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Research Article

Water-Energy Nexus in Power Systems: A Review

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As the world continues to transition towards cleaner and more efficient energy sources, the intricate interplay between water and energy in power systems has emerged as an essential and multifaceted relationship with profound implications for sustainable energy planning. This comprehensive exploration considers a diverse range of academic databases and synthesizes relevant research to systematically investigate the current state of knowledge on the water-energy nexus. By distilling key findings and concepts related to the water-energy nexus in power systems, this work underscores the pivotal role of water in power generation and the energy required for water treatment and distribution. Additionally, this exploration brings into focus the challenges that the water-energy nexus faces, including the far-reaching impacts of climate change and the potential of renewable energy solutions. The complex policy and regulatory frameworks that govern the water-energy nexus in power systems are also examined, highlighting the crucial need for integrated approaches in energy and water management. By identifying key areas for further research and emphasizing the urgency for innovative solutions, this exploration stresses the need to prioritize sustainable management of water and energy resources in an effective, efficient, and resilient manner.

I. Introduction

HE water-energy nexus constitutes a multifaceted, interdependent relationship between water and energy resources that not only reveals the importance of water in energy production and consumption but also reveals the need of substantial amounts of energy in water management [1]. This intricate, dynamic relationship is crucial to sustainable developments, especially amid extreme weather conditions and radical climate changes in which water scarcity and energy security become pressing issues [2]. Take the United States for example, thermoelectric power generation accounts for nearly 45% of all freshwater withdrawals, primarily for cooling purpose [3]. Globally, the energy sector accounts for 10%–15% of total water withdrawals [4]. Hydropower is the most widely used renewable energy source. It accounted for approximately 16% of global electricity production in 2019 [5]. In regions such as sub-Saharan Africa and parts of Asia, access to electricity is severely constrained, due to limited water availability, especially in droughts [6]. In addition, energy-intensive water treatment processes (e.g., reverse osmosis for desalination) can account for up to 40% of the total cost of producing drinking water [7].

Water is an indispensable resource for various forms of energy production. For instance, hydropower generation requires substantial volumes of water to turn turbines and nuclear power plants use substantial amounts of water to cool reactors [8].

Fossil fuel power plants also rely on water for cooling, processing, and transporting fuels [9]. In addition to power generation, water represents a vital component of other energy sources, such as biofuels, which require enormous quantities of water for production [10]. These examples illustrate energy's great dependence on water and reflect its complex relationship with water. Meanwhile, energy also is an indispensable resource for water management, particularly in activities such as pumping, treatment, and distribution. Water treatment plants use energy to pump and treat water, and irrigation systems require energy to pump water to crops [11]. The use and reliance of energy in water management is expected to increase in the near future, as water demands rise and the infrastructures age [12]. The critical importance to understand the water-energy nexus for sustainable developments is again underscored.

The water-energy nexus is further complicated by the impacts of climate change. Rapid changes in precipitation patterns and increasing temperatures significantly affect the availability and quality of water resources, and therefore impact energy production and consumption profoundly [13]. For example, droughts strip water availability for energy production and extreme weather conditions can greatly damage energy infrastructures [14]. Thus, it is essential to develop interdisciplinary, integrated approaches to manage the water-energy nexus with increasing effectiveness, efficiency, and resilience.

Effective management of the water-energy nexus requires sustainable solutions to balance the demands of both resources, prioritize their efficient use, and ensure sustainable management [15]. This calls for promoting the use of energy-efficient technologies, reducing water consumptions, and sensibly switching to alternative water sources such as recycled water and desalination [16]. Toward that end, an integrated approach to water and energy management can promote sustainable energy planning, improve water management, and enhance the resilience of communities and ecosystems [13]. In summary, the water-energy nexus represents a dynamic, multifaceted relationship between water and energy resources, which is crucial to sustainable developments. Recognizing the interdependence of water and energy resources is imperative for empowering sustainable developments and mitigating the impacts of climate change. By developing and implementing such an approach to water and energy management, we can achieve sustainable developments, enhance water and energy security, and improve their resilience in communities and ecosystems.

The comprehensive literature review provides a thorough, in-depth analysis of the existing water-energy nexus research, with a focus on the critical interdependency between power and water systems to advocate the need for more research to understand the environmental and energy production impacts of the water-energy nexus. It also illustrates the role of information and communication technologies (ICTs) to link, monitor, and control different components, and thereby facilitate optimized resource use, reduce waste, and improve system reliability. Moreover, social and environmental aspects of the water-energy nexus are stressed and analyzed to shed light on desirable use of various methods and modeling techniques (e.g., input-output analysis, life cycle assessment, and optimization modeling) to examine the interdependence of distinct economic sectors. In particular, optimization modeling is highlighted as a powerful tool to develop sustainable, efficient solutions in complex water-energy systems. Finally, we review and discuss policies implemented by different governments around the world to effectively manage the interdependent relationship between water and energy resources, with the goal of sustainable management promotion, energy consumption mitigation, greenhouse gas emissions reduction, and resilience enhancement for coping with increasing climate changes, extreme weather conditions, and other challenges.

The reminder of this work is meticulously structured to offer an extensive overview of the latest research on water-energy nexus. Section II provides an in-depth analysis of the role of ICTs to promote optimized resource use, waste reduction, and system reliability. Section Ⅲ comprehensively analyzes essential social and environmental aspects of the water-energy nexus. Section Ⅳ reviews different methods, including modeling techniques, that can be used to examine the interdependence of economic sectors, with a particular emphasis on optimization modeling as a powerful tool to identify sustainable and efficient solutions. Section Ⅴ reviews and discusses government policies and Section VI concludes this literature review by outlining important research challenges and identifying critical areas that warrant further research efforts.

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II. Critical interdependency between power and water systems

The water-energy nexus is a complex and interconnected system that warrants in-depth research to understand its impacts on environment and energy production. This section discusses the interdependency between power and water systems, including energy generation and conversion, water treatment and distribution, energy storage and water consumption requirements, water reuse and recycling, and the role of ICTs. The integration of ICT in water and power systems provides real-time monitoring, management, and control of related, distinct components to allow for optimization of resource use, reduction of waste, and improved system reliability.

A. Energy Generation and Water Usage

Energy generation and water usage constitute two crucial aspects that are closely linked in the water-energy nexus. Energy generation requires a significant amount of water, and water usage is essential for energy production and delivery. Water is used in various stages of energy generation, such as cooling and steam generation, and provides a source for hydropower. Fig. 1 illustrates the cooling process for power plants. The energy sector is one of the largest consumers of water globally. Take the United States for example, thermoelectric power plants account for approximately 40% of all freshwater withdrawals, primarily for cooling purpose [4]. Other forms of energy generation (e.g., hydropower, bioenergy) also require significant amounts of water. Water usage for energy generation has enormous environmental impacts, such as altering aquatic ecosystems and reducing water availability for other purposes [5]. It also has significant economic impacts, such as increasing water costs for energy producers and conceivably leading to energy price increases for consumers. Reducing water usage in energy generation is an essential step towards improving the water-energy nexus's sustainability [6]. Several approaches can achieve this, such as improving the efficiency of cooling systems, developing alternative cooling technologies, and implementing water recycling and reuse systems [7]. In addition, the impact of climate change on water availability for energy generation is also critical to the water-energy nexus. As climate change continues to affect precipitation patterns, water availability for energy generation becomes increasingly uncertain [8].

Thus, it is critical to improve the resilience of energy systems to water-related risks and to explore alternative sources of energy that require less water. This research area is concerned with comprehending the water demands of different energy generation technologies that include conventional fossil fuel-based power plants [9], nuclear power plants [10], and emerging renewable energy sources (e.g., solar, wind, and hydropower) [11]. In this regard, analyses of the essential environmental consequences of water utilization in energy generation are necessary, such as impacts on water scarcity, quality, and ecosystem degradation. For example, Petrakopoulou et al. [12] analyzes the impact of rising ambient temperatures on power plant performance and water use by focusing on coal and natural gas combined-cycle power plants that use recirculating and once-through cooling systems. They report that higher ambient temperatures increase pressure at the steam turbine outlet and thus decrease power plant efficiency, and that recirculating cooling systems are more sensitive to temperature variations, which results in a greater decrease in efficiency and cooling-water mass flow. Coal plants appear more sensitive to temperature changes in cooling water quantity, while natural gas plants are more sensitive to overall temperature changes, due to higher losses in gas turbine systems. Li et al. [13] develop a 3D numerical model to assess the impact of non-uniform water distribution on the cooling efficiency of a counter-flow wet cooling tower with different spray rates. This study considers thermal calculations of a large cooling tower and uses a user-defined function in the fill zone, targeting a three-area water distribution system and verifying the model's accuracy using cooling tower data. The influence of the three areas on the outlet water temperature, velocity field, temperature field, and mass fraction of water in the tower is examined. Vajpayee et al. [14] propose a control design scheme for a pressurized water type nuclear power plant by combining the optimal linear quadratic Gaussian control with a robust integral sliding model. The control architecture yields robust performance with minimal control efforts and effectively tracks the reference set-point in the presence of disturbances and parametric uncertainties. The multi-input-multi-output nuclear power plant model used in this work has 38 state variables, and a linear model is obtained for controller design by linearizing the nonlinear plant model

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around steady-state operating conditions. Solís-Chaves et al. [15] provide a technical overview of two promising and two commercial systems applicable to Hybrid Wind Systems or Extraction Water from Air Systems in the Brazilian northeast. The water extraction capacity and energy efficiency are evaluated for two commercial systems, using a theoretical operating point obtained from the humid air diagram. Minimum environmental conditions for membranes and coils are also taken into consideration. Additionally, three types of electric generators also are examined, with their respective advantages and disadvantages for power and water generation highlighted. Chandrasekar et al. [16] explore the performance of a novel photovoltaic thermal air system with semi length fins for hydrogen generation. Two semi length fin configurations are tested and compared with photovoltaic systems for hydrogen generation. Experiments were conducted during March-June 2019 in India. The results the system with semi length wavy fins capable of producing the highest amount of hydrogen. The downstream fins can improve the cooling of the photovoltaic panel, thereby resulting in increased current supply to the electrolyzer unit.

To address the intensifying challenge of climate change and human impacts on natural resources, it is crucial to develop sustainable, long-term solutions to water scarcity and energy demand in a coordinated manner. Dubreuil et al. [17] develop an optimization model to assess the optimal water-energy nexus by considering opportunities for water reuse and non-conventional water use in the water-scarce Middle East region, and encompassing the Arabian Peninsula, Caucasus, Islamic Republic of Iran, and Near East. The results show that failing to account for the additional electricity demand associated with water use can lead to underestimates of electricity demand by almost 40%. The integrated optimization model enables analyses of water technology allocation and the use of non-conventional resources to address water scarcity and improve irrigation efficiency. In Portugal, wastewater is typically treated at a centralized plant and reused in large public or private areas such as agriculture, golf courses, and public gardens. On the other hand, greywater is often treated and reused at the production site in small-scale decentralized systems. Matos et al. [18] compare the two systems, a centralized wastewater reuse system and a decentralized greywater reuse system, with respect to water quality, energy consumption, and carbon emission. This study provides an in-depth analysis of the characteristics of both wastewater and greywater streams, including the degree of treatment required for each. The advantages and disadvantages of their reuse at different scales are also examined, together with the consideration of water quality, energy consumption, and carbon emission.

B. Energy Conversion and Water Usage

Water is a pivotal integral in the energy conversion process that involves various energy converters. Combined heat and power (CHP) systems represent a type of energy converter that generates both electricity and heat from a single fuel source [19]. Water plays a fundamental role in these systems, as a coolant for the engines and turbines, to prevent overheating and ensure efficient energy conversion [20]. Additionally, water is used for steam generation to drive the turbine and generate electricity [21]. Steam is generated by heating water in a heat recovery steam generator, which utilizes exhaust gases from the engines [22]. Gas turbines are another type of energy converter that combusts a fuel source (e.g., natural gas) to drive a turbine and generate electricity [23]. Water is used in these systems for cooling, as the high temperatures generated during combustion can cause damage to the turbine blades [24]. Moreover, water is used for emissions control in which it is injected into the turbine exhaust to reduce pollutants. Water is also used for steam generation to drive the turbine and generate electricity [25]. Heat boilers represent yet another type of energy converter that generates steam by heating water. Steam is then used to drive turbines and generate electricity [26]. Water is the primary input for heat boilers, as it is heated to generate steam. In some cases, heat boilers may utilize recycled water from industrial processes, which can reduce water consumption and increase efficiency. As shown in Fig. 2, power-to-gas (P2G) systems are a type of energy converter that converts electricity into hydrogen gas through the process of electrolysis [27]. Water is used as the primary input for this process, and it is split into its component parts of hydrogen and oxygen using an electrical current. The hydrogen gas is then used as a fuel source or stored for later use to provide a means for storing renewable energy [28].

Wang et al. [29] seek to improve the flexibility of conventional power plants by developing and verifying a dynamic mathematical model of a CHP unit. The results show that hat the maximum relative

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error of the model is less than 5%. The dynamic characteristics of a coal-fired power plant equipped with a hot water storage tank also is examined with a temperature distribution curve of the hot water storage tank. To address the issue of fluctuation in heating load caused by unit load changes, a new coordinated control system is designed with an integrated hot water storage tank. Block et al. [30] propose the use of demineralised water injection as a viable alternative to reduce NOx emissions and improve gas turbine performance. To evaluate the efficacy of this approach, an experimental study that characterizes the droplet size of a spray nozzle under various conditions (e.g., different injection pressures, water temperatures, axial and radial locations) is conducted. The results indicate that compressor discharge temperature decreased by up to 34K, and NOx emissions were reduced by 25% due to water injection. Xodjiev et al. [31] explore the parameters of thermal conductivity in laboratory conditions, particularly in the context of heat exchangers, and developing an analytical method for assessing their effectiveness. The experimental results are subjected to a double processing method, involving the least squares and high-order polynomial expressions, which enables more accurate analyses and interpretations. The program developed for the least-squares method is used to analyze the heat transfer efficiency of pipes with different cross-sections and to determine the effectiveness of the heat transfer surface. Nazari-Heris et al. [32] propose a multi-objective two-stage stochastic unit commitment scheme for integrated gas and electricity networks which incorporates emerging flexible energy sources, such as P2G technology and demand response (DR) programs, together with a high penetration of wind turbines. Specifically, P2G technology is highlighted as a promising option for increasing wind power dispatch in power systems. The results show that the simultaneous consideration of P2G and DR significantly reduces environmental pollution while reducing costs, indicating that incorporating both P2G and DR in the integrated system can decrease the cost by 2.42% and 1.78%, respectively, in comparison with P2G or DR independently.

C. Water Treatment and Distribution

Investigations of water treatment and distribution are essential to understand the energy required for treating and delivering water, which has significant energy consumption implications. This research area emphasizes evaluations of the energy requirements for various water treatment technologies (e.g., membrane filtration, reverse osmosis) and their associated greenhouse gas emissions. Water treatment and distribution systems optimizations aim to minimize energy consumption and can significantly reduce the carbon footprint of the water sector. Bukhary et al. [33] highlight the potential for using PVs to offset the energy consumption of a drinking water treatment plant and reduce emissions. This study analyzes the energy consumption of an existing water treatment plant located in the southwestern United States and conducts a modeling study that uses PVs to offset energy consumption. The largest consumption of energy is associated with pumping operations, while the energy intensity of the water treatment units remains relatively low. According to the results, a PV system with a 1.5 MW capacity with battery storage has a positive net present value with a levelized cost of electricity of 3.1 cent/kWh. The use of PVs can result in a net reduction in carbon emissions of 950 and 570 metric tons of carbon dioxide each year respectively, independent of battery storage. Yu et al. [34] use a Bayesian semi-parametric quantile regression approach to model the energy consumption of biochemical wastewater treatment. The data set used in the study is obtained from a municipal wastewater treatment plant, where the energy consumption of unit chemical oxygen demand reduction is the response variable of interest. The proposed approach provides a comprehensive understanding of the regression relationships between the energy consumption and the genuine, influencing factors at different levels, including lower, median, and higher energy consumption levels. At the lower level of energy consumption, the temperature of influent wastewater is found to be closely associated with energy consumption, and chroma-rich wastewater also helps reduce energy consumption. Xiang et al. [35] design an adaptive intelligent dynamic water resource planning approach to ensure sustainable water development in urban areas. The Markov decision process is used to address dynamic water resource management issues while taking into account annual usage and released locational constraints. This approach enables the developments of sensitivity-driven methods to optimize several efficient environmental planning and management policies, and therefore can reduce the engagement of supply and demand for water resources, leading to substantial improvements in

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local economic efficiency as demonstrated through numerical outcomes.

D. Energy Storage and Water Requirements

Energy storage and water requirements research focuses on understanding the water demands of energy storage technologies, which often varies significantly with the technology. For instance, pumped hydro storage requires large amounts of water to function [36], while battery storage and compressed air energy storage systems usually have lower water demands [37]. Investigations of water use in energy storage also involve the environmental impacts of water use, such as probable water depletion, degradation, and contamination [38]. In addition, there is a growing interest in exploring the potential for integrated energy-water systems in which energy storage systems could help to balance water supply and demand.

Bhayo et al. [39] provide an in-depth analysis and optimization of a standalone hybrid renewable energy system that is designed to power a 3.032 kWh/day housing unit. The hybrid system is specifically designed to leverage rainfall harvesting while integrating a pumped-hydro storage with a solar photovoltaic-battery system. To ensure reliable power supply management and minimize component over sizing, the system is optimized using particle swarm optimization techniques. The objective function of the optimization process is to minimize the levelized cost of energy for a loss of power supply. The results show that integrating a rainfall-based hydropower system of only 100 W with effective water storage of 6.5 m3 at 7.0 m of net water head can lead to a 13.0% reduction in installed photovoltaic capacity, compared with the power system without the rainfall-based hydropower system. Javed et al. [40] design a hybrid pumped and battery storage system as a solution for enhancing the reliability and sustainability of off-grid renewable energy systems. This strategy considers the operating range of the reversible pump-turbine machine to extract maximum stored energy by operating the system at optimal efficiency. The battery is only used to meet very low energy shortfalls, while the pumped hydro storage serves as the primary storage for high energy demand. The overall storage performance, energy utilization ratio, and storage usage factor are used as indicators for performance analysis.

E. Role of ICTs in Enhancing the Water-Energy Nexus

With the advent of ICTs, water and power systems have become increasingly interconnected [41]. In general, ICTs offer a framework to integrate various data and communication technologies into water and power systems, which in turn enables real-time monitoring, management, and control of various system components. Fig. 3 demonstrates the coupling between the communications and power systems. This integration offers numerous benefits that include improved efficiency, cost savings, and enhanced sustainability [42][43].

An important application of ICTs in the water-energy nexus is smart grid which uses sensors, meters, and communication systems to provide real-time monitoring of electricity consumption, production, and distribution [44]. These technologies facilitates energy use optimization, energy waste minimization, and system reliability improvement [45]. Similarly, smart water systems use ICTs to monitor and manage water resources in real-time, thus enabling utilities to track water usage patterns, detect leaks, and manage water quality [46]. The use of ICTs helps reduce water waste, enhance water security, and improve the overall efficiency of water systems [47]. Another exemplary application of ICTs in the water-energy nexus is the use of data analytics to optimize the energy and water efficiency of buildings [48] by deploying automation systems that use sensors and data analytics to monitor, management, and control various building systems (e.g., lighting, heating, ventilation, and air conditioning) [49]. By optimizing these systems, building automation systems can reduce energy and water consumption, lower operating costs, and improve occupant comfort.

III. social and environmental aspects of Water-energy nexus

A. Impacts of Climate Change on Water-Energy Nexus

The relationship between the water-energy nexus and climate change is complex and multi-faceted. On one hand, climate change is expected to have profound impacts on water and energy resources, which can exacerbate grand challenges concerning the water-energy nexus [50]. For example, changes in precipitation patterns and temperature greatly

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influence water availability and quality, which in turn can impact energy generation and distribution [51]. In addition, extreme weather events (e.g., floods, droughts, storms) can damage energy infrastructure, disrupt energy supply, and thus significantly impact water treatment and distribution systems [52]. Yalew et al. [53] analyze 220 studies that project climate impacts on energy systems at both global and regional scales. According to the results, cooling demand may increase and heating demand may decrease globally, and hydropower and thermal energy capacity could decrease noticeably. The regional impacts could be more uncertain, with the strongest impacts potentially occurring in South Asia and Latin America. The uncertainty of climate impacts on energy systems at both global and regional scales can be partially attributed to the diverse methods and data sets used. Souto et al. [54] design a method to enhance the resilience of transmission substations in regions vulnerable to floods, focusing on mid-term power system resilience. This method combines hardening strategies and quantitative metrics to examine the impact of floods on the electrical grid. Flood forecasts from a hydrological model and the location of electrical equipment are used to perform impact assessment under present circumstances and with resilience planning strategies. The analysis encompasses a variety of practical flood scenarios, with the impact evaluated on the basis of accumulated cost, load energy unserved, and future transmission system expansion capacity projections. To minimize accumulated cost and load energy unserved by optimizing the hardening of substations, it utilizes a mixed-integer linear programming formulation, assuming that any non-hardened substation disabled by flooding must be repaired. Jääskeläinen et al. [55] perform an analysis of the Finnish energy system for the years 2020 and 2030, using the EnergyPLAN simulation tool to examine different energy policy scenarios and assess whether they lead to plausible generation inadequacy. Because the deep reliance of the Nordic energy system on hydropower production with the potential impacts of a severe drought on the Finnish energy system, it simulates hydropower availability according to the weather conditions during the worst drought of the last century (1939-1942), using the Finnish Environment Institute's Watershed Simulation and Forecasting System. The process of supplying energy in CHP systems usually involves significant water consumptions, including for temperature control and steam generation from waste heat boilers. In light of the global water shortage crisis, it is crucial to explore the relationship between energy production and water consumption in CHP systems to reduce water consumptions while meeting user demands and maximizing system benefits. Wang et al. [56] examine the CHP system in an industrial park in Jinan City (Shandong Province, China), for which hourly water consumption data is available through site surveys and literature review. It fits monthly water consumption data to a normal distribution and calculates water consumption quotas under various water guarantee rates using the mean value and variance coefficient. An energy-water nexus-based CHP operation optimization model is then developed to incorporate the relationship between energy supply and water consumption as well as maximum water availability.

On the other hand, the water-energy nexus plays a significant role in contributing to climate change too [57]. Energy production and consumption constitute major sources of greenhouse gas emission, the primary driver of climate change [58]. Water and energy systems are highly interdependent, and energy production requires large amounts of water and can create substantial greenhouse gas emissions from energy-related water use [59]. For example, water treatment and distribution systems are energy-intensive, and the energy required for operating these systems contributes to greenhouse gas emissions. Chhipi-Shrestha et al. [60] develop a system dynamics model that integrates water, energy, and carbon components for urban water systems to provide decision support for municipalities, urban developers, and policy makers, which is tailored to the operational phase of UWSs and is validated with historical water and energy consumption data (2005-2014) from Penticton (British Columbia, Canada). High Spearman's correlation coefficients (i.e., 0.94, 0.89, and 0.83) reveal strong interconnections between water-energy, water-carbon, and energy-carbon components, respectively. Monte Carlo-based sensitivity analysis is performed to identify residential outdoor irrigation and water heating energy for showers and dishwashers as major contributors to model variability. The intervention analysis shows significant savings in water, energy, and carbon for various water and energy-based interventions in systems. Gómez-Gardars et al. [61] suggest a multi-objective optimization approach that emphasizes the significance of thermal storage integrated with CHP systems. A nonlinear programming model is employed to determine the size of the CHP unit and thermal storage tank to supply energy utilities to a residential building. The objective functions target water consumption, direct carbon emissions generated by fuel consumption, global efficiency in energy supply, and total annual cost of the system to address the water-energy-carbon nexus. The Utopia tracking approach is applied to normalize the assessment of the economic-nexus performance. According to the results, thermal storage significantly reduces water consumption (by 15.5%) and emissions (by 67.5%) and enhances efficiency (by 75%) of the system. The multi-objective analysis provides a systematic metric for the nexus assessment and a strategy for balancing the elements considered in the nexus, as well as for determining the system performance limits for resource consumption. Bukhary et al. [62] investigate the interconnection between energy, water, and carbon emissions in a large-scale drinking water treatment plant that treats 1 Mm3 of raw Colorado River water daily, using fossil fuels as its energy source. The energy consumption of each treatment process is determined and validated with treatment plant data. The results reveal the energy intensity for various processes that include ozonation (19.6 Wh m-3), coagulation (1.3 Wh m-3), flocculation (1.22 Wh m-3), filtration (1.24 Wh m-3), the sodium hypochlorite generation system (31.7 Wh m-3), chlorination feed pumps (1.27 Wh m-3), and residual management (0.07 Wh m-3). Additionally, a modeling study is conducted to reduce carbon emissions by offsetting the energy consumption of the DWTP through the use of a photovoltaic system. The cost-effectiveness and performance of the PV system in three different locations are evaluated: Nevada, New York, and Massachusetts. The expansion of urban areas has brought about significant environmental challenges, particularly in terms of energy consumption, water use, and greenhouse gas emissions. As shown in Fig. 4, to address these challenges, Zhao et al. [63] develop a co-optimization approach for the water-energy-carbon nexus in integrated energy systems. This approach is designed to model the complex interdependencies of power, gas, and water systems, with the aim of achieving reliable and cost-effective energy operations that minimize water waste and carbon emissions. A two-stage distributionally robust optimization method is proposed to incorporate uncertainties in renewable power generation, while minimizing reserve capacity scheduling for the next day and enabling real-time dispatch. Carbon emissions are considered in both stages to ensure low-carbon operations. The proposed moment-based distributionally robust approach uses mean vectors and covariance matrices to capture and represent the ambiguity set of distributions, thereby generating a family of distributions that account for various uncertainties in renewable generation.

B. Social Impacts on Water-Energy Nexus

The social impacts on water-energy nexus can be significant but vary [64]. One of the most notable impacts is the effect on public health [65]. Lack of access to clean water and sanitation facilities can lead to widespread of waterborne diseases, which has profound impacts on the health and well-being of communities [66]. Understandably, the availability of water and sanitation services has the potential to prevent the spread of waterborne diseases and mitigate their devastating impacts, particularly among children and underprivileged populations. Abundant Evidence suggests a direct correlation of investment in water and sanitation services with hospital admissions that result from waterborne illnesses. In addition, water scarcity can create elevating conflicts over resources, which can lead to displacement, social unrest, and even violence [67]. Ferreira et al. [68] suggest an approach to model the linkage between upstream investment and downstream hospitalization in serially connected subsystems. This approach enables measurement of the efficiency of both subsystems, estimate of the efficient investment necessary for achieving universal access to adequate water and sanitation services infrastructure, and mitigation of hospital admissions due to waterborne diseases. Leal Filho et al. [69] review water scarcity trends in Africa and analyze the impact of climate change on various water-related sectors. A systematic review of 240 articles identifies important adaptation characteristics of planned and autonomous responses to water scarcity across Africa, shows that drought and precipitation variability are the most common drivers of water scarcity, and indicates common actors that include individuals, households, local and national government agencies. This study reveals that the most common types of response are behavioral and cultural, followed by technological and infrastructural, ecosystem-based, and institutional responses. While most planned responses target low-income communities, women, and indigenous communities, the needs of migrants, ethnic minorities, and people with disabilities are often overlooked. The lack of coordination of planned adaptation at scale and the absence of legal and institutional frameworks represent key challenges, with most responses being coping and autonomous with limited adaptation depth. Addressing these challenges requires coordinated institutional responses, careful planning for projected climate risks (such as extending climate services and increasing climate change literacy) and integrating indigenous knowledge. The Middle East faces significant challenges that pertain to water, energy, and food security associated with climate change, population growth, and economic development. Zarei et al. [70] study the security in the Middle East impacted by such drivers as water scarcity, migration, extreme events, economic growth, urbanization, population growth, poverty, and political stability. The water-energy-food security concerns in this region must be appropriately examined to understand the underlying dynamics. According to the analysis results, most Middle Eastern countries are facing water-energy-food (WEF) resource insecurity, due to weak planning or management strategies. Specifically, Iran, Iraq, and Turkey respectively have scores of 0.68, 0.65, and 0.75 in the Water-Energy-Food Security Index.

Another important social impact of water-energy nexus is the effect on livelihood [71][72]. For example, water scarcity reduces agricultural productivity, which has a significant impact on the livelihood of farmers and rural communities that depend on water and agricultural productivity [69][73]. Similarly, energy insecurity has an important impact on livelihood too, particularly for communities that rely on traditional energy sources such as wood and charcoal [74]. Mabhaudhi et al. [75] apply an analytical livelihood model of the WEF nexus to assess rural livelihood, health, and well-being in southern Africa, and recommend adaptation strategies for building resilient rural communities, using the WEF nexus as a decision support tool. The integrated WEF nexus index for the region is 0.145, suggesting its exposures to vulnerability and failure to meet developmental targets. This study analyzes the trade-offs and negative consequences of silo approaches for poor rural households' livelihood, and suggests desirable mechanisms for sustainable enhancement of household water, energy, and food security. Wolde et al. [76] explore how local communities can offer nexus resources and their role to support livelihood, based on survey data collected from a community in the studied area. The analysis shows that community perceptions of nexus resources are formed on the basis of social, natural, economic, human, physical, and environmental indicators of livelihood. However, these perceptions tend to focus on the benefits of individual resources rather than their interrelationships, probably due to the importance of food as a central nexus resource for the community. Hence, there is an urgent need to bridge the gap of cross-sectoral resource utilization and management with the adoption of the WEF nexus to enhance living conditions, but there is a lack of understanding of WEF nexus resource use and management and tends to focus on the livelihood benefits of individual resources. To evaluate sustainability, Wolde et al. [76] use a synthesized methodology, which identifies well-defined, shared, and holistic methods, to analyze land-water-energy-food (LWEF) nexus and livelihood indicators. An analytical hierarchy process and pair-wise comparison matrix are employed, in combination with a weighting model, to assess the LWEF nexus sustainability. Food production is the primary focus, which may not have an explicit synergy by providing, supporting, or regulating nexus resources to address and enhance livelihood. Overall, this study reveals a strong correlation between LWEF nexus resources and livelihood, as evidenced by the social, natural, and physical livelihood indicators that have a significant, positive correlation with LWEF nexus resources.

IV. Methods for investigating water-energy nexus

Methods for analyzing the water-energy nexus can incorporate various modeling techniques to analyze the interdependence of different economic sectors, such as input-output analysis, life cycle assessment (LCA), and optimization modeling. In general, an input-output analysis helps quantify the relationships between water and distinct energy sectors by tracking their flows within the focal economy. It can be applied to guide policy making for sustainable water and energy management. In addition, LCA assesses the environmental impacts of the entire life cycle of an element in water-energy systems and helps explore the most environmentally sustainable water and energy options. Optimization modeling depends on mathematical algorithms to produce the optimal solution to a problem and can identify the most efficient ways of allocating water resources and energy inputs to cope with varying demands. Linear programming (LP), mixed-integer linear programming (MILP), and nonlinear programming (NLP) represent common optimization models that can be used to analyze the water-energy nexus. Overall, optimization modeling is central to complex water-energy systems analyses, and facilitates seaerches of the most cost-efficient solutions for sustainability, and resilience, while maximizing the benefits.

A. Input-Output Analysis

In general, an input-output analysis uses an established modeling technique to examine the interdependence of distinct economic sectors. In the context of water-energy nexus, such analyses provide a means to quantify the relationships between water and energy sectors by scrutinizing their flows through the economy [77]. This approach emphasizes the direct and indirect impacts of shifts in water availability, energy usage, and prices across different sectors. It produces essential information that can be used to guide policy making for sustainable water and energy management [78].

Chen et al. [79] showcase the water-energy mixed-unit input-output approach through an analysis pf Hong Kong and its hinterland in mainland China. To elucidate the water-energy nexus in 2015, as well as for future urban development with planned water and energy infrastructures in Hong Kong, a Sankey diagram and a range of indicators are elaborated. Through a comparison of the interaction of water and energy systems with hinterland dependency, several indicators in the results demonstrate different scenarios in Hong Kong. This study yields modeling outcomes showing that the current water infrastructures can possibly fulfill the water treatment demand in 2050. The indicators produced by this study reveal that all water types for energy and energy types for water are projected to increase by 7.8%–9%. The lack of a unified base for analyzing energy and water flows represents a challenge to sustainable resource utilization. To address this issue, Wang et al. [80] perform a modified input-output analysis, as a unified framework, to balance urban energy and water use. The study targets Beijing (China) and inventories energy-related water consumption and water-related energy consumption using the energy metric. It combines the hybrid water flow with the hybrid energy flows to construct a hybrid network, using input-output analysis to explore the complex interactions between economic sectors and nexus impacts. Li et al. [81] examine the water-energy nexus at the city level in the Beijing-Tianjin-Hebei region, conducting an input-output analysis using city-level input-output tables to analyze consumption-based accounts. According to the results, Beijing, Tianjin, and Tangshan consume the largest amounts of water for energy, while Shijiazhuang and Tianjin have the greatest carbon emissions for production and consumption, respectively. The electricity sector is identified as a priority for water management, accounting for a significant portion of water usage in the energy sector. This study also highlights the stressing need for integrated management in cities with low water and energy efficiency (such as Baoding and Zhangjiakou), as well as for large carbon emitters in Hebei province, to ensure sustainable developments.

B. Life Cycle Assessment

Life cycle assessment (LCA) represents a prevalent method to examine the environmental impacts of the entire life cycle of an element in water-energy systems, which considers its different stages from a life time perspective, from extraction of raw materials to end-of-life disposal [82]. Such assessments identify the environmental impacts that result from the production and consumption of water and energy, in conjunction with their interconnections and feedback loops. For the water-energy nexus, an LCA can be applied to evaluate the environmental effects of different water and energy supply and demand options that include desalination, wastewater treatment, hydropower, and renewable energy sources. It considers the energy and water inputs and outputs of the system, as well as the potential environmental impacts associated with these inputs and outputs (e.g., greenhouse gas emissions, water consumptions, pollutions). The outcomes of LCA can help identify the most environmentally sustainable water and energy options, taking into account the trade-offs between these distinct resources, and to develop policies and strategies for increased sustainable usages [83].

Existing carbon capture and storage (CCS) technologies offer high energy requirements and cooling capacity, leading to increased stress on energy and water resources in the power sector. To better understand the relationship of water with energy consumption and carbon emissions, Wang et al. [82] take a plant-level nexus approach to analyze four different types of available post-combustion carbon capture power plants from a life cycle perspective. The results show integration of CCS technology leading to a life-cycle primary energy demand increase by 21%–46%, and water resource depletion by 59%–95%, in comparison with a reference power plant utilizing a wet cooling tower system. Among the CCS technologies investigated, the membrane-based system performs the best. Yet, at a 90% capture rate, the life cycle greenhouse gas emission reduction drops to 65%–70%. This study also quantifies the life-cycle energy and water costs of GHG mitigation, which reach 3.06-7.32 kJ/kg carbon dioxide-eq and 1.72-3.00 kg/carbon dioxide -eq, respectively. Overall, the results suggest significant trade-offs among GHG reductions, energy demand, and water consumption for carbon capture technologies. Nanofiltration seems promising for lithium extraction from salt-lake brines but the environmental impact of lithium nanofiltration extraction is ignored. Li et al. [84] employ a combination of LCA, life-cycle cost, and water consumption methods to examine the environmental impact of lithium nanofiltration extraction, using a functional unit of 1 kg Li_2CO_3 products. The results show that the nanofiltration stage has the greatest environmental effect, as reflected by higher values of global warming potential, acidification potential, photochemical ozone creation potential, soot and ashes, and nutrient enrichment than those associated with any other stage of lithium extraction. Electricity consumption is the main contributor to global warming potential. The total life-cycle cost is recorded at 18.01 USD, with internal cost accounting for 99.99% of the cost. Direct water consumption is 22 times higher than indirect water consumption. The water and energy consumption of the nanofiltration stage accounts for 98.05% and 53.95% of total consumption, respectively. Friedrich et al. [85] apply a regional life cycle assessment approach to investigate the environmental impacts of various system alternatives that aim at enhancing resource and energy efficiency by separating wastewater into greywater and blackwater and co-digesting blackwater with organic municipal solid waste. The study compares the impacts of different alternatives with those of an existing system in a German medium-sized urban neighborhood. The impacts under consideration pertain to two resources (i.e., fossil and metal depletion) and three emissions (i.e., climate change, photochemical oxidant formation, and terrestrial acidification). The results indicate that alternative systems significantly reduce environmental impacts relative to the status quo, showing a decline ranging from -68.0% (metal depletion) up to -96.5% (climate change). Even with existing settlements, transitioning from the current linear system to a more circular one could represent a promising strategy to improve the resource efficiency of water-wastewater-waste-energy systems. Rogy et al. [86] conduct a territorial life cycle assessment (T-LCA) to determine the environmental viability of hydraulic projects as a means of securing water supply for agricultural areas. Three agricultural land-use planning scenarios are defined and evaluated with the T-LCA method: a business-as-usual case without irrigation, irrigation with an Inter-Basin Water Transfer (IBWT), and irrigation with an Agricultural Reservoir (AR). Territorial eco-efficiency ratios, which measure the services by land planning scenarios against their environmental impacts, are used to assess the environmental performance in each scenario. The T-LCA method then is used to examine the water-energy-infrastructure nexus between the two hydraulic projects. The results show that eco-efficiencies of the scenarios vary with the land use and the particular service considered. For land management or economic functions, the scenario without irrigation performs better, while hydraulic projects are more eco-efficient for functions related to biomass production. An analysis of the water-energy-infrastructure nexus reveals trade-offs between these two types of project. Specifically, IBWT allows for the use of a low-stress water resource and less energy, but may require high material consumption, while AR uses less material but relies on more scarce water resources. In addition, IBWT outperforms AR if the pipe length is less than 100 km, with a water allocation of 1% for the investigated agriculture area.

C. Optimization Modelling

Optimization modeling is a formidable technique that has the potential to analyze complex water-energy systems and thereby produce solutions that minimize costs or maximize benefits [87]. Mathematical algorithms form the core of optimization models that can generate optimal solutions to various problems, with an adequate consideration of several constraints and objectives [88]. In the water-energy nexus, optimization modeling is useful for identifying the most efficient ways of allocating water resources and energy inputs to cater to varying demands [89]. According to Moazeni et al. [90], optimization models can be applied to analyze the water-energy nexus, with linear programming (LP), mixed-integer linear programming (MILP), and nonlinear programming (NLP) representing some common ones. A typical LP model can solve straight-forward problems characterized by linear relationships between inputs

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and outputs, whereas MILP models are more appropriate for complex problems that involve binary or integer decisions, and NLP models are effective for nonlinear problems marked by intricate interactions between inputs and outputs.

Optimization modeling is relevant to a wide range of applications that include water treatment and distribution, energy generation and distribution, and irrigation systems [91]. For example, an optimization model can be employed to ascertain the most optimal allocation of water resources for irrigation in a region, while accounting for important factors such as crop water requirements, rainfall patterns, and soil characteristics [92]. An optimization model also can also be applied to optimize the operations of hydroelectric power plants, in combination with essential factors such as river flow rates, turbine efficiency, and electricity demand. In essence, optimization modeling is indispensable for analyses of complex water-energy systems; it can identify cost-efficient solutions that provide maximal benefits. By accounting for the intricate interdependencies between water and energy resources, such modeling can help identify sustainable, efficient, and resilient solutions [93].

Mehrjerdi et al. [87] develop a joint water and energy supply system for a remote island that lacks access to utility networks. Optimization modeling is applied to design and optimize the system. Freshwater is produced by desalination units and different desalination approaches are considered, such as reverse-osmosis, multi-stage flash, and multi-effect distillation. These approaches are evaluated on the basis of technical and cost factors to select the most optimum one. To meet the energy demands of both consumers and desalination, a hybrid solar-wind renewable energy system is adopted to supply the required electrical and thermal energy. A battery energy storage system is used to balance the time period of renewable energy production with peak load demand. Additionally, diesel generator units are included in the design to enhance the supply system's reliability level. Simulation results show optimization modeling capable of optimally determining the capacity and characteristics of the system components, as well as the most suitable desalination approach. Moazeni et al. [90] develop an approach to optimize the energy consumption of water-energy systems at the community level, which aims at achieving a more sustainable energy process. A formulation that uses single-objective, bi-level, and co-optimization modeling to minimize the energy consumption of a micro water distribution network across three scenarios: standalone operations, integration with a grid-connected micro energy system with no storage unit, and integration with an off-grid micro energy system with storage units. The optimization problems are solved with a mixed integer nonlinear programming formulation that considers the different statuses, flow rates, and speeds of pump operations. A quadratic function is employed to formulate the micro water network's energy consumption for the pump's energy head changing with flow rate. The network is designed according to a diurnal pattern of water demand and includes one reservoir, one water tank, six nodes, and two pumps. The micro energy system has a microgrid with a CHP, diesel generator, natural gas generator, renewable sources (solar and wind), and energy storage units. To balance time periods of renewable energy production with peak load demand, energy storage units are employed.

Soleimani et al. [94] delve into optimizing integrated electrical and water energy networks, with a focus on the distribution level and demand response program. The water network, which consists of reservoirs, tanks, pumps, and control valves, is modeled with the Newton-Raphson method to solve the water flow problem. The Newton-Raphson method can be applied to any network topology, whether radial, circular or hybrid. The electrical network is also modeled with the consideration of relevant constraints. Coupled with the water network, it can provide the necessary electrical power. The optimization problem, which aims to minimize total operation costs, is solved using a learning-based optimization algorithm, a parameter-free method. A practical energy system, comprising a standard IEEE 33-bus electrical network, and the North Marin water network, is utilized for evaluation. By participating in a demand response program, the water network has optimal charging and discharging of tanks, and pumps scheduling, resulting in a reduction in operating costs. Moreover, the results also show the use of variable speed pumps to reduce total costs by approximately 7%. Zhao et al. [3] develop a two-stage distributionally robust operation model for integrated water-energy nexus systems, which considers the interdependencies among power, gas, water and energy hub systems at the distribution level, together with wind uncertainty. To minimize the day-ahead and real-time operation cost, a coherent risk measure, conditional value-at-risk, is combined with the optimization objective. The Bender's decomposition is applied to solve the two-stage mean-risk distributionally robust optimization. Evaluation results show the economic effectiveness of IES in optimally coordinating multi-energy infrastructures, providing system operators with an effective two-stage operation scheme to minimize operation costs under water-energy nexus, while considering risks caused by renewable uncertainties.

Oke et al. [95] design a framework to optimize the water-energy nexus in shale gas production and distribution networks, while taking into account various uncertainties. This framework involves the use of thermal membrane distillation for wastewater treatment, with an integrated (design) model that considers the energy requirements of the unit. The model also addresses the scheduling problem of hydraulic fracturing using a continuous time formulation. Uncertainty is incorporated in the model by considering uncertainties associated with price and demand. Stochastic modeling is applied to a case study with the goal of maximizing net profit. The results show the incorporation of uncertainty in the model leading to an increase in profit, compared with the deterministic approach. Three scenarios are considered and each has a profit increase of 11% or more. When all the scenarios are solved jointly, the expected profit increase reaches 13.74%. The proposed framework can create significant savings in freshwater requirements for fracturing and energy associated with water management, amounting to 23.2% and 42.7%, respectively. Wang et al. [96] develop a robust operations model for the water-energy nexus to account for the uncertainties of wind generation outputs and to explore the interdependency between the integrated energy system and the water distribution system. The overall model involves two-stage programming with a NLP in each decision stage, while considering the ubiquitous pressure-flow equations and the on-versus-off switching of device operation status. To yield a solution of good quality, a two-step procedure is developed, which includes a mixed integer second-order programming according to an approximation of the original NLPs and a convex optimization-based feasibility recovery. Then, the procedure is embedded into the traditional column-and-constraint generation algorithm to generate a robust solution. Simulation results validate the overall model's utilities. Zhao et al. [97] develop a two-stage risk-averse mitigation method for water-energy systems against false data injection attacks on the water-energy nexus. A risk-averse distributionally robust optimization is applied to mitigate uneconomic operations and suggests a coordinated optimal load shedding scheme for system security. Empirical results indicate the method's effectiveness for mitigating the risks created by potential attacks and renewable uncertainties. The proposed method provides a means for optimizing energy infrastructures and determining load shedding in the presence of cyberattackes.

V. Policies

Many governments around the world have developed policies regarding the interdependent water and energy resources, known as the water-energy nexus [98]. The United Nations recognizes this nexus and incorporates it in the Sustainable Development Goals (SDGs) [99]. To foster the sustainable management of water and energy resources, reduce energy consumptions and greenhouse gas emissions, and enhance resilience to climate change and other challenges, many countries establish various policies and programs, including water conservation initiatives, energy efficiency standards, and renewable energy incentives [100]. Some exemplary policies implemented at difference levels are reviewed and analyzed in the followings.

A. International Policies

Recognized by the United Nations as a crucial issue, the water-energy nexus must be addressed to achieve sustainable developments [101]. The 2030 Agenda for Sustainable Development represents a comprehensive global plan of action adopted by the United Nations General Assembly in 2015. This agenda includes 17 SDGs and 169 targets that aim to tackle some of the most pressing challenges that the world faces, such as poverty, hunger, inequality, climate change, and environmental degradation [102]. Specifically, two critical challenges emphasized in the SDGs, SDG 6, and SDG 7 pertain to water and energy [103]. In general, SDG 6, Clean Water and Sanitation, aims at ensuring the availability and sustainable management of water and sanitation for everyone [104]. The goal includes provision of universal, equitable access to safe and affordable drinking water, improvement in convenient access to adequate and equitable sanitation and hygiene, enhancement in water quality by reducing pollution and increasing wastewater treatment, and protection and restoration of water-

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related ecosystems [105]. Additionally, SDG 6 highlights the criticality of international cooperation and capacity-building support for developing countries in water and sanitation management. Meanwhile, SDG 7, Affordable and Clean Energy, aims to ensure access to affordable, reliable, sustainable, and modern energy for everyone [106]. Its goal includes providing universal access to affordable, reliable, and modern energy services, increasing the share of renewable energy in the global energy mix, improving energy efficiency and reducing energy intensity, expanding infrastructure and upgrading technologies for clean energy, and enhancing international cooperation to facilitate access to clean energy research and technology, especially in developing countries [107]. The goals of both SDG 6 and SDG 7 recognize the interconnectedness of water and energy systems and underscore the importance to effectively manage them in an integrated manner. Achieving these goals would ensure the sustainable management of our water and energy resources and foster a more sustainable and equitable future for all [108][109].

B. National Policies

Many countries recognize the importance of the water-energy nexus and have developed policies and strategies to tackle issues related to this nexus. Take the United States for example, the Department of Energy has created the Water-Energy Nexus program to address key challenges in water and energy supply, demand, and management in the country. Launched in 2014 as part of the Obama Administration's Climate Action Plan, this program continues to be active under the Biden Administration [99]. In Australia, the National Water Initiative (NWI) was established in 2004 to improve water management and address the water-energy nexus [110]. The NWI aims to enhance sustainable water use and management by developing better water allocation, planning, and pricing policies. The Australian government also has implemented various policies and programs to encourage the use of renewable energy and improve energy efficiency, including the Renewable Energy Target and the Emissions Reduction Fund [111]. Similarly, the Canadian government has established a range of policies and programs to address the water-energy nexus, such as the Clean Energy Dialogue with the United States, which encourages cooperation on clean energy issues. The ecoENERGY for Renewable Power program, which provides incentives for the development of renewable energy projects that include hydropower, is also launched [112]. The Canadian Energy Strategy aims to promote sustainable energy developments throughout the country. Moreover, China has developed various policies and programs to address the water-energy nexus, such as the National Energy Administration's Water-Energy Nexus Management Plan, which aims to enhance water-use efficiency in energy production and promote the use of renewable energy. The Chinese government has implemented policies and programs to encourage renewable energy development, including the Renewable Energy Law and the Golden Sun Demonstration Program [113]. Overall, national policies that address the water-energy nexus aim to enhance sustainable management of water and energy resources, reduce energy consumptions and greenhouse gas emissions, and improve the resilience of water and energy systems to climate change and other challenges.

C. Local Policies

In line with national policies, states and local governments establish policies and programs to address the intricate relationship between water and energy. For instance, California has formulated a Water-Energy Nexus Strategy, which outlines a wide range of actions to mitigate the energy intensity of water supply, increase the utilization of renewable energy, and improve the efficiency of water and energy systems. The strategy focuses on promoting water-use efficiency, which includes increasing the usage of recycled water and enhancing irrigation technologies. It also includes measures to elevate the usage of renewable energy in water supply and treatment, such as constructing small hydropower projects and installing solar panels at water treatment plants [114]. Similarly, New York City has implemented a Green Infrastructure Plan to reduce the ecological impact of stormwater runoff and increase the energy efficiency of buildings [115]. This plan encompasses various measures to capture and reuse stormwater, such as installing green roofs and rain gardens. It also involves measures to decrease energy consumptions in commercial and residential buildings through enhanced insulation and energy-efficient lighting deployment [116]. Key steps to boost the energy efficiency of the city's wastewater treatment plants are included too, such as upgrading equipment and utilizing biogas to produce electricity. Many other states and local governments also formulate policies and programs to address the water-energy nexus. Take the city of Austin (Texas) for example, a Water Conservation Plan is launched, which includes measures to minimize water consumption and elevate the utilization of renewable energy in water supply and treatment [117]. The state of Colorado has implemented a Water Plan, which encompasses measures to enhance the efficiency of water and energy systems, reduce water usage in energy production, and encourage the development of renewable energy [118]. The state of Hawaii has instituted a Clean Energy Initiative, which includes key steps to promote the usage of renewable energy in water supply and treatment, and provides measures to augment energy efficiency in buildings and transportation [119]. Overall, policies about the water-energy nexus at the state and local government levels seek to foster sustainable management of water and energy resources, in congruence with the national policies, and take into account the unique challenges and opportunities of each city or state.

VI. Challenges and Conclusion

The interdependence between water and energy systems represents a complex and multifaceted challenge that has become increasingly important over time. As the demand for both water and energy continues to increase, it is imperative to understand how these distinct resources are linked and can be managed in a sustainable and integrated way.

A. Complex Synergies Between Water and Energy

A fundamental challenge for understanding the water-energy nexus is measuring and assessing the impacts of changes in one system on the other system. For example, a decrease in water availability, due to droughts or excessive consumptions, can create significant impacts on energy production, particularly in regions where water is used for cooling in thermal power plants. Similarly, an increase in energy demand requires a greater water consumption for energy production (e.g., hydropower, biofuels). To address these challenges, researchers have developed different integrated modeling approaches to assess the impacts of water scarcity on energy production or the impacts of energy demand on water consumption. Existing approaches rely on complex mathematical modeling for approximating the behaviors of water and energy systems under different scenarios and conditions. By using these models, researchers can analyze potential trade-offs and synergies between water and energy systems, and develop strategies for managing these resources in an effective and integrated way. Developing sustainable and integrated water and energy systems requires appropriate technologies and practices that help reduce water and energy use while maintaining or even improving the availability of these resources. Toward that end, green infrastructure represents an effective technology that involves rainwater harvesting, graywater reuse, and green roofs. The resulting solutions can help reduce the demand for freshwater while decreasing the energy necessary for transporting and treating water. Another exemplary technology is renewable energy, such as solar and wind power, which generates electricity with minimal water use. But implementing these solutions at a larger scale can be difficult, due to factors such as cost, technological readiness, and policy barriers. Thus, researchers should develop strategies for deploying sustainable and integrated water and energy systems at various scales, from individual buildings to entire cities and regions, by identifying and engaging key stakeholders, formulating policies and incentives to encourage adoption, and bringing enabling technologies and practices into existing infrastructure and systems.

B. Water-Energy Nexus for Urban Areas

Managing the water-energy nexus in urban areas constitutes a unique, critical challenge, due to the high population density and limited direct access to freshwater resources. At the same time, urban areas provide opportunities for innovative solutions, such as using renewable energy technologies to power water treatment plants or developing urban agriculture to reduce the demand for transported food and water from other areas. This calls for more efforts to develop integrated approaches for managing the water-energy nexus in urban areas, which most likely involve collaboration among different sectors and stakeholders that include government agencies, utilities companies, businesses, communities, and individuals.

C. System Efficiency

Enhancing water and energy efficiency is a critical area that deserve significant research attention to formulate and implement strategies capable of reducing the demands for water and energy resources and improving their sustainability. This is particularly important amid the population growth, increasing urbanization, and worsening climate change, all of

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which have important implications for water and energy availability and environmental sustainability. A key approach for improving water and energy efficiency is the adoption of innovative technologies and practices that elevate sustainable uses of water and energy. Take the agriculture sector for instance, precision irrigation technologies can help reduce water consumptions by moving water directly to the root zone of crops, which optimizes water use by reducing water loss through evaporation and runoff. Similarly, adoptions of more efficient production processes and equipment in the industrial sector also can help reduce water and energy consumptions, and minimize waste and pollution. Improving energy efficiency is essential for commercial and residential buildings that account for a significant portion of energy consumption and greenhouse gas emission. A viable way to achieve this is through the adoption of more efficient heating, ventilation, and air conditioning (HVAC) systems (e.g., variable refrigerant flow systems) which use inverter technology to optimize energy use and improve indoor air quality. In addition, effective building energy management systems also help optimize energy use by monitoring and controlling various building systems, such as lighting, HVAC, and plug loads, according to occupancy and usage patterns. Transportation is another important sector of which water and energy efficiency enhancement is critical, because it also accounts for a significant portion of energy consumption and greenhouse gas emission. Strategies for more sustainable transportation are needed, such as adoptions of fuel-efficient vehicles, use of public transportation, and developments of alternative transportation modes (e.g., cycling, walking). Furthermore, integrations of renewable energy sources, such as solar and wind power, into transportation systems can reduce reliance on fossil fuels and promote sustainable resource use. Overall, improving water and energy efficiency is a critical step toward sustainable resource use and ensuring water and energy availability for future generations. It requires innovative technologies and practices that optimize resource use, reduce waste and pollution, and minimize the environmental impacts of resource use

D. Water-Energy-X Nexus

The Water-Energy-X (WEX) nexus is a complex and multi-dimensional concept that recognizes the intricate and interdependent relationships among water, energy, and other crucial resources and systems. Interdisciplinary approaches are central for expanding the traditional water-energy nexus and including additional important aspects, such as carbon, food, and health. In general, the WEX nexus is characterized by the interconnectedness of these sectors and the need for an integrated management strategy to address them. The water-energy-carbon nexus is an important dimension of the WEX nexus, which seeks to reduce the carbon footprint of energy and water systems, while considering the entire life-cycle of these systems, from production to consumption. By considering the carbon footprint of water and energy systems, researchers and policymakers can identify opportunities to reduce greenhouse gas emissions and enhance sustainable energy and water management. Another important dimension of the WEX nexus is the water-energy-food nexus, which explores the interconnectedness between water and energy use in food production and distribution by considering the use of energy for irrigation, processing, packaging, and transportation of food, as well as their impacts on water resources. By examining the interdependent relationship among water, energy, and food systems, researchers and policymakers can devise more sustainable and efficient approaches to food production and distribution. The water-energy-health nexus is yet another important dimension of the WEX nexus, which targets the relationship between water and energy systems and their impacts on public health by considering the provision of clean water and sanitation services, access to energy for heating, cooling, and medical equipment, and the impact of water and energy systems on the spread of diseases. By examining the relationship among water, energy, and public health, researchers and policymakers can develop strategies that improve access to clean water and energy services, reduce disease transmission, and enhance public health outcomes. Overall, the WEX nexus requires a holistic approach to effectively manage water, energy, and other critical resources and systems. By considering multiple distinct but related dimensions of the nexus, researchers, policymakers, and practitioners can generate integrated solutions to enhance sustainable, equitable management of these resources. Yet, the WEX nexus also poses research challenges in data availability and integration, cross-sectoral coordination, and stakeholder engagement. Addressing these challenges will require collaboration among various disciplines, sectors, and stakeholders to ensure a more sustainable and resilient future.

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