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Energy Water Nexus Resilience Analysis Using Integrated Resource Allocation Approach

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ABSTRACT

This work presents a macroscopic, high-level representation of the interconnected nexus system, utilizing a resource allocation model to capture the interactions between the power and water subsystems. The model is employed to assess the system's performance under various external stressor impact scenarios, determining the thresholds at which the system can no longer maintain a continuous supply of functional services (i.e. power and water), which reveal the system's vulnerabilities. Resilience metrics are incorporated to interpret these results and characterize the nexus performance. The proposed methodology is generalizable, and its capabilities will be demonstrated through a case study on the energy-water nexus in the Gulf Cooperation Council region.

Keywords: Resilience, Energy, Water, Nexus

INTRODUCTION

Energy and water are essential for societal progress and sustainability, necessitating robust management approaches to address economic, social, and environmental imperatives [1]. The demand for these vital resources rapidly evolves due to population growth, industrial developments, and external events such as climate change and instability. Consequently, the systems producing these resources are subject to multidimensional stressors and must be well-designed and operated to meet these dynamic demands [2]. Energy and water systems, commonly referred to as the Energy-Water Nexus, are interconnected through flows of water, electricity, and heat, which are fundamental to maintaining continuous operation and functional service supply [3]. While distinct in processes and infrastructures, they are highly interdependent, increasing the complexity of the system. Water is needed in energy production for cooling, while energy is essential for pumping, treatment, and desalination. This codependency has guided recent research to view these two systems as a coupled unity with two key directions: "water for energy" and "energy for water" [2,4].

The Gulf Cooperation Council region, GCC, is known for its abundance of energy resources, such as oil and natural gas, making it a global energy hub. However, it faces a severe scarcity of freshwater resources, ranking it among the world's most arid regions [5,6]. As a result, water solutions like desalination plants and wastewater reuse have become the primary strategies in these areas. Seawater desalination, a widely adopted process to address freshwater shortages, is a highly energy-intensive endeavor that requires continuous supplies of heat and/or power, depending on the technology used [7]. Currently, desalination plants account for the majority of the region's freshwater supply, with fossil fuel-based power plants providing the necessary energy input [8]. Wastewater treatment facilities further contribute to the nexus by supplying treated wastewater, primarily for greening, irrigation, and limited agricultural activities [9]. This complex interconnection of power plants, freshwater production plants, and wastewater treatment plants enables the exchange of material and energy resources to support domestic, industrial, and agricultural demands. However, this strong dependency between water and energy systems raises critical concerns about the resilience and sustainability of resource management in the region.

Interconnected Energy-Water Nexus systems face a variety of internal and external events that can disrupt their operations. These disruptions may decrease the system's efficiency or lead to partial or complete production failure, preventing the system from meeting demand constraints [10]. Potential external factors that may disrupt the operational stability of the nexus include governance frameworks, suboptimal management approaches, resource constraints, and the impacts of climate change [11]. Extreme weather events, policy shifts, geopolitical tensions, or technical failures further intensify nexus vulnerabilities [12]. The inherent uncertainties associated with these events render these critical systems fragile and threaten the continuous provision of essential power and water services. Ensuring resilience to such disruptions is crucial as the unpredictability of these stressors jeopardizes system stability, increasing risks to infrastructure networks and resource security. Climate change, in particular, is one of the primary drivers of instability. Hence, enhancing resilience within the nexus is essential for adaptation [3]. A system’s resilience is defined by its ability to withstand, adapt, absorb, and recover from disturbances while maintaining functional service delivery [13].

Resilience Challenges within the Energy-Water Nexus

Many resilience assessments in energy-water systems focused on evaluating individual subsystems in isolation, limiting their ability to capture the cascading impacts between interconnected components [4,10]. Additionally, some studies rely on static resilience analyses, overlooking the temporal variations in supply and demand that influence real-world infrastructure performance [3]. Emerging research highlights the need for integrated approaches that optimize resource allocation in the energy-water nexus to improve system resilience [14,15]. Process system optimization provides a structured framework for modeling interdependencies and resource flows, enabling cost-efficient decision-making. Adopting these models to the energy-water nexus to represent the subsystems as resource integration networks allows for scenario-based testing and performance evaluation.

A key limitation of current resilience studies is the lack of dynamic modeling to track system behavior over time. Accordingly, introducing a temporal scale into the steady-state resource allocation can bridge this gap by capturing the dynamic behavior of power and water production, as well as fluctuating demands [16]. Resilience must be quantified through scenario analysis to identify deviations from operational targets and expose system vulnerabilities. Incorporating resilience principles into the process system optimization provides a structured decision-making tool for addressing potential disruptions at both design and operation stages [13].

Before implementing resilience planning strategies, it is essential to assess the performance of the existing system and evaluate its vulnerabilities. This pre-assessment allows for optimization-driven solutions tailored to system characteristics and constraints [17]. While such vulnerability assessments have been widely applied in transportation networks and energy supply chains, they remain underutilized in the water-energy nexus domain [18,19].

Approach and Key Contributions

This study adopts a superstructure-based optimization approach to assess the resilience of an energy-water nexus system under disruption scenarios. The resilience assessment focuses on the measurable impacts of capacity losses on functional service delivery, helping to identify system vulnerabilities and inform resilience enhancement strategies. By simulating disruptions, this approach aids in designing optimal operational adjustments

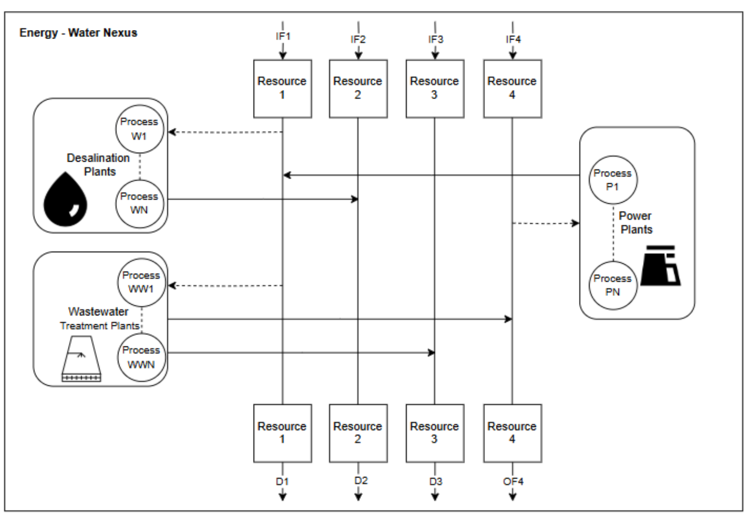

Figure 1: Shematic representation of the nexus superstructure

that minimize service interruptions and support system recovery.

To advance resilience modeling, this study introduces a resilience-driven optimization framework that:

- Integrates system-level scenario analysis to investigate cascading disruptions.
- Uses optimization-based resilience assessment to improve resource allocation.
- Incorporates time-dependent resource dynamics, capturing fluctuations in demand and production.
- Identifies key vulnerability thresholds to guide proactive mitigation strategies.

This quantitative approach provides a structured method for evaluating interdependencies and optimizing resource allocation under disruptions. By leveraging scenario-based stress testing, the framework offers actionable insights for policy and infrastructure planning.

METHODOLOGY

Energy-Water Nexus Resilience Optimization Framework

The proposed resilience-driven optimization framework integrates system modeling, resource allocation, and resilience quantification. The framework consists of three core stages:

- System Representation & Resource Allocation Modeling: This stage establishes the interconnections between power generation, desalination, and wastewater treatment systems. It defines the material and energy exchange pathways necessary for effective resource allocation and formulates resource balance equations to capture the interdependencies among the subsystems.
- Optimization & Operational Analysis: The second stage implements a cost-minimalization optimization model to balance supply and demand. It incorporates plant capacities, resource availability, and operational flexibility constraints to identify optimal operational configurations under stress scenarios.
- Resilience Assessment & Scenario Testing: The final stage introduces disruption scenarios ranging from partial to complete power losses to evaluate cascading impacts on the nexus. The Resilience

  Index and System Reliability are quantified metrics used to assess the system's performance under stress, revealing key vulnerability thresholds of the nexus.

System Modeling and Optimization

The energy-water nexus system is represented at a macroscopic, high level in **Figure 1.** The system is modeled using a resource allocation model that captures the interactions between the main components: power plants, desalination plants, and wastewater treatment plants. These components are interconnected through resource lines, where main and auxiliary resources, including materials and energy, are exchanged within the physical constraints imposed by resource availability and plant capacities, adopting the method developed by Ahmed et.al [20]. The model has been advanced to incorporate a temporal scale, which is essential to reflect the dynamic behavior of the energy and water production systems, as well as the dynamic demands for functional services, following the model advances developed by Lameh et.al. and customizing it to the characteristics of the energy-water nexus [16]. The resource balance equation governing the model is:

$$IF(r,t) + \sum \varphi(r,p)CAP(p,t) + OF(r,t) = D(r,t) \quad \forall\, r \in R, p \in P, t \in T \tag{1}$$

Where $IF(r,t), OF(r,t), D(r,t) and\ CAP(p,t)$ are input resource flowrate, output resource flowrate, resource demand rate, and plant capacity respectively. $R, Pand\ T$ are the sets of resources, processes and time periods respectively. $\varphi(r,p)$ is a factor that represents the ratio of resource production or consumption to the main resource produced by the process P. The resource allocation model is utilized in an optimization formulation that minimizes the total cost of the integrated system, accounting for components and resources capital and operation cost as given by the objective function:

$$Min\ (C_{CAPEX} + C_{OPEX} - R_{Total}) \tag{2}$$

Where, $C_{CAPEX}, C_{OPEX}, R_{Total}$ are the total capital cost, total operational cost, and total revenues, respectively. The aim is to meet water and electricity system demands at minimum cost. The incorporated subsystems are defined in the model on a technological basis (i.e., technologies for each type of production plant) and incorporate distinctive parameters for each type in terms of CAPEX, OPEX, and minimum and maximum capacities. These parameters are collected from peer-reviewed and reputable literature resources.

Resilience Analysis

The system's performance is analyzed by observing the optimal solution of the optimization problem. It provides the most optimal operational load at which each production technology must be operated, revealing how much of the total capacity is utilized to meet the demand. The net balance of resources across the network is tracked to indicate the success or failure of the system to meet the demand. A balance of zero ensures that a demand was met, while a negative balance indicates a shortage. In the later case, the model is directed to provide the needs through virtual, highly costed water and power reservoirs resulting in substantially high overall cost indicating system failure. The study focuses on revealing the nexus's vulnerability to potential losses of power production capacity as an impact of external stressors and how that impact cascades onto water and wastewater plants. Accordingly, disruption scenarios where the model is subjected to gradual losses of power production capacities, ranging from 0% to 100% power losses, are analyzed based on production technology type. This gradual reduction contributes to the loss of plant capacities that are associated with the technology under consideration.

A comparison between the demand variation over time and the system's output of water and electricity is conducted to reveal the system's bottlenecks. The resilience index and reliability of the system are evaluated in each scenario as metrics reflecting the resiliency level, according to the following equations:

$$RI = \frac{D - S_{Op}}{D} \quad (3)$$

$$SR\% = \frac{TD_{met}}{TS_{Op}} \times 100\% \quad (4)$$

where RI is the Resilience index; D is the demand for a functional service; SR is the System reliability, reflecting the system's capability to meet the demand without failure; TD_{met} is the total times the demand is met; and TS_{Op} is the total times the system is operated.

CASE STUDY

To demonstrate the method, an energy-water nexus system serving an arid region is investigated. The nexus comprises power generation facilities, desalination plants, and wastewater treatment facilities. The power plants produce both electricity and heat to meet external power demands and the needs of the desalination and wastewater treatment processes. The desalination plants generate potable water for domestic and industrial use, while the wastewater treatment facilities produce treated effluent to satisfy water demands for landscaping, irrigation, and limited agricultural activities in the region. The power production facilities incorporate three primary technologies: combined-cycle gas turbine with waste recovery (CCGT-CHP), open-cycle gas turbine (OCGT), and photovoltaic solar panels. The desalination plants employ thermal multi-effect desalination, multi-stage flashing, and reverse osmosis technologies. The wastewater treatment facilities range in scale from medium to large, utilizing secondary and tertiary treatment processes.

Table 1 and

Table 2 below summarizes the characteristics of the power plants, the featured nexus subsystem in this study, and the monthly demands for functional services. For demonstration purposes, disruption scenarios in which the production capacity of the dominant power generation technology is subjected to a loss percentage ranging from 0% to 100% are required to evaluate the nexus resilience and reliability to each of these impacts using the resource allocation model.

Table 1 Power Generation Parameters

Technology	CAPEX ($/MWh)	Max Capacity (TWh/yr)
CCGT-CHP	10.7	77.6
OCGT	9.06	17.4
PV	7.5	3.07

Table 2 Monthly demands of functional services

Month	Power Demand (TWh)	Water Demand (Mm^3)	Treated Water Demand (Mm^3)
Jan	2.96	52.0	11.0
Feb	2.66	47.7	10.4
Mar	3.43	54.1	12.3
April	3.98	55.9	15.7
May	4.82	58.0	17.5
Jun	5.45	57.4	18.5
Jul	5.86	58.5	18.3
Aug	6.35	60.2	18.4
Sep	4.48	34.0	17.4
Oct	4.02	33.7	17.3
Nov	3.25	30.7	15.1
Dec	2.76	29.6	14.0

RESULTS AND DISCUSSION

The model was employed to examine the impact of losing varying proportions of the power production capacity associated with the predominant technology, the combined cycle gas turbine with waste heat recovery, denoted as T1 in **Figure 1**. This technology accounts for an average of 79% of the total power generation within the existing nexus system. The findings indicate that the nexus can tolerate up to a 20% loss of this technology's capacity, which is equivalent to a 16% reduction in the overall power production capacity of the nexus, while still being capable of meeting the demands for power, water, and treated wastewater effluent. This is demonstrated in **Figure 1(a)** where the resilience index of the system for all of the 3 subsystems involved maintains a value of 1. This is associated with an overall nexus reliability of 100% ensuring the nexus's ability to meet all the demands at all periods despite the impact of the external shocks by relying on the remaining 84% of total capacity for power generation. As the loss percentage of this technology goes up to 40%, the integrated system succeeds in meeting the demands for both water and treated sewage effluent for all periods while it fails at delivering external power demands for the June to August period. This is reflected by a resilience index that drops to 0.975, 0.9, and 0.825 for these three months, respectively, as shown in **Figure 1(b)**. Alongside the massive loss of generation capacity, another main contributor to the declined system performance is associated with higher demand registered in these summer months. The overall nexus reliability registered for this scenario is 91.7%. **Figure 1(c)** reveals that the impact of losing 60% of T1 production capacity propagates to the water subsystem as reflected by the resilience index drop for this subsystem between the January and September period in addition to the system's inability to meet power demands in May to September. The observed differences in the failure frequencies between the two subsystems potentially hint at cost-based prioritization for power production over water desalination governed by the optimization algorithm, an interesting point that calls for further investigation. In **Figure 1 (d)** 80% loss of T1 led to insufficient power and water supplies for all periods except January and December, where water and power insufficiency altered, respectively bringing the nexus reliability down to 39%. At 100% loss of T1 capacity illustrated in **Figure 1 (e)**, the nexus system 79% of its power generation activities resulted in insufficient supplies of power and water at all periods with resilience indices below 0.6 for the associated subsystems and an overall reliability of 33%. The wastewater treatment subsystem maintained its resilience index at 1 in all scenarios, ensuring that the demand for treated sewage effluent was met. This may be attributed to the relatively lower power requirements and costs associated with the wastewater treatment processes.

CONCLUSIONS

Using a resource allocation model within an optimization framework is a promising approach to guide decision-making for interconnected energy-water nexus systems. This method has demonstrated the ability to assess the system's resilience against quantified impacts of external stressors. In the examined case, the system could withstand up to a 21% loss of power production capacity before being unable to meet the demand for the interconnected subsystems' functional services. Furthermore, this method facilitates the analysis of each technology's contribution to the overall resilience scheme of the nexus. The optimization component ensures an optimal target is achieved as the system responds to a stressor impact, which may inform strategies that prioritize economic or environmental goals, depending on the set target. Consequently, this method can assist in

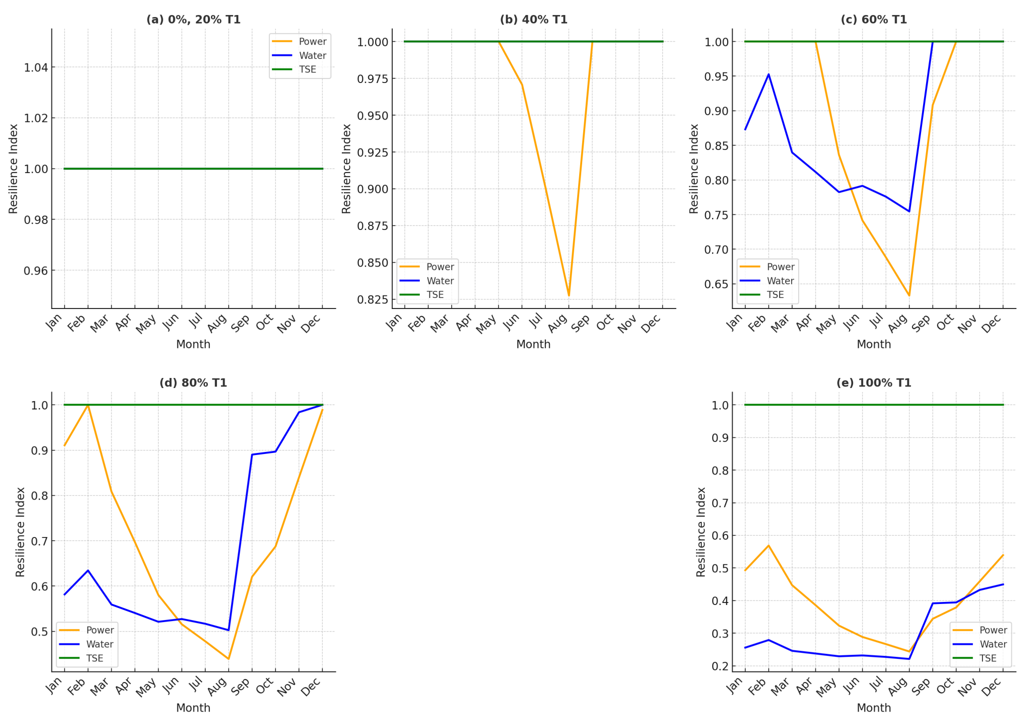

Figure 1: Resilience index of the energy-water nexus at various impacts of external stressors (a) 0%,20% T1 capacity loss (b) 40% T1 capacity loss (c) 60% T1 capacity loss (d) 80% T1 capacity loss (e) 100% T1 capacity loss

developing system hardening and emergency response plans to guarantee meeting all or prioritized demands from the nexus. These potential warrants further investigation in future work to help tailor strategies that enhance the resilience of the integrated nexus.

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