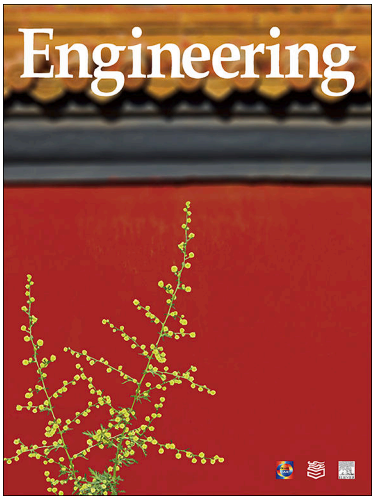

Article

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Research
Environmental Frontiers for Water–Energy Nexus—Article

Integrated Systems Modeling for Assessing the Water–Energy Nexus in Pakistan: Lessons Learned From Coupling LEAP–WEAP Planning Approaches

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Abstract

Systems thinking is crucial in developing strategies for managing and allocating resources in complex scenarios. In the Global South, Pakistan faces challenges such as water scarcity and energy crises, which require integrated approaches. This study combines long-range energy alternatives planning (LEAP) with a water evaluation and planning system (WEAP) to explore potential strategies for managing interconnected water and energy resources in Pakistan. The aim of this work is to identify policy flaws and assess the consequences of water–energy decisions in Pakistan. The findings suggest that maintaining the current status quo will hinder Pakistan's goal of reducing its water consumption by 30% by 2027 and its energy usage by 50% by 2030. Innovative modeling scenarios suggest that energy and water consumption reductions in the agricultural, domestic, industrial, and transport sectors could save up to 15% energy usage by 2050. However, water-saving strategies can inadvertently lead to increased energy consumption, particularly in the agricultural and industrial sectors, with projections reaching an additional 2.8 million tonnes of oil equivalent (MTOE) by 2050. Realizing Pakistan's policy goals and meeting its targets present considerable challenges for the government, especially against the backdrop of severe economic conditions. Current policies necessitate significant investments of 145 billion PKR (~500 million EUR or USD) for water conservation and an additional 10 billion PKR for energy-conservation measures by 2030. Despite international financial aid, the success of these initiatives is at risk due to political instability, administrative weaknesses, and institutional shortcomings.

Keywords Urban and regional energy governance; Water spatial planning; Water–energy nexus; Sustainable development

1. Introduction

Dealing with the complex and unpredictable global landscape presents significant obstacles to achieving lasting and environmentally friendly social progress, especially in ensuring consistent water and energy resources while preventing environmental harm [1–3]. By 2050, global demands for water and energy are expected to rise by 55% and 80%, respectively, compared with 2015 [4]. It is therefore crucial to conduct thorough studies on water–energy systems to ensure more sustainable use of those resources. Water and energy are strongly linked, with energy being essential for utilizing water resources. About 8% of total global power generation is dedicated to water pumping, treatment, and transportation [5,6]. Moreover, energy transformation and distribution involve the use of water, especially in hydroelectric, nuclear, and thermal processes [7]. Around 15% of the world's water usage is attributed to energy-related industries [8].

In Asian and African regions, energy demand is rising due to water scarcity and climate change. Both the Millennium Development Goals (MDGs) and the current Sustainable Development Goals (SDGs) focus on addressing this issue in depth [9], with special regard to SDG 6 (clean water and sanitation) and SDG 7 (affordable and clean energy) [10]. Increased recognition and understanding of these issues, along with cross-disciplinary collaboration and strong political will, can overcome existing barriers. The United Nation's transition from MDGs to SDGs emphasizes the global urgency to address issues linked to human prosperity, planetary peace, and proactive fulfillment of basic needs [11].

Pakistan heavily relies on fossil fuels for about 80% of its energy supply, with domestic oil only meeting about 16% of demand [9,12]. Imported oil contributes to higher expenses, while reducing imports would benefit the economy [13] on top of bringing obvious socioecological benefits. As a response to all of this, Pakistan is investigating its untapped renewable energy sources, which include hydroelectric, solar, and wind power [14]. Energy resources are often associated with pollutant and greenhouse gas (GHG) emissions, further highlighting the importance of energy conservation in sustainability-related goals. In parallel to energy-related issues, the issue of water scarcity is escalating with each passing day. According to UNESCO report [15], approximately 3.6 billion people around the world reside in regions with limited access to water, accounting for nearly half of the global population. By 2050, experts predict this number may rise to 5.7 billion [15]. According to the World Bank [16], 68% of the global population has access to basic sanitation, leaving the remaining one-third of humans without this essential service. Only 39% of individuals with access to sanitation have safe sanitation measures in place.

Old projections about Pakistan experiencing water shortages and decreased water supply [17] have been confirmed by records: Water availability dropped from 5260 m^3 per capita per year in 1951 to below 1000 m^3 per capita per year in 2016 [18], as expected due to demographic growth, increased industrial use, and overall resource mismanagement. Climate change may negatively impact these data by further decreasing water availability. In comparison with other developing (or Global Southern) countries, Pakistan has a limited per capita water storage capacity of approximately 100 m^3, representing just 10% of the total annual streamflow [19].

Significant progress has been made in the quantification of the water–energy nexus through various sustainability approaches, including national footprint accounts (NFAs), ecological footprints (EFs), life-cycle assessment (LCA), material flow analysis (MFA), environmentally extended economic input–output analysis (EEIOA), emergy assessment (EMA), and exergy analysis (EXA) [20]. Numerous research efforts have modeled the intricate dynamics of the urban water–energy nexus, with notable studies such as that by Kenway et al. [21] delving into this complex interplay. Venkatesh et al. [22] employed input–output analysis (IOA) modeling to scrutinize the interdependencies between the energy and food sectors in Turkey. Chen and Chen [23] combined economic input–output analysis (EIOA) and LCA to assess water consumption and CO_2 emissions in China’s wind power sector, providing insights into the water requirements of wind power generation and its environmental implications. Among these studies, multi-regional input–output (MRIO) accounting, which utilizes regional economic input–output tables and inter-regional trade matrices, has been frequently employed to explore urban energy and water systems, often focusing on single elements such as virtual water, energy, or carbon footprints [24].

There has been a growing focus on the water–energy nexus because of its worldwide significance and the effects of global environmental changes. The *UN World Water Development Report 2014* focused on the theme of “water and energy,” highlighting their interrelations [25]. Given the strong connections between water and energy systems, it is important to consider them jointly [26]. Water and energy are crucial resources that are vital for the functioning of human societies, and the way we exploit these resources has a significant impact on the environment in the Anthropocene [27,28].

The impacts on energy are expected to be substantial as pollution increases and global water resources come under increased pressure in the future [29,30]. Research on the water–energy nexus has been instrumental in enhancing our understanding and examination of water–energy interactions. Investigations have progressively expanded to include a comprehensive analysis of related elements such as climate factors [31], resource reuse [32], urbanization [33], new energy applications [34,35], and specific sectors [36,37]. These comprehensive studies have broadened the field and led to new methods of studying the water–energy nexus.

Looking at the literature on long-range energy alternatives planning (LEAP) and water evaluation and planning system (WEAP) model use for nexuses, Lin et al. [38] established a LEAP–WEAP model for Xiamen City by devising 11 scenarios and examining the impacts of various demand and supply factors on urban energy–water nexus relations at the urban and metropolitan levels. Li [39] previously employed a LEAP–WEAP model to investigate the energy–water relationship in Ningxia—namely, water consumption by energy systems and energy consumption during water resource use—by dividing that Chinese autonomous region into five prefectural-level subregions. Sun et al. [40] utilized a LEAP–WEAP model to examine energy–water nexus relationships in the power sectors of the Beijing–Tianjin–Hebei region under different climate and development scenarios. Agrawal et al. [41] integrated WEAP and LEAP to investigate the effects of climate change on GHG emissions and water consumption in the power sector of Alberta, Canada. Malik et al. [42] used a LEAP–WEAP integrated model to quantify the water–energy–carbon nexus of a coal-fired powerplants in a water-stressed area of Pakistan.

These models have tools for scenario analysis; they also examine the effects of created solutions for water resources and energy consumption on GHG emissions in the region [43]. There are surprisingly few national studies on the relationship between water and energy in Pakistan. Moreover, no study has been done to examine the relationship between all the sectors taken into consideration at the national level and the policy nexus approach. To close this gap, we have conducted a study using a cutting-edge methodology that considers every industry in the nation that uses energy and water. We create a nexus framework that clearly illustrates the impacts of the water and energy laws in place today. This is the first research from Pakistan in which Pakistan’s sustainability goals have been taken into consideration when planning the water and energy systems of several economic sectors, such as transportation, agriculture, industry, and power production. In addition, we identified a sub-sectorial link to thoroughly examine the synergistic impact of water policy on energy policy, which can assist a developing nation in accomplishing both short- and long-term goals.

With their abundance of data, these updated integrated models can be useful for nations like Pakistan that are trying to define and establish water–energy targets. Understanding the interdependencies between energy and water resources in Pakistan is essential for achieving sustainable development. Building upon previous analyses, we introduce an analytical framework for the coupled planning of energy and water resources in Pakistan that integrates LEAP and WEAP models simultaneously. Through this integrated approach, we aim to formulate and assess tailored policies and strategies for the holistic management of energy and water resources at a national scale. This study follows an integrated methodology, marking it as the first comprehensive attempt to address and explore the water–energy nexus at sub-sectoral levels at a country scale. The work successfully results in the development of a methodology that can be used to find water- and energy-saving solutions and measures across all economic sectors. The systems-based thinking and modeling approaches presented herein help identify areas requiring improvement in multi-resources management, planning, and optimization. Some of the key objectives and recommendations of this study include energy conservation, efficient energy resource management, the promotion of renewable energy sources, water conservation practices, and their collective impact on enhancing sustainability and mitigating GHG emissions. This approach can be instrumental in formulating priority development policies and resource allocations compliant with the SDGs while ensuring maximum positive impact across sectors. In contrast to other models, the proposed framework incorporates the interconnections between energy and water resources, delving into specifics such as the energy and water resources utilized in water extraction, transportation, and supply processes. Additionally, within scenario settings, we evaluate the ramifications of sector-specific energy- and water-saving policies, considering the essential prerequisites for achieving long-term sustainable goals.

2. Methods

2.1. The water–energy nexus: Modeling approaches

When it comes to water–energy footprint accounting, two main methodological families are typically used: the bottom–up and top–down approaches [44]. The bottom–up method targets a reduction in resource footprints at the product level by examining basic processes and technologies, whereas the top–down method conducts a broad review of sectoral performance, models resource stocks and flows within water–energy systems across an economy, and then assesses potential footprint reductions at sector and end-use levels. According to Meng et al. [45], developing a robust analytical framework is crucial for advancing sustainable water–energy systems. This framework should encompass a solid conceptual basis, dependable algorithms, and comprehensive datasets to accurately measure the water–energy relationship and address related trade-offs.

Many developing countries implement sectoral policies, that address objectives individually and overlook their interconnectedness. Bazilian et al. [46] indicates that barriers to a collaborative approach to climate action, affordable and clean energy, sustainable communities, and water use efficiency include complex interdisciplinary connections, economic factors, weak political motivation, and underdeveloped institutional structures. Taking a sectoral approach under the SDGs leads to inequity and duplication in resource allocation, negatively impacting resource use. Moreover, translating study findings into government policies is challenging due to differences in research focus and data [47]. For instants, Howells et al. [48] has mainly focused on connections between two sectors at a time, capturing only part of the interrelationships among water, energy, and food.

The climate, land, energy, and water (CLEW) tool provides an integrated framework for quantifying sustainable systems and assessing resource interconnections in developing economies. It keeps track of the resources and technologies needed to achieve particular development objectives, going beyond the constraints found in single-sector modeling tools such as LEAP for energy policy analysis and WEAP for water resource assessment [49]. Expanding the CLEW model's structural scope to incorporate societal and economic simulations—such as population dynamics, gross domestic product (GDP), urbanization trends, and international trade—would enhance water–energy nexus assessments. Addressing trade-offs in water–energy systems requires a spatially specific approach that focuses on prioritized technology deployment and policy management. For instance, study [50] have proposed utilizing a spatially varying water stress index to assess water usage, considering resource scarcity in various regions and assisting in decision-making regarding bioenergy technology implementation. Collaborative efforts among governmental authorities, organizations, research agencies, and institutes are vital in establishing datasets tailored to local resource conditions and conflicts for robust water–energy nexus quantifications.

For examining energy–water connections in cities, the LEAP–WEAP model [51] stands out, having unique benefits compared with other models. WEAP differs from other dynamic models by including advanced hydrological analysis tools for water supply simulation. This allows for detailed representations of river runoff, water intake points, and water transfer distances. WEAP models are known for their user-friendly interfaces and straightforward operation procedures in comparison with computable general equilibrium models. In 2012, the Stockholm Environment Institute (SEI) conducted an integrated study using LEAP and WEAP, aimed to analyze the potential effects of desalination on California's water and energy systems and related GHG emissions [52]. LEAP–WEAP models possess integrated data-transmission functions that enable the sharing of core parameters and simulation results between energy and water domains, thereby facilitating nexus analyses [51].

2.2. Development of a LEAP–WEAP integrated model for Pakistan

2.2.1. Energy demand module construction in LEAP

The demand module encompasses five key economic sectors: domestic, commercial, industrial, transport, and agriculture. It serves as the foundation for modeling final energy consumption requirements. To forecast energy demand and supply, consumption data from the reference year 2020 were employed. The demand analysis relies on factors such as activity level, total energy, and demand cost. The final energy intensity is established by assessing each sector's activity level and total annual consumption. More specifically, the activity level pertains to the number of electric consumers, while the final energy intensity reflects electricity consumption per consumer.

For energy demand estimation, the energy sectors can be divided into sub-branches, if data are available. For the final energy demand (ED) of a sub-branch, Eq. (1) is used:

$$\mathrm{ED} = \sum_i \sum_j \sum_k \mathrm{AL}_{i,j,k} \times \mathrm{EI}_{i,j,k} \tag{1}$$

where AL is the activity level, EI is energy intensity, *i* is the partial aspect, and *j* and *k* respectively denote the sub-sector and energy type. The variable *i* is used as an index representing different partial aspects related to energy consumption. These partial aspects could represent different dimensions or components of energy usage within the system being modeled. AL encompasses various energy-related activities, comprising socioeconomic indicators such as population, GDP, energy users, and land use.

Energy branches are structured based on the nature of energy-consuming activities and the types of energy utilized. Data-collection methods, including fieldwork, enterprise investigations, expert consultations, and literature reviews, are employed to gather relevant data and evidence for branch establishment. Key references for further analysis include documents such as the *Pakistan Energy Yearbook 2020* [53], the *Economic Survey of Pakistan*, and *State of Industry reports* [54], along with information from the Pakistan Bureau of Statistics. These references have aided in identifying sectors of particular importance within Pakistan. For a more detailed analysis, interested readers are referred to Text S1 in Appendix A.

2.2.2. Water demand module development in WEAP

In the WEAP model, three methods are used to predict demands [51]:

(1) **The standard water use method:** In this method, users define activity levels (e.g., people, households, and land area) for each decomposition level and multiply them by annual water use.

(2) **The FAO crop water requirement method:** This method estimates irrigation requirements for demand points based on simplified hydrological–agricultural processes, including precipitation and evapotranspiration.

(3) **The direct method:** In this method, water demand can be imported directly from files or entered manually into the model. For more detailed analysis for the sectorial demand estimation, interested readers may refer to Section S2 in Appendix A.

In our study, the estimation of water consumption (WC) in the power sector is derived from calculations provided in Ref. [55]. In determining the WC of hydropower, our initial step involves calculating the total $\mathrm{WC}_{h.\mathrm{total}}$ ($\mathrm{m}^3\cdot\mathrm{year}^{-1}$) for each hydropower plant *h*, as per Eq. (2):

$$\mathrm{WC}_{h.\mathrm{total}} = 10^3 \times \sum_{i=1}^{n} \mathrm{Ai}_h \times E_h \tag{2}$$

where Ai_h represents the surface area (m^2) and *n* represent the number of the open water surface *i* of power plant *h*, while E_h ($\mathrm{mm}\cdot\mathrm{year}^{-1}$) is the average annual evaporation from the reservoirs of power plant *k*. In some cases, the hydropower plants have multiple open water systems the total surface area and evaporation rates must be calculated by summing the contributions of each individual system.

The WC in a thermal power plant depends on factors such as the plant's electricity generation, cooling method, and fuel type. Therefore, a first step involves compiling an inventory of all thermal power plants, along with their cooling systems, fuel types, and installed capacities—data taken from Ref. [56]. The total WC_t per fuel type *t* ($\mathrm{m}^3\cdot\mathrm{year}^{-1}$) is calculated based on Eq. (3):

$$\mathrm{WC}_t = \frac{\mathrm{IC}_{k,t}}{\sum_{k=0}^{n}\binom{n}{k}\mathrm{IC}_{k,t}} \times \mathrm{El}_{k,t} \times \mathrm{WC}_{t,c} \tag{3}$$

where $\mathrm{IC}_{k,t}$ is the installed capacity (MW) of thermal power plant *k* using fuel type *t*; $\mathrm{El}_{k,t}$ is the total electricity generation ($\mathrm{TJ}\cdot\mathrm{year}^{-1}$) utilizing fuel type *t*, cooling system type *c*; and $\mathrm{WC}_{t,c}$ ($\mathrm{m}^3\cdot\mathrm{TJ}^{-1}$) is the water footprint of the electricity generated by a plant with a specific cooling type and fuel.

2.3. Coupling LEAP–WEAP models: The water–energy nexus framework

For this study, the energy and water planning tools LEAP and WEAP—both created by the SEI—were chosen due to their relatively easier modeling environment in comparison with other available options, as well as their seamless integration. The model is divided into two sections: a water systems model and an energy systems model. These parts were developed in WEAP and LEAP, respectively, and were eventually combined to form the nexus. Operating on the energy balance principle, LEAP is used for energy policy analysis, tracking the energy production, consumption, and related accounting of GHG emissions. WEAP, which is based on the mass balance principle, is used for water spatial planning and policy formulation [57].

This study incorporates sector settings for LEAP and WEAP within the analytical framework of the energy–water nexus model, illustrated in **Fig. 1**. The framework encompasses the supply and demand aspects of both energy and water systems, along with their interconnections. Each system comprises three main sectors—namely, domestic, agricultural, and industrial; these sectors are then subcategorized based on energy and water consumption. Thus, the descriptions of water and energy resources made by WEAP and LEAP can be successfully linked from one model to another, allowing the simulation of interactions between energy and water systems.

In the WEAP model, the total water supply is predicted. Based on these predictions, the energy consumption for water withdrawal, transport, and treatment is estimated, with reference values available for different components of the water supply [50]. These linkages are summarized in **Fig. 1**. Following Lin et al. [38] and Liu et al. [51], we divided the connections into two categories:

(1) **Interactive links:** These represent the use of one resource to produce another resource's services, such as energy for water treatment and water for thermal power cooling, primarily occurring on the supply side.

(2) **Connected links:** These represent water and energy resources connected in devices that are designed to provide other services, such as water heating and clothes washing, mainly occurring on the demand side.

The provided nexus framework simulates the relationship between energy production/consumption and water supply/demand across three primary sectors: household, agricultural, and industry. It does this by integrating the LEAP and WEAP models. In linking WEAP to LEAP interactions between sectors and socioeconomic connections, in the domestic sector, the WEAP model takes into consideration the amount of water used for drinking, cooking, and sanitation, while the LEAP model monitors energy use for tasks, such as lighting, cooking, and water pumping. Water demand is affected by changes in energy consumption (e.g., energy-efficient appliances) and vice versa, as reflected in the interactions between these activities. With WEAP simulating water consumption for livestock and irrigation, the model in the agriculture sector depicts how energy is utilized for machinery and water pumping. A key interaction is how shifts toward energy-efficient irrigation systems affect water consumption, thereby influencing agricultural output and economic performance. LEAP monitors energy usage in the industrial sector for processes including steam generation, heating, and cooling, while WEAP monitors the amount of water used for such purposes. Using the nexus approach, we can examine how energy and water efficiency can lower operating costs and environmental effects, which in turn affect industrial productivity and sectoral economic contributions.

Feedback loops—in which modifications to one system have an impact on another—are captured by the framework. For example, a major premise of our model is that population growth would increase the energy requirement for water treatment, which would increase water withdrawals and affect patterns of energy consumption and the water supply system. This relationship is crucial in comprehending how policy changes targeted at one area might have repercussions for the entire nexus.

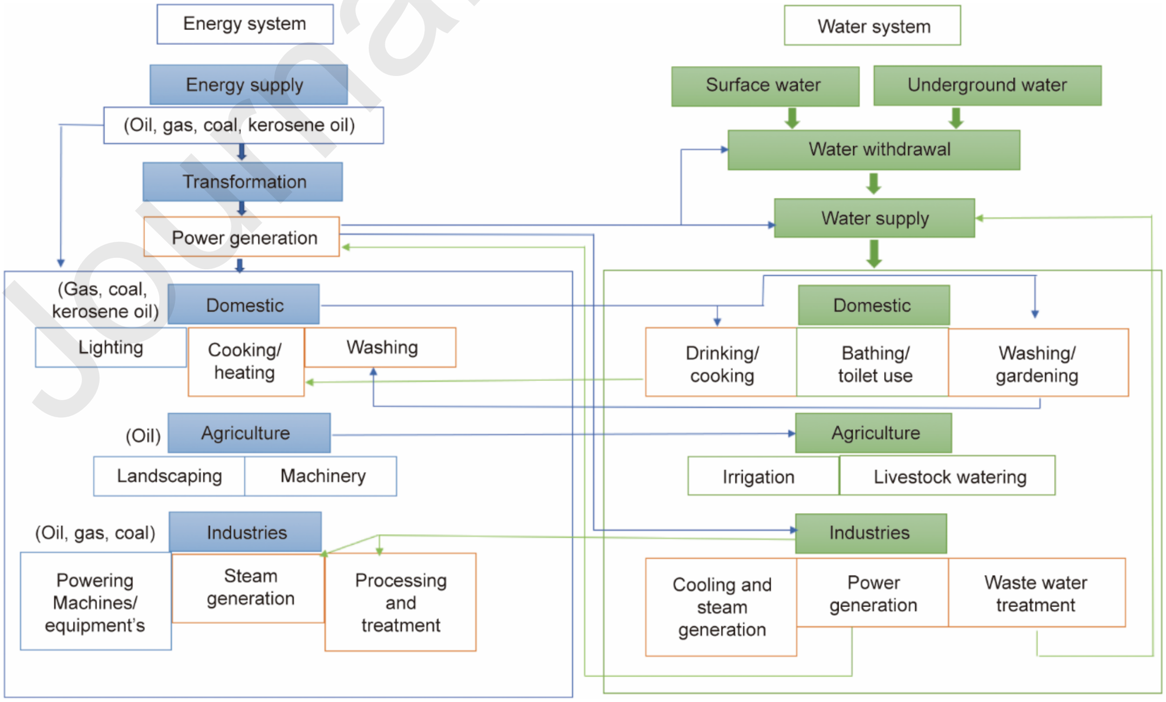

Fig. 1. The energy–water nexus analysis framework.

2.4. Scenarios construction in the LEAP–WEAP coupled model

To define and design various scenarios for analysis, business-as-usual (BAU) scenarios were initially developed separately in LEAP and WEAP (Fig. 2). These scenarios were configured based on activity levels derived from core parameters and on extrapolation, reflecting current consumption trends without interventions. Next, 24 sub-scenarios were designed to support ten main scenarios, each illustrating the energy and water conservation performances along with the combined impacts of individual national policies (Tables S1 and S2 in Appendix A). This integration of sub-scenarios from the main sectors (i.e., domestic, transport, agriculture, industry, and power generation) was carefully carried out to establish the links and nexus between both models' sub-sectors. Scenarios with parameters were adjusted based on Pakistan's governmental policy measures; future trends in energy and water use follow current consumption trends.

The key assumption set for the LEAP–WEAP integrated model is shown in Fig. 2. LEAP includes four modules: key assumptions, demands, transformations, and resources. Of these, the demand and transformation modules are the most important. The WEAP model was applied to predict urban water supply and demand under various scenarios. Key assumptions provide the key variables of the model, such as GDP, GDP growth rate, total population, population growth rate, number of households, per-capita income, and sectorial GDP contribution. The basic assumptions used in the Pakistan LEAP model are the social, economic, and demographic indicators. The population growth rate of 2.4% from *Statistics 2017* [58] was used for this analysis. Pakistan's total GDP of 300 billion USD refers to 2019–2020.

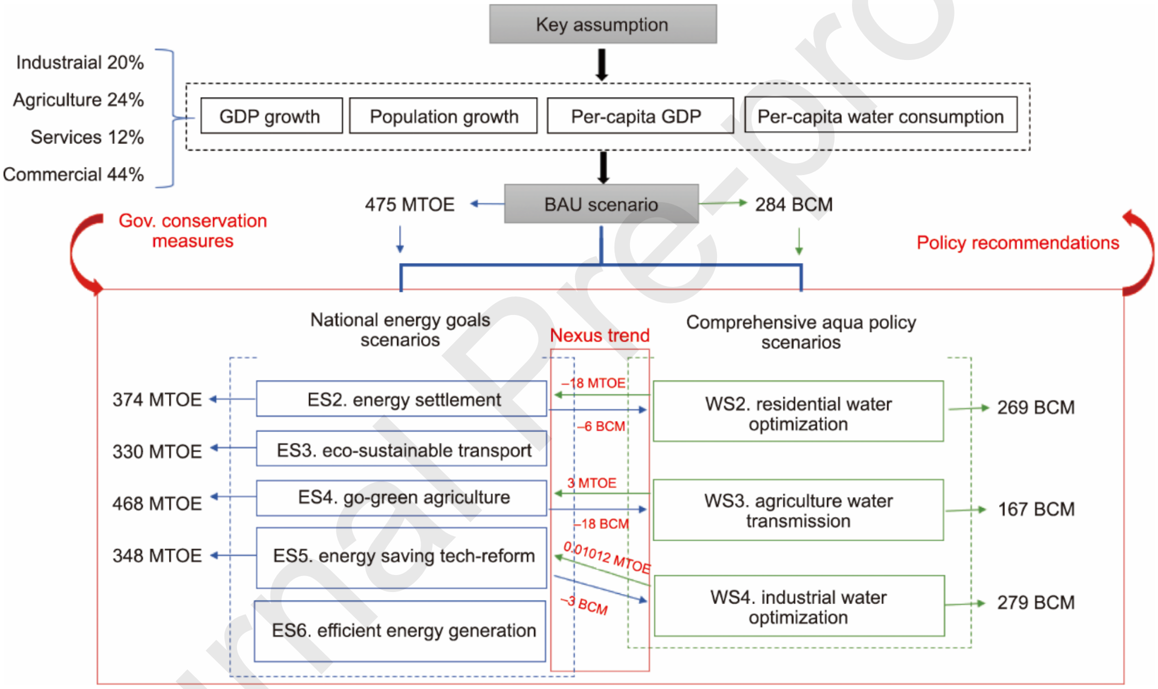

Fig. 2. Scenario setting for energy–water modeling. ES: energy system; WS: water system; MTOE: million tonnes of oil equivalent; BCM: billion cubic meters (10^9 m^3).

3. Results and discussion

3.1. Policy intervention and sectorial energy–water consumption: A comparative analysis

In the BAU scenario, energy consumption steadily increases over time, with demand being driven by factors such as population growth, economic growth, and technological advancements (Fig. S1 in Appendix A). Between 2020 and 2030, an approximately 200% increase in energy consumption is calculated, up to 164 million tonnes of oil equilalent (MTOE), linked to growing industrial activities, urbanization, and an increasing dependence on energy-intensive technologies and appliances. Between 2030 and 2040, a slower yet significant growth rate is expected (nearly 80% in that decade alone), resulting in a total energy consumption of 296 MTOE. From 2040 to 2050, the energy consumption is projected to keep increasing (a 10-year increase of 60%), reaching 475 MTOE. Following BAU, overall growth greater than 750% is estimated from 2020 to 2050, highlighting the critical importance of planning for energy conservation in the future.

In light of the problematic BAU scenario, a national energy-saving goal (NESG) scenario was also built, with particular measures and policies being put in place across different sectors to decrease energy consumption and increase energy efficiency. The annual energy consumption also starts at 55 MTOE in 2020 but then takes a distinct path from that of BAU, at 88 MTOE in 2025 and 110 MTOE in 2030—that is, 100% compared with BAU in 2020 but –33% in 2030 (Fig. S3 in Appendix A). The consumption peaks in 2035 at 115 MTOE, and then reaches 96 MTOE in 2050, increasing by 75% compared with 2020 but –80% less than in the BAU scenario in 2050.

If no action is undertaken (BAU scenario), water consumption is projected to rise from 207 billion cubic meters (BCM) in 2020 to 229 BCM in 2030—that is, 11% (Fig. S2 in Appendix A)—driven by ongoing urbanization, industrial expansion, and increased agricultural need due to economic growth. Water use is expected to reach 254 BCM by 2040 (11% since 2030, 23% since 2020), in the presence of growing industrial and agricultural activities and, in parallel, of rising demands from the domestic sector as a result of population growth and lifestyle changes. The trend continues upward, with water consumption projected to reach 284 BCM by 2050 (12% since 2040, 37% since 2020).

In contrast, a declining trend in water usage is expected under the application of the comprehensive water policy scenario (CWPS), which focuses on sustainable water management practices and encourages the use of technologies to minimize water wastage and enhance usage efficiency in different sectors. In this scenario, water consumption is projected to decrease to 174 BCM in 2030 (–24% compared with BAU, –16% since 2020), driven by the adoption of water-saving practices in residential areas, improved irrigation methods, and more stringent regulations on industrial water consumption. Under the water policy in 2040, water use declines to 161 BCM (–37% compared with BAU, –7% since 2030, –22% since 2020), in the presence of expected success in sustained efforts to reduce water usage, enhance water efficiency, and encourage water-saving practices among stakeholders (i.e., after investments in public water infrastructures and public awareness campaigns). By 2050, water use under CWPS will decrease to 147 BCM (i.e., –48% compared with BAU, –9% since 2040, –29% since 2020; Fig. S4 in Appendix A).

3.2. The water–energy nexus at the sub-sectoral level

Detailed insights into the connection between the energy system (ES) and the water system (WS) are provided in Table S3 in Appendix A. A comprehensive analysis was conducted on 24 scenarios, consisting of six primary scenarios and 18 sub-scenarios, specifically addressing energy–water interconnections.

Among these, seven scenarios (three main: ES2, ES4, and ES5, and four sub-scenarios: ES2.2, ES2.3, ES4.3, and ES5.3) reveal a positive impact, indicating that implementing energy-saving strategies contributes to water conservation in the respective sectors. Conversely, two main scenarios (ES3 and ES6) and the remaining 14 sub-scenarios show no significant impact of energy conservation efforts on water consumption. Similarly, the relationship between WS and ES was analyzed across 10 scenarios (four main and six sub-scenarios). Among these, one main scenario (WS2) and three sub-scenarios (WS2.1, WS2.2, and WS3.1) demonstrate a beneficial effect, suggesting that water-saving practices help reduce energy consumption. On the other hand, two main scenarios (WS3 and WS4) and two sub-scenarios (WS3.2 and WS4.1) exhibit an opposite effect, where water conservation measures lead to higher energy usage. Additionally, one scenario (WS4.2) shows no significant impact of water-saving efforts on energy consumption.

3.2.1. Moving toward efficiency: Energy-saving measures and effects on energy conservation

An examination of the projected energy-saving efforts in different sectors under various scenarios lead to consistent improvement in efficiency and effectiveness over time. Between 2020 and 2050, these efforts consistently lead to increased energy savings due to continuous enhancements, broader implementation of sustainable methods, and technological progress, with varying percentage contributions from different sources. The implementation of specific measures customized for different sectors helps to conserve energy. Efforts to improve energy efficiency in homes, encourage eco-friendly transportation, adopt sustainable farming methods, and update energy technologies in factories prove to be crucial in lowering energy usage.

The ES1 scenario represents the BAU scenario in which no energy-saving measures are applied and no deviation is shown, indicating zero energy conservation efficiency. In the ES2 scenario, the national energy saving initiative is centered on enhancing energy efficiency in households and buildings, leading to energy savings of around 9 MTOE by 2030 compared with the current trend. By 2040, ongoing advancements in energy efficiency result in significant savings, totaling approximately 41 MTOE. By incorporating more energy-efficient appliances and renewable energy sources by 2050, the initiative is projected to achieve significant savings of around 101 MTOE. In the ES3 scenario, by investing in environmentally friendly transportation options and promoting the adoption of public transit and electric vehicles, significant energy savings of around 24 MTOE can be achieved by 2030. In 2040, the initiative will grow, leading to an increase in energy savings of approximately 72 MTOE as more individuals switch to sustainable transportation options. In the year 2050, through the ongoing promotion and acceptance of environmentally friendly transportation options, the project will reach its peak savings, totaling around 145 MTOE. Within the ES4 scenario, sustainable farming practices and the integration of renewable energy lead to modest energy savings of approximately 2 MTOE by 2030. In 2040, the adoption of energy-efficient techniques by more farms will result in approximately 5 MTOE savings, thanks to the encouragement of more environmentally friendly agricultural practices. By 2050, the initiative manages to achieve a small increase in energy savings, reaching around 6.5 MTOE thanks to the ongoing adoption of sustainable farming practices, despite challenges. In the ES5 scenario, industrial energy reforms are projected to save around 18.7 MTOE by 2030, due to the increased adoption of energy-efficient technologies and processes. By 2040, through ongoing improvements, along with the incorporation and encouragement of energy-efficient technologies, savings are projected to rise to approximately 68 MTOE. In 2050, due to advancements in energy technology and the widespread adoption of sustainable practices, the initiative results in substantial savings of around 126.4 MTOE, as depicted in **Fig. 3**.

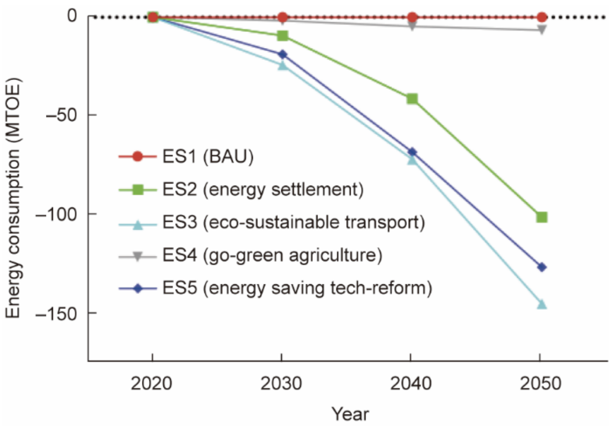

Fig. 3. Energy-saving potential along the main scenarios. ES6 scenario represents power generation, while the transformation of this generated power into electricity is accounted for in other scenarios.

Although each project functions separately, they have synergies that enhance the overall effect. For example, advancements in eco-friendly transportation can help decrease energy usage in the transportation industry while simultaneously promoting reduced emissions and healthier surroundings. These improvements align with initiatives in local energy production, environmentally friendly farming, and sustainable economic development. The consistent rise in energy savings over time demonstrates a dedication to long-term sustainability and resilience. Through the exploration of energy-efficient technologies, the encouragement of sustainable practices, and the promotion of behavioral changes, societies have the potential to alleviate the negative impacts of climate change, decrease reliance on limited resources, and create stronger and more successful communities. To achieve significant energy savings, it is essential to constantly innovate, collaborate, and receive policy backing at various levels—local, national, and global. It is essential for governments, businesses, communities, and individuals to collaborate in advancing the shift toward a more sustainable energy future.

3.2.2. Energy-saving effects by sector: A detailed analysis

In the ES1 scenario, no energy-saving measures are put into place. As a result, no energy savings are shown for any of the years. The results of the ES2 scenario emphasize the need to implement different approaches to enhance energy efficiency in household environments. Within the ES2.1 sub-scenario, the increase in energy consumption of 26 MTOE suggests that the electricity expansion plan based on government policy will lead to increased energy consumption in comparison with the ES1 scenario. This would entail an expansion of renewable energy sources or increased grid efficiency. Meanwhile, despite the negative energy consumption value of 51 MTOE in sub-scenario ES2.2, which reflects the impact of energy-efficient electrical appliances, significant energy savings are still achieved. This highlights the benefits of adopting energy-efficient technologies such as light emitting diode (LED) bulbs, energy-efficient refrigerators, and smart thermostats. In sub-scenario ES2.3 the government policy on expanding natural gas access for domestic users, along with the adaptation of energy efficient appliances is projected to lead to energy savings of 76 MTOE by 2050. This scenario ES2 centers on switching to natural gas for heating and cooking needs, while ensuring the use of energy-efficient appliances, highlighting the energy-saving possibilities of various scenarios under the domestic energy settlement initiative (Fig. 4(a)). With different approaches such as expanding electricity availability to users, using efficient appliances, and increasing natural gas usage, all the sub-scenarios result in energy conservation when compared with the BAU scenario, as shown by their negative MTOE values. These efforts focus on enhancing energy efficiency, cutting down on energy usage, and supporting a greener domestic energy environment.

The results of the ES3 scenario emphasize the importance of using sustainable transportation methods to minimize energy usage and environmental harm. The ES3 data show the energy-saving efficiency expected to result from the measures taken as part of the National Electric Vehicle Policy [59] of shifting to electric vehicles in different years (2030, 2040, and 2050). This scenario delves into the extensive use of electric cars as a substitute for conventional gasoline-powered vehicles. The results from ES3.1 show that the decrease an energy consumption of 43 MTOE is achieved by switching from gasoline cars to electric cars. Simultaneously, the ES3.2 sub-scenario emphasizes the introduction of electric two-wheelers and three-wheelers to replace traditional gasoline-powered vehicles. ES3.2 demonstrates a decrease in energy consumption to 45 MTOE compared with ES3.1, thanks to the use of electric two-wheelers and three-wheelers, leading to decreased energy consumption in urban transportation. The ES3.3 scenario involves the implementation of electric buses in public transportation systems, leading to a decrease in energy consumption of 37 MTOE in the public transportation sector. In the ES3.4 sub-scenario, electric trucks are incorporated into freight transportation fleets to decrease energy consumption by 20 MTOE in the freight transportation sector by 2050. Fig. 4(b) showcases the potential for energy savings in different scenarios within the Eco Sustainable Transport Initiative, focusing on the adoption of electric vehicles in various transportation sectors. These data reveal the role electric vehicles can play in promoting sustainability within the transportation industry.

The ES4 scenario emphasizes the adoption of sustainable practices in the agricultural sector to lower energy usage and minimize environmental harm. The Fig. 4(c) illustrates the energy-saving potential of different mitigation measures in various years (2030, 2040, and 2050), with negative values indicating energy savings. Sub-scenario ES4.1 focuses on the installation and maintenance of mechanical pumps in agricultural operations, highlighting the potential energy savings of 2.5 MTOE that could be achieved through the use of mechanical pumps, resulting in decreased energy usage for irrigation. In sub-scenario ES4.2, the emphasis is on maximizing the use of high-performance electric motors and diesel engines in agricultural machinery and equipment, with a decrease in energy consumption of up to 1.6 MTOE during agricultural activities. Scenario ES4.3 involves incorporating variable-speed drives (VSDs) into agricultural machinery and equipment to enhance control and optimize energy usage, resulting in more efficient operation of agricultural equipment and ultimately reducing energy consumption by 2.4 MTOE by 2050. Overall, the trends shown in Fig. 4(c) illustrate the energy-saving potential of implementing different mitigation measures in agriculture under the specified scenario. The negative values for ES4.1, ES4.2, and ES4.3 demonstrate that these measures could be successful in decreasing energy usage and encouraging sustainability in the agricultural industry as time progresses.

Scenario ES5 illustrates the potential for energy conservation across different industries under various policy changes. These data highlight the potential for energy savings resulting from reforms and technological advancements in various sectors. According to the findings from sub-scenario ES5.1, changes made in the textile industry could lead to energy savings of up to 22.4 MTOE by the year 2050. There is also the potential for energy savings in ES5.2 of 1.6 MTOE by 2050 through reforms in sugar mills, leading to decreased energy consumption in that industry. Significant energy savings in ES5.3 of up to 41 MTOE by 2050 can be attained by implementing variable-frequency drives (VFDs) and insulating steam lines, effectively minimizing energy loss in industrial operations. An energy-saving potential of 32 MTOE resulting in ES5.4 from reforms in the cement industry is highlighted, indicating reduced energy consumption in cement manufacturing processes. In sub-scenario ES5.5, an energy-saving potential of nearly 7 MTOE is achieved through reforms in the pulp and paper industry, leading to decreased energy consumption and a positive environmental impact. ES5.6 reveals an energy-saving potential of 7 MTOE attained through reforms in the fertilizer industry, demonstrating enhanced energy efficiency and decreased resource consumption. Sub-scenario ES5.7 highlights the potential for energy savings of 15 MTOE by 2050 due to reforms in brick kilns, decreasing energy consumption and emissions during brick production. In summary, Fig. 4(d) shows the potential for energy conservation in various sectors under the ES5 scenario, indicating the impact of reforms and technological advancements on reducing energy consumption (i.e., negative values) and promoting sustainability in different industries.

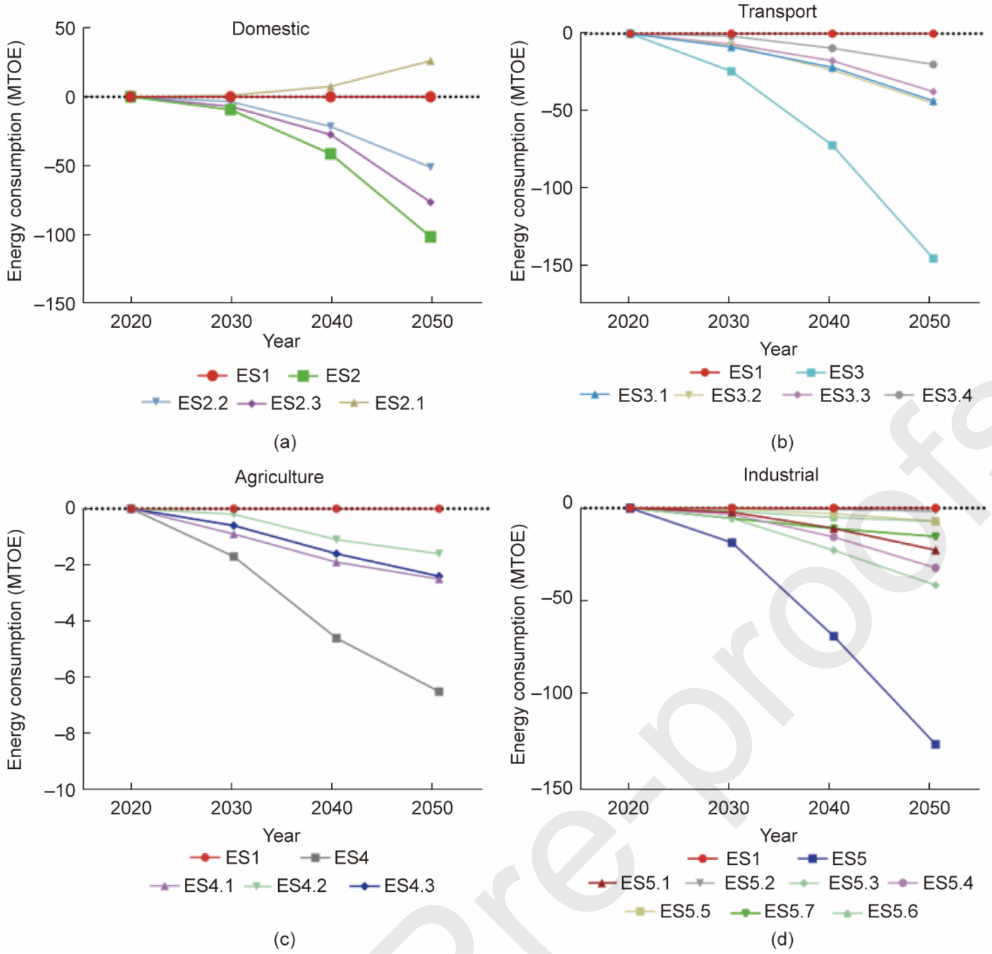

Fig. 4. Scenario-based energy-saving potential by (a) domestic sector, (b) transport sector, (c) agriculture sector, and (d) industrial Sector.

3.3. Aligning water savings with energy-conservation objectives

Fig. 5 illustrates the energy savings resulting from water-conservation efforts in various sectors (i.e., residential, agricultural, and industrial) from 2020 to 2050. Values below zero show a decrease in energy usage compared with scenario WS1 (BAU), while values above zero indicate potential increases, possibly caused by the energy needed for water-saving measures. Scenario WS1 describes a situation in which no particular water-conservation strategies are put into place. Therefore, this scenario shows no notable variations in energy usage over the years from 2020 to 2050. In contrast, the WS2 scenario illustrates a focus on optimizing residential water usage and its influence on energy usage. By 2050, a 4% decrease in overall energy usage is expected, based on significant advancements in residential water-conservation practices and their long-term energy-saving benefits. The results from scenario WS3 highlight the energy implications of enhancing agricultural water transmission, projecting a 0.6% rise in energy consumption by 2050 as a result of such measures, such as promotion of drip irrigation. The energy impact of scenario WS4 is minimal compared with those of the residential and agricultural sectors. By 2050, an almost negligible rise in energy usage (0.002%) is expected due to energy consumption for wastewater treatment in scenario WS4, linked to progress in industrial water-conservation methods and their impact on energy.

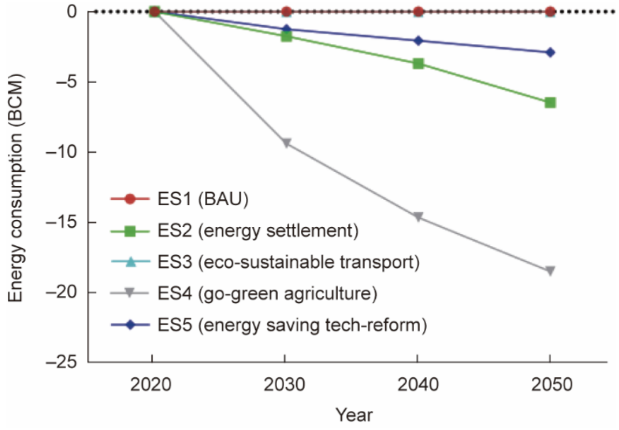

Fig. 5. The energy-saving potential of various water-conservation goals.

3.3.1. Sectoral insights: Evaluating the consequences of water-saving efforts on energy consumption

Fig. 6 shows how energy conservation can vary in various scenarios (residential, agriculture, and industrial) and their different elements (technological progress, shifts in human behavior, use of modern technologies, optimized land use, recycled wastewater, and renewable energy production) by 2030, 2040, and 2050. The domestic sector demonstrates a total energy-saving potential of around 1 MTOE by 2030. Moreover, water-saving measures in residential areas (WS2) lead to a decrease in energy consumption of 5 MTOE by 2040 and 18 MTOE by 2050, demonstrating substantial reductions in residential energy usage over time. As shown in Fig. 6(a), the results from sub-scenario WS2.1 reveal how technological advancements can positively influence residential water consumption while resulting in significant energy savings equivalent to 8 MTOE. The data presented here highlight the positive impact of technological advancements on water conservation, leading to reduced water consumption in residential areas. Sub-scenario WS2.2 demonstrates how alterations in human behavior and lifestyle could affect residential water usage and energy consumption, ultimately reducing energy consumption by up to 10 MTOE by 2050.

The overall results from the WS3 scenario (Fig. 6(b)) suggest that the agricultural sector is projected to experience a steady increase in energy consumption, rising by 0.5 MTOE by 2030. This trend indicates that water-transmission methods in agriculture contribute significantly to energy demand, with consumption expected to reach 1 MTOE by 2040 and further escalate to 2.8 MTOE by 2050. These findings highlight the evolving impact of agricultural water-transmission strategies on energy use over time. In sub-scenario WS3.1 through incorporating modern technologies in agriculture can help conserve water and improve water efficiency in agricultural practices, leading to potential energy savings of 1 MTOE by 2050. Moreover, in sub-scenario WS3.2, optimizing land use and leveling to permit the use of unconventional watering technologies in agriculture may lead to an increase in energy consumption of almost 4 MTOE by 2050.

Additional investigation reveals in scenario WS4, that energy consumption in the “other industries” sector, despite being negligible, gradually rises from 0.003 MTOE to 0.010 MTOE (33%) between 2030 and 2050. This finding highlights the impact of industrial water-management practices, such as wastewater reuse, which contribute to an increase in energy consumption. The positive findings in WS4.1 indicate that energy consumption rises in comparison with the water-saving benefits attained from reusing wastewater in industrial processes to support water-conservation initiatives. Green energy generation does not have a direct impact on energy savings, as shown by the straight line for sub-scenario WS4.2 illustrated in Fig. 6(c).

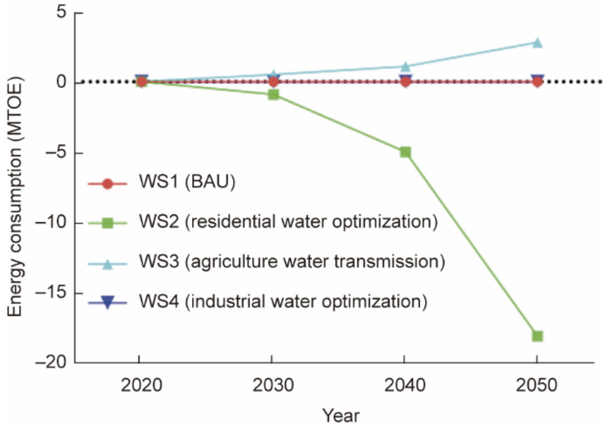

Fig. 6. The energy-saving potential of various water-saving goals by (a) domestic sector, (b) agriculture sector, and (c) other industries.

3.3.2. Water-saving measures and their effects on water conservation

The decreasing trends shown in Fig. 7 indicate that water-conservation measures can result in a decrease in water usage. Decreasing values in the figure indicate a reduction in water usage or consumption compared with the baseline scenario, which assumes zero change. Scenarios WS2, WS3, and WS4 explore various water-saving approaches involving different methods, technologies, or policies to preserve water resources. These measures could involve the implementation of water-efficient technologies, the promotion of water-saving practices, enforcement of water usage restrictions, or improvements in water-management systems. Over time, the negative values tend to increase, showing a greater focus on water conservation efforts as the years go by. This trend indicates that the efforts become increasingly successful in reducing water usage. The magnitude of the values indicates the level of water savings accomplished by each scenario. For example, WS3 seems to be the most efficient in water conservation, resulting in water savings of 41% by 2050 compared with WS2 and WS4, which save 5% and 2% respectively.

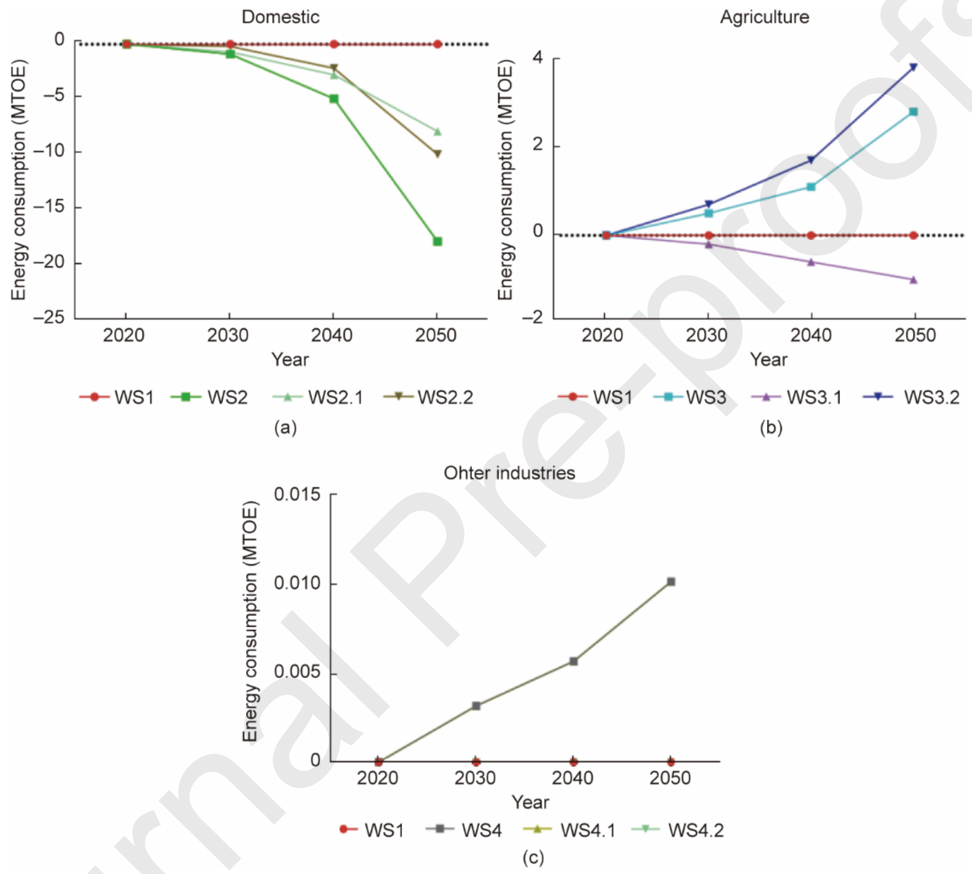

Fig. 7. The water-saving potential of various water-conservation goals.

3.3.3. Sectoral insights: Evaluating the consequences of water-conservation efforts on water usage

Fig. 8 shows projected reductions in water usage by 2050 across different scenarios and sub-scenarios, highlighting the effectiveness of implementing water-saving measures and optimizing water usage across the residential, agricultural, and industrial sectors. These measures include technological advancements, changes in human behavior, and the utilization of alternative water sources, which contribute to sustainability efforts and help conserve water resources for future generations. In the WS1 (BAU) scenario, in which no specific water-saving measures are implemented, there are no projected reductions in water usage by 2050. That is, water consumption remains constant under this scenario, in contrast to other scenarios. WS2 shows significant reductions in water usage in the domestic sector of up to 14.2 BCM by 2050, suggesting that implementing optimal usage measures for residential water can yield substantial savings. Sub-scenario WS2.1, which focuses on technological advancements, contributes 7.3 BCM, while sub-scenario WS2.2, which emphasizes changes in human behavior, contributes 7.6 BCM to reducing residential water consumption by 2050 as shown in Fig. 8(a). In Fig. 8(b), scenario WS3, the agriculture sector shows reductions in water usage of 117.4 BCM by 2050, indicating the effectiveness of implementing water-saving measures in agriculture. Sub-scenario WS3.1 focuses on the adoption of modern technologies in irrigation and farming practices, which contribute to the conservation of 40.8 BCM of water. Sub-scenario WS3.2 involves changes in land use and the utilization of unconventional water sources, further reducing water consumption by up to 76.5 BCM.

The reductions as illustrated in Fig. 8(c) in water usage projected for scenario WS4 by 2050 demonstrate the potential for optimizing water usage in industrial processes, which can efficiently save 4.8 BCM of water in the long term. Sub-scenario WS4.1 emphasizes wastewater reuse, with treated wastewater from industrial processes being recycled and used for non-potable purposes; this reduces the demand for freshwater sources by up to 4.8 BCM by 2050. Sub-scenario WS4.2 focuses on green energy generation, utilizing renewable energy sources to reduce the water consumption associated with conventional energy-production methods, such as thermal power plants; this sub-scenario shows a decrease in water usage of 0.2 BCM.

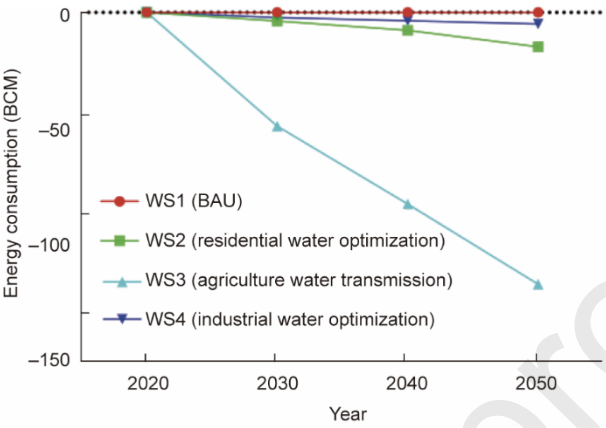

Fig. 8. The water-saving potential of various water-saving goals by (a) domestic sector, (b) agriculture sector, and (c) other industries.

3.3.4. Aligning energy savings with water-conservation objectives

Fig. 9 illustrates the significant water conservation resulting from the adoption of energy-efficient practices in diverse sectors such as households, farming, and manufacturing. These values show water conservation compared with the baseline, where BAU conserves no water. Considering the energy–water connection, adopting energy-efficient practices can have a beneficial effect on water conservation. In scenario ES2 by the year 2050, water savings of around 6.5 BCM are projected due to technological advancements, making up 2% of the total water usage in that year. These findings indicate that efforts to save energy in households play a significant role in decreasing water usage and helping achieve water-conservation objectives.

This study demonstrates that energy-saving goals in scenario ES3 do not affect water consumption in the transportation sector, with a contribution of zero percent, suggesting that energy-conservation efforts in the transportation industry do not have a direct impact on water consumption. However, in scenario ES4 around 18 BCM, significant water-saving potential by 2050 is projected in the agricultural sector, highlighting the impact of energy-efficient practices and technologies in agriculture on water conservation and total water savings. Scenario ES5 indicates potential water savings of around 2.9 BCM by 2050; it has been found that implementing energy-saving measures such as VFD installation and the thermal insulation of steam lines in the industrial sector can help decrease water usage, saving up to 1% of total water usage.

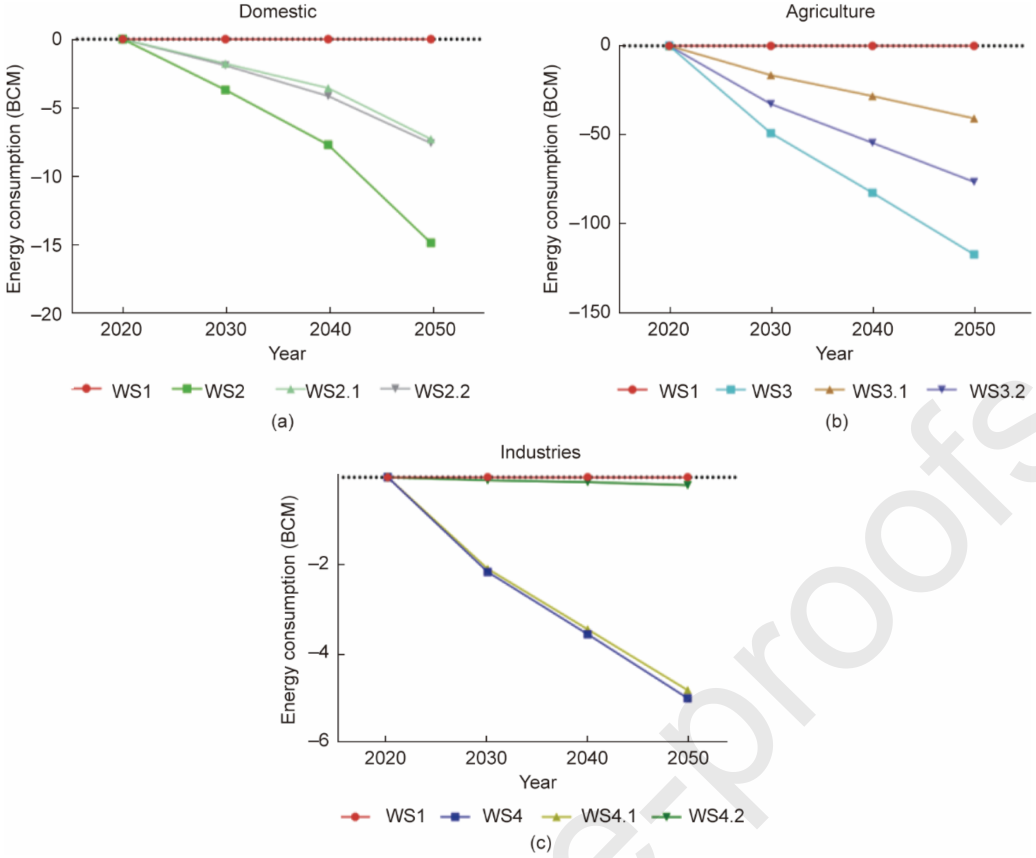

Fig. 9. The water-conservation potential of energy-conservation goals, compared with values from 2020.

3.4. Examining the synergistic impacts of energy and water policies

In efforts toward conserving energy and water resources, various policies are designed and measures are proposed to attain sustainable development objectives. While synergistic effects exist between energy- and water-conservation measures, the nexus between energy-saving measures and water-conservation efforts reveals predominantly beneficial impacts of energy and water conservation efforts across various sectors, including the domestic, agricultural, and industrial domains. It is possible to achieve joint energy- and water-saving effects by implementing energy-saving measures; similarly, water-saving measures can result in energy conservation. In general, the water savings achieved by energy-conservation measures are more remarkable than the energy savings due to water-conservation measures. This is because more water is required during energy utilization than energy is required during water utilization.

Energy-saving measures often directly contribute to water savings. For instance, energy-conservation measures yield potential savings of –27%, –2%, and –33% in the domestic, agricultural, and industrial sectors respectively, while their corresponding impacts on water conservation amount to –2%, –6%, and –1%, respectively. Conversely, energy-saving measures in the transport sector result in significant reductions in energy consumption of up to –38% but do not directly affect water conservation efforts.

Regarding water-conservation objectives, notable achievements are observed across various sectors, including domestic (5%), agriculture (41%), and industrial (2%). However, water-saving policies have varied impacts on energy conservation. In the domestic sector, water conservation has a beneficial impact, contributing to energy savings of approximately 4%. Conversely, in agriculture and industry, water conservation results in increases in energy consumption of 0.6% and 0.002%, respectively. The increases in energy consumption within the agricultural and industrial sectors can be attributed to specific factors such as land-management practices for irrigation, which necessitate increased energy usage for activities such as leveling through machinery. Additionally, industrial wastewater treatment processes contribute to the increasing energy consumption observed in the industrial sector. These trends underscore the complex interplay between water policies and energy-conservation efforts, highlighting the need for comprehensive strategies to address both resource conservation and efficiency.

3.5. Evaluating the combined impact of energy–water saving measures: Perspectives from the short to long term

Our comprehensive evaluation using integrated modeling techniques reveals significant potential for joint energy- and water-saving measures. By the year 2030, these measures could collectively save approximately 54 MTOE, with projections rising to

186 MTOE in 2040 and 379 MTOE by 2050. These substantial impacts shown in (Tables S3 in Appendix A) are attributable to the implementation of energy-saving measures across diverse sectors, including the domestic, transport, agricultural, and industrial sectors, alongside corresponding water-saving measures excluding the transport sector, which alone could save an estimated 18 MTOE by 2050. Due to wastewater treatment and land-use management, the energy demand is expected to increase to 2.8 MTOE, making the net energy saved approximately 15 MTOE by 2050 (i.e., 15% of the total energy consumption in 2050).

Moreover, water-saving initiatives demonstrate promising outcomes, indicating a potential total water saving of 55 BCM by 2030, which is projected to increase to 94 BCM by 2040 and 137 BCM by 2050 as shown in (Fig. S4 in Appendix A). Remarkably, water-saving measures are forecasted to contribute to conserve 28 BCM of water due to a total reduction in energy consumption by 2050, amounting to nearly 19% of the total water consumption projected for the same year. These findings underscore the significant potential of coordinated energy- and water-conservation efforts in addressing resource sustainability challenges.

3.6. Analyzing the energy–water–carbon nexus: Toward the sustainable development goals

Overall, this study offers a long-term pathway extending up to 2050. The results underscore the importance of ongoing policy support and technological innovation in maintaining a trajectory of energy conservation. To evaluate various measures for achieving the SDGs, it is necessary to estimate the country's efforts toward reducing energy consumption, water usage, and emissions related to the energy sectors [51,60]. With its current energy- and water-saving measures, Pakistan is trying to achieve the SDGs. After identifying the impacts of policies on energy and water conservation, the next step is to evaluate the impact of these measures on GHG emissions. The four identified sectors (industrial, transport, domestic, and power sectors) have the highest emissions as illustrated in (Fig. S5 in Appendix A), with a projected total of 661, 1178, and 1940 million tonnes of CO_2 equivalent ($MtCO_2eq$) for the years 2030, 2040, and 2050 under BAU. After a careful analysis of the energy-saving measures in each sector, our results show that the total GHG emissions are expected to be reduced to 490 $MtCO_2eq$ by 2030—a significant decrease in total emissions. After reaching a peak in 2030, the GHG emissions gradually decline. In 2040, GHG emissions will be 392 $MtCO_2eq$, decreasing to 184 $MtCO_2eq$ by 2050, with reduction trends of GHG emissions by 26%, 67%, and 90%. Pakistan intends to showcase the institutional frameworks, governance strategies, and national efforts that have been implemented since 2016 to increase participation in the updated nationally determined contributions (NDCs), with plans to establish a cumulatively ambitious goal of voluntary and conditional contributions to reduce Pakistan's expected emissions by 50% overall by 2030 [61]. Unfortunately, the nation's current decrease in emissions, given the combined effects of water conservation on energy consumption, will only reach 32% by 2030, which falls short of the goal.

An assessment of the water situation in Pakistan shows that the nation's total available water resources stand at approximately 263 BCM. According to the water resources vulnerability index (WRVI), if annual withdrawals fall within the range of 20%–40%, a country is classified as being under water scarcity. Pakistan's WRVI currently stands at 77%, indicating extreme water scarcity in this country, necessitating urgent water scarcity management efforts [62,63]. In light of ongoing policy implementation, modeling results indicate a modest reduction in the WRVI to 66% by 2030 and 56% by 2050 if current water resources remain the same. Although this reflects progress, these levels of water scarcity remain high. The National Water Policy of Pakistan (NWPP) has set ambitious targets to curb water consumption by 30% by 2027 through enhanced water use efficiency measures across various sectors [64]. However, current study findings suggest that existing water-saving measures may only yield a 24% reduction in water consumption by 2030, falling short of the targeted goal. This result underscores the need for more effective and comprehensive strategies to address Pakistan's water scarcity challenges, emphasizing the importance of innovation, conservation, and sustainable water-management practices across sectors.

Pakistan's response to the challenge of water security materialized in the form of the NWPP in 2018. While the policy was initially perceived as a participatory and fruitful endeavor involving relevant stakeholders, further evaluations and analyses are warranted to assess its implementation feasibility and pinpoint any existing gaps or priority areas within the policy [65,66]. An examination of the sectoral water demand revealed that the agriculture sector is the largest water consumer, accounting for up to 178 BCM, which is projected to increase to almost 190 BCM by 2030. Current water-conservation measures could potentially reduce this consumption to 141 BCM by 2030, indicating an 18% reduction capacity attributed to existing policies. However, the government's target of saving 30% of water highlights the necessity for revising current water-management policies, which necessitates new amendments and measures. To enhance water-conservation practices, several policy suggestions are proposed below, drawing inspiration from practices adopted by both developed and developing nations to optimize water-conservation efforts.

3.6.1. National water policy: A critical review and recommendations

Pakistan's agricultural sector grapples with irrigation challenges, with approximately 70% of cultivated land relying on irrigation. This vital sector draws its irrigation water from wells, dams, canals, and rivers. However, numerous barriers hinder agricultural productivity, including resource mismanagement, technological limitations, inadequate investment, infrastructure deficiencies, trade issues, and severe electricity and energy shortages [67,68]. Water pricing policies, as dictated by the Indus River System Authority (IRSA), are crucial for water resource management. The Indus River System receives an average annual water inflow of approximately 146 million acre-feet (MAF), primarily sourced from snow and glacial melting. However, Pakistan's actual water availability at canal head works stands at around 98 MAF, with estimated annual losses of 48 MAF. These losses exacerbate water scarcity issues and contribute to escalating water pricing challenges over time. Chen et al. [69] emphasize that irrigation water shortages predominantly result from the rigid structure of the current irrigation water supply system, rather than existing water pricing practices. Moreover, simulations of water pricing dynamics reveal that irrigation water demand exhibits minimal responsiveness to variations in alternative irrigation water prices.

Qamar et al. [70] elucidates that Pakistan's irrigation department has only managed to recover approximately 20% of the full supply cost, with the provincial government bearing the remaining burden. Over the previous 14 years (2003–2016), the provincial government had contributed a substantial amount, totaling 111.4 billion PKR, with an average of 8 billion PKR per year. During this period, the full supply cost surged from 4.3 to 114 billion PKR, while revenue collection declined from 1.2 to 1 billion PKR. This persistent underfunding of irrigation-related infrastructure underscores its financial unsustainability. Moreover, it is alarming that nearly 70% of the total full supply cost is allocated to operational needs (establishment cost), leaving only 30% for infrastructure maintenance.

Fig. 10 [71] illustrates the annual water consumption per hectare of the world's top agriculture-producing countries in 2020. This comparative metanalysis suggests that Pakistan's water policy could still place it last among these water-consuming nations, with a consumption of up to 6.1 BCM per hectare by the agriculture sector after effective policy implementation. The combined effects of the water–energy–policy nexus indicate that a reduction in water consumption of up to 4.3 BCM per hectare is achievable, which is considered satisfactory. To realize these water-saving goals, Pakistan must enhance its water-saving measures and review its current policies based on the recommendations provided below, drawing insights from other studies.

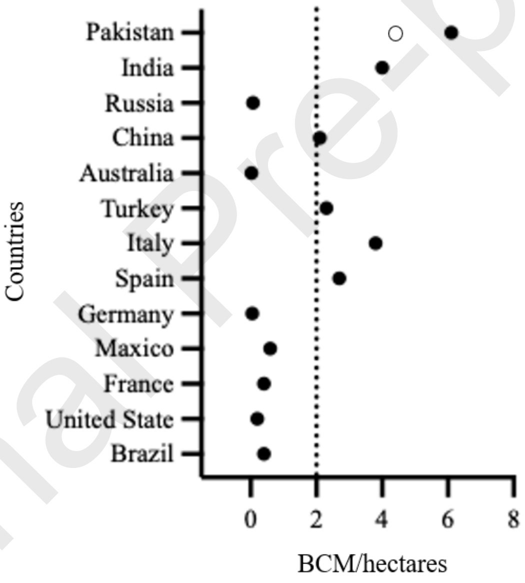

Fig. 10. Comparison of achievements in the water–energy–policy nexuses of Pakistan and other countries [71].

Agricultural mechanization has revolutionized farming worldwide, freeing societies from the arduous manual labor traditionally associated with agriculture. Disparities in agricultural mechanization contribute significantly to variations in global agricultural labor productivity, contributing to world income inequality [72,73]. Addressing Pakistan's reliance on low-power tractor machines for soil plowing is crucial, necessitating subsidies to facilitate the transition to more powerful technologies.

Baumhardt and Jones [74] present the impact of deep-plowing on ponded infiltration, evaluating it twice for maize: first at 4 years and again at 31 years after profile modification. Following significant rainfall, deep-plowed plots exhibited a six-fold increase in steady infiltration rates compared with control plots, indicating improved soil permeability and water storage. In subsequent assessments with multiple water applications, deep-plowed plots consistently demonstrated 30% faster water infiltration compared with control plots. These findings underscore the efficacy of deep plowing in enhancing soil permeability and facilitating efficient water infiltration, which are crucial for sustainable soil management and agricultural productivity. Furthermore, Xue et al. [75] demonstrated that deep plowing and subsoil treatment enhanced soil water storage in the 0–300 cm soil layer during sowing and soil organic carbon in the 0–20 cm soil layer at maturity. Deep plowing and subsoil treatment in the 0–180 cm soil layer from seeding to anthesis and in the 120–300 cm layer from anthesis to wheat maturity also increased soil water consumption. Furthermore, in comparison with traditional tillage treatments, these methods increased grain yield by 31%

and 26%, precipitation use efficiency by 32% and 26%, and water usage efficiency by 12% and 11%, respectively.

The adoption of drip irrigation has led to notable improvements in water use efficiency, increasing crop yields in agricultural practices. However, it is important to acknowledge that drip irrigation entails a 13% increase in energy consumption compared with flood irrigation, due to the additional energy needed for water pumping [76]. The integration of VFDs into agricultural pumping operations is an effective method for conserving natural resources and improving farming efficiency. Properly installed VFDs increase pump efficiency, extend product lifespan, reduce energy consumption, and mitigate stress on electrical systems [77,78]. In one study [79], it was found that the environment and the irrigation methods used significantly impact the energy input, output, and GHG emissions from irrigation practices. Drip irrigation requires the highest energy input (75.59 GJ·ha^{-1}), followed by flood irrigation (62.67 GJ·ha^{-1}) and surface irrigation systems (49.81 GJ·ha^{-1}).

Adjusting cropping patterns is another sustainable strategy for water conservation. Hulio et al. [80] suggests that replacing cash crops such as sugarcane, cotton, and rice with maize while maintaining the total cropped area can reduce the water footprint per area by up to 35%. Furthermore, substituting sugarcane with cotton and replacing sugarcane and rice with cotton offer more balanced cropping patterns, leading to reductions in water consumption of 13% and 18%, respectively.

3.6.2. Navigating challenges in the implementation of energy and water policies

This study highlights the importance of developing a comprehensive and unconventional energy policy to utilize abundant renewable energy resources. However, challenges such as non-binding objectives, unclear implementation strategies, and financial constraints impede policy effectiveness. Despite the potential benefits, it is difficult for Pakistan to achieve its renewable energy goals due to these limitations [81]. In light of the nation's current economic situation, meeting the electricity demand by 2035 will require a cumulative investment cost of 170 billion USD. The RE-40 scenario, which aims for environmental sustainability, necessitates 179.2 billion USD in investment, with 96.0 million tonnes of GHGs being emitted. Conversely, the Coal-40 scenario entails the highest GHG emissions at 338.9 million tonnes, with an investment cost of 184.8 billion USD [82]. The government plan aims to save 3 MTOE by 2025, representing the energy released from burning 1 tonne of crude oil. However, it will be challenging to achieve these targets on time, given the current progress. Energy specialists are skeptical about the plan's implementation, citing concerns about replacing fans and enforcing building codes. They question the authorities' capacity to execute the plan effectively, noting a lack of institutional capacity and delayed recognition of the importance of energy efficiency [83]. According to the investment plan by the National Energy Efficiency and Conservation Authority (NEECA) for 2030, it is estimated that energy conservation in the domestic sector alone will need funding of approximately 10 billion PKR in 2030, regardless of the transport, agriculture, industrial, and power sectors. Institutionalization and operationalization will require an estimated 126 million PKR and nearly 1 billion PKR, respectively. If the total cost is converted to the percentage difficulty is convert to the percentages of the total investment needed 89% is required for technical improvement, while 1% and 10% are allocated to institutionalization and operationalization.

In the water sector, human and financial resources are crucial for policy implementation. The NWPP recognizes the importance of these resources and highlights Pakistan's lack thereof. Financial scarcity has hindered public policy implementation in Pakistan. The allocation of 145 billion PKR—7% of the federal-provincial development budget for 2017–2018—has been deemed inadequate [18]. The policy advocates increasing public-sector investment in the water sector by the federal government from 3.7% in 2017–2018 to at least 10% in 2018–2019 and 20% by 2030 [65]. The total estimated cost for the current policy is given in Table 1. The progress and success of the measures outlined in the NWPP will be defined by the implementation process over time. Achieving these targets may prove challenging for the government due to Pakistan's current economic situation. Barriers to achieving these targets include water storage (52%), technical advancement (26%), drainage improvement (5%), flood control (15%), and the institutional investment difficulties (2%).

Table 1 Estimated cost for Pakistan's national water policy.

Investment plan 2030	Estimated cost (billion PKR)
Water storage	1600
Technical advancement	800
Drainage improvement	150

Flood control & irrigation system	466
Research & institutional purposes	30

The Pakistani government receives support from international institutions such as the World Bank and the Asian Development Bank for Water Resource Management (WRM) initiatives [84]. Despite external financial assistance, political instability, weak administration, and institutional deficiencies undermine the effectiveness of these efforts. Inadequate adherence to regulatory processes and enforcement challenges contribute to illegal agricultural water extraction, leading to the overconsumption and depletion of local water reservoirs in certain regions.

4. Conclusions

In conclusion, this examination of the synergistic impacts of energy and water policies reveals crucial insights into resource management for sustainable development. While policies aim to conserve energy and water resources, there is often inequity and duplication in resource allocation, negatively impacting overall effectiveness. The nexus between energy-saving measures and water-conservation efforts demonstrates predominantly beneficial impacts across various sectors, although challenges persist in translating study findings into actionable government policies due to differences in research focus and data. Notably, energy-saving measures directly contribute to water savings, with significant potential for joint energy- and water-saving effects across diverse sectors. The exception is the transport sector, which demonstrates a significant slowing down in energy demand due to energy conservation that does not directly impact water-conservation efforts. Despite notable achievements in water-saving objectives across sectors, challenges remain in evaluating the impacts of water policies on energy conservation, with varied outcomes being observed.

Looking ahead, our integrated modeling techniques reveal significant potential for joint energy- and water-saving measures, projecting substantial impacts by 2030 and beyond. While water-saving initiatives demonstrate promising outcomes, coordinated efforts but still current efforts are not essential to address resource sustainability challenges effectively. Furthermore, examining the energy–water–carbon nexus underscores the importance of ongoing policy support and technological innovation to achieve the SDGs. Pakistan’s water sector presents significant challenges, including water scarcity exacerbated by rapid industrialization and urbanization, which is expected to worsen due to the ongoing climate emergency. Policy implementation and evaluation play pivotal roles in addressing these challenges, with the NWPP offering a critical framework for sustainable water management. However, challenges such as financial constraints and inadequate institutional capacity hinder effective policy implementation, necessitating comprehensive strategies and international support to overcome these obstacles.

In conclusion, a multifaceted approach is needed to address the challenges of Pakistan’s water resource management—one that is tailored in both space and time, occurs over the epochal term, and encompasses policy reforms, institutional strengthening; and international cooperation. By prioritizing sustainable water-management practices and enhancing policy implementation mechanisms, Pakistan can navigate its water security challenges and work toward achieving the SDGs. By cutting its reliance on fossil fuels and boosting its proportion of renewable energy sources, Pakistan is decreasing emissions, enhancing energy security, and lowering air pollution. The country is following a low-carbon, climate-resilient path by incorporating climate-friendly policies into its economic planning and development strategies. This approach not only reduces emissions and strengthens resilience to climate impacts but also promotes socioeconomic growth. To fully realize these policies and meet emission reduction targets, Pakistan needs sufficient climate funding and international support.

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With Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: