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Next generation decentralized water systems: a water-energy-infrastructure-human nexus (WEIHN) approach

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The escalating challenge of water scarcity, intensified by water-energy interdependency, demands an urgent shift towards sustainable solutions. As this concern heightens, the focus on water-energy-infrastructure-human nexus (WEIHN) becomes pivotal to achieving sustainable and resilient water management strategies. In the context of rapid urbanization and population growth, decentralized water systems (DWS) have emerged as a promising alternative to centralized water systems (CWS), offering cost-effective and environmentally sustainable solutions tailored to local water needs and demands. However, a comprehensive and integrative analysis of the economic, social, and environmental impacts needs to be considered before the implementation of DWS in WEIHN. Therefore, analyzing WEIHN at a cross-sectoral level and exploring the roles of infrastructure and humans can provide valuable insights into the challenges and opportunities associated with DWS development. This review provides a forward-looking roadmap that highlights the critical roles of the infrastructure and human perspectives in WEIHN. First, we identify roadblocks in the CWS and then point out the targeted areas supporting DWS. Second, we investigate the current capability and limitation of infrastructure spatial configuration, safety-related metrics, and interdependency in WEIHN. Third, we emphasize the significance of various human roles, including end-users, operators, and decision-makers in WEIHN. Finally, based on the review findings in water, energy, infrastructure, and human dimensions, we conduct a comprehensive in-depth analysis of innovative technologies (*e.g.*, sensor fusion, digital water infrastructure) and effective management policies.

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Water impact

This review critically examines the evolving roles of decentralized water systems (DWS) within the water-energy-infrastructure-human nexus (WEIHN) framework. We focus on infrastructure and human perspectives to identify opportunities and challenges, propose innovative technologies for water management, and suggest potential policies. Our insights are expected to guide future research and practice in designing and implementing DWS with significant impacts on water sustainability and resilience.

1. Introduction of the water-energy-infrastructure-human nexus (WEIHN)

As the world population is expected to increase by 2 billion to around 9.7 billion in 2050,[1] pursuing sustainable solutions for water scarcity and energy crisis, producing renewable energy, and protecting humans and the ecosystem are increasingly highlighted for future water-energy nexus (WEN). The WEN refers to the interdependency of the two most significant resources, water and energy, in which they are produced, treated, distributed, and(or) recycled with different scales varying from community to global field.[2–5] As the demand for water resources to satisfy the requirements of the water-energy interdependency continues to grow (*e.g.*, water demand for power generation is expected to increase 74% between 2005 and 2030 in the Rocky Mountain region[6]), a comprehensive analysis that considers the infrastructure and human dimensions is critical to ensure the efficient and sustainable water supply and management in the next generation water-energy-infrastructure-human nexus (WEIHN).

Traditional water supply and treatment systems within the WEIHN are primarily centralized, encompassing water collection, treatment, and energy generation managed from a

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single core unit.[7,8] These centralized water systems (CWS) have typically been favored, particularly in densely populated areas, due to their economies of scale and the capacity to handle large-scale water treatment and distribution.[9,10] For instance, a life cycle assessment (LCA) for the City of Atlanta's CWS revealed that the CWS contributed 81% of the average impacts of a single family home resident per year in terms of the annual water use.[11] However, the burgeoning pace of urbanization and population growth escalates the distances required for water and energy collection and conveyance. This expansion leads to increased inefficiencies within CWS as sprawling urban areas result in greater energy loss during transmission in the WEIHN, making the system uneconomical and unsustainable.[12,13] In response to these challenges of CWS, decentralized water systems (DWS) have begun to emerge as a promising alternative, which offers cost-effective, environmentally sustainable solutions tailored to local water needs and demands.[14] Despite facing historical impediments, such as a lack of technological advancements, financial constraints, and inadequate policy support,[14–16] DWS implementation has become increasingly feasible due to advancements in water treatment, recycling, and monitoring technologies,[17] robust policy support,[18] and a heightened awareness of community participation.[19] However, a comprehensive and integrative analysis of the economic, social, and environmental impacts should be considered before the implementation of DWS in a WEIHN.[20] In this context, analyzing WEIHN from a cross-sectoral

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perspective and understanding the roles of infrastructure and human engagement can provide valuable insights into the challenges and opportunities associated with DWS development, including the need for reliable and resilient infrastructure, as well as the importance of engaging with stakeholders and communities to promote sustainable water and energy use.

Our systematic literature review reveals that research on WEIHN has grown rapidly in the last decade, as demonstrated by 3470 papers published between 2012 and 2022 (Fig. 1). However, limited attention has been given to the infrastructure (278 papers) and human (389 papers) dimensions of WEIHN, which are critical to achieving sustainable and resilient water and energy systems. Most existing studies and reviews on WEIHN have only focused on the flow of resources (water and energy) and thus fail at elucidating their interactions with infrastructure and human factors in a systematic framework. Such deficiency is concerning as infrastructures play a crucial role in generating and delivering resources, and their performance is dependent on the reliability of their components as well as human behaviors.[21,22]

Although there has been some exploration of infrastructure-based interdependency in WEIHN, these studies predominantly focused on physical interdependency and cost optimization but overlooked the critical safety-based performance metrics to understand the vulnerability of interdependent infrastructures.[23,24] In addition, the various roles of human behaviors, including water and energy consumption and decision-making among end-users, operators, and policy makers, immensely influence WEIHN.

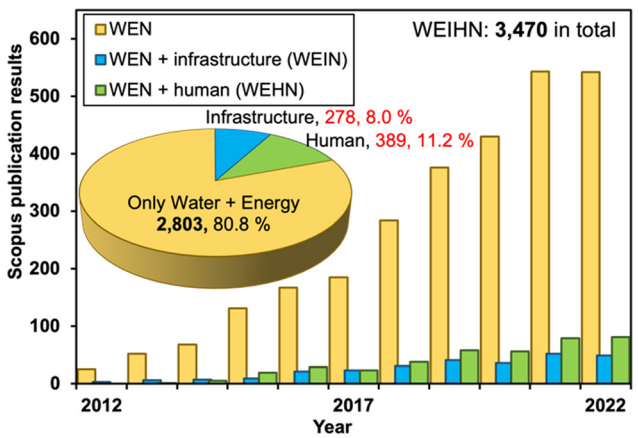

Fig. 1 The number of articles on WEIHN since 2012. The yellow block indicates WEIHN-related research, the blue block denotes articles considering an infrastructure perspective (water-energy-infrastructure nexus, WEIN) and the green block stands for articles considering human perspective (water-energy-human nexus, WEHN). The data was obtained from a comprehensive literature search conducted on Scopus by searching with the article title, abstract, and keywords. The following keywords and their combinations were used: WEN: "Water-Energy Nexus"; WEIN: "Water-energy Nexus" AND "Infrastructure"; WEHN: "Water-Energy Nexus" AND "Human"; WEIHN: WEN+WEIN +WEHN.

Capturing human behavior data, both qualitatively and quantitatively, however, poses a significant challenge, thus underscoring the need for more methodological advancements in this area of the WEIHN.[25]

This review focuses on bridging the knowledge gap between the DWS and the current understanding of resources, infrastructure, and humans in WEIHN. We first identify the roadblocks in the CWS and then point out targeted areas supporting innovations in the DWS. Secondly, we delve into the current capabilities and limitations of infrastructures within WEIHN, concentrating specifically on spatial configuration, safety-related metrics, and interdependencies, with reference to both centralized and decentralized systems. Thirdly, we emphasize the significance of various human roles, including end-users, operators, and decision-makers in centralized/decentralized WEIHN. Finally, we propose a forward-looking roadmap for the next-generation WEIHN. Based on the review findings in water, energy, infrastructure, and human dimensions, we present a comprehensive and insightful analysis of innovative technologies (*e.g.*, sensor fusion, digital water infrastructure), and suggest the potential effective policies on water sustainability and water management.

2. Critical analysis of water systems in WEIHN

This section delivers an inclusive overview of water systems within WEIHN, particularly emphasizing the challenges embedded in the existing CWS that leans heavily on traditional technologies for extensive water treatment and conveyance and is unsustainable in the face of escalating water and energy demands (Fig. 2a). We delve into water sustainability within the existing WEIHN framework, spotlighting the current state and challenges tied to water-energy interdependency, distribution networks, monitoring methods, and process control models of CWS. Furthermore, we offer insights into the prospective evolution of DWS within the future-generation decentralized WEIHN, and illuminate the pathways towards more sustainable and efficient water management strategies.

2.1 Current status of centralized water systems (CWS)

The symbiotic relationships between water and energy within the WEIHN are pivotal to ensuring energy generation, resource recovery, and preservation of water safety and quality.[26] The CWS inherently offers advantages due to its economies of scale. Operating on a large scale allows for more efficient resource utilization, with the costs of major infrastructural investments distributed over a larger consumer base.[27] The centralized water-energy models enable standardized processes and large-scale treatment facilities, which typically result in lower per-unit treatment costs.[28] The cost dynamics of water reclamation and distribution in a centralized plant can be influenced by population density.

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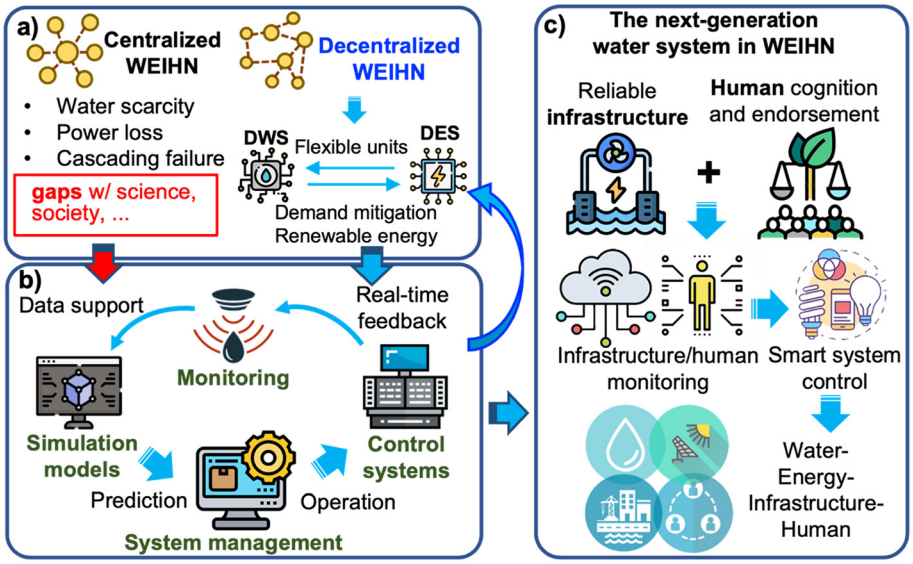

Fig. 2 Comprehensive scheme demonstrating the centralized and decentralized WEIHN. a) Current status of centralized and decentralized WEIHN. b) Future perspective of monitoring, models, and control strategies in WEIHN. c) The next-generation water systems in WEIHN by combining infrastructure and human perspectives.

For example, when considering a hilly topography, the total cost is estimated to be around \$33.24 per m^3 for a sparser population density of 96 people per km^2, while this cost dramatically decreases to \$4.94 per m^3 when the population density increases to 3860 people per km^2.[29] This comparison illustrates the profound impact that population density can have on the economic efficiency of CWS, highlighting an advantage in denser areas. Furthermore, the centralized networks allow for the strategic placement of treatment facilities, minimizing transport costs and enhancing operational efficiency.[30] These economies of scale contribute to the potential for greater affordability and consistency in water quality and supply within CWS.

However, in the face of steadily growing water demands and stringent water quality regulations, water extraction and distribution within the existing CWS becomes energy-intensive. Regrettably, the corresponding energy demand is predominantly met by the centralized energy system (CES), which is heavily dependent on traditional fossil fuels and centralized water-energy infrastructure.[31] This structure results in extensive water consumption during energy production, specifically for cooling, while processes such as coal mining have caused severe water pollution.[32] For instance, in the United States, thermal power plants accounted for ~41% (~200 trillion liters) of the total annual water withdrawals in 2017.[33] Although efforts to improve wastewater treatment and water transport/reuse efficiency present a path towards enhanced energy efficiency and accompanying environmental and economic benefits, current centralized infrastructures present huge challenges, including substantial energy losses along extensive transmission and distribution lines, and the potential for cascading failures within interconnected networks (Fig. 2a). Addressing these challenges to ensure sustainable water management is critical, particularly in the context of shifting towards a more decentralized and sustainable WEIHN.

In the pursuit of addressing the various challenges in CWS, substantial strides have been made in developing innovative technologies and strategies to reduce energy consumption and improve treatment efficiency. One notable example is the development of capacitive deionization (CDI) technology, which has gained popularity in recent years as a means of recovering nutrients and metals from water and wastewater streams by electrosorption.[34–36] The estimated energy consumption of the CDI process has been proved to be more than an order of magnitude lower than traditional recovery techniques such as reverse osmosis.[37] Despite this promise, CDI suffers from poor scalability (limit to cm^3 size[38]), deficient conductivity, and low specific surface area of electrodes.[39] Although high conductivity and large surface area electrodes have been developed, their economic feasibility for widespread use remains a barrier, limiting the applicability of CDI in CWS.[40,41] An alternative approach for enhancing energy efficiency in CWS is the implementation of integrated basin management strategies for freshwater management (Fig. 2b). However, striking a balance between energy efficiency and water contaminants removal - particularly for specific pollutants like heavy metals,[42] microplastics,[43] or perfluoroalkyl substances (PFAS)[44] – is challenging due to existing technological constraints and knowledge gaps (*e.g.*, studies often overlook the system-level context and the manufacture scalability of new membrane materials at reduced energy expenditure[45]) (Fig. 2a and b). Hence, there is an imperative need to develop alternative water systems capable of circumventing these limitations and enhancing water treatment efficiency.

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2.2 Next-generation decentralized water systems (DWS)

To address the challenge of balancing contaminant removal efficiency and energy consumption in the CWS, decision-makers are turning to a decentralized resource management strategy – decentralized WEIHN that involves supplying energy and treating water through a series of on-site processes rather than gathering all sources into a hub.[46–48] In a decentralized WEIHN, DWS combines small-scale advanced water treatment technologies, such as granular activated carbon (GAC)-electrochemical systems[49] and constructed wetlands,[50] to meet water quality requirements at lower energy consumption than a centralized WEIHN. The cut-off point at which DWS becomes more economically feasible is context-specific and influenced by various factors such as population density, technological advancement, availability of local resources, and regulatory environment. In areas with sparse populations or regions that require adaptive responses to fluctuating demands, the economics of DWS may outweigh those of CWS.[51] For instance, the decentralized rural wastewater treatment systems generally produce effluents with chemical oxygen demands, 5 day biological oxygen demands, and NH_4^+–N concentrations below 50 mg L^{-1}, 10 mg L^{-1}, and 5 mg L^{-1}, respectively, which allows the water to be reused on site for irrigation in some of the rural areas in China.[52] Localized systems might enable the leverage of specific renewable resources, reduction in transmission losses, and the provision of more resilient services in the face of systemic failures, contributing to a potential economic advantage in certain circumstances.[53] Identifying this cut-off point requires a detailed cost-benefit analysis, taking into account both immediate operational expenses and long-term impacts on sustainability, resilience, and adaptability. In order to reduce energy usage, a decentralized energy system (DES) can be incorporated into the DWS, thus enhancing efficiency and flexibility in the decentralized WEIHN, especially during periods of power loss propagation caused by component failures (Fig. 2a).[54] Furthermore, DWS can independently maintain resource supplies under critical system failures in traditional water and energy supply systems.[14] A multi-site DES incorporating renewable energy sources such as biofuels and hydroelectric power can alleviate the demand for CWS built in densely populated areas with diminishing natural resources.[55,56]

However, the implementation of decentralized WEIHN still faces hurdles, such as scaling up early-stage novel treatment technologies like CDI, microbial fuel cells (MFCs), and solar-driven membrane desalination due to high material cost and energy consumption.[57,58] In addition, limited political legislation and governance attention remain a challenge, as the importance of scale in space and time has been largely ignored.[59] One major concern for these challenges is the poor availability of human resources, specifically trained personnel, to operate and manage decentralized systems.[60] The need for specialized skills and local expertise poses an obstacle in many regions, particularly in remote or underserved areas. Determining a balance between reliable and sustainable resource supply and reasonable capital costs remains a major problem.[61] Despite DWS markedly improving contaminant removal efficiency and lowering energy consumption *via* the integration of small-scale advanced water treatment technologies, its implementation can be difficult in areas with scarce water resources and limited water collection options, often resulting in CWS as the sole solution.[62] Considering that DWS is frequently managed by a diverse array of stakeholders, such as decision-makers, operators, and end-users, it becomes critical to prioritize investments in infrastructure and policy frameworks that support the deployment and expansion of decentralized WEIHN to ensure a reliable and sustainable supply of resources for future generations (Fig. 2c).[63]

2.3 Current state and future perspective of monitoring, models, and control strategies in the water systems of WEIHN

Understanding the water systems in DWS is critical for ensuring efficient and sustainable resource management. The challenges of managing DWS arise from the diverse range of consumers from different cultural backgrounds, income/expenditure levels, education levels, and individual habits, which result in perceived risks to human health and inconsistent knowledge cognition.[64] To address these challenges, the legal and regulation institutes set for DWS and DES have been established and developed worldwide in the past decades.[65–67] However, the distribution and treatment systems of DWS/DES cannot be categorized or supervised according to one legal department, leading to ambiguous attribution of responsibility and liability towards the institutes involved.[68] Furthermore, with the development of advanced technologies that can improve the removal and purification efficiencies in DWS, various influencing factors, such as weather,[69] geometry,[70] shocks,[71] land types,[72] and water contaminants (*e.g.*, metals,[73] nutrients,[74] bacteria,[75] microplastics,[76] pharmaceuticals,[77] and pesticides[78]) must be analyzed precisely and comprehensively. Therefore, it is crucial to understand the current status of monitoring and control technologies in DWS in order to ensure efficient and sustainable resource management (Fig. 2b).

Traditional sensor technologies used in the water systems of WEIHN have primarily focused on water-based applications, geared towards enhancing wastewater treatment efficiency and producing clean drinking water.[79,80] However, for the next-generation WEIHN, the application of sensors must extend beyond the water dimension and incorporate the perspectives of infrastructure and humans to meet the divergent demands of centralized and decentralized systems (Fig. 2c). Although sensors and sensing technologies have made headway in water-energy infrastructures, particularly in the precise measurement of resource flow,[81] several key challenges persist in the monitoring processes, such as poor

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accuracy in long-term data collection and processing capacity due to the limitations of sensor materials and data processing capabilities. For instance, the lack of effective materials to prevent biofouling, and the absence of robust data processing algorithms to correct sensor data drifting, have been identified as the major barriers.[82–84] The data sparsity problem impedes the assessment of WEIHN performance and hinders stakeholders and decision-makers from foreseeing emerging problems and executing efficient control methodologies.[85] In addition, the optimization of sensor networks within DWS is a key consideration for economic viability. By focusing on a minimum viable product, unnecessary sensors can be removed, reducing both capital investment and maintenance costs.[86,87] For instance, to optimize resource use and minimize cost, a system utilizes data fusion and reconstruction techniques has been developed to enable the sensor network, enhance its utility (>95%), and reduce energy consumption (by >20%).[88] This approach promotes a more streamlined and cost-effective deployment of decentralized WEIHN, making them more accessible and attractive to various stakeholders. Therefore, there is a pressing need to develop more advanced sensor technologies, algorithms, and sensor networks for the next generation of WEIHN.

Various models can be established to optimize the WEIHN performance based on the monitoring results obtained from different sensor technologies (Table 1). For instance, the system-wide economic-water-energy model (SEWEM) has been used to explore the correlation between energy requirements and supply constraints and determine its impacts on water and land allocation decisions.[89] Because most of the current models mainly focus on operation, economic, and management principles to obtain information and understand interactions and interdependencies of WEIHN,[7,90–93] it is important to consider human factors in the model development for future WEIIHN as human behaviors can enormously affect the WEIHN performance (Fig. 2c). For instance, operators can properly operate water and energy infrastructures to ensure the stability of resource supply at the community level.[94] Similarly, decision-makers can formulate policy initiatives (*e.g.*, non-potable water storage and reuse in irrigation and the installation of mini power generator sets) to effectively deal with uncertainties in the availability of water and energy fluctuations.[95] However, political and practical aspects are often not considered in the existing WEIHN models. To address this challenge, innovative methods have been developed to incorporate political and social perspectives into the WEIHN simulation. For example, an agent-based spatiotemporal model has been used to simulate water-energy consumption under different scenarios of human activities,[96] and a system dynamics model has been applied to investigate water and energy use under different scenarios using household resource consumption data.[97] The inclusion of infrastructure and human parts in the model development can render a more comprehensive understanding of WEIHN, enabling the stakeholders and decision-makers to identify emerging problems and execute efficient smart control methodologies (Fig. 2c).

Table 1 Current models applications in WEIHN

Methods	Model type	Purpose	Limitation	Ref.
System-wide economic-water-energy model (SEWEM)	Qualitative	Explore the (un)importance of energy requirements	Do not consider long-term dynamics	89
Water–energy–food (WEF) Nexus tool 2.0	Quantitative	Identify sustainable national resource allocation	Empirically based, only assumes linear relationships	98
The climate, land, energy, and water systems (CLEWs) framework	Qualitative	Discuss two or more resource interactions under different political contexts	Not stable at the different levels of the analysis	99
Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)	Quantitative	Generate a robust quantitative assessment of the energy, water and food nexus	Extensive data required	100
Water evaluation and planning (WEAP)	Quantitative	Calculate water and carbon footprints	Did not model resources and transformation sections	101
Computable general equilibrium – system dynamics and water environmental model (CGE-SyDWEM)	Quantitative	Predict future energy use, CO_2 emissions, economic growth, water resource stress, and water quality changes	Extensive data required	102
Multi-regional input–output (MRIO) model	Quantitative	Quantify the energy for water and water for energy in the city- and regional-level scales	Unstable at different population density areas	103
Urban water optioneering tool (UWOT)	Qualitative/quantitative	Facilitate the selection of combinations of water-saving strategies and technologies	Inability to handle complex decision-making algorithms	104
Integrated computable general equilibrium (CGE) mode	Qualitative/quantitative	Study the impacts of energy tax policy on water withdrawal	Complex with too many inputs	105

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After acquiring and processing data, water and energy models can be developed and applied to implement efficient control strategies in the water systems to formulate effective solutions for energy-intensive water treatment and distribution by achieving system visualization and virtualization towards enhanced resilience (Fig. 2b).[82] Control systems enable multi-variable systems management by applying physical constraints and maintaining the balance between generation and demand in WEIHN, as well as facilitating data acquisition efficiency by improving serviceability.[106] Traditional optimization of water system control models primarily aims to minimize system costs. For example, a multi-objective mixed-integer optimization model has been developed to optimize the energy and water networks for a neighborhood of residential units, with the goal of maximizing sustainability.[107] Evaluative control models (*e.g.*, life-cycle assessment,[108] total economic assessment,[109] and scenario analysis[110]) and adoption methods (*e.g.*, individual DWS and hybrid water system by integrating DWS with CWS[111]) have been proposed to testify the possibility and feasibility of implementing DWS into WEIHN. Control models such as Advanced Process Control systems were utilized for data collection and system management, reliant on programmable logic controllers.[112] Addressing the limited availability of human resources may involve automating key processes to minimize the need for human intervention, building capacity to develop training programs for local operators, and integrating remote monitoring and support to provide remote assistance and expertise that can overcome localized human resource constraints. These controllers play a pivotal role in overseeing the system and executing process commands.

Currently, the data collection on infrastructure and human aspects is still limited due to the lack of consensus on defining data for system failure and quantifying concerns related to security.[113] To solve this problem, crowd sensing/sourcing has been developed to supply enormous datasets and engage infrastructure and human aspects in the WEIHN analysis.[114] However, crowd sensing hasn't demonstrated consistent success across all the relevant domains (*e.g.*, detection of microplastics[115]) due to scarce incentives for public participation. As for infrastructure, flow-based and graph-based models have been widely used to investigate the interactions between water and energy resources.[116–118] The optimal design and control of infrastructures meet the resource demand and prevent inept infrastructure investment.[119] Nonetheless, the strategic planning and management of infrastructure operations at different levels – from individual units like solar panels[120] to larger systems like local power grids[121] – remains an unmet research need. This complexity arises from the intricate nature of policy-making and resource allocation necessary for effective operation. Consequently, the development of WEIHN models should consider not only operational, economic, and management principles but also infrastructure and human factors to advance performance and resilience (Fig. 2c).

3. Consideration of multifactorial infrastructure for WEIHN

The performance of infrastructure plays a critical role in linking water and energy resources in WEIHN. Existing WEIHN studies have largely focused on large-scale infrastructure such as water treatment and power plants,[122–124] while the decentralized nature of next-generation WEIHN requires a reexamination of the link between water-energy and infrastructure since it involves more diverse and dispersed infrastructure elements, including DWS (*e.g.*, rainwater harvesting,[125] on-site wastewater treatment[126]), DES (*e.g.*, solar energy,[127] micro-hydro power,[128] biogas,[129] and biomass[130]) and integrated water-energy systems (*e.g.*, water-energy microgrids[131]). The unique characteristics of infrastructure within a WEIHN imply that component failures caused by extreme weather events or aging can result in large-scale system breakdowns, as seen in the 2021 Texas power crisis.[132] Although the State of Texas narrowly escaped a total grid failure, power outages still affected 4.5 million customer premises. These blackouts not only caused severe inconvenience but also resulted in a minimum economic loss of $130 billion, in addition to the tragic loss of numerous lives.[133] Consequently, inclusive consideration of infrastructures is vital in serving customers and constructing resilient systems with advanced capabilities of withstanding natural disasters. This section focuses on a multifactorial assessment of WEIHN performance from the infrastructure perspective, highlighting three critical aspects to bridge the knowledge gap in this area.

3.1 Evaluation of infrastructure performance in WEIHN

The evaluation of infrastructure performance in WEIHN can be categorized into three essential aspects: spatial configuration, performance metrics, and interdependency (Fig. 3). Specifically, infrastructure spatial configuration pertains to the planning of utility infrastructure in WEIHN,[134,135] infrastructure performance metrics refer to resource consumption or infrastructure safety indicators in WEIHN, and infrastructure interdependency highlights the associations between water and energy infrastructure systems.[136,137]

Infrastructure spatial configuration. Infrastructure spatial configuration plays a vital role in the deployment of WEIHN since the spatial pattern of patches makes up the infrastructure networks and determines the efficiency and resilience of WEIHN.[138] In a traditional centralized WEIHN, infrastructure networks are typified by a small number of large-scale production facilities, such as drinking water plants serving a vast range of isolated consumers. Although this configuration efficiently minimizes the number of routes required to reach various endpoints, it remains vulnerable to cascading failures incurred by natural disasters or targeted attacks (Fig. 3a).[139] Especially, centralized infrastructure networks necessitate extensive transmission lines, increasing

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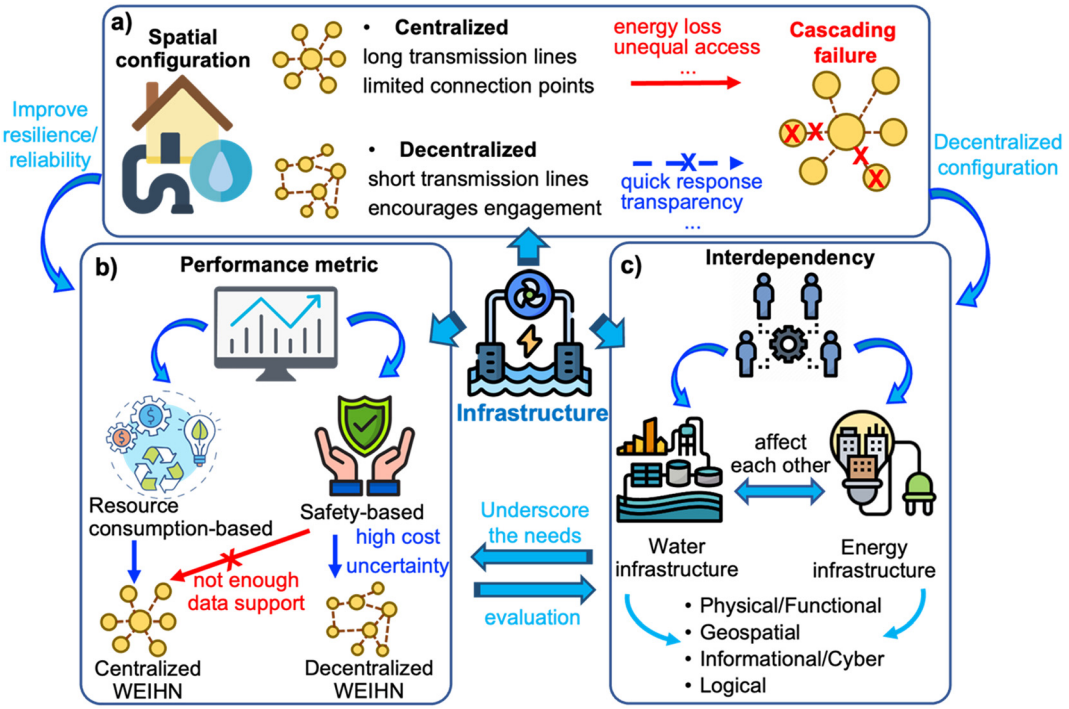

Fig. 3 The comprehensive scheme of the roles of infrastructure in WEIHN. a) The spatial configuration performance in the centralized and decentralized WEIHN. b) The performance metric in the centralized and decentralized WEIHN. c) The interdependency between water and energy infrastructures.

the risk of energy loss and failure during transmission under targeted attacks triggered by hurricanes or earthquakes.[140] Furthermore, centralized WEIHN usually has a limited number of connection points often located in urban areas, which creates an urban–rural divide and leads to unequal access to water and energy resources.[141] To address these challenges incurred by the complexity of infrastructure systems, adaptation strategies should be vigorously examined in the context of infrastructure distribution, connection, and disaster response.

Transitioning from a centralized WEIHN to a decentralized WEIHN involves substantial changes in terms of infrastructure spatial configuration and disaster handling approaches. The decentralized WEIHN configurations feature relatively smaller producers than centralized systems, with generation and potential storage capacities co-located with end-users (Fig. 3a). This configuration allows infrastructures to serve as a generator and distributor of resources and as storage to reduce cascading failures by shortening the length from generators to end-users and responding quickly to failure requests.[47] For example, the integration of renewable energy sources with electrolyzers can allow for the local production and storage of hydrogen, alleviating reliance on large-scale infrastructure and enhancing the system's responsiveness to failure requests.[142] Furthermore, compared to a centralized WEIHN that often relies on a limited number of stakeholders (*e.g.*, government agencies) to make decisions related to infrastructure spatial configuration, a decentralized WEIHN integrates emerging technologies (*e.g.*, smart meters[25] and internet of things (IoT) devices[143]) (Fig. 3a), and bolsters community engagement and participation throughout the decision-making processes related to water and energy infrastructures. When exposed to cascading failure and natural disasters, high transparency and accountability in the decentralized WEIHN can improve system performance and provide real-time data for resource use. However, DWS in rural settings may face challenges in ensuring the reliability of drinking water from wells and drainage to septic systems during disasters, since wells can become contaminated due to flooding or other disruptions, while septic systems may fail if drainage is compromised.[144] Consequently, households in these areas may need to rely on generators or other DES to ensure the continuous operation of DWS during disasters.[145]

Infrastructure performance metric. Infrastructure performance metrics are crucial for evaluating the effectiveness and efficiency of WEIHN, and can be classified into two categories: resource consumption-based and safety-based (Fig. 3b). Resource consumption-based performance metrics provide information on the WEIHN status and are directly related to end-users and decision-makers.[146–148] For example, it was estimated that a middle-sized reverse osmosis (RO) plant with a capacity of ~25 000 m^3 per day and energy demand of ~5 kW h m^{-3} could provide water to 48 000 households. This is comparable to providing electricity to 10 300 households of the same size, underlining the significant energy demand in the current WEIHN.[149] The excessive dependence on resource-based metrics may obscure

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the impact of damages or failures on the overall behavior of WEIHN, underscoring the importance of safety-based metrics. Different from the resource consumption-based metrics, safety-based metrics explore the infrastructure components' behavior concerning the failure and dysfunctionality in infrastructure.[150] Unfortunately, most existing studies tend to assess the infrastructure performance from a resource perspective, and neglect safety considerations due to the sparse availability of data on resource consumption and generation (Fig. 3b). Consequently, the current WEIHN infrastructure is characterized by high resource consumption and low system safety.[151]

On the matter of performance metrics, the key advantage of decentralized WEIHN lies in its potential for rapidly enhancing the resilience (the capacity to recover from damage) and reliability (the ability to resist internal or external disruptions) of crucial infrastructures. Decentralized WEIHN facilitates resource transportation and reduces losses compared with centralized WEIHN.[152,153] For example, the cost of energy in Sub-Saharan Africa was saved by approximately 90% when the majority of the region's energy was provided by decentralized solar energy systems.[23] However, decentralized storage infrastructures pose certain challenges (Fig. 3b). For instance, the elevated initial costs associated with installation and construction may obstruct their broad deployment, particularly in settings with limited resources.[154] Furthermore, water resource generators in decentralized WEIHN are typically subject to considerable uncertainty and low reliability due to the environmental variations encountered over temporal and spatial scales.[155] Thereby, it is crucial to balance the benefits and challenges of the infrastructure performance metrics in the decentralized WEIHN. Decisions about water and energy systems design and planning should take into account the specific context in which these systems are implemented.

Infrastructure interdependency. Interdependency in the WEIHN refers to the interactions between different water and energy infrastructures within a system. In a centralized WEIHN, water and energy infrastructures are tightly interdependent, with the functionality of one system directly affecting the other (Fig. 3c). For example, power plants often require large amounts of water for cooling, and the failure of water distribution pipelines could cause the loss of functionality of the power generators.[156,157] While standard data collection, such as supervisory control and data acquisition (SCADA), can identify physical interdependency in terms of resource consumption,[150] other forms of interdependencies may remain undetected until a disruptive event triggers a cascade of failures within the WEIHN. Future studies could explore the role of physical-cyber interdependencies in the WEIHN, including the identification and detection of possible data errors that may affect resource flow.[158] Digital twin (DT) is a promising technology to address this need by receiving input from infrastructures and simulating failure scenarios.[159,160] However, comprehensively integrating all forms of interdependencies – physical, cyber, geographical, and logical – necessitates further exploration through complex and costly mathematical modeling techniques. Therefore, the intricate interdependence of water and energy infrastructures must be considered to ensure the resilience and sustainability of the WEIHN (Fig. 3c).

Decentralized WEIHN introduces a more intricate web of interdependencies between water and energy infrastructures. Integration of multiple decentralized resource generators reduces the physical interdependency between the central plant and end-user, while the physical interdependence between these decentralized resource generators and the main plant is strengthened, as the stored resources are dispatched to the central plant for backup.[91,161] In addition, decision-makers within a decentralized WEIHN need to determine the trade-offs concerning nexus-related issues, since the choice of power generators can substantially influence the physical interdependency between water and energy infrastructures. For example, escalating the use of renewable resource generators (*e.g.*, distributed solar panels) in decentralized WEIHN could diminish reliance on traditional resources (*e.g.*, coal and fuel). For example, with a conservative estimate of 1 kWp solar photovoltaic (PV) capacity per 10 m^2 of building roof surface in key sectors, the technical potential for solar power in Malaysia is approximately 11 000 MWp or 11 GWp. This potential could be translated into more than 12 000 GW h of solar-generated electricity, which would account for 20% of the nation's energy demand.[162] This transition will assuage the physical interdependency between water and power infrastructures compared to the centralized WEIHN.

3.2 Challenges and future perspectives in next-generation decentralized WEIHN

Infrastructure spatial configuration. Compared to centralized WEIHN, the decentralized WEIHN typically feature a more distributed and flexible infrastructure spatial configuration, allowing for easier integration of renewable energy sources and improving the system's energy efficiency and reliability.[163] However, variations in consumers' access to resources within the decentralized WEIHN could exacerbate inequality of supply across marginalized areas and make the system susceptible to random attacks.[164] Consequently, developing efficient methods to detect and/or diagnose failures before the occurrence of potential hazards has been a key area of innovation. Existing approaches (*e.g.*, failure mode and effect analysis (FMEA) to determine the main failure mechanisms and data-driven strategies) require detailed and sufficient failure/maintenance logs,[165] posing difficulties for sensor deployment and data processing algorithms. In a decentralized WEIHN, there are numerous small-scale producers and end-users, creating complexity in collecting data related to the status of infrastructure components and resources.[166] To address this challenge,

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wireless sensor network technology presents a solution by enhancing failure diagnosis with real-time high-fidelity data and complementing the sensors for resource flow.[167] Moreover, emerging technologies such as geographic information systems (GIS) and optimization algorithms can improve the design of infrastructure spatial configurations by optimizing network connectivity, minimizing costs, and improving system performance.[168] However, even if the incorporation of advanced tools such as FMEA and GIS can elevate the capabilities of the infrastructure in decentralized WEIHN, the potential trade-offs in complexity and cost should be recognized. For instance, exploring the integration of machine learning algorithms (MLA) for optimizing energy consumption in the DES requires specialized expertise of personnel and might increase operational costs.[169] Implementing these advanced tools should be aligned with the specific needs and budgetary constraints of the WEIHN, ensuring that technology adoption does not inadvertently hamper economic feasibility.

Infrastructure performance metrics. Given the increased complexity and heterogeneity of decentralized WEIHN infrastructure, new performance metrics that consider the technical aspects of the system, as well as the social and economic aspects (*e.g.*, social equity, environmental sustainability, and economic efficiency), should be developed to better capture the multidimensional nature of the decentralized WEIHN infrastructure.[170] Moreover, deploying advanced sensors and data processing algorithms becomes vital to furnish precise and timely information about the performance of infrastructure components.[83,171] Real-time monitoring and control can augment the capabilities of failure detection and diagnosis and enable swift response and reorganization of individual components without disrupting the overall system.[80] Furthermore, the incorporation of emerging technologies such as artificial intelligence (AI) and MLA can foster the development of predictive maintenance strategies.[172] These strategies will enhance the overall infrastructure performance and mitigate

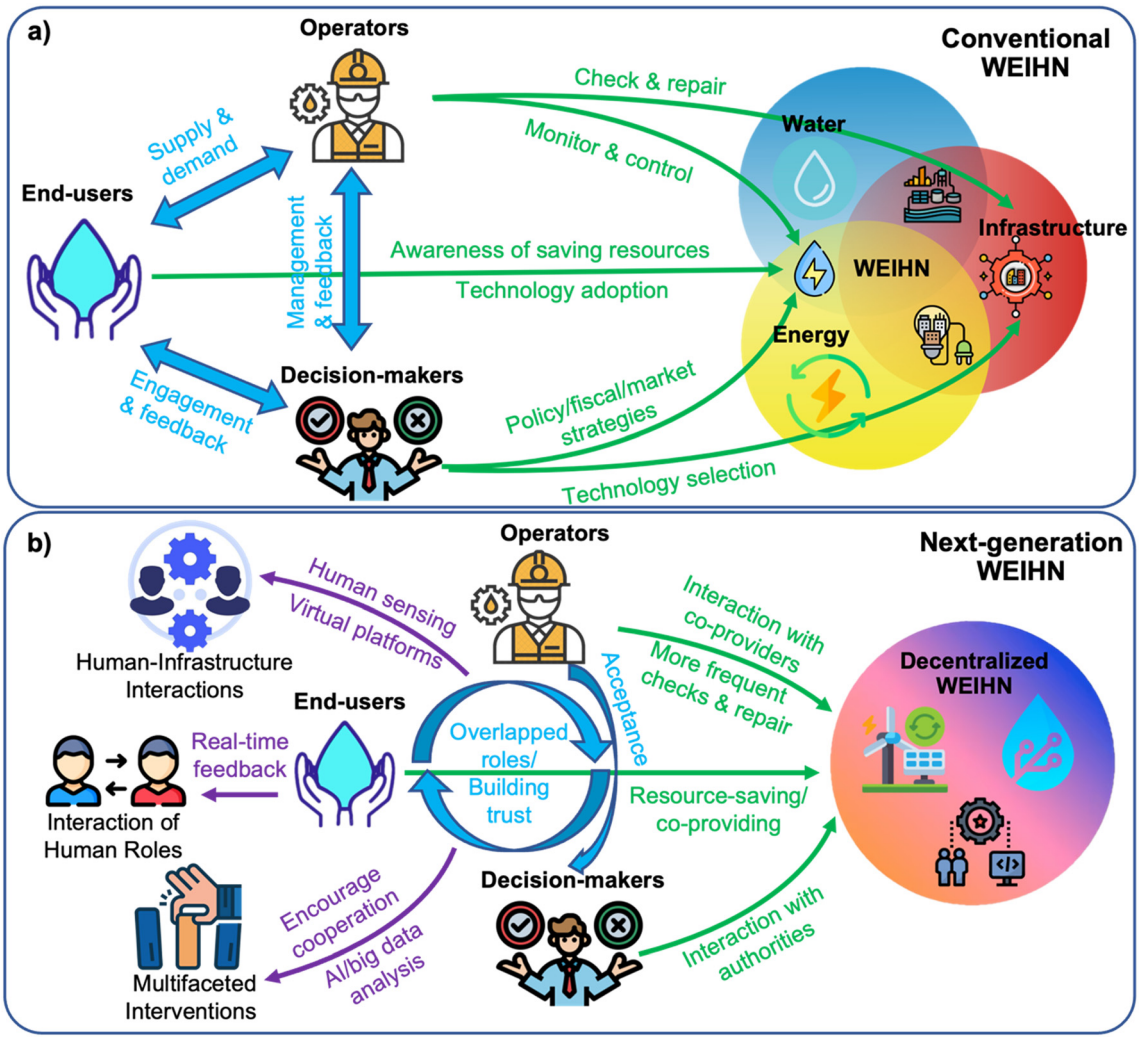

Fig. 4 The roles of human behaviors in WEIHN. a) The human behaviors and the interactions of the three human roles (end-users, operators, and decision-makers) in a conventional centralized WEIHN. b) The human behaviors and the interactions between the three human roles in a decentralized WEIHN, and the possible solutions to address the potential challenges of the human behaviors in the next-generation WEIHN.

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the risk of cascading failures, thereby fostering more robust and efficient decentralized WEIHNs.[173,174]

Infrastructure interdependency. Interdependence between the water and energy systems requires meticulous consideration to ensure the resilience and sustainability of decentralized WEIHN, in which the increasing use of renewable resource generators can reduce the reliance on traditional resources, and diminish the physical interdependency between water and power compared to centralized WEIHN.[175] However, this transition towards renewable resources could inadvertently escalate water demand, potentially straining water resources, instigating water scarcity, and thereby compromising the sustainability of the entire system.[176] Additionally, the remote or rural location of decentralized infrastructure presents a unique set of challenges in maintaining and operating the interdependent water and energy infrastructure. These areas typically rely on wells for water and septic systems for drainage, thereby raising the risk of failures and outages without reliable energy support.[14] Addressing these challenges calls for the implementation of strategies such as leveraging advanced monitoring and simulation technologies to detect and quantify the interdependencies between water and energy infrastructures.

4. Consideration of the human dimension in decentralized WEIHN

As indispensable resources for human survival, water and energy necessitate sustainable management to ensure societal welfare. A wide variety of human behaviors become significant within the context of WEIHN, including resource production, consumption, recycling, and the operation and maintenance of water and energy infrastructures (Fig. 4a).[177] Characterizing human behaviors in WEIHN can elevate our understanding of the spatially and temporally disaggregated water-energy demands resulting from individual consumption patterns. Furthermore, studying human

Table 2 The analysis of human behaviors in current WEIHN

Human type	Behaviors	Analysis methods	Analytical results	Ref.
End-users	Awareness of resource-saving	Literature review, a survey of academic experts and two interdisciplinary expert workshops	Identifies four attributes that need to capture to reflect the uncertainty associated with the paradigm shift	178
		Participant observation, survey, participatory action research	Brings a more holistic understanding of human and nature relationships at the household level	179
	Resource-saving adoptions	Hierarchical and K-means cluster analysis	Provides water conservation information and engagement opportunities that effectively engage and resonate with complex consumers	180
		An agent-based spatiotemporal integrated approach	People living in the central districts tended to consume more water and related energy	181
Operators	Monitor and control	Operational scenario	Increases resource efficiency and environmental performance of water distribution networks	182
		Open loop optimal and model predictive control (MPC) controllers	A grey water recycling system has a huge potential to conserve water while ensuring efficient use of energy	183
	Check and repair	Conceptual framework	Provides a robust capacity for future development of energy and water resources	184
Decision-makers	Policy initiatives	A multi-criteria decision-making (MCDM)-based social network analysis	The current WEIHN do not exploit maximum capacities to establish relationships with one another	185
		A fuzzy-cognitive mapping approach	Reveals the interdependencies among nexus sectors and the existence of unanticipated effects	186
	Fiscal measurements	A macro-management theory	Districts with a high welfare mass (WM) do not suffer when a defund is applied, but districts that have a low WM gain from subsidies	187
	Technology selection	Strategic decision-support modeling	Presents a quantified dependence between the target reliability level and the penalty for exceeding water use	188
Interactions of different roles	Sustainable development goals	The SDG synergies approach based on available information	Raises important issues for understanding and managing cross-scale interactions	189
	Marketing strategies	Agent-based models (ABMs)	The need to integrate richer and more realistic human behavior into WEIHN research has been recognized	190
	Resource-saving adoptions	Sensitivity analysis of an agent-based model	Provides an innovative framework that simulates human interactions and evaluates how these interactions can affect WEIHN	191

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interventions and their impact on WEIHN can enable efficient solutions to improve system performance. This section explores various human behaviors and interactions in WEIHN, and analyzes interventions to change these behaviors in the next-generation decentralized WEIHN. Critical challenges regarding the human dimension in WEIHN are also identified. A comprehensive human-centered framework is proposed as a potential opportunity to improve WEIHN performance from the human perspective.

4.1 Human behaviors in decentralized WEIHN

The optimal operation of WEIHN hinges not only on technological systems and policies but also pivots on the behaviors of three human constituents: end-users, operators, and decision-makers (Fig. 4a). The roles these individuals wield an extensive influence on the sustainable management of existing WEIHN resources. Strategic interventions of these roles can notably influence resource supply and demand, operating conditions of infrastructures, and emissions within the WEIHN framework. Table 2 offers a thorough exploration of human behaviors within WEIHN, accompanied by interventions that may inspire behavioral alterations. It is crucial to understand and address the complex dynamics of these human behaviors in order to achieve effective and sustainable resource management in WEIHN.

End-users. The consumption of water and energy within WEIHN is shaped by the behaviors, attitudes, and habits of end-users, particularly their proclivity towards resource conservation and the adoption of resource-saving technologies (Fig. 4a). To accurately capture and analyze consumption patterns at a regional level, it is crucial to elucidate end-users' behaviors on an individual basis. End-users' awareness of saving water and energy and their adoption of resource-saving appliances differ depending on their socio-demographic backgrounds (*e.g.*, age, income, education level, and social connections).[192,193] In order to effectuate changes in end-users behaviors within WEIHN, interventions can be instituted *via* policy measures, fiscal incentives, marketing techniques, and social networks.[194] For example, policies related to promoting the use of reclaimed water for irrigation have the potential for potable water savings (ranging from 1.7% to 50.5%) and reduction in sewage generation (between 2.1% and 52.1%) among end-users in Joinville, Southern Brazil, according to city-scale analysis.[195] Fiscal measures such as penalties for excessive resource use can motivate end-users to conserve water and energy resources.[196] These interventions require collaboration among various stakeholders, including government policy-makers, water and energy resource providers, and sustainability campaign initiators. Implementing such interventions would have a long-term impact on reducing total resource usage in a region, as end-users are the primary consumers of water and energy resources.

Operators. Operators are crucial in maintaining the stability and safety of the water and energy infrastructures within WEIHN. Their daily monitoring and control activities, combined with periodic inspections and repair work, contribute to both resource supply stability and infrastructure safety (Fig. 4a). Operators can improve the efficiency and reduce waste of WEIHN by detecting and repairing infrastructure damage and checking and repairing water leaks in a water distribution system.[197] Changing operator behaviors can be achieved through cross-sector coordination efforts, such as team-building activities,[198] and educational programs.[199] These changes can ensure optimal infrastructure conditions in the long-term, contributing to consistent resource production, supply, and recycling.[200] However, a lack of resources, technical capacity, and motivation can hinder operators' ability to detect and address infrastructure damage, reducing the overall efficiency of the WEIHN.[201,202]

Decision-makers. Decision-makers are vital to WEIHN as they orchestrate the implementation of policies, fiscal measures, and marketing strategies that influence water and energy production, use, and recycling (Fig. 4a).[203,204] A sufficient consideration of decision-makers' behaviors in WEIHN could improve resource availability and reduce resource consumption and thus facilitate regional sustainable development.[205] For example, mandates that require the use of solar photovoltaic technology for supplemental energy production can mitigate water demand in traditional power plants, thereby enhancing the system's efficiency.[206] Changing decision-makers' behaviors in WEIHN can be achieved through communication with operators and end-users, such as conducting interviews to obtain feedback on critical decisions (Fig. 4a).[207] Additionally, cooperation among different sectors (*e.g.*, integrated and coordinated policy-making between water and energy sectors) could lead to more effective decision-making.[208] Therefore, engaging stakeholders and ensuring their cooperation in decision-making processes is crucial to achieving sustainable development in a more effective manner.[209]

Human behaviors in WEIHN have substantial impacts on resource availability, consumption, and sustainability. One key aspect of this is the impact of population increases, particularly due to in-migration. Projections to 2100 estimate that water demand could rise by 28.9% more than in scenarios without labor in migration based on a case study in Tieling City, China.[210] End-users, operators, and decision-makers together hold crucial positions, and their behaviors must be acknowledged to augment the precision and fidelity of WEIHN consumption patterns, improve infrastructure safety and stability, and boost regional sustainable development. In most studies, these three human roles are usually considered independently.[211,212] A more effective approach towards sustainable development in WEIHN is to engage and cooperate with all stakeholders in decision-making processes, and improve WEIHN efficiency and resource sustainability.

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4.2 Human behaviors in the next-generation decentralized WEIHN

Compared to the conventional centralized WEIHN, the next-generation decentralized WEIHN provides end-users with enhanced control of resource consumption, which can be achieved by offering end-users real-time data on their consumption patterns, thereby raising awareness of resource conservation (Fig. 4b).[213] For example, smart water metering systems provide end-users with real-time data on their water consumption patterns, enabling them to identify opportunities to conserve water and reduce costs.[214] These systems can also detect leaks caused by pipeline aging problems in water supply systems, alerting end-users to potential problems and enabling them to take action to prevent further damage.[215] It is important to note that the roles of end-users, operators, and decision-makers in decentralized WEIHN can overlap and evolve over time based on the needs and preferences of the community (Fig. 4b). For instance, in a community-managed rainwater harvesting system, the end-users could also be decision-makers and operators who make collective decisions on the allocation of harvested rainwater, the maintenance and repair of the infrastructure, and the adoption of new technologies or practices.[216] DWS brings immense resource-saving opportunities from the human perspective since end-users are expected to play a more active role. To maximize the benefits of decentralized WEIHN, it is essential to develop strategies that engage end-users in the development and operation of DWS.

Within the decentralized WEIHN, operators are required to carry out more frequent monitoring and inspections due to the inherent vulnerability of the decentralized configuration's water and energy infrastructure (Fig. 4b).[217,218] This susceptibility originates from the intermittency of renewable resources, such as rainwater and solar radiation, attributable to weather fluctuations.[219] Moreover, extreme weather conditions could potentially cause infrastructure damage – for example, heavy rainfall could lead to leaks, while intense solar radiation could result in damage to solar panels.[220] In some cases, operators may also be end-users, such as individual property owners who may operate and maintain their own water supply and treatment systems in rural areas.[221] Furthermore, industrial parks or estates might operate their decentralized water systems that are designed to cater to their specific water requirements. These systems could encompass treatment facilities, distribution networks, and storage tanks, all under the management of the park or estate.[222] Thereby, the roles of operators, end-users, and decision-makers in decentralized WEIHN are highly interrelated and overlapped, highlighting the need for a comprehensive and integrated approach to WEIHN management, which takes into account the diverse perspectives and interests of all stakeholders (Fig. 4b).

In decentralized WEIHN, decision-makers are critical for selecting appropriate technologies and formulating standards to ensure safe and reliable service delivery. Because the decentralized rainwater harvesting and greywater reuse systems require hybrid water treatment technologies to remove numerous types of contaminants (*e.g.*, heavy metal, pathogens, microplastics), decision-makers are responsible for selecting and adopting hybrid water treatment technologies suitable for DWS (*e.g.*, combining human intervened-based and nature-based technologies).[223,224] In addition, decision-makers may also be operators and end-users when the agricultural cooperatives operate and manage their own water supply and distribution systems (*e.g.*, wells, pumps, irrigation systems, and storage tanks) owned and operated by the cooperative. In this case, the agricultural cooperative is responsible for maintaining the system and ensuring the water quality and availability for their use.[225] Furthermore, decision-makers' choices within decentralized water and energy systems profoundly affect end-user benefits such as public health and electricity costs. Prompt decisions on infrastructure investments, water treatment technologies, and pricing policies can directly influence end-users' access to clean and affordable water (Fig. 4b).[226] Hence, it is of paramount importance for decision-makers to engage in open dialogue with end-users and incorporate their feedback into the decision-making process, thus enhancing the effectiveness and responsiveness of management strategies in the decentralized WEIHN.

4.3 Challenges and potential opportunities of the human dimension in WEIHN

Effective management of the next-generation decentralized WEIHN requires an insightful understanding of human behaviors within the systems, as well as the development of multifaceted interventions that target different human agents. Herein, we identify three major human-centered challenges and propose a framework for better understanding and management of human dimensions in decentralized WEIHN.

Challenge for human-infrastructure interactions. Although many studies have assessed and improved the performance of infrastructures in WEIHN,[227,228] few have investigated the human behaviors related to these infrastructures.[229] Because the complexity of infrastructures requires extensive technical knowledge and expertise to operate and maintain the decentralized WEIHN, a major challenge of human-infrastructure interactions is to ensure that the infrastructures and technologies are designed to meet the needs of local communities in a broader social and environmental context.[230] For example, the water and energy policy decisions are progressively influenced by the social dimensions of WEIHN, a fact underscored by the ongoing large-scale energy transitions worldwide. These transitions encompass the adoption of hydraulic fracturing technologies for oil and gas extraction, the deployment of renewable energy generation to combat climate change, and the development of alternative fuels, as well as hybrid and

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electric vehicles.[231] Another challenge is to develop effective governance structures and policies that can manage the different human roles in the planning, design, and operation of WEIHN.[232] Coordination and cooperation between these human roles are critical for ensuring the efficient and sustainable management of DWS. In the future WEIHN, establishing transparent communication channels and delineating roles and responsibilities will be critical, which can be facilitated through collaborative tools (*e.g.*, digital water infrastructure and virtual platforms), real-time communication, and data sharing.[233,234] Furthermore, advanced sensors and evaluation tools can enable the continuous monitoring of infrastructure performance, fostering prompt and effective responses to anomalies. The long-term continuous monitoring provided by reliable water sensors is expected to save 44.9% NH_4^+ discharge, 12.8% energy consumption, and 26.7% greenhouse emission under normal operational conditions.[84] The use of these advanced technologies enhances predictive maintenance, reducing the likelihood of unexpected failures and improving the overall performance of infrastructures (Fig. 4b). It should be noted that these advanced technologies require specialized knowledge and skills for operation, maintenance, and troubleshooting. For instance, in a decentralized water treatment facility utilizing advanced sensor networks for real-time monitoring, the complexity of these sensors demands trained technicians and more intricate maintenance procedures.[235] Therefore, meticulous consideration of the corresponding human challenges and potential cost implications is essential to achieving a harmonious and economically viable integration within decentralized WEIHN.

Challenge for interaction of human roles. In the decentralized WEIHN, a major challenge in understanding the interaction and feedback mechanism between end-users, operators, and decision-makers is the difficulty in collecting accurate and real-time feedback data (Fig. 4b). For instance, end-users may exhibit different levels of compliance with specific policies due to their diverse socio-economic backgrounds and transient psychological status,[236,237] while operators' comprehension of decisions and level of acceptance may vary over time and affect their operation behaviors.[238] The scarcity and varied skill levels of human resources can create discrepancies in implementation, understanding, and compliance with policies across different regions and communities. Hence, gathering precise, real-time feedback from end-users and operators is essential for decision-makers to fine-tune their policy initiatives and management behaviors, enhancing policy acceptance among these key stakeholders. In the decentralized WEIHN, aggregating end-users' feedback regarding a specific policy (*e.g.*, water quality standards) is necessary to estimate potential effects before implementing the policy.[239,240] Thus, achieving alignment in infrastructure planning, design, and operation with regulatory needs and public interest hinges upon effective communication and collaboration among diverse human agents within WEIHN.[241,242] As an example, frameworks focusing on sustainable environments and circular economies often garner more public acceptance, as they resonate with values deemed increasingly vital to personal and societal identities.[243] Future research could strategically encourage bottom-up acceptance of emerging technologies and concepts like climate change mitigation and energy transition, through carefully framed messaging that addresses public concerns and underscores how these innovations can foster a more sustainable society.[244] In addition, leveraging automated systems, digital tools, and innovations in remote support can minimize the dependency on extensive human intervention, thereby enhancing efficiency and precision.[245]

Challenge for multifaceted interventions. The third major challenge faced in WEIHN management is the lack of effective multifaceted interventions combining various interventions that act on end-users, operators, and decision-makers to achieve optimal management.[242] Interventions on any type of human agent alone usually cannot lead to the most desirable outcomes. For instance, in the context of water sustainability, targeting decision-makers solely may not be sufficient to achieve optimal management when implementing a greywater recycling system.[246] Decision-makers must interact with end-users and operators in communities and obtain acceptance and support, potentially through a co-design approach.[247] However, implementing multifaceted interventions is challenging as it requires cooperation and collaboration among various stakeholders, including academic and research institutions, water and energy equipment manufacturers, media and communications organizations.[248] Designing multifaceted intervention strategies depends on a thorough understanding of large-scale human behavior data that can be obtained through data-driven approaches. Potential future strategies encompass the development of incentive mechanisms to foster stakeholder cooperation, enhancing public awareness of integrated WEIHN management, and exploiting emerging technologies like AI and big data analytics for designing more effective interventions (Fig. 4b). Incentives such as tax credits or financial subsidies can encourage the adoption of sustainable practices, such as water conservation and the use of renewable energy sources, which can reinforce the overall sustainability of the WEIHN.[249] Leveraging big data analytics can track infrastructure performance, pinpoint areas necessitating improvements, and provide crucial insights that shape policy and investment decisions.[250]

5. Conclusion, future perspective, and outlook of next-generation WEIHN

5.1 Conclusion

In this critical review, we elaborate on a forward-looking roadmap of WEIHN from a systemic framework. We identify the roadblocks to the centralized WEIHN systems and point out the targeted areas supporting innovations in the decentralized WEIHN systems. We highlight the limitations

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of traditional CWS and analyze the potential of DWS to provide cost-effective and environmentally water-sustainable solutions tailored to local water needs and demands. Although the studies on WEIHN have grown rapidly in the last decade, limited attention has been given to the infrastructure and human dimensions of WEIHN. Therefore, we emphasize the need for a comprehensive analysis of infrastructure and human dimensions to ensure the efficient and sustainable supply and management of water and energy in the next generation of WEIHN. We then pinpoint the current capabilities, limitations, and future perspectives of infrastructure and human dimensions in WEIHN. In this section, we lay out future opportunities for next-generation WEIHN and cover emerging topics ranging from fundamental scientific exploration to engineering implementations.

5.2 Future perspective and outlook

Water safety and resource recovery. The advent of next-generation decentralized WEIHN is set to enhance water safety and resource recovery *via* innovative water transport/supply approaches and treatment technologies. These innovations will enable the prudent production and utilization of water close to the point of use in an energy-efficient manner, with wastewater smoothly reintroduced into the water cycle without excessive energy consumption.[251,252] Specifically, solar-powered low-energy water purification/harvesting technologies may obviate the need for complicated device configurations and additional electricity input.[253] This offers the possibility of creating highly integrated, portable devices for use in off-grid, remote, decentralized WEIHN settings. For example, solar-driven membrane distillation (MD) with an active volume of $\approx$ 1 m^2 can produce $\approx$4 L per day under 8 h of sunlight in the summer (700 W m^{-2}) without any form of heat recovery to meet the basic drinking water requirements.[184] Moreover, the next-generation WEIHN enables integrated onsite energy generation, nutrient recycling, and water reuse in wastewater treatment facilities to achieve maximal resource recovery. Zero liquid discharge (ZLD), an advanced multi-step water treatment process that involves ultrafiltration,[254] reverse osmosis,[255] and electrodialysis,[256] can be a future solution to both maximizing water recovery in decentralized WEIHN while minimizing the liquid waste from a power generation cycle, resulting in a closed cycle of water treatment and reuse. For instance, ZLD involves multiple mineral precipitation and crystallization steps capable of producing useful salts such as calcium carbonate ($ 350 per ton), which partially compensates for the operation costs of ZLD.[257] To further improve the water treatment and energy generation in next-generation WEIHN, reliable sensors with materials innovations (*e.g.*, anti-fouling coating layer) and accurate data processing algorithms can generate data-driven models to predict pollution events and guide contaminant removal processes. For example, multi-sensor fusion techniques based on extended machine learning algorithms (*e.g.*, neural network) can be applied to integrate multiple water parameters (*e.g.*, flow rate, pH, and inlet/outlet contaminant concentrations) at different spatiotemporal resolutions for fault detection and process control in the next generation WEINN.[258]

Environmental footprints. Next-generation WEIHN targets assessing water and energy footprint refers to the total freshwater and energy directly and indirectly required to produce a commodity or service.[259] Decentralized WEIHN helps reduce CO_2 emissions by promoting the use of renewable energy sources such as solar, wind, and hydropower instead of fossil fuels which are the major contributors to carbon emissions.[260] Various methods can be employed to measure the carbon footprints of WEIHN. For instance, LCA helps identify areas where carbon emissions and energy consumption can be reduced in different unit processes (*e.g.*, water treatment, pumping, distribution) in WEIHN.[261] The close interaction between water and energy in WEIHN also makes it possible to assess virtual water consumption and energy usage by quantitative models. For instance, a fuzzy stochastic multi-objective mixed-integer non-linear optimization model has been used to calculate the water, energy, and carbon footprint to optimize the irrigation rate with an error $<$5%, possessing the potential to maximum net economic benefit, maximum renewable energy production, minimum water footprint, and minimum carbon footprint in WEIHN.[262] In addition, failure detection or diagnosis with efficient methods can be a future solution in next-generation WEIHN. Innovative automatic failure detection techniques such as support vector machine (SVM) can be deployed to assess the condition of infrastructure components.[263] With the development of advanced data-driven and physics-driven techniques, failure detection could be realized more accurately and immediately.

Data sharing, human behaviors, and workforce development. To overcome the long-standing problem of data scarcity in WEIHN, open-source databases should be developed to collect and share data in a standard specification and facilitate calibration and validation of system models. Technologically, advanced methods such as physiological sensors and models can be leveraged to decipher real-world human behaviors and interactions.[264] These efforts can underscore the principles of diversity, equity, inclusion, and accessibility (DEIA) in water systems, maximizing data access among all groups involved in WEIHN. For example, physiological sensors and models could be used to explore an individual-level understanding of operators' acceptance of new technologies, or an individual-level understanding of end-users' acceptance of non-potable water reuse.[265] Consequently, low-cost user-friendly water quality sensors (*e.g.*, nutrients sensors, heavy metal sensors) can be deployed for real-time water quality monitoring across WEIHN in underdeveloped areas to promptly identify water quality problems and present first-hand data for decision-making.[82] In addition, the insights gained from these real-

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time water-energy data can guide the design of multifaceted interventions such as training workshops to enhance operators' skills or policy initiatives in target households.[266] Implementation of renewable energy technologies (*e.g.*, microbial electrochemical systems for hydrogen generation) ensures that the sensor-data-resource in future WEIHN can be reflected in the transition to a sustainable water future.[267]

From the human perspective, solutions centered on human understanding, development of social norms, and trust-building can be implemented in conjunction with human-sensing techniques. By enhancing individual understanding of resource crisis and inequality of resource availability, end-users are encouraged to save water and energy.[268] Developing social norms of appropriate resource use can also reduce waste generation under peer pressure and change human behaviors through social connections.[269] In conclusion, the future of WEIHN hinges on the advancement of data science techniques and the adoption of human-centric solutions, fostering a more sustainable and efficient water-energy system, and involving the cultivation of the necessary workforce skills to support the DEIA in water sustainability.

Conflicts of interest

There are no conflicts to declare.

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