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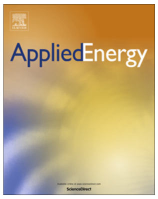

A multi-criteria model analysis framework for assessing integrated water-energy system transformation pathways

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HIGHLIGHTS

- Integrated capacity planning model incorporating water and energy systems decision-making.
- Modified version of the reference point methodology applied to balance multiple design criteria.
- Application to the water-stressed country of Saudi Arabia.
- Multi-criteria tool efficiently identifies ambitious solutions across sustainability objectives.

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ABSTRACT

Sustainable development objectives surrounding water and energy are interdependent, and yet the associated performance metrics are often distinct. Regional planners tasked with designing future supply systems therefore require multi-criteria analysis methods and tools to determine a suitable combination of technologies and scale of investments. Previous research focused on optimizing system development strategy with respect to a single design objective, leading to potentially negative outcomes for other important sustainability metrics. This paper addresses this limitation, and presents a flexible multi-criteria model analysis framework that is applicable to long-term energy and water supply planning at national or regional scales in an interactive setup with decision-makers. The framework incorporates a linear systems-engineering model of the coupled supply technologies and inter-provincial transmission networks. The multi-criteria analysis approach enables the specification of diverse decision-making preferences for disparate criteria, and leads to quantitative understanding of trade-offs between the resulting criteria values of the corresponding Pareto-optimal solutions. A case study of the water-stressed nation of Saudi Arabia explores preferences combining aspiration and reservation levels in terms of cost, water sustainability and electricity sector CO_2 emissions. The analysis reveals a suite of trade-off solutions, in which potential integrated water-energy system configurations remain relatively ambitious from both an economic and environmental perspective. The results highlight the importance of identifying suitable tradeoffs between water and energy sustainability objectives during the formulation of coupled transformation strategies.

1. Introduction

Energy systems place tremendous pressure on water resources around the globe, primarily for applications in thermal power plant cooling, hydropower generation and fuel production [1]. For example, about half of all freshwater withdrawals in North America and Europe are related to the energy sector [2,3]. At the same time, a significant amount of energy is required to extract, treat and distribute water resources [4]. Globally, it is estimated that 3% of primary energy supply is used by water systems, with water-stressed regions consuming most on a per capita basis due to the prevalence of energy-intensive water processing and long-distance

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conveyance [5]. Energy and water are also required for meeting the development goals of societies. The interdependencies between engineered systems and human development objectives promote integrated water-energy infrastructure planning over wide geographic areas.

Infrastructure here refers to the technologies or processes that enable supply of energy and water services to consumers. Planners tasked with designing regional energy and water infrastructures are faced with a plethora of technologies and a wide variety of economic, social and environmental conditions, which make it difficult to decide which technologies to invest in and promote, and in what order. The optimal combination of technologies and level of investments will be difficult to determine without appropriate analysis methods and tools. From this perspective, mathematical programming models have provided crucial decision support by enabling planners to identify system designs that perform well under anticipated operational conditions [7–11].

Previous studies explored impacts of water constraints on energy system operation by coupling water supply and electricity generation dispatch models [13–16]. Several other previous studies note the importance of future capacity decisions (the size and location of technologies) in terms of enabling effective adaptation to future water constraints, and examined the impact of water availability on the development of regional power systems by adding explicit water constraints to an optimal infrastructure planning model [18–24]. Water constraints are found to primarily cause a shift towards water-efficient cooling technology for thermal power generation, as well as increased siting in regions with greater access to water availability [21]. Increased hydrologic variability under climate change was also found to cause further long-term capacity challenges in regions where hydropower plays an important role in electricity supply [16,23]. A key limitation of these previous analyses of water constraints is the inability to incorporate feedbacks from future water supply development, which will impact the availability of water for energy and water-related energy demand. To reconcile development interdependencies, a number of other studies link freshwater and energy infrastructure planning models directly [26–32]. This approach enables modeling of system configurations that adapt to undesirable interactions between water and energy during infrastructure development.

Most previous coupled planning models focus on identifying system configurations that minimize costs or maximize consumer surplus. Yet, there are often other social or environmental objectives of concern to regional decision-makers and stakeholders, thus requiring a more integrated approach to assessing system performance [33]. Metrics of interest include limiting greenhouse gas emissions and air pollution, and securing food, water and energy resources. Previous analyses addressed such objectives as constraints, values of which were explored using parametric optimization [17,30,28,34]. Parametrization of constraints requires not only skilled analysts but also specification of a large number of optimization problems, many of which are either infeasible or result in dominated (inefficient) solutions. Multi-criteria analysis (MCA) of discrete alternatives can be applied to the results of parametric model optimization [34], but such a two-stage process is by far less effective than a direct linking of the model with the MCA tool. Another popular approach is based on weighted-sum criteria aggregation into a composite goal function. This approach has, however, serious shortcomings [35], e.g.,: (1) in some situations the same solution is returned even if substantial changes are made to the weights; (2) many efficient solutions[1] cannot be obtained by varying the weights; and (3) increasing a weight does not guarantee improvement of the corresponding criterion value.

In this context, appropriate MCA methods offer an improvement to traditional optimization approaches, as illustrated by a sample of applications relevant to the case study presented in this paper [37–39]. MCA supports analysis of tradeoffs between all relevant objectives, and interactive exploration of diverse efficient solutions across multiple objectives. Despite the potential to apply this type of methodology and tools to effectively model coupled economic-environmental decision-making [40], application of MCA to the integrated planning of energy and water systems has been limited to cooling technology choices in the power sector [41].

This paper presents a novel systems analysis tool for integrated regional planning of energy and freshwater supply systems. The framework incorporates a multi-objective decision support system to enable analysis of long-term infrastructure strategies that balance economic, energy and water sustainability objectives. The integrated decision support framework is demonstrated within a case study of the water-stressed, carbon-intensive nation of Saudi Arabia. The results of the analysis provide important new insights into the following research questions:

- How can multiple design criteria be incorporated into long-term infrastructure planning models covering both the water and energy supply sectors?
- What is the potential scale of tradeoffs between environmental and economic development objectives in the case study region, and how might relaxing ambition levels for water and energy sustainability impact affordability?

The paper proceeds as follows. The methodology of model-based decision-support and its implementation for integrated water-energy systems is presented in Section 2. The case study demonstrating model application is described in Section 3 followed by the discussion of results in Section 4. Conclusions from the research are summarized in Section 5.

2. Methodology

This section presents the approach for coupled water-energy supply planning and its integration with the MCA methods and tools. The framework is based around a water-energy infrastructure planning model developed previously for Saudi Arabia [31]. Previous research with this framework demonstrated that transitioning away from nonrenewable groundwater use by the year 2050 in Saudi Arabia could increase electricity demand by more than 40% relative to 2010, due to rapid development of desalination and water conveyance infrastructure, and require investments similar to strategies aimed at transitioning away from fossil fuels in the electricity sector. These results highlight the need to incorporate multiple policy objectives into system design, and is the key feature of the enhanced MCA tool proposed in the current study. Following a description of the mathematical model for coupled water-energy supply planning, we discuss its integration with the applied MCA methodology. Finally, we describe the input data and scenarios explored in the case study demonstrating model application.

2.1. A core model for integrated water-energy infrastructure development

The planning challenge dealt with in this paper is the sustainable long-term development of water and energy systems. These decisions are typically made at national or regional-scales, and

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[1] Solutions are called efficient or Pareto-optimal if there exists no other solution for which at least one criterion can be made better without sacrificing performance of the other criteria.

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