64. The Water–Energy Nexus as a Sociotechnical System under Uncertainty

Setting the scene

The global goal of sustainability requires an integrated viewpoint in order to take into account natural resources protection and energy transition concerns, along with economic growth, environmental improvement and social prosperity. In this scene, the concept of the water–energy nexus, which aims to address both vital elements from a unified perspective, is recognized as a critical turning point and the means to enhance both water and energy security (Scanlon et al., 2017; Cai et al., 2018).

We underscore that the 'nexus' approach originates from the multidimensional role of water as (a) energy producer, not only direct, namely for hydropower generation, but also indirect (e.g. irrigation of biofuels, cooling of thermal power plants, photovoltaics (PVs) over open water); (b) energy consumer (e.g. pumping, water treatment, desalination); and (c) energy buffer (water stored in hydroelectric reservoirs, energy regulation through pumped storage systems). The key role of water is further strengthened by the ongoing energy crisis, which, among others, disputes the feasibility of the European Green Deal. It is now clear that this pan-European goal can be achieved by relying on wind and solar power generation, only if these are balanced by hydropower and other dispatchable generators, which also requires revising the current operation policies of hydroelectric plants (Bogdanov et al., 2019; Gøtske and Victoria, 2021).

So far, two strategies represent the interdependencies in the water–energy nexus. The most common is to couple single-system models and run them within an iterative procedure, internally representing all interactions within a single model (Payet-Burin et al., 2019). Instead, state-of-the-art attempts clearly promote a more holistic path (Khan et al., 2018), emphasizing the representation of the diversity in the scales of interest (spatial, temporal, political) at which water–energy interactions occur (McCarl et al., 2017).

Nevertheless, the reliability, resilience, economic effectiveness and, ultimately, the long-term sustainability of water–energy systems are substantially affected by complex social dynamics, which is the footprint of individual human actions. In this vein, the anthropogenic behaviour and its multiple interactions and feedback loops with the technical system components, that is, water and energy fluxes, and associated infrastructures, make it essential to extend the nexus rationale in order to explicitly embed the crucial social dimension (Molajou et al., 2021). However, the experience so far reveals that most of the analyses of the water–energy nexus mainly focus on the physical processes, while rarely considering the social ones, which refer to human responses to the nexus (e.g. Elshafei et al., 2014; Di Baldassarre et al., 2019).

A major obstacle to representing the water, energy and social dynamics under a really unified modelling paradigm originates from the issue of uncertainty, which is an intrinsic characteristic of all associated processes (Koutsoyiannis et al., 2009). While the representation of individual uncertainties is by definition a challenging task, this becomes even more demanding if the three elements are considered as a nexus. In fact, the nexus approach makes it essential to consider all kinds of interactions and feedbacks among water, energy and society, eventually accounting for dependent uncertainties across scales, both temporal and spatial.

In this vein, we argue that, in practice, the linkage of technical systems with social processes, especially under the prism of uncertainty, is rather fragmented. In fact, conventional modelling approaches for the wide range of water–energy problems, including strategic planning, engineering design, strategic management and long-term financial assessment, generally consider a deterministic and thus controllable and predictable world. Under this premise, the multiple and multidimensional uncertainties across water–energy systems, induced by their perpetually changing physical and anthropogenic environment, are only marginally accounted for, for example, by means of investigating alternative scenarios with respect to socioeconomic assumptions (Morris et al., 2022), or even neglected.

This chapter has a twofold objective. The first is to manifest the water–energy nexus under the rationale of stochastic sociotechnical systems, thus highlighting the major role of social drivers, which are affecting and are affected by water and energy fluxes. In this vein, we provide a brief review of state-of-the-art approaches for embedding the social feature within the technical description of the water–energy nexus. The second objective is to outline a holistic probabilistic-stochastic framework for recognizing, classifying, representing, quantifying and eventually interpreting uncertainties across the unified water–energy–society nexus. These two objectives are developed herein.

Modelling the triptych of water–energy–society

In the last years, the social impact across hydrological systems has been progressively recognized as an essential feature, thus leading to the development of the cross-disciplinary domain of socio-hydrology and the fostering of the so-called hydro-social research (Ross and Chang, 2020). As pointed by Di Baldassarre et al. (2019), emphasis has been given to human–flood, human–drought and human–environment interactions and feedbacks, while the linkage of socio-hydrology with energy (as well as food) production is still poorly investigated.

The social footprint across water–energy systems is expressed via multiple means, not only in terms of water and energy uses, but also through multiple other human-induced procedures, such as legal controls, management policies, market rules and so on. We underline that in common modelling approaches, all these elements are handled under the steady-state hypothesis. For instance, water and energy demands are typically considered as known model inputs, which follow a priori specified seasonal patterns, while in fact they are strongly dependent on social actions and reactions against the system's state and its various facets of change (e.g. changes in bills causing changes to consumption, which in turn trigger changes to management policies).

As already emphasized, all these complex tradeoffs reveal the need for a unified approach to the triptych of water, energy and society as a nexus. Its importance is further highlighted when these sociotechnical systems are diverted from their normal operation, due to disruptive and unpredictable events and abnormal circumstances, which may affect both the micro- and macro-behaviour of an entire society in the longer run. These may include geopolitical shifts, economic crises and extreme hydroclimatic conditions (e.g. persistent droughts), causing long-term water and/or energy shortages, which are in turn reflected in the associated demands, prices and operation policies.

Currently, agent-based models (ABMs) are recognized as the state-of-the-art approach for representing human behaviour in a wide range of applications, including water and energy systems (Berglund, 2015). The agent-based theory has been formalized by Bonabeau (2022) in an attempt to provide an elegant mathematical description of the human factor, from a bottom-up perspective, by integrating complex adaptive system theory and distributed artificial intelligence. Their key principle is to explain the extremely complex social processes by means of representative modelling elements, called agents, which are characterized by their own data, knowledge and behaviours. The adaptation of a bottom-up approach to study the agent interactions both with the technical (in our case, water–energy) system and among each other at the micro level, allows conclusions to be drawn about the system's behaviour at the macro level.

Although ABMs have quicky gained in popularity across several disciplines, there are still open questions with respect to their practical use. Magliocca (2020) remarks that most of the studies employed so far do not contain agent interactions nor do they base agent decision-making on existing behavioural theories. In the field of water resources, the use of ABMs so far has mainly focused on the spatiotemporal evolution of demands (e.g. Koutiva and Makropoulos, 2019; Huber et al., 2019), which is an important yet not the sole aspect of anthropogenic effects across the water cycle. Regarding energy systems, Yazdanie and Orehounig (2021) manifest the need for improving uncertainty analyses through AMBs, with respect to factors such as socioeconomic development, population changes, technology development, future costs and policies, as well as sudden large-scale changes, also referred to as 'black swan' events. Nevertheless, the integration of the social dimension within the water–energy nexus seems to be still underdeveloped in modelling and research (Zeng et al., 2022).

The need for a holistic sociotechnical modeling paradigm is strengthened due to the emerging challenges induced by running global crises (environmental, geopolitical, financial, energy) that have gone beyond the borders of national economies. All crises are interlinked with the social factor and, consequently, affect the evolution and the long-term sustainability of water and energy resources.

Water, energy and society as a stochastic sociotechnical system

Since water, energy and social dynamics are subject to multiple sources of uncertainty, their recognition, representation, classification, quantification and eventual interpretation are a key objective to be addressed, in order to represent this nexus under the novel prism of stochastic sociotechnical systems.

Following the typical classification of environmental modeling (e.g. Beven, 2016), uncertainty can be classified into two major categories:

- Process uncertainty, where the term ‘process’ refers to a randomly varying quantity and is mainly associated with natural phenomena, the random behaviour of which can be macroscopically described via probabilistic and stochastic laws (e.g. hydroclimatic variables). In particular, under the stationarity hypothesis, these laws can be extracted on the basis of past (i.e. observed) data.
- Model uncertainty, which spans all aspects of the modelling procedure, including its conceptualization and underlying assumptions, the mathematical description of the system dynamics and the assignment of parameter values to governing equations. These uncertainties can be quantified if there are available observations of the real system’s response to compare with modelled responses.

In the context of water–energy–society systems, and according to the rationale of Sakki et al. (2022), uncertainties can also be identified as exogenous and endogenous, where the first refer to the system’s drivers and the second to its internal processes. In particular, the production of water and energy (particularly renewable energy) is driven by inherently uncertain hydrometeorological processes that exhibit significant peculiarities across scales (e.g. intermittency, intra-day and seasonal periodicity, long-term persistence and complex dependence structures). However, since these are natural and thus ‘pristine’ processes, their probabilistic regime is, at least partially, explained by the statistical information provided by past observations. In contrast, social behaviour is strongly unpredictable, thus displaying emergent properties with respect to highly uncertain environmental, (geo)political and economic drivers, and interactions among different societal groups, as well. On the other hand, the internal uncertainties involve all kinds of spatiotemporal propagations, exchanges and transformations across the sociotechnical system (e.g. conversion of river flows to hydropower), which are represented through simulation models, including ABMs.

The various disciplines involved in the representation of the individual components of the water–energy–society nexus, and also the different (and often contrasting) uncertainty assessment ‘schools’, have not yet established a generally accepted framework to handle the full spectrum of uncertainties, particularly to translate them into practice. The issue of uncertainty across such complex systems requires a holistic viewpoint in order to take advantage of current methodological and computational advances in probability and statistics, emphasizing stochastic models and copulas.

We remark that such approaches, particularly stochastic models, have quite a long history in water resources and other environmental sciences, as the means to generate long synthetic data for the model inputs that reproduce, in statistical terms, the regime of the observed processes. However, a fully coupled stochastic approach, allowing an explanation for all the aforementioned cascades and dependencies under the prism of uncertainty, is still missing. In this vein, the research effort with respect to the water–energy–society nexus should focus on formalizing the concept of stochastic sociotechnical systems, not only as a theoretical tool but also as a means to support decision-making in the real world (Will et al., 2021).

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