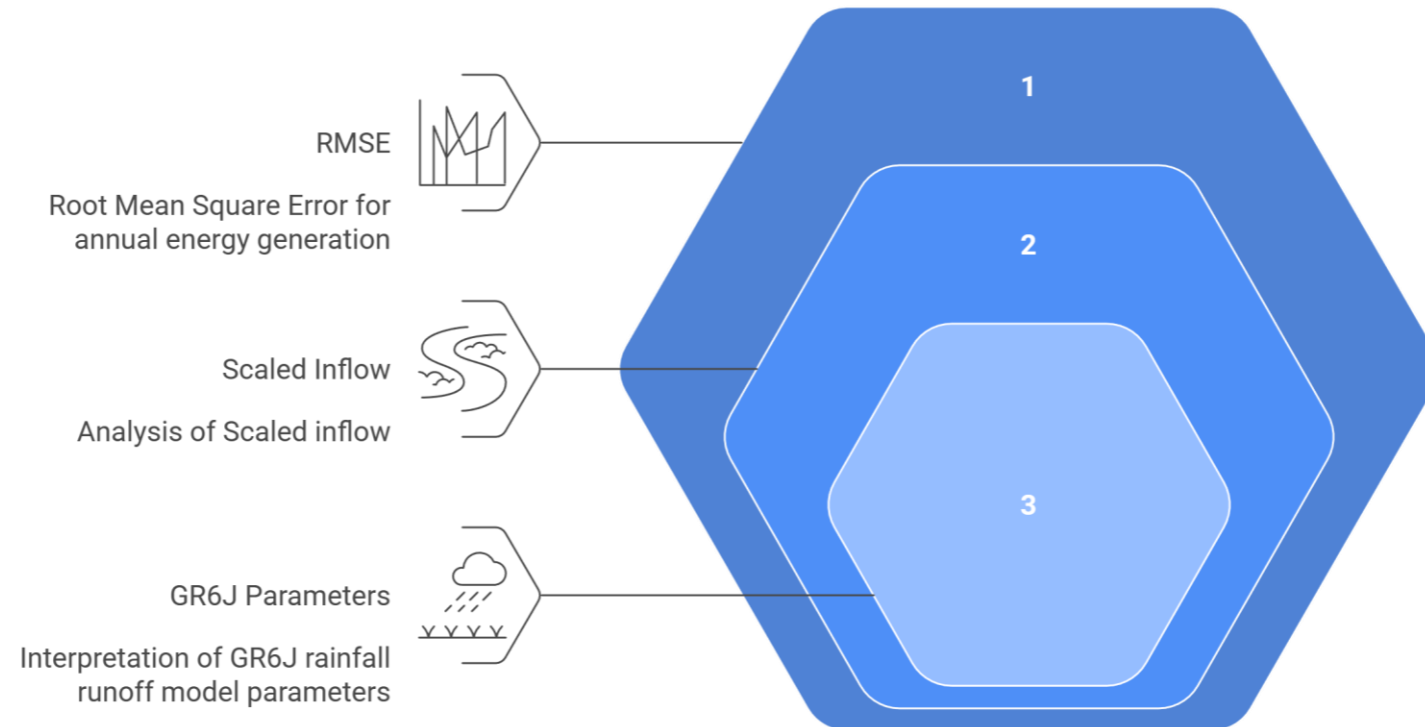


Figure 10: Hierarchy of performance evaluation metrics [7].

Performance Evaluation: GR6J rainfall runoff parameters

Interpretation of **GR6J parameters** for the different rainfall runoff receiving node types such as Reservoirs, Collection works or River Points.

PARAMETERS	RESERVOIR NODE	RIVER / COLLECTION NODE
X1: Maximum soil water storage capacity (Soil Storage)	Medium to High	Medium to Low
X2: Groundwater exchange coefficient (Water loss)	Low to Medium	Medium to High
X3: Routing store capacity (Water retention)	Medium to High	Medium to Very Low
X4: Unit hydrograph time constant (Runoff response)	Low (slow response)	Medium to High (flashy response)
X5: Inter-catchment exchange coefficient (Inter-catchment flow)	Low	Medium to High
X6: Baseflow drainage time constant (Drainage Speed)	Low (slow drainage)	Medium to High (rapid drainage)

Table 1: GR6J Interpretation table based on viable nodes [7].

Normalized GR6J Parameter by Node Hintermuhr Scheme



Figure 12: Hintermuhr GR6J Simulation Parameters [7]

Performance Evaluation: Scaled inflow

Using the reported annual inflows and the catchment area sizes for the schemes from 2018 as reported by [4] to evaluate the hydrological performance of the simulation

$$I_{sc} = I_{sim} \cdot \frac{CA_{mod}}{CA_{ref}}$$

Where:

- I_{sc} : scaled inflow [hm^3]
- I_{sim} : simulated inflow [hm^3]
- CA_{mod} : modelled catchment area [km^2]
- CA_{ref} : reference catchment area [km^2]

Figure 14: Scaled inflow equation [7].

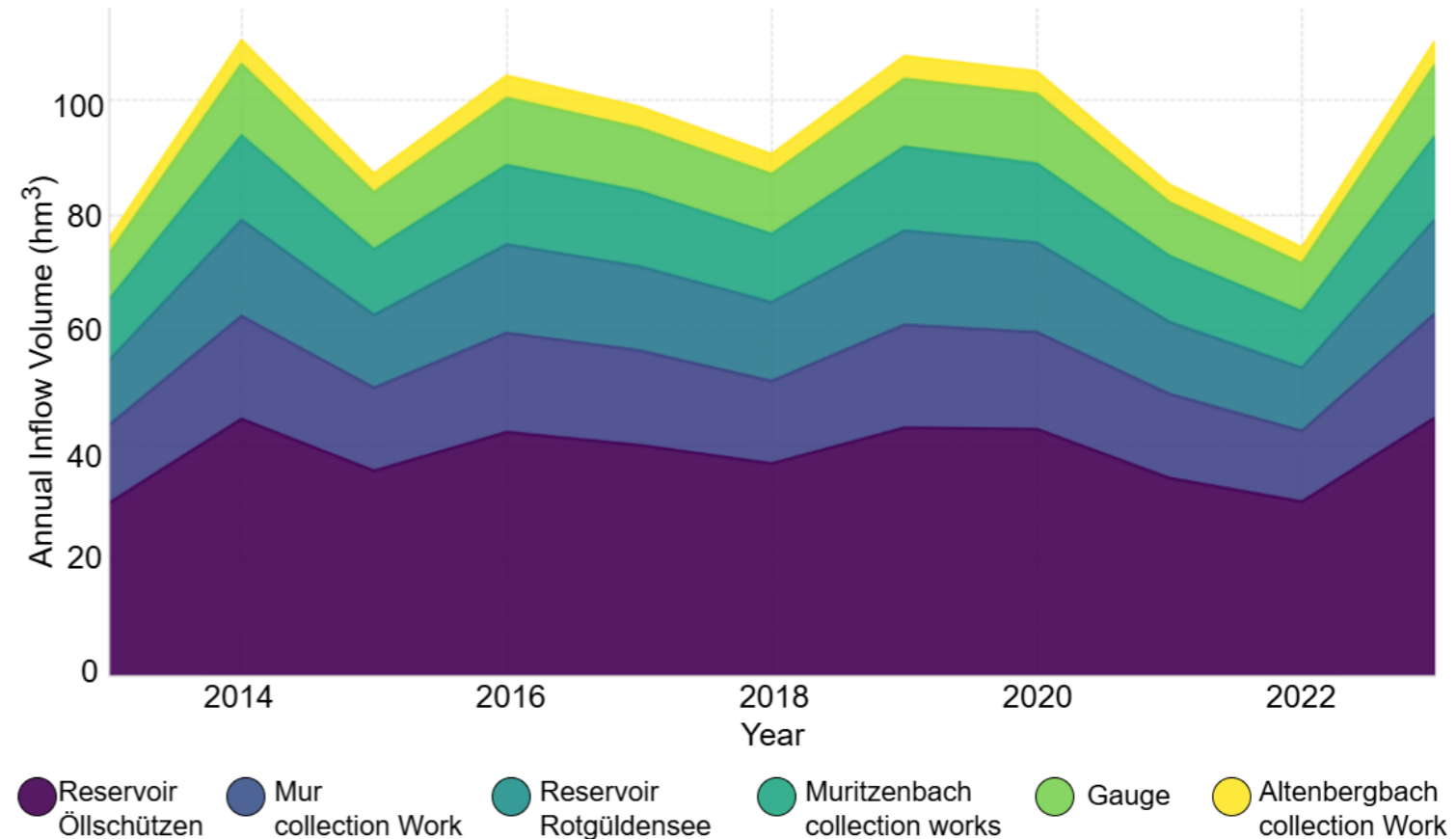


Figure 13: Hintermuhr Inflow [7].

Performance Evaluation: Scaled Inflow

Scheme Name	Reported Catchment [km ²]	Model Catchment [km ²]	Simulated (Model) Inflow [hm ³]	Reported Inflow [hm ³]	Scaled Inflow [hm ³]	Error [%]
Hintermuhr	67.34	64.83	98.64	98.47	94.96	3.56
Koralpe	67.67	53.25	64.09	50.31	50.43	-0.24
Nassfeld	63	61.95	130.64	127.1	128.46	-1.07
Feldsee	69.84	61.12	125	143.4	109.39	23.71
Limberg I	209.1	96.16	172.84	147	79.48	45.93

Table 2: Scaled inflows of simulated inflow results with their respective error [7].

Performance Evaluation: **RMSE** (Energy and Volume)

RMSE for annual average simulation results for the energy generation of the five simulation cases.

SCHEME NAME	TARGET ENERGY (MWh)	RMSE (MWh)	ERROR (%)
Hintermuhr	120,000	7,067.79	1.66
Koralpe	121,000	544.65	5.85
Nassfeld	36,000	658.95	1.51
Feldsee	240,340	2,682.50	0.27
Limberg I	150,400	658.95	1.78

Table 3: RMSE (MWh) [7].

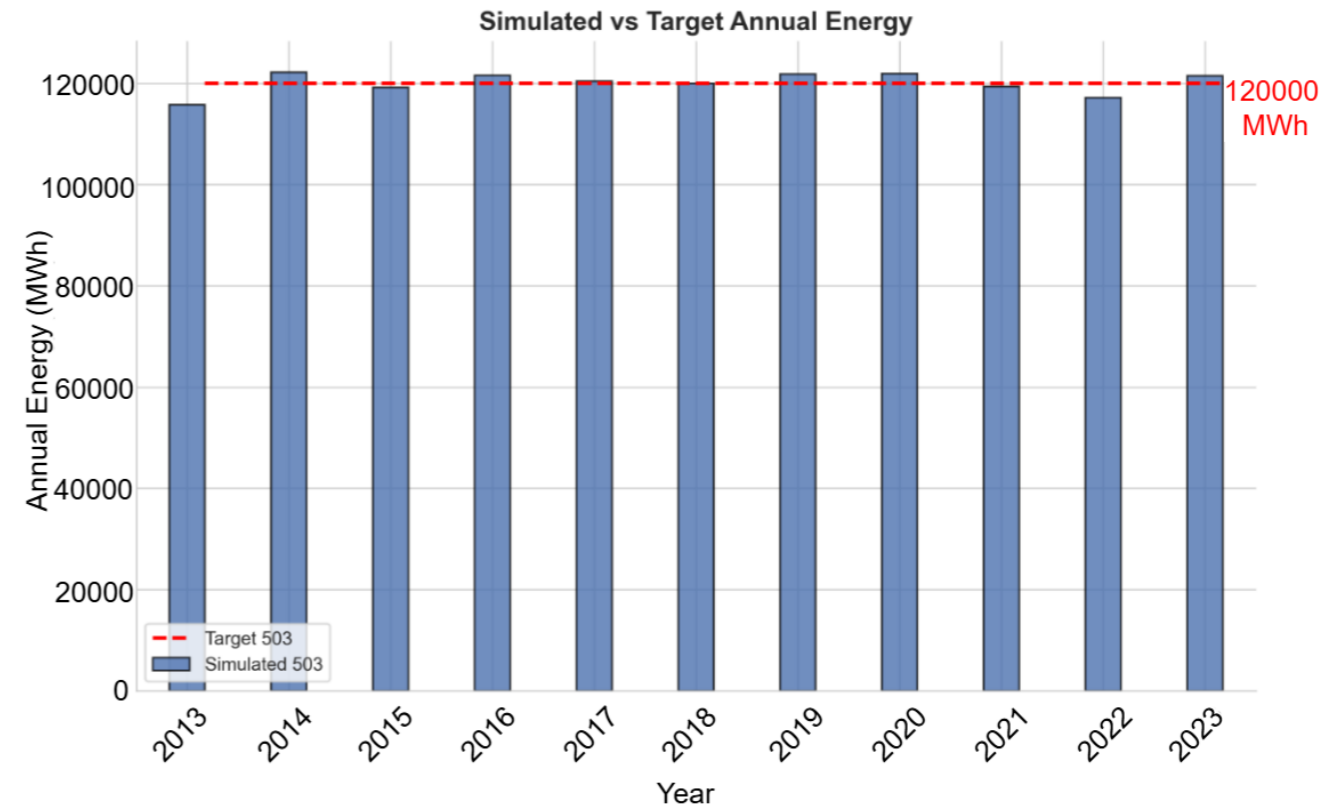


Figure 15: Hintermuhr Energy Simulation [7].

The average annual inflow measured at the gauge is **110 hm³**, with a simulated inflow to the gauge of **98.03 hm³** this results in a **10.88%** RMSE in average inflow to the gauge.

Conclusion & Discussion

- Flexible hydropower system representation.
- Need for finer temporal and spatial validation.
- Support future decision-making and optimisation.

Future Studies:

- Collaborative Model Enhancement Using Detailed Operational Data from Scheme Operators.
- Remote Sensing-Based Reservoir Level Estimation for Ungauged Systems.
- Eco-Hydrological Assessment of Reservoir Operations.

Thank You!



SCIENCE
PASSION
TECHNOLOGY



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