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Spatial and temporal synchronization of water and energy systems: Towards a single integrated optimization model for long-term resource planning

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HIGHLIGHTS

- New hard-linked, linear optimization model for coupled water and energy analysis.
- Life-cycle energy and water flows tracked both spatially and temporally.
- Water quality changes tracked through individual processes.
- Temperature change impacts on power plant cooling considered.
- Coupled model shows lower costs, better efficiency and improved robustness.

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ABSTRACT

Predictions show that pressure on already limited water and energy resources is expected to increase in many parts of the world as a result of growing populations, rapid urbanization, increasing pollution and climate change impacts. With water and energy playing a critical role in socio-economic development, ensuring resource security is a top policy concern. However, achieving this efficiently requires taking into account the various links between the two sectors through their joint management. Feedback between the water and energy sectors exists across system life-cycles and links the resources both spatially and temporally. Tracking the impacts of policies made in one sector on the other can thus be complicated and several 'nexus' methodologies have been developed to try and address these issues. However, the different physical, temporal and spatial characteristics of the water and energy systems present several hurdles in analyzing the two resources simultaneously. This paper overcomes many of these problems with a new, fully coupled water-energy optimization model. Based on a review of contemporary literature, the model develops an original methodology to hard-link the two systems in detail across spatial and temporal scales, as well as between individual system processes throughout the life-cycle of each resource. In addition, the model also tracks changes in water quality through each process, allowing for detailed accounting of the energy needs for water treatment. The methodology proposed in this paper can be used to investigate various cross-sectoral issues and policies such as: water availability and temperature impacts on power plant cooling; emission constraint and biofuel expansion planning impacts on water resources; and the implications of water infrastructure expansion on the energy system. The capabilities of the coupled model are investigated in an example case study for Spain. An integrated approach is shown to have several benefits including lower total costs, better resource efficiency and improved robustness for a wide range of variations in several uncertain parameters. Coupled water-energy planning thus provides a critical opportunity to improve resource security and prevent inefficient decisions which could exacerbate problems even further.

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1. Introduction

In several regions of the world such as California, the Mediterranean region, China, India and the Middle East, concerns about future energy and water security are increasing due to various factors including, growing populations, increasing pollution, overuse of non-renewable resources and the impacts of climate change. Interdependencies between the two sectors make the situation even more urgent and several international organizations have conducted various water-energy nexus studies [1–7] leading to a better understanding of the inter-relationships between the two sectors. Energy is used for water extraction, pumping, desalination, purification and distribution while water is used in energy extraction and mining, hydro-power generation, power plant cooling and to irrigate bio-energy crops.

Several energy production alternatives such as concentrated solar power (CSP), bio-fuels, hydraulic fracking for shale gas, coal-to-liquid plants, nuclear power and carbon capture and storage (CCS) can be more water intensive than their traditional counterparts and will increase water stress if not planned strategically [8]. Expansion of water infrastructure to ensure water security can also have important impacts on the energy sector. For example, a study from Texas [9] estimates desalination and long-haul transfer to be between nine to twenty-three times more energy-intensive per unit of water than conventional treatment of local surface water, while in the Middle East, ignoring the additional feedback of electricity demand from future water system needs has been shown to lead to an almost 40% underestimation of future electricity needs for 2050 [10].

Such nexus impacts are causing concern and call for more holistic, integrated assessments, to better evaluate the robustness of different policies across both sectors. Taking the links between the sectors into consideration gives rise to new questions that nexus models must answer: What will be the impacts of particular energy technologies on water resources and how will these impacts vary spatially? How will future water quality, quantity and temperature changes impact existing energy technology efficiencies? How much additional energy will be consumed by additional water extraction infrastructure and what alternatives are available? How will these impacts play out with seasonal changes in demands and resource availability? What role can demand side management play in cross-sectoral efficiency?

In response, many attempts have been made to incorporate elements of the water-energy nexus in several modeling efforts. A review of some of these studies, discussed in more detail in Section 2, reveals various hurdles that have prevented the development of the kind of tool that can reliably answer the nexus questions asked in the previous paragraph. These hurdles include: difficulties in identifying relevant water-energy links; managing the trade-offs between increasing model details and solution efficiency; capturing life-cycle cross-sector feedback; synchronization of spatial and temporal scales; differences in the physical characteristics of water and energy; sparse data; and large uncertainties.

This paper presents the SPATNEX-WE (**SPA**tial and **T**emporal **NEX**us - **W**ater **E**nergy) model which addresses several of these issues. The model is a hard-linked partial equilibrium linear optimization model which tracks energy flows throughout the life-cycle of the water system and both water withdrawal and water consumption[1] throughout the life-cycle of the energy system. The model represents both water and energy systems in equal detail across spatial and temporal scales as well as through individual processes, allowing users to pinpoint where, when and in which processes changes occur as a result of policy, socio-economic or climatic changes. In addition to volumetric flows, the model also tracks changes in water quality through each process. Given appropriate data availability, the model can be spatially dis-aggregated to the desired geographical boundaries. Different temporal scales can be used to characterize different processes such as monthly precipitation or varying energy demand levels for weekend or weekdays. Data is aggregated to the finest common spatial and temporal scales across the water and energy sectors. The two sectors are linked based on cross-sector life-cycle resource consumption, water temperature impacts on power plant cooling, a common objective function and via the management of multi-use reservoirs.

After establishing the initial state of existing water and energy capacity and infrastructure, the model is run to give the optimal investment and operation decisions for both resource systems to meet exogenous demands for a chosen year of analysis. The model can also be run in a recursive mode to explore investment pathways, in which investment decisions for each intermittent year are used as the initial state for the subsequent analysis. This paper only discusses the static mode for a single year. More details of running the model are discussed in Section 3 on the methodology.

The integrated methodology developed in this paper can be used to address several 'nexus' issues impacting both the water and energy systems. Such issues include: managing increasing constraints on water availability and temperature for power plant cooling; energy implications of expanding water infrastructure such as long distance water transfers or new desalination plants; and the impacts of energy policies such as greenhouse gas emission constraints or biofuel expansion on water security. The results show that an integrated plan considering a coupled water and energy system provides several additional insights into cross-sectoral resource flows through different processes and life-cycle periods. These additional insights provide the opportunity to build a more robust system which is shown to lower costs, improve efficiency and increase the security of supply across a range of variations in several uncertain parameters such as resource demands and precipitation.

Section 2 reviews some of the existing models and summarizes recommendations from various studies. Section 3 discusses the methodology of the SPATNEX-WE model and how it incorporates the recommendations made from the review. Section 4 develops a baseline case study for the country of Spain which is validated by comparing it with historical values and results from other water-energy nexus studies in the region. In Section 5, the capabilities of the model are demonstrated by investigating a hypothetical future scenario. The performance of the model and benefits of integration are explored by comparing several model runs with and without water-energy inter-linkages. Detailed spatial and temporal variations in various parameters as well as the robustness of the solutions are analyzed as part of the outputs. Section 6 discusses the limitations of the model and possibilities for future developments. Finally, conclusions are offered in Section 7.

2. Literature review

With rising populations and growing economic activity in many regions of the world, water-energy nexus issues are becoming critical concerns due to increasing pressures on the two resources. The methodology discussed in this paper is designed to provide additional insights for policy makers and equip them with a tool to better address such issues. Examples of nexus issues which planners have to address include: reduced power plant capacities due to diminishing cooling water availability or increasing cooling water

[1] Water withdrawal is defined as the total volume of water extracted from a system, part or all of which may be returned to the system, for example when water is withdrawn for hydropower production and then subsequently returned for further use downstream. Water consumption is defined as the part of water withdrawn which is not returned to system for example during evaporation.

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