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REVIEW ARTICLE

Energy simulation modeling for water-energy-food nexus system: a systematic review

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Abstract
Since essential nexus variables were not considered in the energy subsystem, this study focused on the role of energy in the Water, Energy, and Food nexus (WEF nexus) system. The energy subsystem interacts with water and food on the supply and demand sides. The WEF nexus-based energy model has not been reviewed recently. This study provides a systematic review of 459 articles regarding energy simulation modeling issues relating to the WEF nexus system. The keyword ("energy" AND "simulation" AND "nexus") as well as "water" OR "food" OR "climate" OR "land" OR "carbon" OR "environment" is used for searching WEF nexus documents for energy simulation. The review highlighted that the energy subsystem is modeled online (One-way) and offline (Two-way), and the energy simulation struggles to represent its system boundary with the water and food subsystems in different spatial scales (household to global). The energy subsystem of the WEF nexus did not address return flow from cooling towers and crop energy consumption comprehensively. In the research, the supply and demand section of the energy subsystem demonstrated that a comprehensive simulation model for energy can be developed using the nexus system approach. The energy subsystem's supply, primarily power plants, interacts with the water subsystem, and the energy generation policy is based on water use. The WEF nexus system assesses renewable energy effects to reduce tradeoffs. In addition, energy demand is related to energy consumption, so the energy consumption for each crop can be calculated and explained the appropriate cultivation pattern based on it.

Keywords Energy model · Energy security · Energy simulation · Water-energy-food nexus · Supply side and demand side · Basin and national scale

Introduction

By 2050, the global demand for Water, Energy, and Food (WEF) is expected to increase by nearly 50% due to population growth, urbanization, and climate change (Ferroukhi et al. 2015; Zhang et al. 2018). According to estimates from the United Nations in 2019, 821 million people were undernourished in 2017 compared to 784 million in 2015. Providing food for the world's starving population will require more land than is available now (United Nations 2019). Also, according to statistics in 2019, 785 million people worldwide lack access to safe drinking water, and two billion are affected by water scarcity. In 2030, it is anticipated that 700 million people will migrate or seek refuge in other locations due to severe water stress. Regional wars are more likely to occur when many people cross a country's border, and the receiving country refuses to let them in (United Nations Report 2019; United Nations 2019). According to the World Bank, in 2019, 840 million rural residents lacked access to electricity, and 3 billion lacked access to clean cooking fuels such as natural gas (United Nations 2019). Research indicates that in 2018, the Earth's temperature was 1 °C above the value established by the Paris Agreement. If current trends continue, Arctic glaciers will melt, resulting in rising oceans and seas and the submergence of 150 million people by 2050 and 360 million by 2100 (Kulp and Strauss 2019).

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The abovementioned trend is expected to worsen soon. Because WEF security risks are interconnected, the research and policy communities increasingly recognize the need for a unified resource planning and management approach. Each resource security requires a trade-off with the others (Laspidou et al. 2020; Qi et al. 2022). Climate change exacerbates resource interdependence, synergies, and trade-offs, affecting the economy and people's livelihoods (Markantonis et al. 2019; Wan and Ni 2021; Azizi and Nejatian 2022; Yavari et al. 2022). To address the issues mentioned above, the WEF nexus system concept refers to the interaction between these subsystems and provides insight into how strategies in one sector will affect the other sectors and vice versa (Afshar et al. 2022; Molajou et al. 2021a; Soleimanian et al. 2022). The research community has recently recognized the significance of the WEF nexus and its interdependencies as it continues to develop and adopt integrated modeling approaches that can potentially contribute to efficient resource management and holistic decision-making (Endo et al. 2020; Mahdavian et al. 2022).

The energy subsystem is a critical component of the WEF nexus system for water withdrawal and consumption by cooling and hydropower plants. Electricity production is worth noting that it is 90% water-intensive (Smith 2014). Official global statistics in 2010 show that an estimated 583 billion cubic meters (BCM) of water was withdrawn globally to produce energy (representing approximately 15% of total withdrawals or approximately 75% of industrial water withdrawals), with 66 BCM consumed (IEA 2010). Environmental concerns, the generation of electricity, and other water-dependent industries are increasingly at risk of conflict. Furthermore, the production of energy through the use of alternative energy sources, such as solar and wind power, has almost no negative impact on the environment, requires almost no water, and emits almost no carbon dioxide. As part of the nexus approach, renewable energy is an essential component of the energy supply. By achieving this minimal interaction, the energy and water subsystems can achieve the required amount of water without conflict or synergy.

On the other hand, energy consumption in various water and food production processes is critical under the WEF nexus system. The agricultural and food industries consume 30% of global energy (Sims 2011). At every stage of the food value chain, energy is required, including the production of agricultural inputs, crops in the field, food processing, transportation, marketing, and consumption. Primary agriculture consumes only 20% of the world's energy, while food processing and transportation consume approximately 40% and thus significantly contribute to global energy consumption (Sims 2011).

Groundwater pumping, desalination plants, and water treatment are some processes that consume energy during water production. Water's share of global electricity consumption is expected to stay around 4% in 2040, but regional differences are expected to be significant (IEA 2017; D'Odorico et al. 2018). In the USA and the European Union, the water industry accounts for about 3% of total electricity consumption (IEA 2017). On the other hand, desalination cost reductions have increased the Middle East's share of global desalination capacity from 9 to 16% since 2015 (IEA 2017).

According to the aforementioned energy issues, the significance of the energy subsystem modeling in the WEF nexus system to establish interaction with the other two subsystems is further highlighted due to its high importance in energy production and consumption in different parts of the water and food production process. In addition, the availability of a comprehensive simulation model for the energy subsystem within the context of the nexus system approach is essential for researchers and policymakers to examine and observe the effects of their actions and, as a result, select the most effective policy. Several WEF nexus system review papers have mainly assessed the interactions and interrelations between water and food subsystems (Chang et al. 2016; Zhang et al. 2018; Yuxi et al. 2021). The energy subsystem has not been assessed in detail in the review papers, while the energy subsystem interacts with the water subsystem in the supply sector to supply power plants' consumed water and the energy demand sector to calculate the consumed energy with the water and food subsystems. For example, Zhang et al. (2018) did not include supply and demand sectors in the energy subsystem. In the demand section, the energy consumption of agricultural machinery and their operation and the energy consumption of agricultural inputs are significant and were not addressed in the abovementioned review paper. The energy supply sector did not evaluate the interaction between hydro and thermal power plants with water bodies. Chang et al. (2016) analyzed methodological and practical issues related to WEF interconnection calculations and summarized the estimated results for WEF interconnections. Additionally, this review paper highlighted chances for future robust WEF nexus quantifications. The study mentioned earlier evaluated each WEF subsystem's internal and external effects on one another.

Therefore, a holistic review needs to be conducted to develop a comprehensive energy subsystem simulation model so that the requirements of the WEF nexus system can be met. Hence, the interactions are appropriately addressed to lead to accurate and logical solutions to make a holistic decision. This systematic review aims to present the main technical features of energy modeling. The models are used in the WEF nexus system to evaluate their advantages, disadvantages, and blind spots. To identify a research path to overcome the significant shortcomings to thoroughly address WEF nexus system simulation to improve energy subsystems and make holistic decisions.

Research methodology of the review process

A systematic review of energy subsystem simulation modeling within the WEF nexus system was performed to determine how scholars in this field conducted and simulated energy subsystems under the nexus system approach. To conduct this systematic review checklist for Preferred Reporting Items for Systematic Reviews and Meta-analyses was followed (PRISMA; Liberati et al. 2009), shown in Fig. 1.

For this study, a thorough literature search was conducted to identify papers that discuss energy subsystem simulations under the nexus system approach. These included articles published between 2010 and the end of 2021. A protocol was created to document the analysis method and the inclusion criteria. As depicted in Fig. 1, a systematic collection of publications on using energy subsystem simulation modeling in the WEF nexus system approach has been compiled. The Elsevier Scopus and Web of Science databases were used for the search.

An MS Excel spreadsheet was created by exporting each identified record's title, abstract, keywords, author names, affiliations, journal names, and year of publication. Abstracts and titles of the records were independently screened for relevance to the energy simulation models within the nexus system. The papers that were descriptive, conceptual, and unrelated to the energy within the nexus simulation models were discarded. Afterward, the full texts of the remaining papers were carefully screened independently to determine their eligibility. The researchers included all papers that, to some extent, indicated that the methods they used to identify and select the literature were explicit, reproducible, and without a priori assumptions about the relevance of the selected literature (Pickering and Byrne 2014; Booth 2016).

The review initially focused on modeling the nexus, the different types of nexus simulations, and the specific roles of the energy subsystem. The search for "nexus" and "energy" keywords in scientific literature includes article types of English-language documents that use key phrases in their title, abstract, and keywords. In the last decade, both keywords have significantly impacted the literature; the results are limited to journal papers from 2010 to 2021.

The various key phrase combinations are tested to include only the most relevant documents and exclude

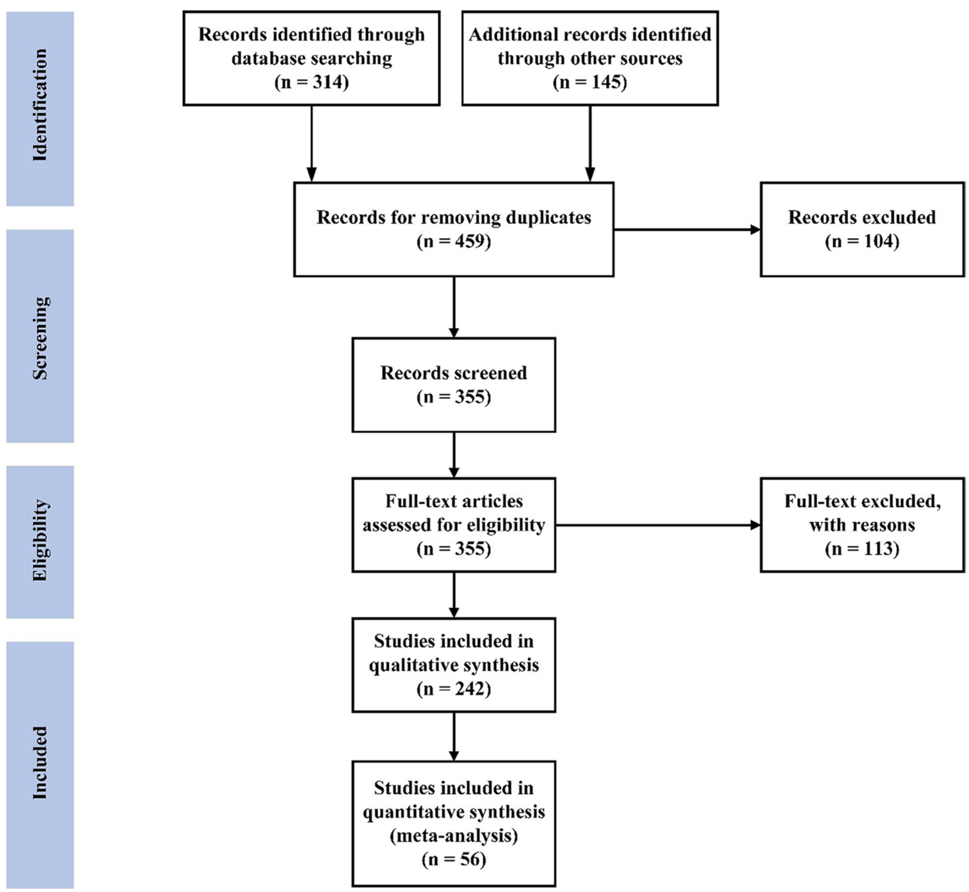

Fig. 1 PRISMA flowchart for the energy subsystem simulation under the WEF nexus approach

irrelevant search results. According to the test results, the terms "energy" and "nexus" have been used broadly in different forms and for different purposes, for instance, as "suitable energy-type functional and Euler–Lagrange equation" in the field of mathematics in applied sciences and engineering (Karki and You 2020), or "nexus between the emerging creators of innovative products and services and the necessary funding sources in the area of psychology" (Popescul et al. 2020). To limit the search results for energy simulation under the WEF nexus system approach to the context of the natural resources field, the phrase ("energy" AND "simulation" AND "nexus") AND "water" OR "food" OR "climate" OR "land" OR "carbon" OR "environment" has been selected for the search phrase for energy simulation within WEF nexus documents.

The keywords ("energy," "simulation," "nexus"), "water," "food," "climate," "land," "carbon," or "environment" were searched in the Scopus and Web of Science databases, yielding 314 and 145 articles, respectively. Second, we reviewed the titles exported to Excel and removed 104 duplicate papers. There were 355 articles left. We then chose final-status papers from 2010 to the end of 2021 and articles published in English-language journals. A total of 242 articles were chosen for qualitative examination. The energy simulation articles were chosen using the nexus approach during the first round of qualitative evaluation of article abstracts. Articles that investigated the concept of energy were not considered. In the second round of qualitative evaluation, the remaining articles were scrutinized more closely, and those that examined only energy simulation and the relationship between the energy subsystem and other subsystems, such as water and food, were chosen. Finally, only 56 articles were left for quantitative analysis.

Results

Types of simulation

Based on studies conducted in the literature, various energy subsystem simulation models are presented within the WEF nexus model, and the desired results are described next. An offline and online template is used to model the nexus system's energy subsystem. Offline energy modeling is a one-way flow of nexus variables model (Mounir et al. 2019). In other words, once the energy scenario is defined, the effects on the other two subsystems (i.e., water and food) are assessed using the nexus system approach. Similarly, if a scenario for a water subsystem is defined, the effects on the other two subsystems are investigated. The disadvantage of this type of energy modeling under the nexus system is that it cannot examine the entire system comprehensively. The term "online energy modeling" refers to models in which nexus variables flow in both directions between the energy subsystem and the other two subsystems (Araujo et al. 2021). In other words, all three subsystems receive nexus variables from each other during a simulation time step, which is why nexus systems are referred to as multi-centric. For example, the response of the water and food subsystems at any given time can be measured by exporting nexus variables like "the amount of energy allocated to groundwater pumping," "the amount of energy allocated to agriculture," and "the amount of energy allocated to desalination plants." (Ravar et al. 2020). In the same time step, the energy subsystem receives the nexus variables "groundwater level," "groundwater abstraction volume," and "crop cultivation area" from the water and food subsystems and evaluates its response (Wicaksono et al. 2020a). Regardless of its complexity, online modeling of the energy subsystem contributes to more accurate modeling of the WEF nexus system and

Table 1 Types of energy subsystem simulation under WEF nexus system approach

	Offline interactions	Online interactions
Linkages	One-way relationship	Two-way relationships
Advantages	• Less time-consuming for energy modeling in the nexus system • Demonstrates how the energy subsystem affects or is affected by water and food subsystems	• The energy subsystem can be linked to the other two subsystems holistically • Simulating nexus system thoroughly from an energy perspective • Import/export nexus variables to/from water and food subsystems
Disadvantages	• Cannot reflect the mutual impacts of energy with water and food subsystems • Defining the scenario in the energy subsystem and getting the response of the other two subsystems and vice versa	• Time-consuming modeling to link with other subsystems • Data-intensive
Features	• Not holistic simulation of energy under nexus system • Simple energy modeling	• Simulation of the WEF nexus system comprehensively • Sophisticated energy modeling

leads to more holistic decisions. The main characteristics of online and offline modeling are shown in Table 1.

Modeling scale

On the other hand, several spatial and temporal scales are systematically considered in the energy modeling under the WEF nexus approach based on the reviewed literature (see Fig. 2).

Relevant processes at the household level, such as Hussien et al. (2017), may include electricity usage, cars, cooking, cleaning, etc. Similarly, the community is made up of a collection of households. Local governments and municipalities are essential in distributing and selling energy to households (Martinez-Hernandez et al. 2017; Toba et al. 2021). Furthermore, regional (basin and national) WEF networks serve community aggregation. At the basin scale, the energy production process and its water consumption from thermal and hydroelectric power plants and other energy components are considered. The operational energy demand of water (for example, groundwater pumping) and food (for example, agricultural activities) subsystems is highlighted (Bakhshianlamouki et al. 2020). In general, decision-making, operation, and policymaking are critical on this study scale. The operation of hydropower reservoirs and related thermal power plant formulation are ignored on the national scale, but the national grid and its dispatching rules are considered (Wicaksono et al. 2020).

It should be noted that most of the energy simulation's relationships are considered databases in the form of energy or water intensity. Furthermore, global or continental energy processes also include global/continental energy supply chains, in addition to natural processes, which are very similar to but much broader and more varied than those at the regional level (Pavičević et al. 2021). It is worth noting that international diplomatic relationships, GHG emissions, and transportation costs are all vital on the global scale of energy modeling within the WEF nexus system.

It is also critical to consider the energy subsystem's temporal scales. Water levels in reservoirs and rivers fluctuate hourly, weekly, monthly, and yearly, generating hydropower. Furthermore, water temperatures fluctuate throughout the

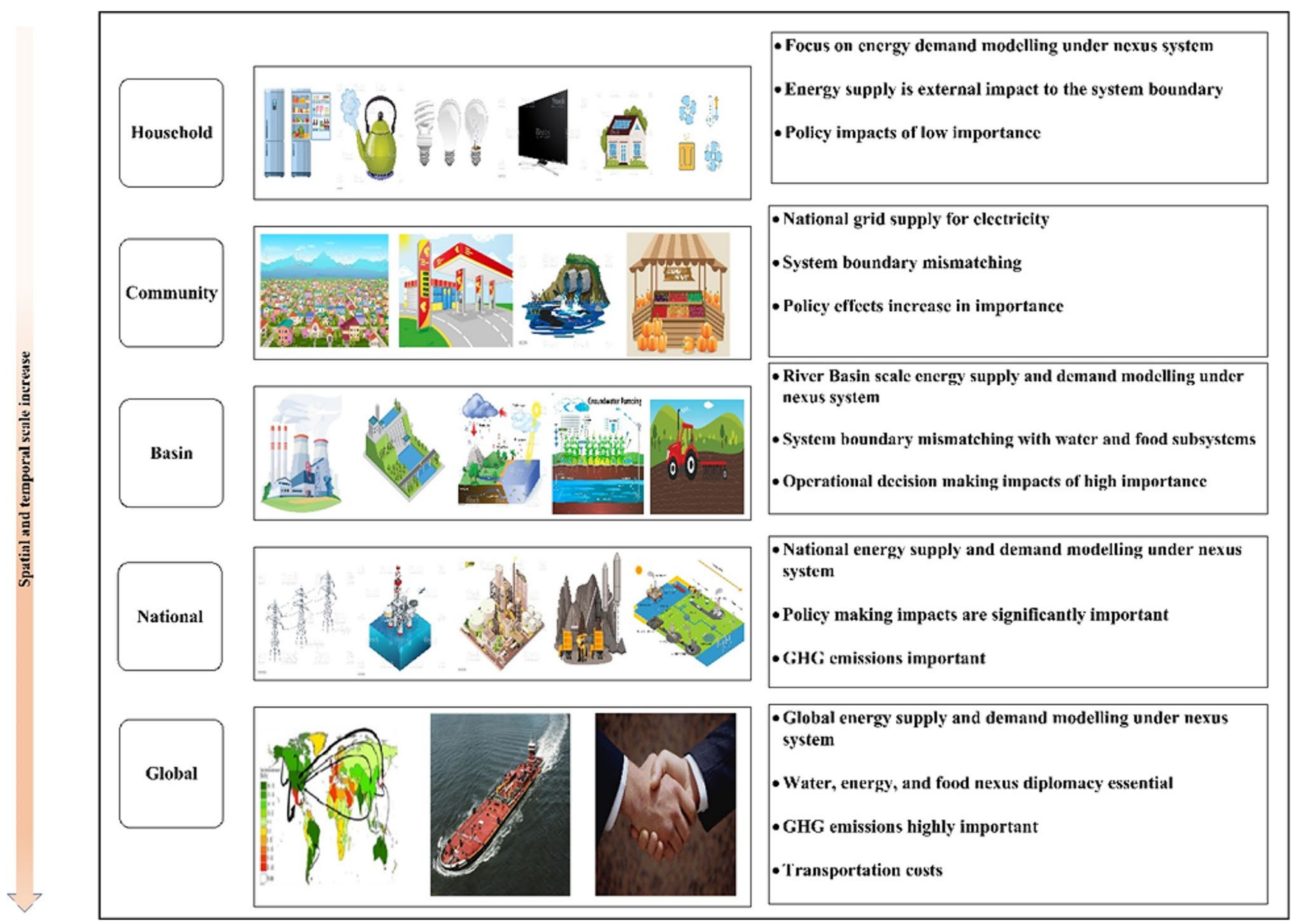

Fig. 2 Energy subsystem simulation spatial scale within the WEF nexus system

year, which is critical for power plants that require heating and cooling. Crop cultivation occurs worldwide during the growing season and ceases in winter. During the winter months, irrigation water and energy requirements are drastically reduced, allowing for the implementation of alternative uses. In addition, there is a connection between spatial and temporal scales. As the spatial scale increases, for instance, from a household to a global scale, the temporal scale also increases (Garcia and You 2016).

Supply and demand are the two main components of the energy subsystem. The energy subsystem interacts with the water and food subsystems within the nexus approach. This sector deals with energy production, mainly interacting with the water subsystem to provide cooling water and hydropower to power plants. In the energy demand section, the energy consumption of the defined scenarios is calculated for each water and food subsystem. The primary energy consumption for the water subsystem is related to groundwater pumping. The energy subsystem calculates the pumping energy consumption by receiving the nexus variables simulated by the water subsystem. Similarly, for the food subsystem, the energy subsystem calculates the amount of energy consumed by receiving different cultivation patterns and related nexus variables, such as the area under cultivation (Afshar et al. 2021). Tables 2, 3, 4, 5, and 6 illustrate the articles relating to the energy subsystem simulation within the WEF nexus system approach in diverse spatial scales and its interactions with other subsystems bilaterally and unilaterally.

At the household scale, the energy demand section is further investigated. In other words, for example, how much water and energy are needed for cooking. Although the energy supply sector at home is an external impact, this sector is not modeled. Also, the importance of policymaking is low, and the temporal scale of the household planning for the WEF nexus system is hourly to daily.

On a local scale, the supply sector boundary of the WEF nexus system is slightly expanded, and water and energy supply, which is related to water pumping stations and distribution of the electricity network, enters the nexus system. However, at this scale, food distribution to consumers is the essential component of the food subsystem, and crop growth under optimal cropping patterns, specifically policymaking, is not evaluated.

The nexus system's spatial scale increases the importance of energy subsystem planning and policymaking. At the provincial level, it becomes more essential to produce energy from thermal power plants (centralized) and consume their water, and interactions between subsystems are well represented. Hydropower plants are also critical on the provincial scale. On the other hand, both centralized and decentralized, renewable power plants, such as solar and wind, can play an important role in energy distribution in the energy supply sector.

The nexus approach considers the basin scale the most important spatial scale for the energy subsystem. Because of significant interactions with water and food subsystems in the water and demand sector at the watershed scale, planning and policymaking are critical. The energy subsystem, for example, receives the nexus variables of crop cultivation area and groundwater level in the energy demand section and then calculates the amount of energy consumed in the water

Table 2 Relevant features and summary of energy simulation research methods and their application under the WEF nexus approach on a household scale

Citation	Interconnectedness	Interaction type	Specific purposes	Underlying methodology	Research priorities
(Hussien et al. 2017)	Water-energy-food	Online	Demand	System dynamic	Developing an integrated model, capturing the interactions between WEF at the end-use level
(Zhuge et al. 2020)	Water-energy	Online	Demand	Agent-based simulation	Developing an agent-based spatiotemporal integrated approach to simulate the water-energy consumption of each household or person agent in seconds throughout a whole day
(Xue et al. 2021)	Water-energy-food	Online	Demand	System dynamic	Developing household WEF nexus dynamic model to explore the influence of various factors on the end-uses
(Casazza et al. 2021)	Water-energy-food	Online	Demand	Simulation	Simulating and providing alternative scenarios to assess the impacts of monetary policies as well as education and communication actions on the enhancement of resource savings

Table 3 Relevant features and summary of energy simulation research methods and their application under the WEF nexus approach on a local scale

Citation	Interconnectedness	Interaction type	Specific purposes	Underlying methodology	Research priorities
(Hernandez et al. 2014)	Water-energy	Offline	Supply–demand	Simulation–optimization	Optimizing the combined wind energy and water production systems
(Martinez-Hernandez et al. 2017)	Water-energy-food	Online	Supply	System dynamic	Advancing the state-of-the-art in nexus tools by dynamic modeling of local techno-ecological interactions relevant to WEF operations
(Li et al. 2017)	Water-energy-food	Online	Supply–demand	Agent-based simulation	Proposing a framework for agent analysis in urban WEF consumption
(Mounir et al. 2019)	Water-energy	Offline	Demand	Simulation	Quantifying the implications of future energy mix alternatives on the water-energy nexus using WEAP and LEAP software
(Tortorella et al. 2020)	Water-energy-food-climate	Offline	Supply	System dynamic	Showing the methodological path toward the implementation of an integrated modeling platform based on the nexus approach
(Huang et al. 2020)	Water-energy-food	Online	Supply–demand	Simultaneous equations model	Exploring interactions between factors as a critical step to understanding, quantifying, and governing the WEF-Nexus by focusing on mapping causal loops
(Reimer et al. 2020)	Water-energy-food-economy	Online	Supply	Simulation	Building a nexus simulation model that incorporates WEF and detailed economic data
(Chen et al. 2020a)	Water-energy-food	Online	Supply	Simulation–optimization	Coordinating deviation degree of the WEF system security and carbon dioxide emission minimization as the target
(Liu et al. 2020)	Water-energy-carbon	Online	Supply	Simulation	Mitigating carbon emissions by using alternative energy sources
(Araya et al. 2021)	Water-energy-mining	Online	Demand	Simulation	Evaluating the water-energy nexus in copper mining companies using a water reduction model
(Mounir et al. 2021)	Water-energy	Offline	Supply–demand	Simulation	Simulating water allocations and energy dispatch
(Ouyang et al. 2021)	Water-energy-food-economy	Online	Supply–demand	System dynamic	Simulating and evaluating relationships among the water-energy-food (WEF) and the economic systems
(Yu et al. 2021)	Water-energy-food-land	Online	Supply	System dynamic	Using system dynamics to simulate the optimal allocation of land use
(Toba et al. 2021)	Water-energy	Online	Supply	Multi-agent system simulation	Examining the system resilience using system performance, quantified as the percentage of met demand of the power and water system
(Zimoch et al. 2021)	Water-energy	Online	Demand	Simulation	Evaluation of the current demand for oversized water supply systems and a preliminary technical analysis of the possibility of energy saving
(Thompson et al. 2021)	Water-energy-food	Online	Demand	Simulation	Enhancing understanding of the urban WEF system to improve system function and management, increase resilience, and enhance sustainability
(Naderi et al. 2021)	Water-energy	Online	Demand	System dynamic	Evaluating the energy intensity of water supply and interconnected water use sectors
(Araujo et al. 2021)	Water-energy-food	Online	Supply	Simulation	Assessing the trade-offs between the production of WEF ecosystem services and the landscape structure

Table 4 Relevant features and summary of energy simulation research methods and their application under WEF nexus approach in Province scale

Citation	Interconnectedness	Interaction type	Specific purposes	Underlying methodology	Research priorities
(Nouri et al. 2019)	Water-energy	Online	Supply	Simulation–optimization	Assessing renewable energy effects on water withdrawal and consumption
(Li et al. 2019)	Water-energy-food	Online	Supply–demand	Interpretive structural modeling	To explain and quantify complex relationships in the water-energy-food nexus (WEF nexus)
(Zhai et al. 2020)	Energy-carbon	Online	Supply	Network simulation	Describing the integral mutual relationships between provinces and distinguishing the control intensity of each province from different CO_2 flows directions
(Zhang et al. 2021)	Water-energy	Online	Supply–demand	System dynamic	Clarifying the embodied linkages and the complicated system interactions in the energy-water nexus network
(Keyhanpour et al. 2021)	Water-energy-food	Online	Demand	System dynamic	Investigating the simulation of sustainable water resources management to assess the impact of socio-economic development on water, food, and energy resources security

and food subsystems. In the comprehensive WEF nexus system, the energy demand section using the defined approach can evaluate the optimal cultivation pattern. Hydropower plants, on the other hand, become especially important in the supply sector due to the presence of reservoirs. Furthermore, because of the use of rainfall-runoff models, the effects of climate change on energy production can be assessed by considering the relevant interactions.

A system boundary that is the same in WEF subsystems should be considered for the WEF nexus system. The national scale is the complete spatial scale for the energy subsystem because its system boundary does not mismatch with the water and food subsystems within the comprehensive WEF nexus system. Because electricity is generated by various types of power plants and injected into the national grid, the watershed and provincial spatial scales are insufficient for the energy subsystem. Only the national scale can provide the same system boundary for all three subsystems. However, interactions will be poorly represented at this scale, and the energy model will be more data-driven.

Another vital component of the supply side is renewable energy. Renewable energy, such as solar and wind power plants, are considered alternative energy in the supply sector. Renewable energy plays an essential role in the energy subsystem within the WEF nexus system. The energy and food subsystems both consume water to produce their products. This issue causes a trade-off between energy and food subsystems, which is increased with the emergence of climate change as a driver. As a result of climate change, crops' evapotranspiration may increase in the food subsystem. As a result, the need for irrigation will increase. Therefore, the water subsystem must allocate more water to the agricultural system. The trade-offs between energy and food subsystems increase for water withdrawal. Compared with conventional energy sources, renewable energy sources (solar and wind power plants) consume a small quantity of water, and this causes little interaction between the energy and water systems. It also reduces the trade-off between agriculture and energy production.

Discussion: Direction of future research for energy simulation under the WEF nexus approach

Based on the necessary interactions within the energy subsystem, the review highlighted how difficult it is to analyze it within the WEF nexus approach. According to the literature, energy subsystem simulations can be modeled offline and online. As these (bilateral) simulations can give more

Table 5 Relevant features and summary of energy simulation research methods and their application under the WEF nexus approach in Basin-scale

Citation	Interconnectedness	Interaction type	Specific purposes	Underlying methodology	Research priorities
(Basheer and Elagib 2018)	Water-energy	Offline	Supply	Simulation	Illustrating the relationship between energy generation and water losses by examining the sensitivity of the Water-Energy Nexus (WEN) to changing dam operation policy
(Khalkhali et al. 2018)	Water-energy	Online	Supply	System dynamic	Developing a hydrologic model, a water subsystem model, and an energy model was integrated into a system dynamic modeling framework
(Stamou and Rutschmann 2018)	Water-energy-food	Online	Supply	Simulation–optimization	Quantifying interactions, trade-offs, and promoting synergies by computational modeling
(Zeng et al. 2019)	Water-energy-food-climate	Online	Supply	Simulation–optimization	Developing a sustainable WEF plan to conduct an optimal framework into multiple water-reservoir systems for confronting regional natural and artificial damages
(Zhou et al. 2019)	Water-energy-food	Online	Supply	Simulation–optimization	Proposing a holistic system-wide solution driven by water resources perspectives encouraging small-hydropower generation
(Amjath-Babu et al. 2019)	Water-energy-food	Online	Supply	Simulation	Quantifying the benefits of proposed water resource development projects in the transboundary basin in terms of hydroelectric power generation, crop production, and flood damage reduction
(Ravar et al. 2020)	Water-energy-food	Online	Supply–demand	System dynamic	Simulating the effectiveness of sectoral municipal, industrial, and agricultural water and energy consumption management and environmental protection policies in improving ecosystem provisioning services
(Bakhshianlamouki et al. 2020)	Water-energy-food-climate	Online	Demand	System dynamic	Simulating the WEF nexus in the basin as a holistic multi-sectoral system and assessing the impacts of proposed lake restoration measures, especially looking for trade-offs
(Chen et al. 2020b)	Water-energy-ecosystem	Online	Supply	Simulation–optimization	Investigating the role of the operation of the cascade reservoirs may play in mitigating existing conflicts and achieving co-benefits in the entire River Basin
(Ravar et al. 2020)	Water-energy-food	Online	Supply–demand	System dynamic	Assessing WEF supply security considering ecosystem provisioning services
(Sharifinejad et al. 2020)	Water-energy-food-economy	Online	Supply–demand	System dynamic	Providing the decision makers with a clear picture of the economic impacts and consequences of the water consumption management policies within the framework of WEF nexus assessment
(Molajou et al. 2021b)	Water-energy-food-society	Online	Demand	Agent-based simulation	Investigating how farmers' dynamic agricultural activities under different socio-economic conditions affect the WEF systems
(Li et al. 2021)	Economy-energy-environment	Online	Supply–demand	Simulation–optimization	Identifying the main factors affecting the economy-energy-environment nexus system as well as generating optimal strategies supporting regional sustainability

Table 5 (continued)

Citation	Interconnectedness	Interaction type	Specific purposes	Underlying methodology	Research priorities
(Ferraz de Campos et al. 2021)	Water-energy	Online	Supply	Simulation	Assessing the influence of adding floating photovoltaic power in the large-scale reservoir
(Mitra et al. 2021)	Water-energy-climate	Online	Supply	Simulation	Developing an integrated assessment approach to quantify the water-energy nexus
(Chowdhury et al. 2021)	Water-energy-climate	Online	Supply	Simulation	Assessing the robustness of hydropower supply concerning the hydroclimatic variability
(Schull et al. 2021)	Water-energy-ecosystem	Online	Supply	Simulation–optimization	Investigating the role of operation of the cascade reservoirs may play in mitigating existing conflicts and achieving co-benefits in the entire River Basin
(Heidari et al. 2021)	Water-energy-food	Online	Supply	Simulation	Simulating various Eucalyptus plantation scenarios that followed physically based rules for land use conversion to study hydrological effects, biomass production, and the green water footprint of energy production
(Gozini et al. 2021)	Water-energy	Online	Supply–demand	System dynamic	Simulating various water- and energy-saving policies and their effectiveness in improving resource security was evaluated using water- and energy-saving indices
(Zhang and Ren 2021)	Water-energy-food	Online	Demand	Simulation–optimization	Investigating groundwater pumping and cropping pattern based on the WEF nexus approach

accurate and comprehensive results under an integrated WEF nexus system, the two-way interactions can provide a more comprehensive and accurate picture of the relationship between the energy, the water, and the food subsystems (Zhang et al. 2018). On the other hand, the energy subsystem simulator under the WEF nexus approach must be able to import the required nexus variables from both the water and food subsystems to calculate the energy produced and consumed. For example, to calculate the pumping energy consumption on the energy demand side, the energy subsystem must receive two nexus variables, the groundwater level and the amount of water withdrawn from the water subsystem. Of the studies conducted, Bakhshianlamouki et al. (2020), Ravar et al. (2020), and Sharifinejad et al. (2020) studies have only been able to simulate the energy subsystem on the basin scale in the form of an online template concerning the other two water and food subsystems and simulate more components of its supply and demand (e.g., hydropower, thermal power plants, groundwater pumping, etc.) than other studies. Also, Wicaksono and Kang (2019), Araujo et al. (2021), and Gozini et al. (2021) simulated both the supply and demand side of the energy subsystem comprehensively to capture nexus variables among WEF subsystems. Wicaksono and Kang (2019) modeled the WEF nexus system nationally using data-based relations in these studies.

One of the most critical parts of the energy subsystem in the WEF nexus system is the return flow from power plants. The studies reviewed in this paper did not cover return water, which is a required nexus variable between energy and water subsystems, thus affecting the amount of water measured at hydrometric stations (Martinez-Hernandez et al. 2017; Bakhshianlamouki et al. 2020; Ravar et al. 2020; Sharifinejad et al. 2020; Wicaksono et al. 2020a; Gozini et al. 2021). As a result, the results of the entire WEF nexus system can be affected. Additionally, on the energy demand side, the energy consumption of the different crops has not been studied separately; however, it is necessary to consider this in the comprehensive simulation of the nexus system to determine the optimal cultivation pattern. In other words, the best cultivation pattern reduces the amount of energy and water spent and maximizes yield.

On the other hand, renewable energy is one of the most significant and influential energy sources in the WEF nexus system. This means that alternative energy, such as solar and wind power plants, has very little water consumption and greenhouse gas emissions, and they can be used to reduce the trade-off between energy and food subsystems for water consumption (Nouri et al. 2019; Liu et al. 2020; Sharma et al. 2021).

Furthermore, a system boundary mismatch with two water and food subsystems is one of the problems with the energy subsystem simulation. It is critical for the integrated WEF nexus system simulation to have a unique system boundary,

Table 6 Relevant features and summary of energy simulation research methods and their application under the WEF nexus approach on a national scale

Citation	Interconnectedness	Interaction type	Specific purposes	Underlying methodology	Research priorities
(Manthrithilake and Liyanagama 2012)	Water-energy-food	Online	Supply	Simulation	Describing the value of a computer-based simulation model in the implementation of participatory water allocation policy
(Jääskeläinen et al. 2018)	Water-energy	Offline	Supply–demand	Simulation	Analyzing the energy system using the Energy-PLAN simulation tool to model whether different energy policy scenarios result in a plausible generation inadequacy
(Wicaksono et al. 2019)	Water-energy-food	Online	Supply–demand	Simulation–optimization	Proposing an optimization module to assist stakeholders in making informed decisions concerning sustainable resource management
(Wicaksono and Kang 2019)	Water-energy-food	Online	Supply–demand	Simulation	Introducing a computer simulation model to calculate the supply and consumption, availability, and reliability of WEF resources considering the interconnections of resources
(Lv et al. 2020)	Water-energy	Online	Supply	Simulation	Simulating probability distributions of water availability, reflecting uncertainties derived from economic development and technology choice
(Sharma et al. 2021)	Food-carbon	Online	Supply–demand	Simulation	Evaluating renewable energy and pesticide use interaction and mitigating the effect of pesticide use on GHG emission
(Lee et al. 2020)	Water-energy-food-climate	Online	Demand	Simulation	Assessing the holistic impacts of climate change and irrigation management on food-centric water-energy-land interlinkages in the WEF nexus specialized in agriculture
(Tang et al. 2020)	Water-energy-carbon	Online	Supply	Simulation–optimization	Simulating the deployment of power generation technologies, and further answering whether there is a conflict or not between the water-saving target and CO_2-reduction target in the power sector
(Abdel-Aal et al. 2020)	Water-energy-food	Online	Supply	Agent-based simulation	Considering an integrated WEF nexus approach and accounts for the interdependencies within the nexus
(Handayani et al. 2020)	Water-energy-food-climate	Offline	Supply	Simulation	Presenting a novel methodology to integrate both CO_2 mitigation goals and the impacts of climate change into simulations of a power system expansion by soft-linking WEAP and LEAP software
(Duan and Chen 2020)	Water-energy	Online	Supply–demand	Input–output simulation	Assessing and simulating the water-energy nexus among production and consumption and determining the mechanism behind the nexus

Table 6 (continued)

Citation	Interconnectedness	Interaction type	Specific purposes	Underlying methodology	Research priorities
(Zhai et al. 2021)	Energy-water–air pollution-economy	Online	Supply–demand	Simulation	Examining the energy-related water and air pollution embodied in household consumption at different income levels
(Amin and Dogan 2021)	Energy-environment-economy	Online	Supply	System dynamic	Exploring the function of economic policy uncertainty in the energy-environment nexus
(Pavičević et al. 2021)	Water-energy	Offline	Supply	Simulation	Soft linking between two models: the LISFLOOD model is used to generate hydrological inputs, and the Dispa-SET model is used for mid-term hydrothermal coordination and optimal unit commitment and power dispatch

which should be at least the national level in the case of energy due to the generation of electricity as a national grid. The system boundaries of the food and water subsystems are compatible—precisely, the water subsystem, where production and consumption often occur in the same study area. In contrast, energy production is a national network where production and consumption do not constantly occur in the same study area.

In order to develop a comprehensive energy subsystem simulator that can interact bilaterally with water and food subsystems while, on the other hand displaying its response to the WEF nexus variables more thoroughly and accurately, the problems and gaps mentioned above must be addressed. Consequently, a comprehensive simulation model for the energy subsystem will be developed based on the WEF nexus approach, enabling interactions between the nexus system and the other two subsystems within the holistic simulation of the WEF nexus system, allowing for more accurate and comprehensive decisions.

Conclusion

The energy subsystem is one of the most critical elements of the WEF nexus system, which is interdependent with the water and food subsystems. Hence, simulating an energy subsystem in a nexus approach that can interact bilaterally with water and food subsystems is vital. There has been an offline and online simulation of energy subsystems in the reviewed literature. Offline interactions occur through a soft link between the software, and the interaction between subsystems is one-way only. In online interactions, the interlinkages are hard links, all subsystems are programmed within the WEF nexus system, and the interactions between the subsystems are two-way. Through simultaneous simulation of the WEF subsystems, online interactions can be enabled, leading to comprehensive decision-making within the WEF nexus system.

One of the biggest problems with energy subsystem simulators under the WEF nexus system approach is that its system boundaries do not correspond with those of water and food. Electricity generation occurs in the study area, is injected into the national grid, and the generated energy is not necessarily consumed in the same study area. It is crucial to solving the problem of the incompatibility of the boundary of the energy simulator subsystem on more minor scales than the national scale. The return flow from the cooling systems of thermal power plants is also an essential part of the supply side of the energy subsystem that can affect the amount of water measured in hydrometric stations in the water subsystem with the nexus approach. In future research, the amount of returned water can be evaluated by simulating the water withdrawn and consumed by thermal power plants.

Additionally, renewable energy technologies, which can lead to sustainable development due to the reduction of trade-offs and synergies, have not been adequately modeled in the WEF nexus system. Research can be conducted in the future to evaluate the effects of renewable energy, such as solar and wind power, on the WEF nexus system under various scenarios in terms of saved water.

The energy consumption of agricultural products on the energy demand side has not been studied separately, while in the comprehensive simulation of the WEF nexus system for the optimal cultivation pattern, energy and water consumption is expected to be minimal. In contrast, crop yields are expected to be maximum.

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Data availability The authors declare that the data are unavailable and can be presented upon the request of the readers.

Declarations

Ethical approval The authors declare that there is no conflict of interest.

Consent to participate The authors declare that they agree with the participation of the journal.

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