Integrated Modelling of Hydropower Systems and the Water-Energy-Food Nexus

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water and energy
Energy and water

Extraction
Mining, drilling
(oil, natural gas)
Biomass

Raw Material Refining
Coal, petrol,
natural gas,
uranium, biofuels

Transport & Transmission
Pipelines, waterways

Energy Generation

End Use
Industrial
Commercial
Residential
Public Utilities
Transportation

Energy Recycling
Cogeneration,
desalination

Wastewater
Collection, treatment and discharge or reuse

Resource

Water Source
(e.g., lakes, rivers, aquifers, sea)

Discharge Water

Renewable Energy
Wind, solar,
hydroelectric, tidal

Transportation Fuels, Natural Gas

Note: Water inputs and outputs may be in different water bodies.

1.1 Office-Through (O-Loop) Cooling

Once-through cooling uses an ample supply of water (from an ocean, river, lake, cooling pond or canal) to run through the system’s heat exchanger to condense the low-pressure steam at the exhaust of the turbines (Figure 24). Water is returned to the water body about 10°C to 20°C warmer.

Until the 1970s, thermoelectric power plants commonly used water withdrawal intensive open-loop cooling and were built next to abundant surface waters near large population centers (U.S. DOE, 2006). These are cheap and sturdy systems (about $20/kW – EPRI, 2007). Today, open-loop cooling power plants account for about 31 percent of U.S. generating capacity. Although these plants do not consume much water (i.e., they return about 99 percent of the water to the source), the availability of water is critical to plant operation because of the huge demand. This makes these plants extremely vulnerable to droughts, high-temperature events and competition for water resources. This is particularly exacerbated by the fact that electricity demand is disproportionately high in water-scarce areas such as the Southwest. Moreover, the large intake of water is extremely disruptive for aquatic life, and the discharge temperatures alter aquatic ecosystems considerably. The intake structures kill millions of fish and other aquatic organisms per plant each year and the discharge of heated water can be particularly lethal to native aquatic species. The 1972 Federal Water Pollution Control Act and Section 316(a) of the Clean Water Act (regulating intake structures and thermal pollution discharges) placed restrictions on the impact of open-loop cooling. Following this act, construction of open-loop cooling power plants slowed abruptly. Only 10 such power plants have been built since 1980, mainly along the coast (U.S. DOE, 2006).
Water and energy

Figure 11. Water Flowchart (Highlighting Source)

Source
- Lakes, reservoirs, aquifers

Water Extraction and Conveyance
- Raw Water

Water Treatment
- Leaks

Water Distribution
- Leaks
- Raw Water

Recycled Water
- Recycled Water Treatment
- Leaks

Recycled Water
- Storm Water

Wastewater
- Wastewater Collection
- Leaks

End Use
- Agriculture
- Energy Production
- Industrial
- Commercial
- Residential

Net Loss
- Discharge to ocean

Wastewater
- Biosolids
- Biogas

Energy Production
- Biogas
- Nitrous oxide

Discharge Water
- Energy Production

Net Loss
- Evaporation
- Transpiration

Source: Adapted from Wilkinson, 2000
nexus
Example of nexus 1 – Energy strategy 2050

- Decommissioning of nuclear power plants generates the needs of replacing ~40% of electricity production → hydropower is a candidate to achieve this, but

- Will there be enough water to generate the additional electricity?

- Will the impact of additional hydropower generation on aquatic ecosystems be acceptable?
  - e.g. impact of more abstraction
  - e.g. impact of more flexible and rapid operation → hydro- and thermopeaking

- Will climate change induce a competition of water for energy (hydropower) with water for food (irrigation) and water for the environment (environmental flows)?
Example of nexus 2 – The Omo-Gibe-Turkana basin

- ~140,000 km²
- source in northern highlands with annual precipitation > 1500 mm
- outflow into Lake Turkana (endorheic)
- 80-90 % of annual inflow into Lake Turkana comes from Omo
- 2 riparian states (Ethiopia and Kenya)
- a cascade of large dams is built and planned
- large-scale irrigation schemes for commercial sugar cane production
  - → competing water withdrawal
  - → effects on Lake Turkana water level variability
  - → environmental conservation
Example of nexus 2 – The Omo-Gibe-Turkana basin

- Dams built upstream alter the natural streamflow regime
  - in turn the altered streamflow regime impacts
    - downstream irrigation schemes
    - downstream aquatic ecosystems
    - agricultural practice of riparian indigenous populations (recession agriculture)
    - the variability of inflows into Lake Turkana

- Irrigation schemes planned in the lower Omo valley generate a water demand that
  - alters the streamflow regime downstream of the abstraction points, thus impacting
    - downstream aquatic ecosystems
    - agricultural practice of riparian indigenous populations (recession agriculture)
  - reduces the inflow to Lake Turkana, thus altering its water balance
Nexus in the context of resources management

- A *nexus* implies that *decisions* made to manage one resource/compartment affect another resource/compartment and vice-versa

- A policy that *benefits one* resource/compartment can pose *significant risks* and detrimental effects to *others*…

- … but can also generate *co-benefits*

*analysing the nexus implies understanding the trade-offs of management policies*
approach
Modelling the trade-offs in a nexus context

Principles

- Consistency of model complexity (drivers and system)
- Representative temporal and spatial scales (process scales of drivers)
- Causal modelling and feedback accounting
- Simulation (impact) vs optimisation (Pareto solutions of many objective problem - nexus)
- Uncertainty accounting (stochastic framework)

Issues

- Range of spatial and temporal scales
- Single systems vs nested systems vs large scale systems
- External drivers (e.g. new renewables, market)
Process scales relevance

Issues ideally requiring short temporal scales

- Drivers of electricity demand variable on hourly scale
- Variability of new renewables on sub-hourly scale
- Grid stability
- Extreme events
- Sediment erosion and transport
- Snow- and ice-melt
- …

Issues ideally requiring spatially explicit modelling

- Heterogeneity of hydrological response and of drivers of WE nexus
- Impacts and trade-offs spatially variable
- …
Swiss Energy Strategy 2050 – Integrated modelling of HP systems

Work Package
Hydropower

- Climatic controls and socio-economic drivers of hydropower production
  T2.1

- Demand, market, and CH production strategy scenarios
  T2.2
  (SCCER 2 and SCCER 5)

- Hydropower infrastructure adaptation to requirements of future operating conditions
  (feedback on storage, and system features and operation)
  T2.3

- Technical adaptation of hydraulic machines
  (feedback on operation)
  T3.2

- Environmental impacts of future hydropower operating conditions
  (feedback on release strategy)
  T2.4

- Integrated model simulating water resources availability and operation of HP systems under future climate, demand and market scenarios
  T2.5

- Stakeholders’ input/feedback

- Outputs to SCCER 2

- Assessment of hydropower production contribution to Swiss energy strategy
Why a detailed model of forcing and of hydrologic response
climate change as primary driver → *interactions and causal relationships*

- **Climate Change**
  - Alteration of *hydrologic* regimes (including extremes)
  - Alteration of *hydrology driven* processes (e.g. erosion and sediment transport)
  - Changes to HP “hardware” (e.g. to cope with CC induced *sediment regime*)
  - Energy Market
    - Change of electricity demand due to
      - development of other renewables
      - Seasonal demand shift due to CC
Integrated WEF modelling framework

**drivers**

- **Socio-economic variables**
  - Stochastic long-term price projections
  - Price forecasts

- **Meteorological variables**
  - Stochastic downscaling of Climate Change
  - Meteo forecasts

**Optimal controller**

- Stochastic optimization
- Robust optimization

**Topkapi-ETH**

- Reservoir release
- Reservoir module
- Hydrological module
- Streamflow

**Output variables**

- Hydropower performance
- Hydrological response
- Environment response

**trade-offs analysis**
Component – Advanced stochastic weather generator

AWE-GEN-2d (Advanced WEather GENerator for 2-D grid):

- combine *physical and stochastic* approaches to generate gridded climate variables
- high spatial and temporal resolutions (100s of m to km, min to hour)
- multivariable: P, T, SR, VP, RH, near surface wind fields)
- model re-parameterisation for CC impact studies

[Peleg et al., *JAMES*, 2017]
Component – Hydrological model

Topkapi-ETH key features:
- spatially distributed
- physically explicit
- snow-ice process dynamics
- geomorphological processes (sediment production and transport)
- anthropogenic structures (reservoirs, diversions, irrigation, and water supply)
- reasonably short computation time
- suited for stochastic analysis

 Hourly scale
Component – MO optimisation model

- There are many stakeholders and nexuses and thus many objectives:
  - national energy strategy
  - supply security
  - hydropower companies perspective
  - environment conservation
  - competing water uses

- Relative importance of the objectives may change in time
  - temporal dimension of nexus
  - system configuration can change over time

\[
\max \mathbf{J} = \left| J^1 J^2 \cdots J^n \right| \\
\text{subject to } m_t(\cdot)
\]

Pareto frontier

Each solution represents a different trade-off
example
Example of development and application of integrated model of WE nexus

[Anghileri et al., *JRNWRENG*, submitted 2017; Anghileri et al., *WRR*, submitted 2017]

Objectives

- Development of an **advanced modelling framework** for the **integrated continuous simulation** of streamflow regimes and of **operation** of HP systems under **future climate scenarios**, **operational constraints**, and technical solutions,

- providing a **quantitative** evaluation of the **optimal control** of HPs and of their **production potential**, as well as the effects of their operation on natural water bodies.
Example – research questions

- How much can we increase hydropower production (without infrastructural investments)?

- What is the effect of climate change on water availability and reservoir operation?

- What is the effect of energy demand and price changes on reservoir operation?

- What is the combined effect of climate and price changes?
Example – modelling framework (on-going)

**Socio-economic variables**
- Stochastic long-term price projections
- Price forecasts

**Meteorological variables**
- Stochastic downscaling of Climate Change
- Meteo forecasts

**Topkapi-ETH**
- Reservoir release
  - Reservoir module
  - Hydrological module

**Streamflow**

**Output variables**
- Hydropower performance
- Hydrological response
- Environment response

- **exploration of effects of co-variation of prices and CC signal/variability on HP trade-off production-revenue**
- **accounting for uncertainty**
Example – pilot case study

[Anghileri et al., *JRNWRENG*, submitted 2017; Anghileri et al., *WRR*, submitted 2017]

Mattmark Reservoir

- Pumped Storage system
- *Active storage*: about 100 million m³
- *Total installed capacity*: 256 MW
- *Catchment*: 37.1 km² + 55.1 km² (connected through diversion channels)
- *Hydrology*: ice- and snow-melt dominated
- *Glacier*: 29% of the catchment area

[Map of Switzerland showing the Mattmark Reservoir and its connections to the Rhone and Visp.]
Example – impact of climate change

- temporal shift (early snow melt)
- reduction of annual reservoir inflow volume (glacier retreat and lower icemelt)
Example – price scenarios

Large increase of energy prices (driven by the projections of CO2 emission permit price - according to current EU climate policy)

Large increase in variability because of increased share of Variable Renewable Sources (i.e., solar and wind)

[Schlecht and Weigt, 2014]

Swiss Average price 2015: 83.17 Euro/MWh
Swiss Average price 2045: 163.71 Euro/MWh

daylight hours

hourly scale
Example – results

- Revenue increase because of underlying increase of price projections (≈ effect of CO₂ permit price)
- Decrease in production because of lower water availability
- Overlap at mid century due to stabilisation of glacier retreat

Trade-off between revenue and production

Co-variation of climate change and market prices

Price projections based on generation mix, energy demand, electricity market model (Schlecht and Weigt 2014).

Data driven stochastic variability of prices

Stochastic downscaled transient climate scenarios.

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wef nexus
Components of the WEF nexus

![Diagram showing the components of the WEF nexus with numbers 1.1/2.1, 1.3/2.3, 1.8/2.6, 1.5/2.7, 1.6/2.4, 1.7/2.5, 1.8/2.6, 1.2/2.2, and 1.4/2.7.](image-url)
Integrated model of the WEF nexus

“2-core engine”

• cause-effect simulation

• MO optimisation and trade-off analysis

feedback → policy impact analysis

WP2
DRIVER of WATER-ENERGY-FOOD NEXUS

WP5
DECISION ANALYTIC FRAMEWORK

WP2
DRIVER of WATER-ENERGY-FOOD NEXUS

WP5
DECISION ANALYTIC FRAMEWORK

Direct links

Feeds

Task and subtasks WP3

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DAFNE – A Decision-Analytic Framework to explore the water-energy-food NExus in complex and transboundary water resources systems of fast growing developing countries

http://dafne-project.eu
Concluding remarks

- **Detailed models of integrated water-energy-food nexus are feasible**
  - spatially explicit models of impacts
  - trade-off analysis among different management policies

- **Issues**
  - upscaling to large/national/supranational scale systems
    - nested modelling approach
    - coarse scale(s) optimisation/trade-off analysis $\rightarrow$ refined scale(s) simulation of impacts
    - feedback across coarse and refined models
  - interdependence of systems
    - likely manageable at coarse scale(s)
  - predictability of (some) drivers
    - energy portfolio
    - market evolution
    - international dimension

...*lots of interesting issues to investigate!*
Thank you for your attention

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