A Multi-Parametric Optimization Approach for Bi-Level Decision-Making Strategies in Energy-Water Nexus Supply Systems

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Abstract

The demands for energy and water continue to increase amid depleting natural resource availability and rising sustainability concerns. To address these exigent challenges, systematic shifts are expected to take place in global energy and water supply systems. Therefore, it is pivotal to understand how these two resource supply systems are interconnected for the generation of synergistic systems solutions based on an energy-water nexus (EWN) approach. Effective trade-offs between minimizing cost and maximizing resource utilization, among other objectives, can be identified through this approach for sustainable resource management. In these instances, it is customarily assumed that the decisions made by both systems are dictated at the same level, where there is effectively one single decision-maker to simultaneously satisfy the energy system’s water requirements and the water system’s energy requirements. However, these systems are typically in competition with one another to meet their respective objectives and true synergy can only be achieved in an ideal case. With these antagonistic objectives, the priorities of the involved systems naturally assume a hierarchical structure. To account for such structured decision-making, we present a bi-level programming framework for EWN supply systems based on a multi-parametric programming approach to optimize system design and operation.

**Keywords**: Multi-parametric optimization, Bi-level mixed-integer optimization, Mixed-integer programming, Energy-water nexus

* 1. Introduction

The rapid growth of the population is accompanied with increasingly prevalent economic, environmental, and social concerns that have a profound impact on the global demand for energy and water. To meet the rising demands of these resources and to adapt to the far-reaching challenges of these changing times, it is important to encapsulate the complexity of energy and water supply systems (Di Martino et al., 2023). A fundamental factor that contributes to this intricacy is the interconnected nature of these resources and their supply systems. For instance, 15% of the global water harnessed is distributed for energy use, while 8% of the global energy generated is allocated for water use (Garcia and You, 2016). Therefore, these systems must be analyzed from a holistic perspective using nexus approaches to explore the synergies and trade-offs that exist between them (Liu et al., 2018). When energy and water resources are shared to gain collective benefits in this manner, the two systems must work together to achieve set objectives in an integrated system, specifically referred to as the energy-water nexus (EWN).

The energy transition is a pressing matter for the EWN. For the energy system, the shift towards renewable energy comes with a myriad of challenges such as the intermittency of these resources in addition to the need for new infrastructure and the extreme stresses they exert on land and water resources (Cook et al., 2022). For the water system, water scarcity is a major challenge given that natural resources are depleting and that demands to meet energy generation are expected to increase drastically (Di Martino et al, 2023). To address these challenges, works such as those of Martin and Grossman (2015) and Panagopoulos (2021) harness trade-offs using nexus modeling and optimization approaches for the development of renewable energy infrastructure. The decisions made in these works by each system to meet these objectives are accustomed to hold the same level of priority. Since the decisions are taken at the same level, the nexus approach effectively analyzes the sub-systems as a single integrated system with a single decision maker. In other words, there is a coordinated effort in state-of-the-art approaches to enable synergy without information asymmetry where different systems are considered from a single level of decision-making without different levels. However, it is well-established that external and internal factors of this nature have a more considerable effect on the decisions made by some sub-systems than others. Therefore, the decisions made and the sub-systems they are associated with naturally fall into hierarchical order, for which a structured decision-making framework is essential.

Within the EWN, the incorporation of more renewable technologies in the energy system takes precedence over alleviating strains on resources in the water system, as it not only provides an opportunity to produce clean energy but can also ultimately provide relief to the water system through the deployment of less water-intensive energy production technologies. Therefore, there is a need to enable multi-level decision-making within the EWN to analyze the trade-offs that exist from prioritizing one sub-system over the other. Hierarchical decision-making of this manner, especially from a bi-level perspective within the nexus has already been investigated in literature through the use of multi-level programming. In bi-level programming, there are two different hierarchical levels of decision makers, namely, the upper level decision maker and the lower level decision maker. The works of Avraamidou et al. (2018) using a data-driven solution algorithm and Chen et al. (2022) using graph theory are some instances that enable structured decision-making under nexus considerations.

In this work, we introduce a bi-level optimization framework to leverage prioritized decision-making of a single sub-system on the EWN for the design of renewable energy systems. In this way, the impact of competition and subsequent information access on the design on these systems can be evaluated. The bi-level formulation presented is based on multi-parametric programming. Through this approach, the feasible solution space of an optimization problem with uncertain parameters is represented as critical regions that define the optimal solution in terms of the uncertain parameters offline (Avraamidou and Pistikopoulos, 2022). Therefore, by formulating the lower level problem as a multi-parametric problem, its optimal solutions in term of the uncertain parameters can be integrated as constraints in the upper level problem before its solution. Section 2 provides the framework and Section 3 presents the model and describes the multi-parametric programming approach used to enable the design of these renewable energy systems under EWN considerations. Section 4 illustrates its application to a case study and Section 5 concludes this work.

* 1. EWN Framework

The framework enables the design of renewable energy systems by integrating decisions from the energy and water systems in a hierarchical manner to meet specified resource demands over a time horizon. The decisions effectively describe energy supply through the selection of the optimal renewable energy sources and water supply through the characterization of the operation of the reverse osmosis (RO) desalination plant. Essentially, the energy system provides the energy necessary for the operation of the water system, while the RO system provides the water required for farming maize in the energy system. Therefore, to enable effective decision-making within the components of the EWN, the interconnections that exist between them must be carefully considered.

To account for the interactions within the integrated system, the EWN must be examined as a collective whole of the two sub-systems. Therefore, the integrated energy-water supply system can be considered as the upper level decision maker as it will decide the optimal design and operation of the energy and water systems. The overall objective of the energy system is to maximize the power generated while meeting energy and water demands. The lower level decision maker can then be assigned to the water system, where it will optimize its operation to minimize its energy consumption. Therefore, hierarchical decision-making is embedded in this framework to maximize the total power generated while considering the operational profiles of the water system as illustrated in Figure 1.



Figure 1: Proposed framework with the interactions between system decision makers

* 1. Mathematical Model

The development of the EWN optimization model used, which involves the integration of two independent models that define the energy and water systems, is detailed in this section.

* + 1. Energy supply sub-system

The energy system is defined by a set of energy sources (solar, wind, and biomass), energy conversion technologies (fixed angle and single axis tracking solar panels, turbines, and maize), and energy storage technologies (pumped storage hydropower and compressed air energy storage) to meet a predefined demand target. Model equations pertaining to the energy sub-system resulted in a linear programming model and was simplified based on the mixed integer linear programming model which details the system operation in Cook et al. (2022). The objective of the energy system is to maximize power generation by determining the optimal set of renewable energy sources and technologies that meet energy demands which include those of the water system as well.

* + 1. Water supply sub-system

The water system considered here is a RO desalination unit defined by its feed flow (FF), permeate flow (PF), energy consumption (EC), and water recovery (WR), in addition to its capital and operating costs. The model equations that describe it resulted in a non-linear programming (NLP) model and is a simplified version of the RO unit described in Di Martino et al. (2023). The objective of the water system here is to minimize its energy consumption as shown in Eq. (1) and is defined as a linear expression of its other operational characteristics based on the analysis performed in Di Martino et al. (2022).

|  |  |
| --- | --- |
| $$EC= a+b×FF+c×PF+d×WR$$ | (1) |

As the water system is designated as the lower level decision maker in this case, this equation is the objective function of the optimization problem of the lower level decision maker, herein referred to as the lower level problem. The water system therefore determines the amount of water that is available to meet water demands, which includes those of the energy system as well.

* + 1. EWN optimization model

The model equations of the energy and water systems are integrated by introducing their respective requirements in the overall material and energy balances to obtain the EWN optimization model using insights from Di Martino et al. (2023). The objective function of the energy system which maximizes total power generated, which thereby serves as the objective of the optimization problem of the upper level decision maker, herein referred to as the upper level problem, as shown in Eq. (2).

|  |  |
| --- | --- |
| $$Total power output= Sum of power from all energy sources$$ | (2) |

Other extensions, particularly in the investment and operating costs, are also made to the energy system model to include the operation of the desalination unit.

* + 1. Multi-parametric optimization approach

To implement hierarchical decision-making in the EWN, the lower level problem here is treated as a multi-parametric programming problem, whose resulting explicit solutions are then integrated into the upper level problem to be subsequently solved as single-level programming problems (Avraamidou and Pistikopoulos, 2022). The water recovery of the RO unit, a variable in the upper level problem, is considered the parameter in the lower level problem to enable its reformulation into a multi-parametric problem.

* 1. Case Study

To illustrate the hierarchical decision-making capabilities of the proposed framework, we consider a case study based on an energy-water supply system in Texas. The aim of this system is to meet the energy and water demands of a metropolitan region where hourly energy and water demands must be satisfied for a period of one year. The upper level decision maker will decide the design of the energy system based on lower level decision maker that will determine the optimal operational profile for the water system. For the energy system, data pertaining to the power output of the renewable energy sources, namely, the solar direct normal irradiation and wind speeds, was obtained from the National Renewable Energy Laboratory (NREL), while the biomass power output was determined using crop and net energy yields (Cook et al., 2022). Moreover, the land available to the energy system is set at 10 Mha and is allotted for harvesting maize and installing solar panels and wind turbines. For the water system, it is assumed that the water recovery of the desalination unit is constrained to operate between 45% and 85%, while it’s permeate flow should be at least 227 m3/h. To analyze the impact of prioritizing the operation of the RO unit, three cases are considered where the feed flows of water to this unit are varied as shown in Table 1. For each case, the solution of lower level multi-parametric problem yields one critical region, and therefore, one explicit function that defines the energy consumption of the water system in terms of its water recovery. After this solution was incorporated into the upper level problem, the total power generated by all renewable energy sources is maximized to determine the design and operation of the energy-water supply systems. The optimization results of the integrated energy-water supply systems are detailed in Table 1.

Table 1: Optimization results for annual operation of integrated energy-water supply systems

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Case | RO Feed flow (m3/h) | Total Costs (Billion USD) | Total Power Available (TWh) | RO Water Recovery (%) | RO Energy Consumption (MW) |
| 1 | 1,703.44  | 151.98 | 1,260.541 | 47 | 1,359 |
| 2 | 1,362.75 | 151.93 | 1,260.539 | 59 | 2,276 |
| 3 | 1,022.06 | 161.02 | 1,260.646 | 78 | 3,193 |

Figure 2: Results of varying feed flow of the RO unit on the operations of the water system

The energy system in all three cases comprised primarily of single axis tracking solar panels and some wind turbines to produce 1,259 TWh in each case by utilizing the maximum land available for the deployment of the renewable energy infrastructure. Biomass was not deployed for energy generation due to the water system’s objective of minimizing energy consumption. As such, only the water necessary to meet the metropolitan demands at 800 m3/h are produced. However, as the feed flow of water to the RO decreased, its water recovery and subsequently its energy consumption increases across the three cases as illustrated in Figure 2. Therefore, the total power available, or in other words, the energy available after meeting the demands of the water system also subsequently varied in each case as shown in Table 1 to meet the overall demands which remained constant.

* 1. Conclusion

In this work, a framework for developing bi-level decision strategies in hierarchical energy-water supply systems was presented. The proposed framework was applied to a case study in Texas, where the optimal mix of renewable energy sources and technologies, along with the land utilization and desalination requirements were determined to meet preset energy and water demands. Future work will aim to incorporate dynamic RO operational profiles and assess the impact of competing and non-competing objectives among multiple levels of hierarchy in a system.

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