KTH ROYAL INSTITUTE OF TECHNOLOGY

The value of coordinating the operation of small-scale hydro

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Introduction

- High capacity factor, emission-free, long-life, and high predictability compared to alternative renewable forms.
- For the European Small Hydropower Association (ESHA) and the European Commission, up to 10 MW installed capacity (but can be up to 25 MW for other countries).
- Different classification based capacity limits, the head of the plant (e.g., high, medium, or low), the type of their turbines (e.g., Francis, Pelton, and others), using impoundments or diversion.
- Reliable rural electrification solution.
- Useful for decentralising the power system operation.
- Provide a wide range of flexibility to be used efficiently across many local conditions.

Introduction - Challenges

- However, environmental impacts are also mentioned in the literature and by environmental organisations:
  - Water loss, changed river ecology and connectivity, and impact on migratory fish and other aquatic species.
  - River fragmentation (i.e., interrupting the processes sustaining biodiversity), habitat degradation and landscape-scale changes (in some cases obstructing cultural and recreational services), and others.
- Practical engineering, regulatory and grid integration issues also exist.
- Complex assessment studies need to be performed for potential sites.
- The optimal design of new plants considers: placement (intake location), sizing, and topology of the power plants across a given river stream, identification the penstock diameter and length; the type, number, and discharge of turbines, and other parameters.

Methodology - Coordinated Hydropower Scheduling

- Comparison of two scheduling strategies for the same case study to assess the efficiency in utilising the water resource:

$$\text{Maximise} \sum_{t=1}^{T} \lambda_t P_t - \rho_i \cdot \sum_{i=1}^{I} (\delta_{i,t}^{+} + \delta_{i,t}^{-}) \tag{1a}$$

$$\text{subject to:} \quad M_{i,t} = M_{i,t-1} + V_{i,t} - \sum_{j \in J_i} Q_{i,j,t} - S_{i,t} + \sum_{k \in A_i^Q} \left(\sum_{j \in J_i} Q_{k,j,t-\tau_i^q} \right) + \sum_{k \in A_i^S} S_{k,t-\tau_i^s}, \tag{1b}$$

$$P_t = \sum_{i \in I} \sum_{j \in J_i} \mu_{i,j} Q_{i,j,t}, \tag{1c}$$

$$\overline{Q_{i,j}} \geqslant Q_{i,j,t} \geqslant \underline{Q_{i,j}}, \tag{1d}$$

$$\overline{M_i} \geqslant M_{i,t} \geqslant \underline{M_i}, \tag{1e}$$

$$\overline{S_i} \geqslant S_{i,t} \geqslant \underline{S_i}, \tag{1f}$$

$$\delta_{i,t}^{+} - \delta_{i,t}^{-} = Q_{i,t} - Q_{i,t-1}, \tag{1g}$$

$$\delta_{i,t}^{+},\ \delta_{i,t}^{-} \geqslant 0, \tag{1h}$$

$$\forall\, j \in J_i, i \in I, t \in T$$

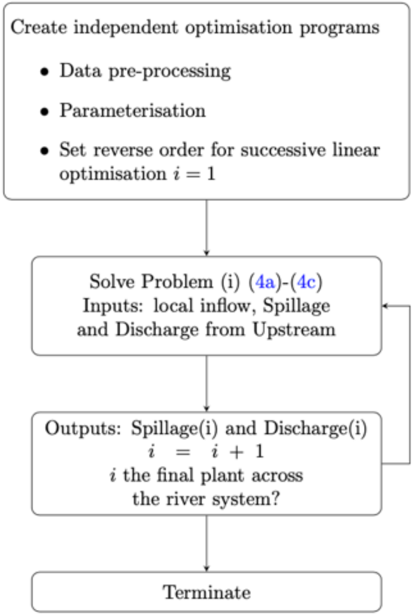
Methodology – Successive-Greedy Scheduling (or leader-follower approach)

- Comparison of two scheduling strategies for the same case study to assess the efficiency in utilising the water resource:

$$\forall i \in I : \text{Maximise} \left[\sum_{t=1}^{T} \lambda_t P_{i,t} - \rho_i(\delta_{i,t}^{+} + \delta_{i,t}^{-}) \right] \tag{4a}$$

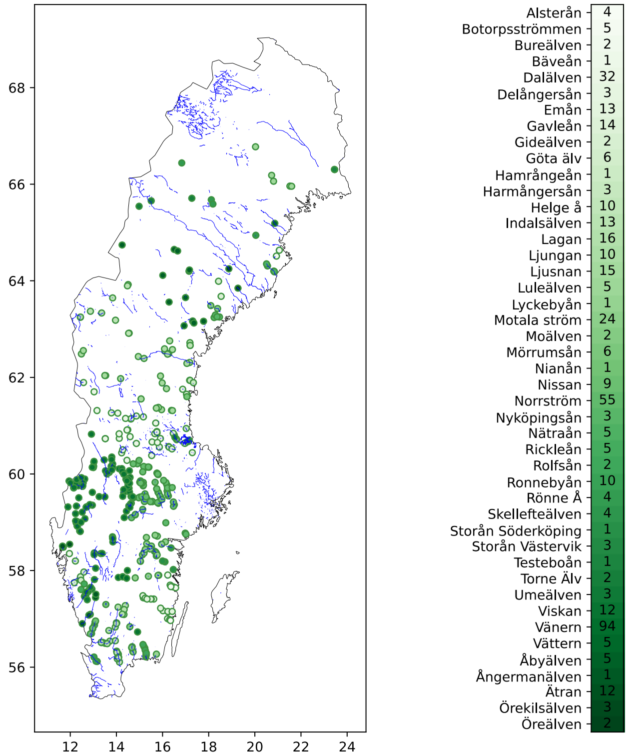
$$\text{subject to: } P_{i,t} = \sum_{j \in J_i} \mu_{i,j} Q_{i,j,t}, \tag{4b}$$

$$(2), (3), (1d) - (1h) \quad \forall\, t \in T \tag{4c}$$



Case study - dataset

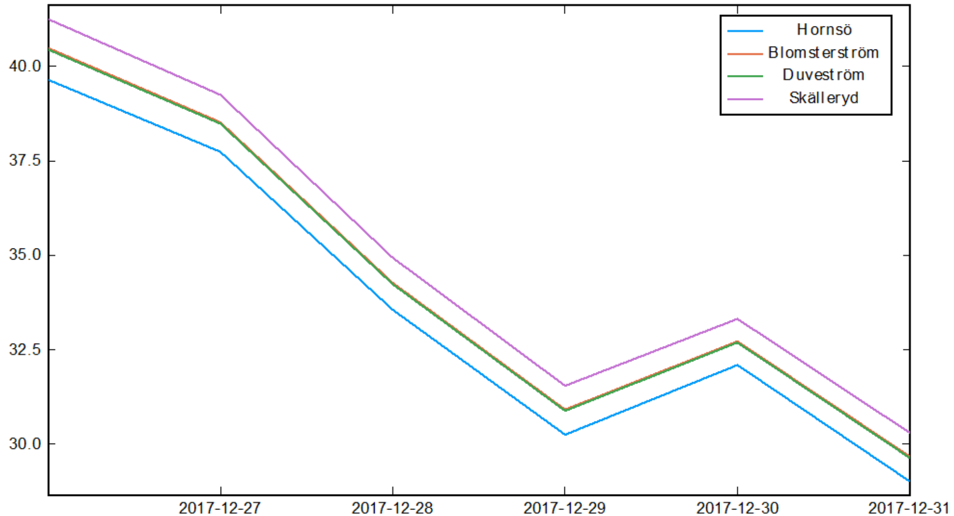
- 430 plants in the range 0.5 MW – 10 MW
- Total installed capacity of 876.16 MW
- Average annual production of 3.558 TWh
- Hydrological data including the average daily inflow in m^3/s for each of the 430 hydropower plants from 1981-01-01 until 2017-12-31 (SMHI).
- The inflow was taken without considering lag time between the basins and regulation effects.



Case study – Plant and inflow data for Alsterån river

Table 1 Hydropower Plant Data for the Alsterån river.

Powerstation	X(WGS84)	Y(WGS84)	Power [MW]	Annual production [GWh]	Head [m]	Q_{max} (100%eff)
Hornsö	16.219047	57.004566	2.3	11	15.5	15.11
Duveström	16.310264	56.984365	0.7	3.2	7.3	9.76
Blomsterström	16.317704	56.981808	0.5	0.85	3.5	14.55
Skälleryd	16.345854	56.966433	0.55	2.8	6.4	8.75



Case study – Modelling assumptions

- Topology approximation of the hydropower plants in river systems
  - acquiring the elevation of each power plant using its GIS coordinates and using the public API *Open Topo Data*. It cannot identify cases where plants are installed in bifurcated parts of a river.
- Water delays and distance between hydropower plants of the same river system
  - using the Euclidean distance between the two plant coordinates, and assuming a fixed water speed.
- Maximum Reservoir Content:

$$\overline{M_i} = reservoir\_scale \cdot \overline{P_i}$$

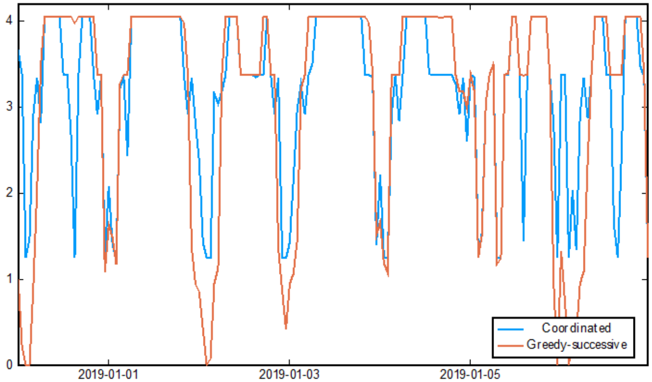
- Inflow Modelling:
  - differencing the inflow values of the timeseries between successive power plants to derive the local inflow after the elevation-based topology was estimated.
- Production equivalents:

$$\overline{Q_{i,1}} = 0.75 \cdot Q_{max}(100\%\text{eff})$$
$$\overline{Q_{i,2}} = 0.25 \cdot Q_{max}(100\%\text{eff})$$
$$\mu_{i,1} = \frac{\overline{P_i}}{(\overline{Q_{i,1}} + 0.95 \cdot \overline{Q_{i,2}})}$$
$$\mu_{i,2} = 0.95 \cdot \mu_{i,1}$$

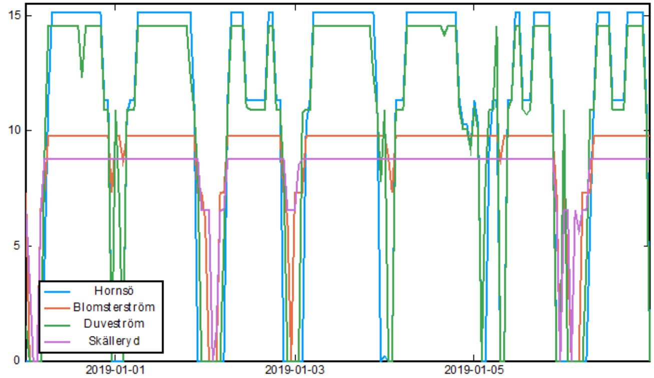
Representative results for a single river system

Table 2 Representative results, total energy produced for the two scheduling strategies.

Operation Strategy	Total Energy [MWh]
Coordinated	536.17
Greedy-Successive	517.29
Relative difference (%)	3.52

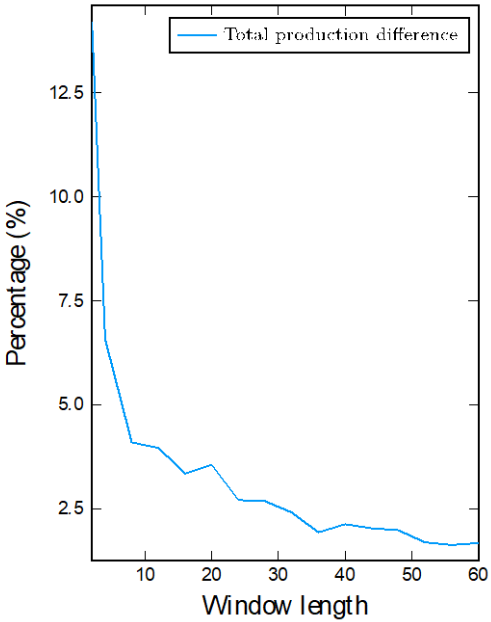


Comparison of the two models, the dates correspond to the historical electricity prices that were used and not the inflow data; the values in y-axis are in MW.



Greedy-successive discharge schedule (self-coordination optimisation model) for the Alsterån river. The water discharge is in m3/s.

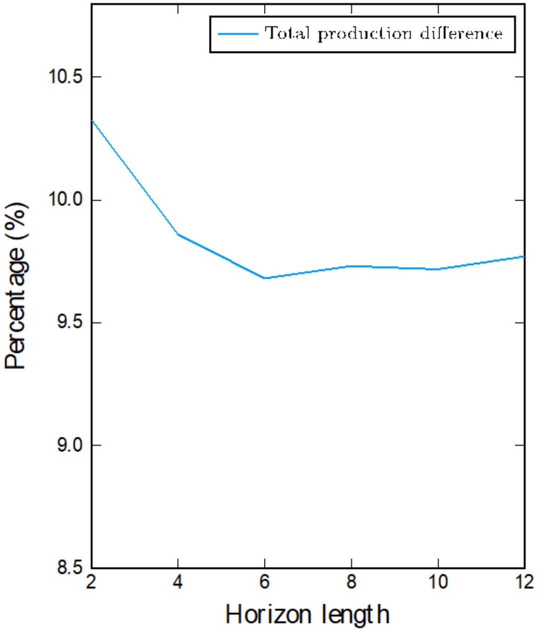
Results - Investigating the scheduling window length



- Total electricity production difference for a rolling horizon optimisation of a whole year by changing the window size (number of days)

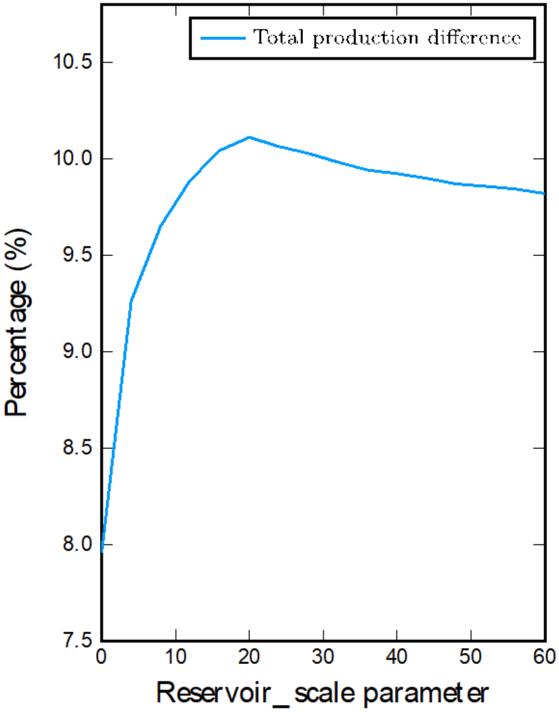
Results - Investigating the horizon length

- Total electricity production difference when the optimisation horizon length (number of months) varies for a rolling horizon optimisation with a constant window size of three days.



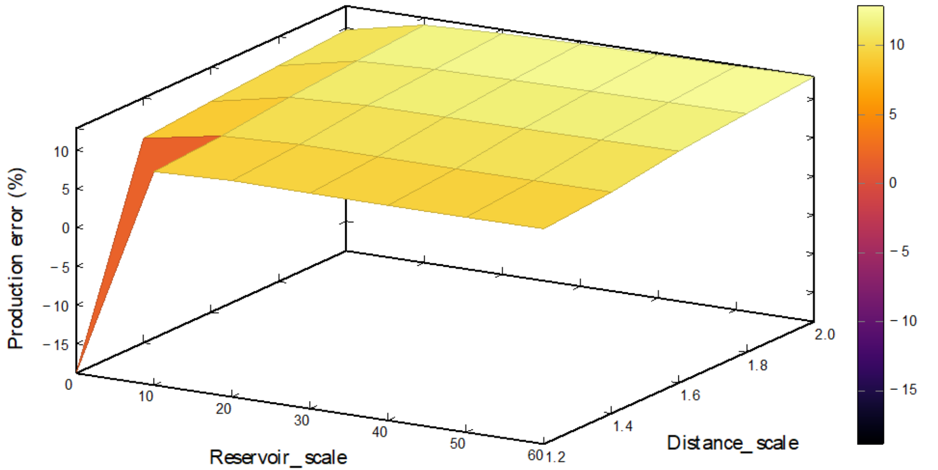
Results - Investigation of unknown hydro modelling parameters

- Total electricity production when varying the modelling parameter *reservoir_scale* for a rolling optimisation with a horizon of four months and a window of 3 days.



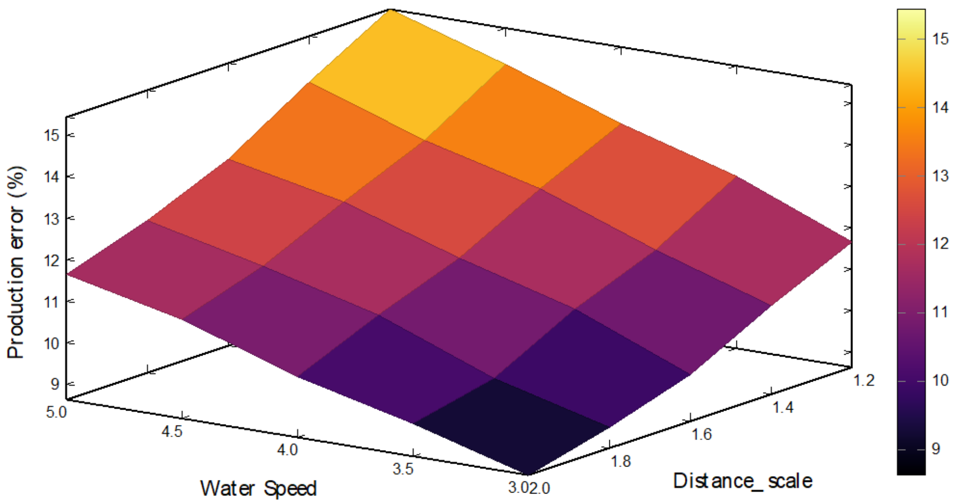
Results - Investigation of unknown hydro modelling parameters

Total production error when varying the reservoir_scaling factor together with the factor for estimating the distances between the plants (distance_scale).



Results - Investigation of unknown hydro modelling parameters

Total electricity production difference for a rolling horizon optimisation of four months and a scheduling window of three days when controlling the *water speed* and the *distance_scale* modelling parameters.



Conclusions

- The value of coordinating the operation of small-scale hydropower plants was investigated through a fictitious case study resembling the Swedish infrastructure by comparing the solutions of two scheduling strategies.
- The unknown parameters of the case study were explored by simulating the two strategies and evaluating the total electricity production difference for a variety of experiments.
- Even though the controlled (and unknown) parameters were varied significantly, the results suggested that the coordinated operation of the whole system achieved an increased electricity production (in an order of 10%).

Future research

- The perfect-knowledge assumption for the coordination strategy needs to be further explored.
- It would be interesting to study efficient coordination schemes that optimally utilise the water resource, as in the assumed coordinated model, without violating any market rules.
- With a multi-year assessment of the two strategies' value, inter-annual changes in the available water resource could be taken into account.
- A multi-parametric evaluation of the unknown parameters and decomposition methods for mitigating the computational complexity of the built optimisation models.

Questions?

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