The value of incorporating technological uncertainty in adaptive infrastructure planning; a conceptual example in hydropower investment

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Research question

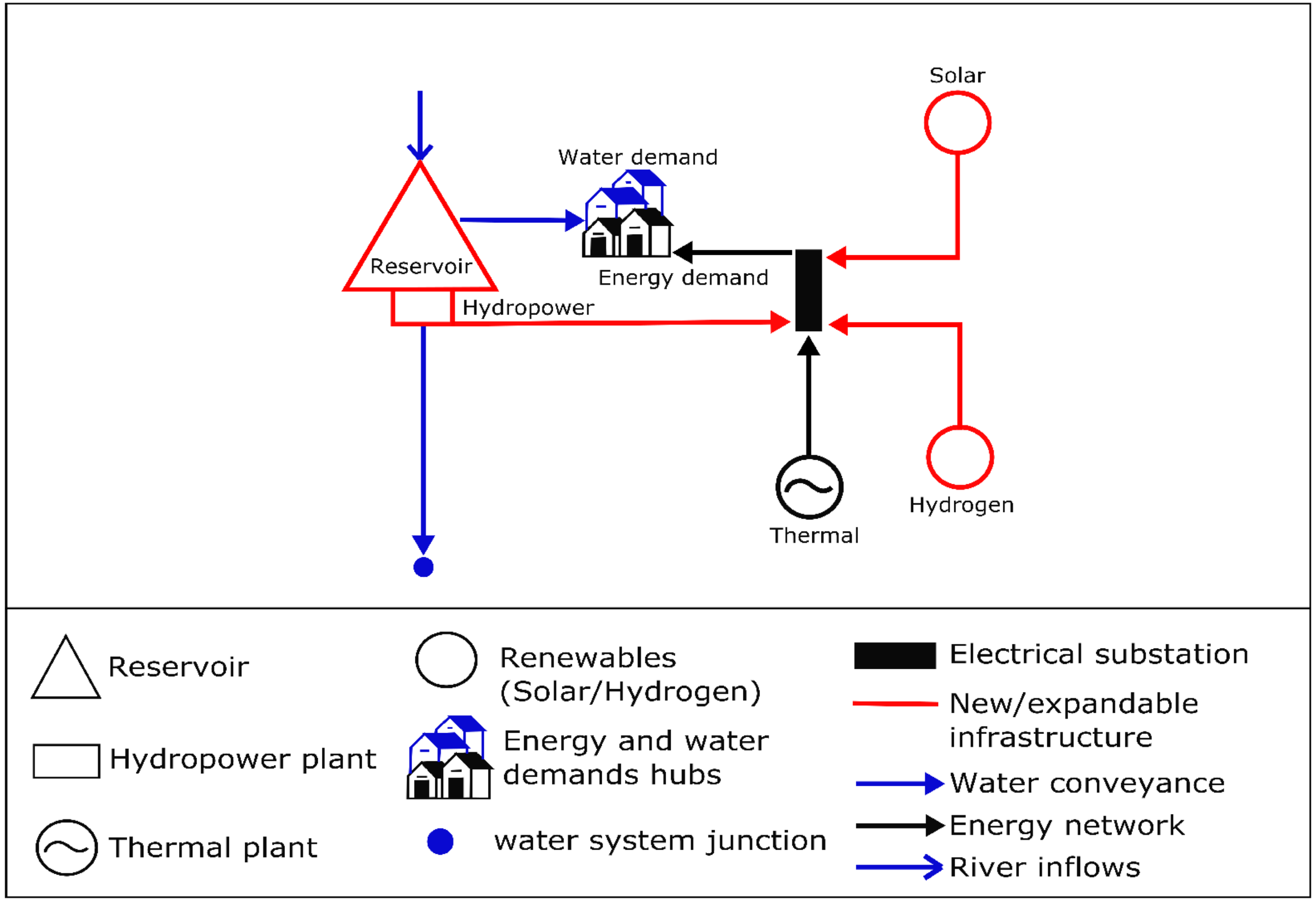
Environmental concerns has led to development of power generation technologies based on renewable energy sources (RES) (e.g., solar and hydrogen)

- technologies are becoming more attractive (higher efficiencies)
- it has become challenging to cost-effectively plan RES technologies as their characteristics have become more uncertain.

How does technological change impact on established renewable generation technologies, such as hydropower?

Water-energy system

- In interlinked water-energy systems, RES impacts on hydropower can have cascading effects on water use
- Decision makers require planning strategies to “adapt” to technological change when making long-term planning



Framework for adaptive planning under uncertainty.

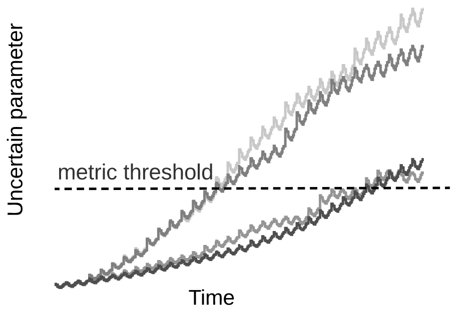
Step 1 - Formulate the water-energy planning problem by defining the objectives and a set of indicators for detecting emerging trends

Discuss with multi-sector stakeholders each system's needs and objectives

Represent exogenous uncertainty (e.g., flow, demand, cost) of both sectors as an ensemble of future scenarios

Select observable indicators to define under what conditions an intervention is implemented

Observable indicator

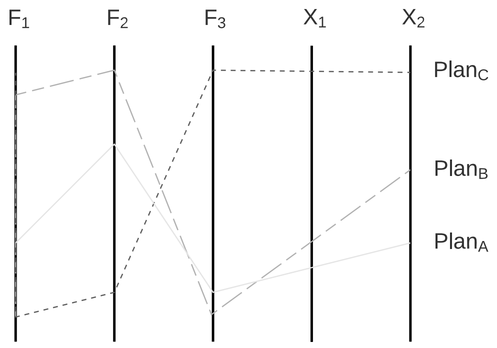


Step 2 - Optimize threshold levels of the observable indicators to trigger water-energy infrastructure options and produce a set of optimal plans given the objectives

Generate adaptation actions using multi-objective optimization to identify trade-offs that balance objectives by varying the decision variables (e.g., size of intervention, sequence of activation based on their indicators and optimised thresholds)

The water-resource energy simulator tracks flows and storages at each time-step to evaluate performance over an ensemble of future conditions

Objectives **Decision variables**

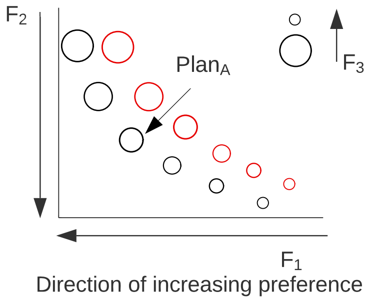


Step 3 - Demonstrate to decision-maker the opportunity cost of not engaging with adaptive planning not considering technological improvements

Decision-makers are shown the benefit of using an adaptive planning that considers technological improvements through the shift in objective performance.

Stakeholders select and implement an action which robustly meets their tolerable levels across the objectives.

Pareto frontier



○ Adaptive with consideration of technological improvements
○ Non-adaptative and / or no consideration of technological improvements

Formulation

'Adaptive' approach interventions are implemented conditionally upon observations of information from the current scenario *s* being simulated, using:

$$f_i(t,s) = \begin{cases} x_{i,c}, & \text{if } g(t,s) \geq x_{i,T} \\ x_{i,c_0}, & \text{otherwise} \end{cases}$$

where,

x : a decision variable vector representing a set of interventions,

z is the ensemble of hydrological flows, dw and tde the ensemble of water and energy demand projections respectively and c projections on installation costs for solar power.

Formulation

We define a vector of objective functions:

$$F(x|z, d_w, d_e, c) = (f_1, f_2, f_3)$$

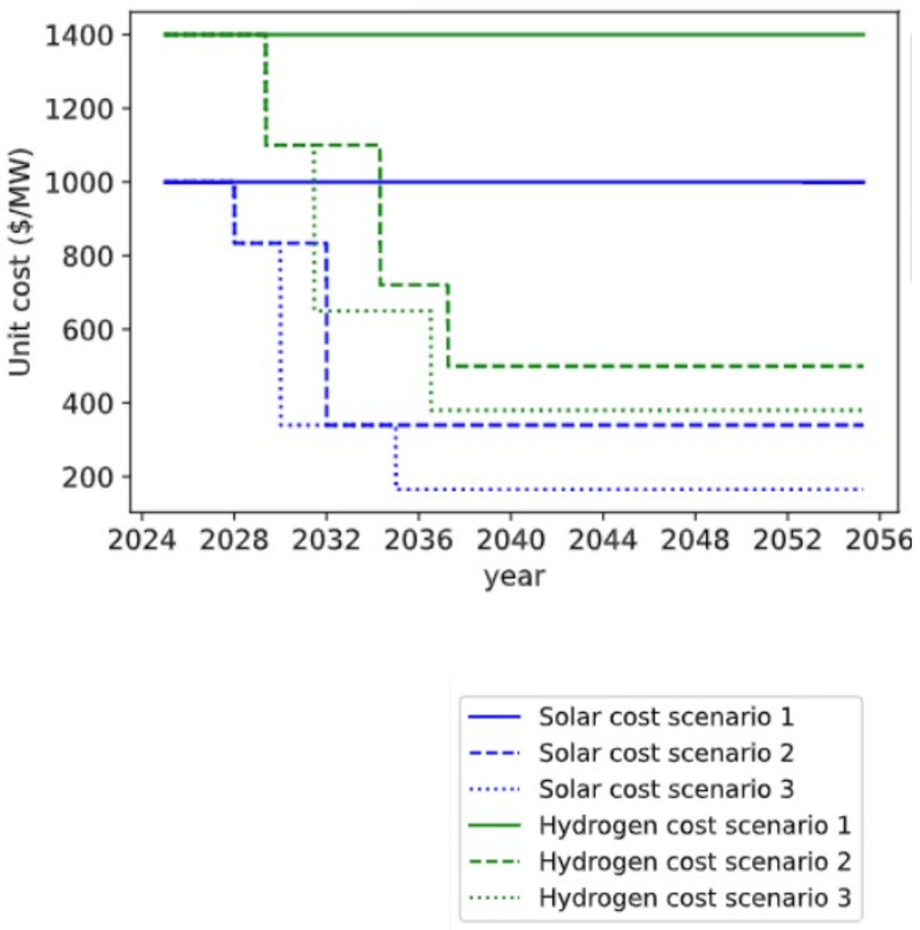
where,

$x_{i,c}$: new capacity

g(t, s) : a boundary condition (e.g., changes in water or energy demand, a climate change signal)

xi,T : is the threshold that triggers intervention i.

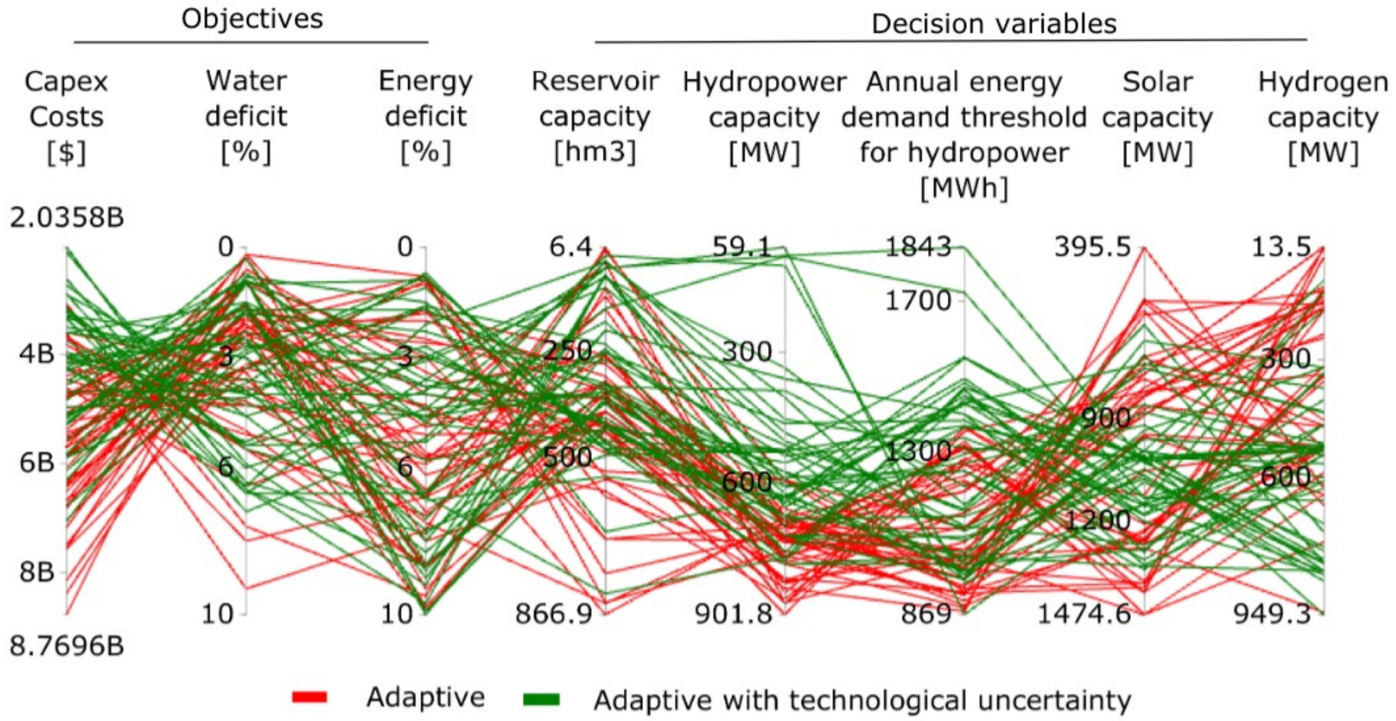
Technological uncertainty



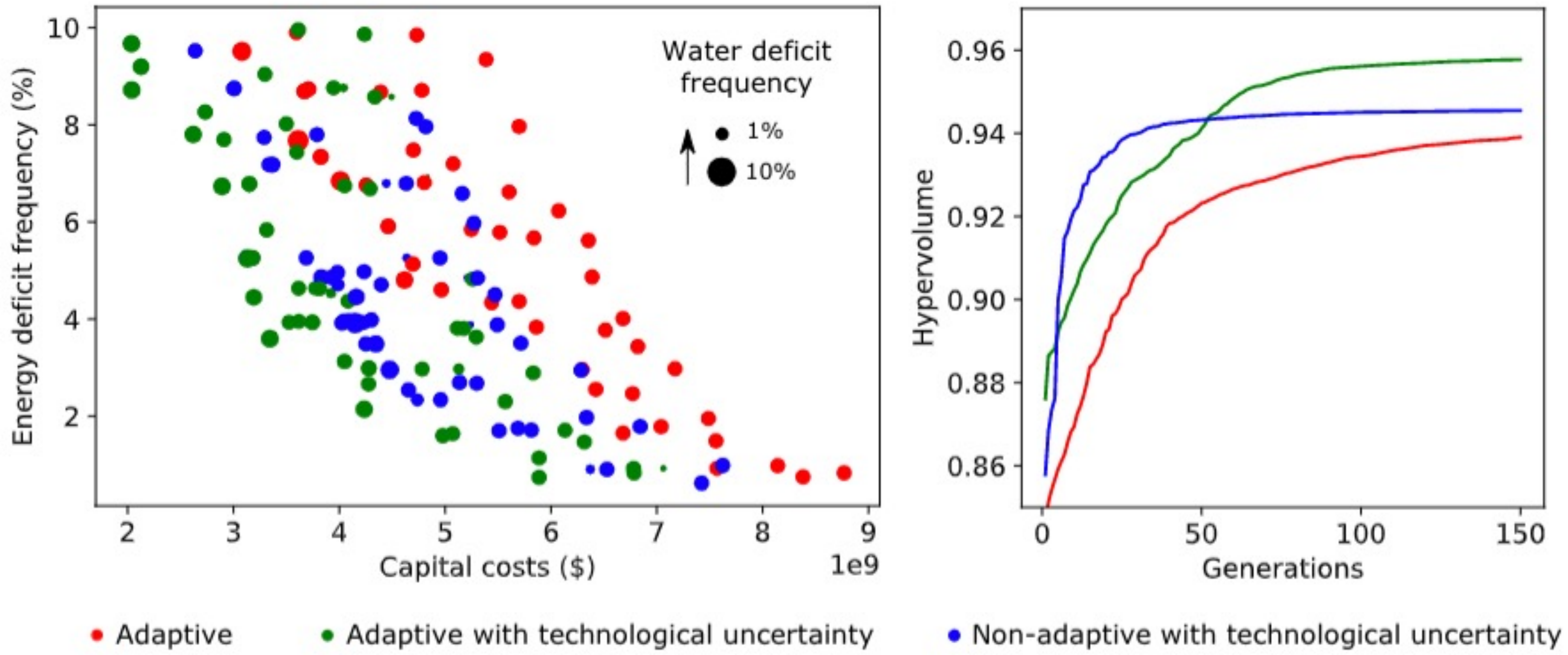
- Projections of solar and hydrogen installation costs reflecting the arrival of technological innovations
- Many important decisions on switching to a clean economy will need to be made between now and mid-century
- Globally, installation costs of solar PV and hydrogen are expected to decline in the next three decades

Impact of technological uncertainty

- Pareto solutions for the adaptive solution with and without technological uncertainty
- Ideal solution would be a horizontal line across the top of the first three axes
- Solutions that consider technological improvements, delay and reduce hydropower investment



Benefit of an adaptive policy compared to a non-adaptive (time-based)



- For the same level of system performance, adaptive plans require less investment costs compared to fixed plans
- This efficiency is enabled by allowing each trajectory to select appropriate options
- Static plans select one schedule of infrastructure options imposed on every scenario

Conclusions

- Technological uncertainty is an important aspect of water-energy system planning as renewable technologies that depend on water availability can be potentially achieve increase cost-efficiencies due to technological innovations
- Adaptive long-term resource planning is an efficient approach for identifying optimal investment plans under technological, socioeconomic and climate change uncertainties

Conclusions

- Model-assisted investment studies in water-energy systems are likely to give different results if technological uncertainty is included
- When the technological uncertainties related to non-hydropower renewable energy sources were considered, average suggested hydropower capacity was reduced by 26%, while solar and hydrogen power generation were increased