Current Research in Environmental Sustainability 4 (2022) 100119

Contents lists available at ScienceDirect

Current Research in Environmental Sustainability

journal homepage: www.sciencedirect.com/journal/current-research-in-environmental-sustainability

Presenting a conceptual model of water-energy-food nexus in Iran

Nima Norouzi

Department of Energy Engineering and Physics, Amirkabir University of Technology, Tehran, Iran

A R T I C L E I N F O

Keywords:
WEF nexus
Supply chain
Energy security
Sustainable economics
Energy economics
Green economics

A B S T R A C T

Due to the increasing demand for water, energy, and food in the coming decades, the pressure on these three sectors has increased. The importance of a systemic approach to water-energy-food interconnection issues has become more apparent. In this regard, the main purpose of this study is to present a conceptual model of water-food-energy interconnection using a dynamic system for Iran and analyze the factors affecting this relationship. For this purpose, first, each of the sub-sectors of water, food, and energy has been modeled. Finally, integrated conceptual modeling has been done regarding the relationship of each of the mentioned sub-sectors. As an application of the interconnection mentioned above, the economic productivity index of water-energy-food for 2005–2018 has been calculated. The trend of this index in the research results has had ups and downs and since 2011 has gone through an upward and gentle trend; However, it has never reached the index level in 2006. With a systematic-analytic view, to reduce the risk of energy-water-food security, these three parts should be examined in regular operation and coordination with each other. The research findings show the need to pay attention to this link in policymaking and regulation in Iran.

1. Introduction

In the last decades, the world faced a growing acknowledgment of the undeniable interconnections of food, energy, and water (FEW) aspects (Bazilian et al., 2011; Scanlon et al., 2017; Cai et al., 2018; Bogardi et al., 2012; Ringler et al., 2013; Madani and Shafiee-Jood, 2020) An acknowledgment which has started an aim and attraction to understand many connections between water and energy (Stillwell et al., 2010; Xiao et al., 2015; Madani and Khatami, 2015), food and water (Kumar et al., 2012), and food and energy (DeNooyer et al., 2016; Sanders and Masri, 2016; Zhang and Vesselinov, 2016), as well as the Water-Energy-Food nexus (Biggs et al., 2015; Liu et al., 2015; Jalilov et al., 2016; White et al., 2018; Mirzaei et al., 2019).

The Water-Energy-Food nexus is a concept which illustrates challenges and opportunities for water management in the transition to a holistic resource management paradigm (Scanlon et al., 2017; Cai et al., 2018) to enhance water, energy, and food security using the development strategies and Iran is located in an arid and semi-arid position facing severe water and environmental challenges (Madani, 2014).

A usual act in water-scarce regions is to use groundwater to offset surface water limitations. Necessarily, the water resources of Iran are mainly falling across the state, significantly highering the energy demand to exploit deeper water resources (Mirzaei et al., 2019) to keep the food industry (Norouzi and Kalantari, 2020) and maintain rural area employment rate in the agricultural industry. Over-pumping of aquifers for agricultural water uses correlated with population blooming are the main causes for falling water availability in various sections of Iran (Karimi et al., 2012; Madani et al., 2016; Ashraf et al., 2017).

In-country management decided to meet these challenges through a large network of dams, inter-basin water transfer, groundwater withdrawal. However, according to the newer development views and research, they have proven ineffective as water consumption grows and resources fade (Madani et al., 2016). This constantly growing water demand and failing resources threaten the country's water bankruptcy state (Jalilov et al., 2016).

Coupled methods and practice analysis frameworks can be helpful in the applicability of the food-water-energy nexus concepts to usher in sustainable development (Endo et al., 2017). Model dynamism conceptualizing is an approach that facilitates analyzing food-water-energy nexus aims by framework non-linear or binary causal correlations and simple feed-forward relationships among correlated and coupled subsystems in particular model limitations and constraints (Hjorth and Bagheri, 2006). This concept is mainly used in water and environmental management studies (Winz et al., 2009; Mirchi et al., 2012), food industry and supply chain (Georgiadis et al., 2005; Xu and Szmerekovsky, 2017), and energy policy and transition systems (Ahmad et al., 2016; Leopold, 2016; Fontes and Freires, 2018). Complex dynamics models of food-water-energy nexus consisting of multiple sub-

E-mail address: nima1376@aut.ac.ir.

https://doi.org/10.1016/j.crsust.2021.100119
Received 28 August 2021; Received in revised form 20 December 2021; Accepted 22 December 2021
Available online 28 December 2021

units and integrated links between resources and their management issues engulf a wide range of technical, economic, and policymaking fields. These implementations cover resource dynamics and their interconnection to thrusts of industrial development (e.g., population, agriculture, economy, non-renewable resources, and emissions (Simonovic, 2002); regional-level assessment of food-water-energy interconnections for resource and consumption taking into account water and energy import and export and water and energy footprints (El-Gafy, 2017). These parameters and concepts are necessary for representing resource constraints and management policies that drive socioeconomic and industrial development (Gohari et al., 2017) and a residential level assessment of the food-water-energy demands and related behavioral, socioeconomic, and technological factors (Wa'el et al., 2017). The mentioned literature clearly states that the previous publications in this field merely consider Iran.

Considering the mentioned considerations, this research seeks to study and present a conceptual model of water-food-energy interconnection for Iran and analyze the factors affecting this relationship. As a result, each sub-sector of water, food, and energy has been studied in detail using the relevant conceptual modeling. Finally, integrated conceptual modeling regarding the relationship of each sub-sector mentioned has been discussed to determine the need to use resources as efficiently as possible to achieve the final product.

Accordingly, the continuation of the research is organized in such a way that in the second part, the theoretical basis and thematic background of the research are explained. Then in the third part, the research methodology is presented. The fourth part of the research is dedicated to analyzing research findings, and the fifth part presents the summary and conclusion of the research.

2. Theoretical foundations and thematic background of the research

This part of the research consists of two parts. First, in the first part, the theoretical basis of the research is presented, then in the second part, the most important studies in the thematic literature are examined (Aboelnga et al., 2019).

2.1. Theoretical foundations of research

Water, food, energy, and security of all three sectors without reducing natural resources are major challenges in the Asian region. To this end, from 2015 onwards, the United Nations has set a set of goals called the Sustainable Development Goals (SDGs) aimed at achieving long-term sustainable development in human societies and ensuring the provision of food, water, and energy for sustainable generations. To implement these goals, researchers have proposed several interdisciplinary and specialized frameworks and approaches to achieve a dynamic and optimal balance in the production and consumption of resources, one of the most important of which is the combination of water, energy, and food (Shimbar and Ebrahimi, 2020; Hoff et al., 2019).

According to this approach, water, energy, and food security are key focal elements for poverty reduction by ensuring sufficient resources to maintain and improve livelihoods fairly while simultaneously maintaining healthy natural environments by exploiting the ecosystem by providing services directly or indirectly for livelihoods. Due to environmental and water crises, the country's food and energy security are jeopardized. It can be inferred that this approach can guide sustainable development policy in the country. Accordingly, in addition to explaining the current situation of the components of this approach, it is necessary to pay attention to it as an appropriate policy strategy for sustainable development.

By definition, water security is "an acceptable quantity and quality of water for health, livelihood, sustainable production and ecosystems with an acceptable level of water risk to people, the environment and the economy." Ideally, water allocation must be economically viable and technically, practically, and socially just. The World Economic Forum addresses water, food, and energy security so that rapid population growth and economic growth put unbearable pressures on resources. Demand for water, energy, and food is expected to increase by 30 to 50% over the next two decades, while economic inequalities and the encouragement of short-term production and consumption responses undermine long-term sustainability. Lack of resources can lead to social and political instability, geopolitical conflict, and irreparable environmental damage. Regardless of the relationship, focusing on one part of the relationship between water, energy, and food carries serious risks and unintended consequences. The concept of water-energy-food (WEF) has emerged in the international community in response to climate change and social change, including population growth, globalization, economic growth, urbanization, growing inequality, and social discontent. The water, energy, and food linkage approach is an overall vision of sustainability that seeks to balance people's different goals, interests, needs, and environments (Hoff et al., 2019).

Water-energy-food linkage can be considered an approach to evaluate, develop and implement policies that simultaneously focus on water, energy, and food security. This approach will strengthen sustainable development and improve the quality of life of communities while protecting natural and social capital to address long-term sustainability issues (Norouzi, 2022). This requires a comprehensive approach that considers the security of the three categories of water, energy, and food and the interactions and dynamics. The link between water security - energy - food can be expressed in the following table:

(Table 2) can be seen as examples of applying dynamic correlation analysis between water-energy-food. Accordingly, activities such as irrigation with electricity system, water desalination process for agriculture, and hydropower generation are among the processes that require simultaneous analysis of three categories of water, energy, and food to explain the dynamics between these categories. Also, the evaluation indicators of each of the links can be seen that with the

Table 2
Some activities related to water - energy – food.

Activity	Food	Energy	Water
Electric irrigation	- Change in the amount of agricultural production to pumping capacity - the field of pumping plant to pumping capacity	- Consumed fossil energy divided into irrigated areas - Fossil energy consumed to produce food	- Pumped water for agriculture divided by the amount of fossil energy consumed - Pumped water for irrigation to the area of irrigated lands
Water desalination for agriculture	- Land used for desalination of water with the amount of desalinated water	- Energy consumed for the amount of treated water - Fossil energy used for the number of agricultural products	-Purified water is used in the number of products produced - The cost of water treatment for agriculture
Hydropower generation	- The amount of citrus products is given at the expense of water desalination	- Total hydropower generated for the total area of the tank - Total hydropower generated for the total area irrigated by the dam	- Change in the water discharged from the river to the amount of electricity generated from hydropower - Water consumed for protein production due to reduced fish in fear of hydropower generation capacity

Reference: Saray et al. (2022)

availability of the required statistics, each of the mentioned economic activities can be quantitatively analyzed (Wu et al., 2021). (See Figs. 1 and 2.) (See Table 1.) (See Table 3.)

2.2. Background research

In this section, some of the most important studies related to the research topic are reviewed. Fang et al. (2014), in a study entitled "Theoretical extraction of the combination of environmental effects, energy, carbon and water footprint: a review of the family footprint" with a general equilibrium approach and examining in related areas, environmental footprint, energy, Carbon and water are used as selected indicators to define the family footprint. This makes it possible to examine the four traces mentioned above, which are completely excluded in assessing environmental impacts associated with the use of natural resources and waste. This article can be conceptually related to the present study due to the environmental impact assessment of the four mentioned footprints, especially water (Nhamo et al., 2021). The key conclusions are that the footprint family, which captures a broad spectrum of sustainability issues, is able to offer a more complete picture of environmental complexity for policy makers and, in particular, in national-level studies. The research provides new insights into the distinction between environmental impact assessment and sustainability evaluation, properly serving as a reference for multidisciplinary efforts in estimating planetary boundaries for global sustainability.

Hang et al. (2016), in an article entitled "Designing integrated local production systems: a study on the food-energy-water nexus," proposed a partial equilibrium approach to study the development of engineering systems tools process in combination with the concept of studying energy resources They have designed local production systems. The proposed method, which reflects the general principles for designing a local production system, represents a case study in the integrated water-food-energy relationship for a UK ecosystem. This paper can be theoretically close to the present study in terms of theoretical foundations due to studying the relationship between water - food - energy to design a local production system. The proposed methodology, which reflects generalised principles for designing local production systems, has been illustrated through a case study on the integrated design of the food-energy-water nexus for a designated eco-town in UK. It demonstrates

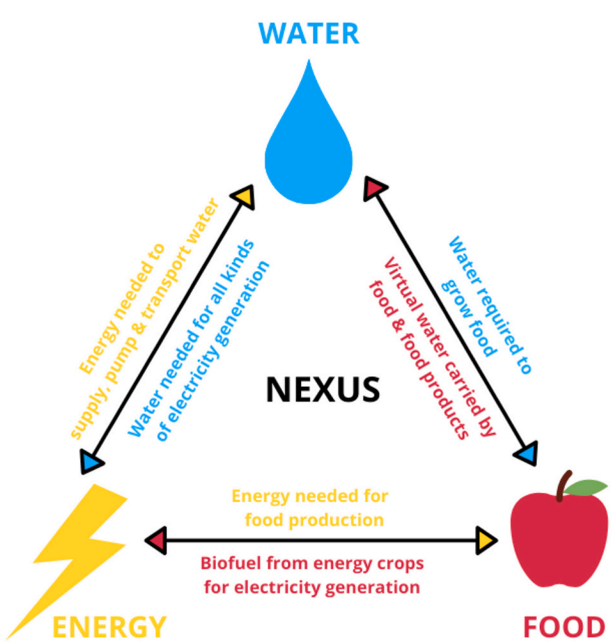

Fig. 1. The relationship between water, food, and energy in the context of politics, climate, and the environment.

the advantages of an integrated design of a system making use of local resources to meet its demands over a system relying on centralised supplies and a design without considering integration opportunities between subsystems.

Artioli et al. (2017), in a study entitled "The water-energy-food nexus: An integration agenda and implications for urban governance" with a partial balance approach, found that beyond the water, energy and food sectors can be found in political tests and Its results and challenges distributed expertise and coordination capacity. This paper can be conceptually related to the present study due to considering an integrated urban plan, coordination capacity, and its relationship with water, food, and energy. Three hypotheses about the interplay between integrative policy framings and urban governance are explored to reconcile integrative policy framings at the urban scale: the appropriation of the nexus narrative by urban governments; re-establishment of political power through integrated management, and implementation of the nexus through smart city approaches. These hypotheses progress the political dimension of the nexus debate and reflect on the role of urban governance in addressing global challenges.

Esfandiari-Baiat et al. (2014), in a chapter entitled "Urbanisation and its effects on water, food security and energy needs in Iran: a case study of the city of Shiraz" with a partial balance approach has examined the issue that the city of Shiraz is encountered with the rapid urbanization in the period 1956 to 2006. As a result, land-use changes in the Shiraz plain, under the influence of urbanization, have led to a serious reduction in horticultural and agricultural products. As a result of the apparent reduction of agricultural water and agricultural products in the region, the main problem of rapid urbanization has occurred. The preliminary analysis in this study through the case study of Shiraz suggests that we need an in-depth study to understand how urbanization has impacted the availability of water supplies, the security of food production around our cities and the energy needs at the national level, and what policy and planning changes are required to achieve sustainable and liveable cities in the future.

Qasemipour and Abbasi (2019), in an article entitled "Virtual water flow and water footprint assessment of an arid region: A case study of South Khorasan province" with a partial equilibrium approach to the study of groundwater abstraction, virtual water exports And have met the need for pure water to ensure food security in this province. This study gives the water authorities and decision-makers of the region a picture of how and where local water resources are used through the food trade network. The generated information can be applied by the regional policymakers to establish effective and applicable approaches to alleviate water scarcity, guarantee sustainable use of water supplies, and provide food security.

Naderi et al. (2021), in a study entitled "Study of energy efficiency - water and economical energy efficiency in sprinkler and surface irrigation systems in the context of groundwater operation (Case study: Qazvin plain)" with a partial balance approach and Using seasonal data of irrigation systems and crop yields of these systems in Qazvin plain, they found that in the case of the combined operation of groundwater and irrigation canal, energy efficiency in irrigation systems is far greater than energy efficiency. In the mode of exploitation of groundwater. An annual groundwater table decline of nearly 1 m is anticipated, indicating a significant overshoot of the plain's natural recharge capacity, which may lead to the depletion of recoverable groundwater in the plain within the next three decades. The groundwater table decline will cause energy consumption of water supply to increase by about 32% (i.e., 380 GWh) to maintain irrigated agriculture. It is critical to implement a combination of water demand and supply management policies (e.g., net agricultural water savings and recycling treated wastewater) to delay the problem of water limits to growth in the region.

Hagemann and Kirschke (2017), in a study entitled "Key issues of interdisciplinary NEXUS governance analyses: Lessons learned from research on integrated water resources management" with a partial balance approach, sought to combine two different systems in the form

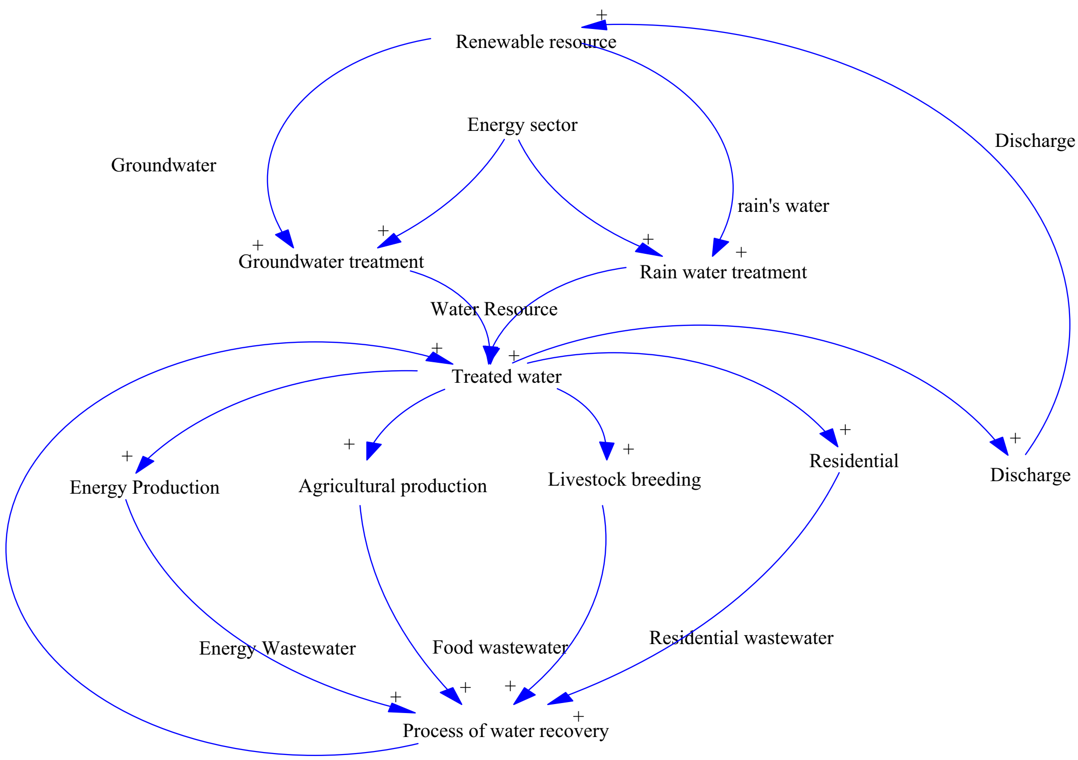

Fig. 2. Structure of water production department.

Table 1
Water-energy-food security link.

Food-related criteria	Energy-related criteria	Water-related criteria
Food security	Energy security	Water security
Food availability	Supply of energy to meet demand	Availability of water
Food accessibility	Physical availability of supply	Water health
Food exploitation	Meet demand at a stable rate	Water cost

Source: Nhamo et al. (2021).

of a systematic framework (toolbox) in which Integrated water resources management is designed to achieve an interconnected approach. The toolbox with a comprehensive methodology has been prepared by integrating WEAP and LEAP models for the Hamoon Helmand catchment. This study shows that if the presented toolbox is used, considering the potential of renewable energies in the catchment, using these energies to recycle the returned water of the agricultural sector, water shortage can be reduced to the horizon 2040.

Sadeghi and Moghadam (2021), in a study entitled “Policy solutions to the water crisis with a water-energy-food linkage approach” with an analytical-descriptive approach, with a partial balance approach of four policy solutions to advance policy goals They have proposed water and energy pricing, development of suitable cultivation and location model of industries, reform of import and export policies with the approach of paying attention to virtual water and water footprint and increasing greenhouse products. From the results and existing evidence, it can be concluded that the WEF nexus would be a practical, adjustable, and adaptive approach for fulfilling increasing demands of the human while there is a glance to limited resources. Based on the available literatures and the case study done by the authors, it can be ultimately concluded that the adoption of the WEF nexus would facilitate better achievements in integrated management of the watersheds.

A review of thematic literature studies shows that due to the nascent concept of water-energy-food linkage in Iran, no very effective efforts have been made to explain the water-energy-food linkage from different angles. In addition, no research has been presented in the country to present a conceptual model of water-energy-food interconnection. Due to the dynamic system approach’s ability to explain the dynamics of the model, the present study is more innovative than other studies.

3. Research methodology

Despite some advantages of multiple non-systematic approaches, including avoiding complexity in modeling, these methods do not provide a holistic view of endogenous variables. Dynamic systems allow the endogenous analysis of research variables. Systematic methods use patterns based on systems thinking. This method was developed in 1950 at MIT by Forrester. Given that the main purpose of this study is to provide a conceptual model of water-energy-food interconnection dynamics in Iran, the relationship between water, food, and energy can be simply shown as follows:

As can be seen, water, energy, and food are intertwined in climate, politics, and the environment. Each section has a broad structure that shows a comprehensive system of communication between the three sections.

4. Analysis of the structure of the integrated conceptual model of water, food, and energy in Iran

4.1. Designing the structure of Iran’s water production sector

Iran is in the global arid and semi-arid zone with an average annual rainfall of less than 250 mm. Although this average is about one-third of the global average rainfall, the increase in water demand can be increased by increasing the amount of land in the cycle of irrigated agricultural production, reducing irrigation, changing the cultivation pattern to crops with high water requirements, and increasing crops significantly. The second is well observed. In addition, Iran’s population is projected to increase from 74 million in 2011 to about 90 million in 2021, while the per capita renewable resources in Iran are a quarter of

Table 3
Indicators of water-energy-food nexus in Iran and deviation from the benchmark (data is only presented for 2017–2018).

Index	Food(F)	Energy(E)	Water(W)
Water avability per capita (m^3/capita)			Index value for Iran: 1659 Deviation from FAO criteria: −76.8%
Food produced per water consumption (USD/m^3)			Index value for Iran: 0.3 Deviation from FAO criteria: −81.6%
Fossil energy per unit of GDP (in 2011 USD)		Index value for Iran: 5.6 Deviation from FAO criteria: 6.24%	
Traditional biomass fuels in household consumption (%)		Index value for Iran: 1% Deviation from FAO criteria: −101%	
Net import value per capita (agricultural products and food) (USD/capita)	Index value for Iran: −5.8 Deviation from FAO criteria: 100%		
Change in forest areas (%/decade)	Index value for Iran: −1% Deviation from FAO criteria: −55%		

Source: World Economic Forum (WEF) (2018) and Centeral Bank of the Islamic Republic of Iran (CBI), 2021.

the world's per capita. Therefore, following the increase in population and the increase of water consumption in urban and rural sectors, agriculture, industry, and environment of the country may face an imbalance between water resources and consumption, so the security of this sector may face an imbalance very important (Norouzi et al., 2022). Furthermore, it is necessary to identify and analyze its various sub-sections. Therefore, by designing a conceptual model of the structure of the sub-sectors related to water resources and consumption of the country, according to the local situation, the strengths and weaknesses of this sector will be more colorful. In this regard, the water production sector for Iran can be shown as follows:

As can be seen, by treating the available water from various sources such as rainwater and groundwater, consumable water (freshwater) is produced to produce purified water, the required energy is received from the energy sector, and Purification is performed. Then the produced water is used in food production (agriculture and livestock and poultry), energy production, and urban and rural housing sector, then the effluent from each of these sectors returns to the water production cycle (Belmonte et al., 2017; Javadinejad et al., 2019).

4.2. Designing the structure of the Iranian food sector

Maintaining food security is one of the most important challenges that different countries face. Family food security means that the family has access to adequate, healthy, and nutritious food to ensure that they receive the minimum amount needed by family members. Food insecurity occurs when people become malnourished due to lack of physical access to food, lack of social and economic access to adequate food, or improper use of food. The World Health Organization estimates that approximately 60% of children in developing countries result from chronic hunger and malnutrition. According to studies on food insecurity in Iran, about a quarter of Iranians are deficient in energy, and the other half are deficient in micronutrients. Therefore, due to population growth, this issue will be very important in studying the food production cycle, creating food security in the country, and identifying different sub-sectors of food production. Therefore, the structure of the food production sector for Iran can be shown as follows:

As can be seen, the food production sector in Iran can be divided into two sub-sectors: agriculture and animal husbandry. Each sub-sector is related to the water and energy sectors (Zera'at Kish and Kamaei, 2017). For example, the cultivation of agricultural products and livestock and poultry breeding requires machinery, facilities, and raw materials whose driving force is energy in various forms (Pahl-Wostl, 2019). Also, agricultural products and livestock and poultry inevitably need water resources to produce their products. It should be noted that, according to (Fig. 3), communication with the outside world can also lead to improved food security through the supply of raw materials required by the two production sectors and the export or import of products (El Zein et al., 2019). (See Fig. 5.)

4.3. Designing the structure of Iran's energy sector

Energy is a strategic commodity whose security plays a central role in international security and the global economy. In the name of security, enter energy into the global security literature and adopt a strategy to provide it. It is of special importance to study and identify the strengths and weaknesses of this section and its sub-sections and its relationship with other sections. Therefore, the structure of the energy production sector in Iran can be shown as follows (Nasresfahani and Bagheri Moghaddam, 2021):

As shown in (Fig. 4), energy production is generated from two main sources, namely renewable sources and non-renewable sources. In Iran, renewable energy sources include solar, hydropower, wind, and biomass, and non-renewable energy sources include oil, gas, and nuclear.

In fact, by receiving primary sources and energy production, this sector provides the energy needed by other sectors; on the other hand, it imports or even exports primary sources and energy production from the outside world. Also, to extract and refine energy resources for energy production, this sector needs water for cooling and other uses connected to the water sector. The food production sector is also connected to the energy sector by receiving energy from this sector and producing biomass and organic waste as a renewable energy source (El-Gafy, 2017).

Based on this index, the amount of plant yield on the amount of water delivered to the plant in each of the irrigation networks was calculated according to Eq. (1) at time t.

$$WP_t = \frac{Y_{c,t}}{w_{c,t}} \tag{1}$$

Where WP_t is applied water productivity, $Y_{c,t}$ is the yield of the plant at time t (tons per hectare) and $w_{c,t}$ is the amount of applied water per hectare for the plant at time t (cubic meters per hectare).

In this study, energy consumption, only the energy required to pump groundwater from wells is considered as the most important source of water-related energy consumption. Based on this index, the amount of plant yield (tons per hectare) is calculated on the amount of energy consumed to pump water from the well according to Eq. (2). EP_t is energy efficiency at time t (kg/kWh), $Y_{c,t}$ is plant yield c at time t (kg), and

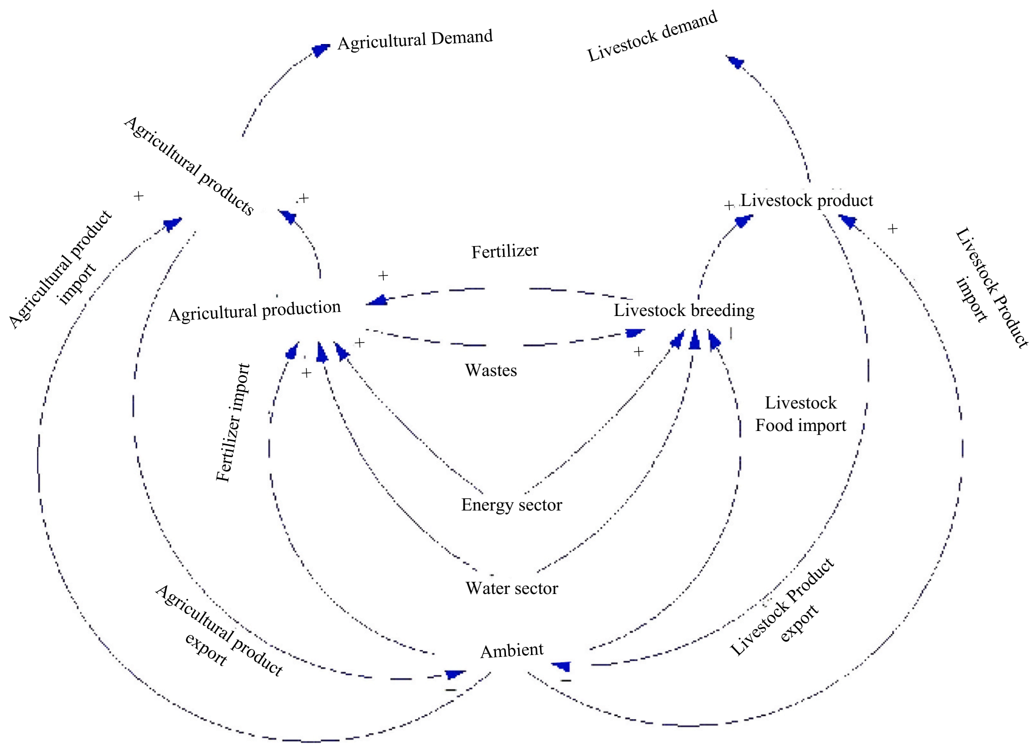

Fig. 3. The structure of the food production sector.

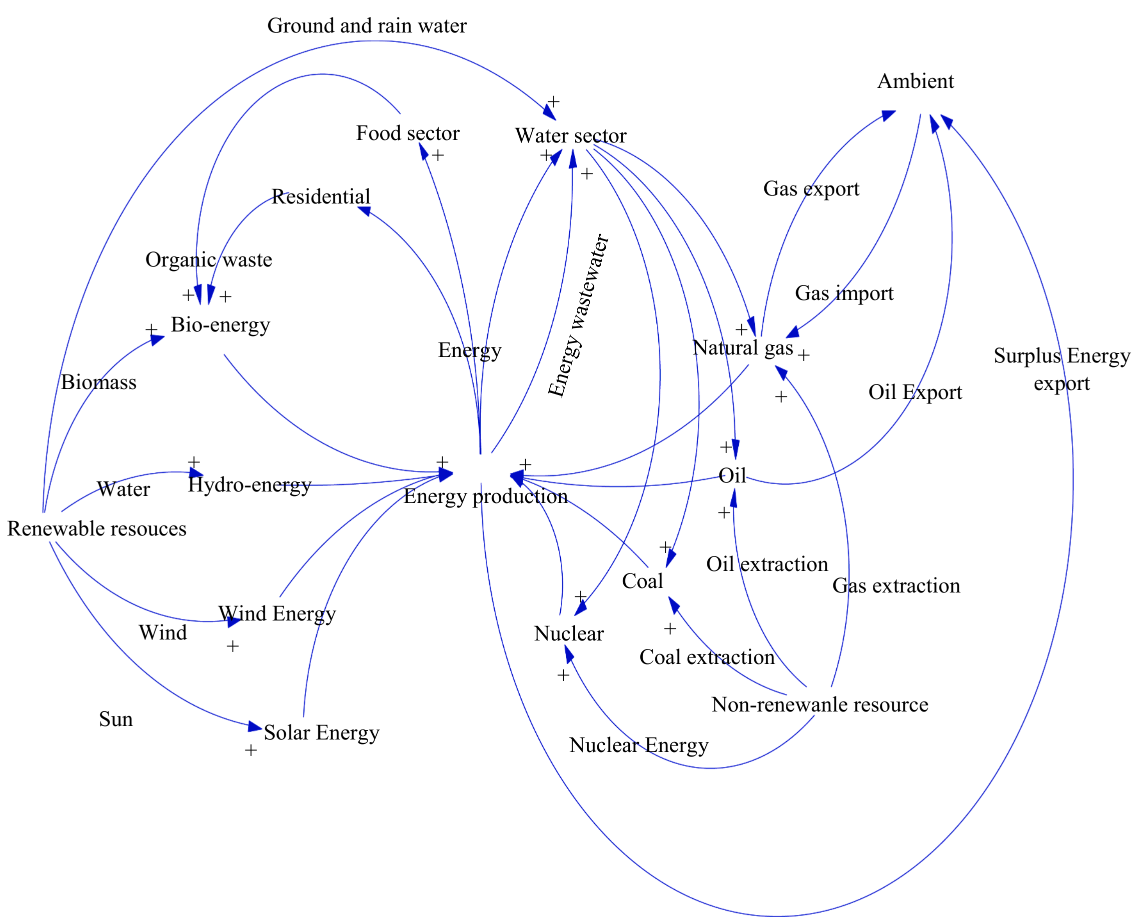

Fig. 4. Structure of the energy production sector.

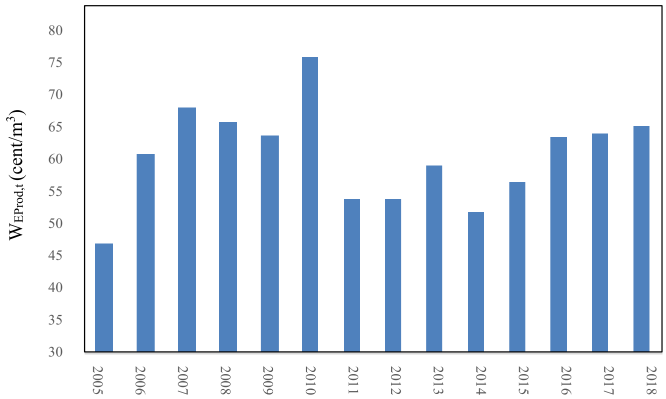

Fig. 6. Economic efficiency of water in agriculture (food production) (cent per cubic meter).

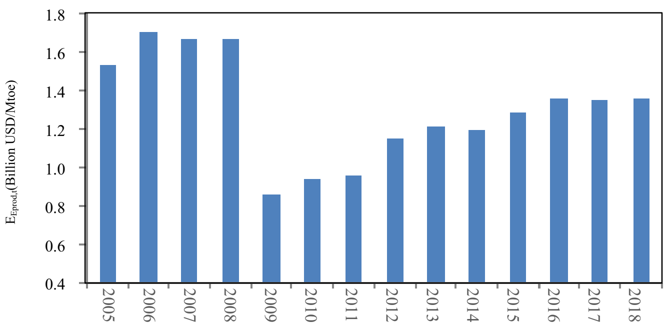

Fig. 7. Economic energy efficiency in agriculture (food production) (billion USD per million tons of oil equivalent).

$E_{c,t}$ is the energy consumption per hectare for plant c and at time t (kWh/ha).

$$EP_t = \frac{Y_{c,t}}{E_{c,t}} \tag{2}$$

In order to calculate the amount of energy consumption, groundwater depth information, annual pump operation time, electric pump efficiency and pump power and pumping flow are required. This information was obtained from Iran Water Resources Management Company. Pump power was calculated by Eq. (3). Energy consumption was also obtained according to Eq. (4).

$$P = \frac{\gamma Q h}{1000\mu} \tag{3}$$

$$E = TP \tag{4}$$

P is pump power (kW), γ is the specific gravity of water (9810 Nm/cubic meter), Q is pumping flow rate (cubic meters per second), h is pumping height (groundwater depth, m), μ is electric pump efficiency (%), E is energy consumption (KWh) and T is the annual operation of the pump.

After explaining the conceptual model of water-energy-food interconnection, various approaches can quantify the existing relationships, including indexing. For example, according to El-Gafy (2017), the economic efficiency of water overtime in the agricultural sector (food production) is calculated as follows:

$$W_{EProdt} = \frac{N_{ct} - C_{ct}}{W_{ct}} \tag{5}$$

Where, W_{EProd} economic water efficiency in agriculture (food production) in dollars per cubic meter, $N_{C,t}$ Net value of the product produced z, $C_{c,t}$ cost of production inputs and $W_{c,t}$ the amount of water used in The agricultural sector (food production) is at time t.

Also, economic energy efficiency overtime in the agricultural sector (food production) is calculated as follows:

$$E_{EProdt} = \frac{N_{ct} - C_{ct}}{E_{ct}} \tag{6}$$

Where, E_{EProd} economic energy efficiency in agriculture (food production) in dollars per joule, $N_{c,t}$ value of product produced c, $C_{c,t}$ cost of production inputs and $E_{c,t}$ amount of energy used for The production of a unit of agricultural goods (food) is at time t.

Based on this, the water-energy-food interconnection index based on the economic efficiency of this interconnection can be presented as follows:

$$WEFNI_t = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{7}$$

Where W_{EFNIt} represents the water-energy-food interconnection index in terms of economic productivity and w_t represents the weight of each index in the total index.

This indicator will help the decision-maker on the efficiency and effectiveness of the management policy in terms of water, food, and energy. The combined index of water, food, and energy are defined

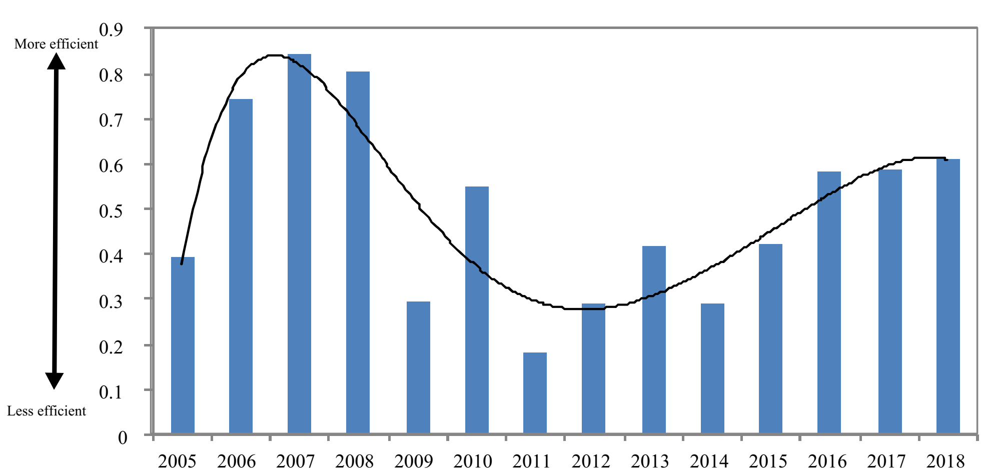

Fig. 8. Economic productivity index of Iran's water-energy-food Nexus.

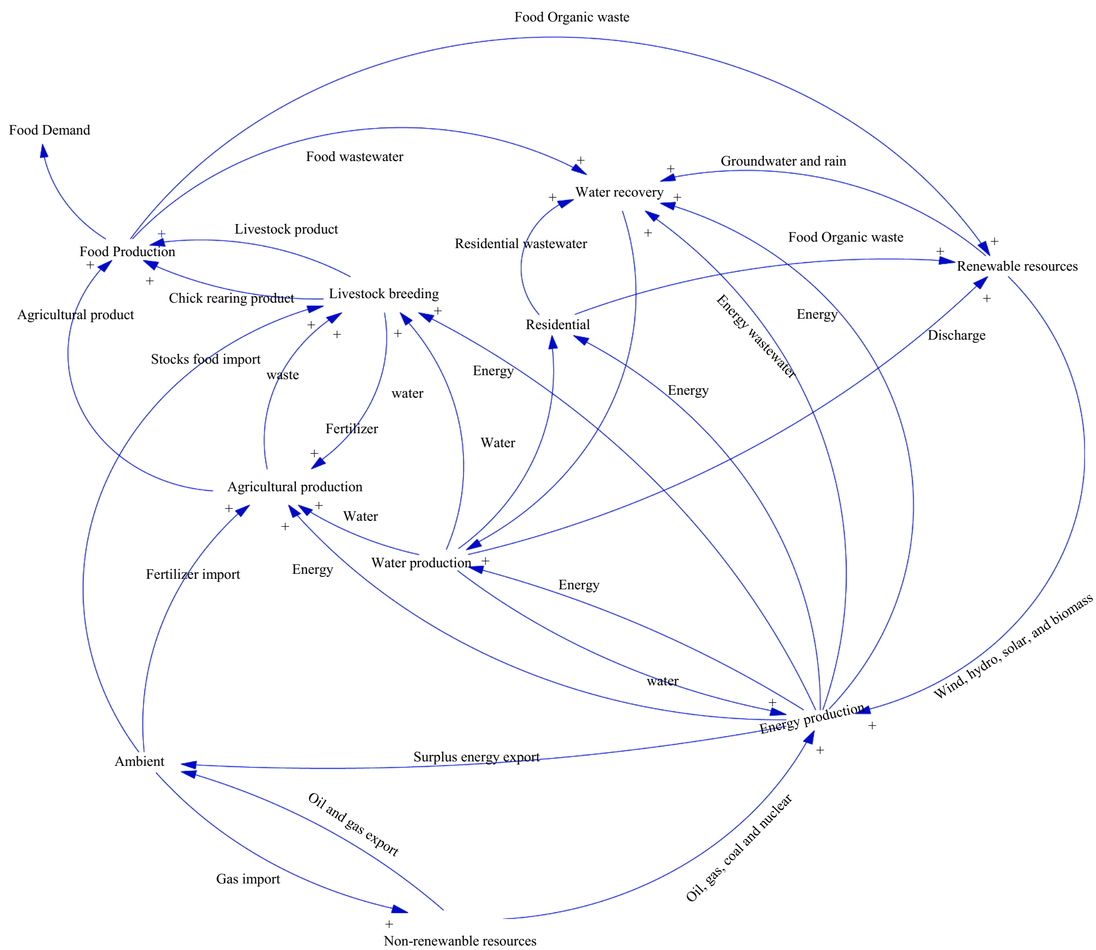

Fig. 5. Integrated water, food, and energy system structure.

according to Eq. (7). The Nexus indices are dimensionless by the Eq. (8).

It should be noted that to avoid the problem of different units of indices, Eq. (8) is used to normalize the indices:

$$X_i = \frac{x_i - Min(x_i)}{Max(x_i) - Min(x_i)} \tag{8}$$

Where X_i represents the normalized index, x_i represents the actual value of the data, and Max (x_i) and Min (xi) represent the maximum and minimum values of the index, respectively.

Briefly, $WFENI_t$ is the combined index of water, food, and energy, n number of Nexus indices and w_i is the weight considered for each index, X_i is the normalized index, xi is the actual value of the desired index and Min(xi) is the lowest value of the index among the case indices check and Max(xi) is the maximum value of the index. In this equations x_i is determined by official reports and databases in the Iran and w_i is determined using literature and opinion of the policymakers and experts.

4.4. Analysis of integrated dynamics of water-energy-food interconnection in Iran

As noted earlier, there is an unavoidable link between the three sectors of water, energy, and food production, and failure to pay attention to any of them can jeopardize the security of other sectors. Therefore, examining all three sections together is of special importance, and it is necessary to pay basic attention to it in macro-policies. Energy is needed to produce, transport, and distribute food and extract, pump, transport, collect and purify water. To understand this connection, these three sections can be seen next to each other as follows:

As can be seen, all three sectors of water, food, and energy production are interconnected and have a production cycle. Therefore, the disruption in any sector or sub-sector of the products of these three areas can disrupt the security of its sector and, by its nature, the security of other sectors. Due to posterior and anterior connections between the three sectors of water - food - energy, it is necessary to pay attention to this link in policymaking and regulation in this area. With a pathological and systematic view, in order to address the risk of energy-water-food security, these three sections should be examined in a regular and coordinated manner. Analyzing a section separately and generalizing the planning and policy of each section to other sections will not be fruitful. As a result, due to these sectors' great importance and dependence, the need for a single policy institution in this area is essential.

In the following, according to the statistics announced by the FAO (2018), some of the indicators used in the water-energy-food link for Iran can be seen. According to the methodology that Fano presents in preparing water-energy-food interconnection reports, criteria are set based on the topology as well as the bio-economic indicators of the countries. Accordingly, countries are divided into several categories, and a criterion is considered for each category, and deviation from it is calculated for each country. In this methodology, countries are divided into categories:

1) Arid country, economy based on agriculture.
2) Water-rich country, economy based on agriculture.
3) Rich countries with limited natural resources.
4) Emerging countries with increasing population growth rates.

For the indicators of each group of the above countries, the FAO determines the relevant criteria based on each group's specific conditions, and the difference between the values of the indicators of each country in each group is measured as a criterion. Accordingly, the situation of Iran in the per capita index of total domestic water resources deviates from the criteria considered by the FAO (−76.8%). Also, Iran's performance in the food index produced for water consumed deviates from the intended amount (−81.6%). Considering the situation in Iran, other indicators presented, it can be seen that the security of each of the water-energy-food links in Iran does not show a good situation.

The data used in this paper was derived from the economic reports of the Iranian Central Bank (Centeral Bank of the Islamic Republic of Iran (CBI), 2021). Price fluctuation can be taken into account due to the trend analysis nature of the model used in the paper. Also, other kinds of data anomalies can be accounted for in this method using the official data. Other researchers can re-produce the results of this study using the data provided by the CBI and the method introduced in this paper.

The water-energy-food interconnected economic productivity index can be calculated according to the proposed methodology to apply the systemic approach used. In (Fig. 6), the economic efficiency of water in the agricultural sector can be seen. In terms of water consumption in different sectors in Iran, surface and groundwater resources are used in agriculture. To calculate the productivity in the agricultural sector, two indicators of economic and physical productivity are used. As mentioned earlier, economic efficiency indicates that for every cubic meter of water, a few rials of added value have been created. Ups and downs have accompanied the trend of water economic productivity in agriculture (food production). However, this trend has been accompanied by a slight upward slope since 2014.

Due to the nature of different activities and the type of consumption of various energy carriers in the agricultural sector, the engine fuel of agricultural machinery and the driving force of electric pumps to pump water from electric wells are among the most important energy consumption in the agricultural sector. In addition, part of the energy consumption is used to heat the space of greenhouses, livestock, and poultry farms. Also, the two energy carriers of oil, gas, and electricity are the most important energy sources used in this sector, and the share of these two carriers in the total energy consumption of the agricultural sector (food production) is about 98%. Examining the trend of (Fig. 7) regarding the economic efficiency of energy in the agricultural sector (food production) shows that this index has been associated with a positive trend after a significant decline in 2009.

(Fig. 8) shows the economic productivity index of the water-energy-food correlation calculated for Iran. It should be noted that, based on the methodology mentioned, energy efficiency and water efficiency indices in the agricultural sector (food production) are normalized based on the Max-Maine method. After weighting, the cumulative economic productivity index for correlation is calculated. An examination of the trend of the mentioned index shows that the economic productivity index of water-energy-food interconnection has reached its lowest level in 2011. After this year and implementing consumption pattern reform policies, a positive trend has accompanied water and energy efficiency in the agricultural sector. Also, implementing the first phase of energy carrier price reform from that year onwards can be somewhat influential in this process.

The MDGs, adopted at the largest meeting of the Millennium Development Goals (MDGs) in New York in September 2000, raised the issue of sustainable development indicators (SDGs) at the Rio + 20 Summit, in Rio de Janeiro, Brazil in 2012(Endo et al., 2017). At this meeting, it was decided that the new goals will replace the Millennium Development Goals in order to become a benchmark for evaluating cutting activities related to sustainable development in the future. Following the meeting, with the participation of experts from around the world, the United Nations developed and approved indicators for sustainable development. Based on these indicators, countries were required to periodically prepare their national and national reports and submit them to international forums (Scanlon et al., 2017).

It is important to note that sustainable development is a comprehensive approach. Focusing on development in only one sector, regardless of its impact on other sectors, has always created many problems that can be found by looking at the history of cutting development. To this end, to avoid serious environmental tensions, the view and approach of solidarity should be considered. The issue of sustainable development and the indicators governing them is a cross-sectoral and comprehensive issue that includes all aspects of economic and social development, cultural as well as environmental health (El Zein et al., 2019). Based on such indicators, countries will be evaluated in the future. In Iran, so far, not much attention has been paid to the issue of sustainable development and its indicators. For this purpose, the integration of these indicators in the formulation of policies in various fields and its implementation in development programs is necessary. It is necessary to pay attention to these indicators as target indicators in various fields of development (Hang et al., 2016).

Social and political instability is caused by a lack of resources, which also leads to irreparable environmental damage. Focusing on one of the areas of water, energy, and food Nexus, regardless of the relationship between them, will have serious risks and unintended consequences (Stillwell et al., 2010).

Nexus formed; But in the last few years, the term has become more widely used and has found an important role in world literature of the sixth World Water Summit in 2008, including the French Summit in 2012 and the Rio + 20 negotiations in 2012. The nexus is the impact of drivers such as climate change, socio-economic change, and the pressures of overpopulation and examines the resulting pressures. What is important is that the approach of connecting water, food, and energy can not be considered as a slogan, but in fact, it expresses the interdisciplinary reality. This approach demonstrates the relationship between the various components of complex social and environmental systems. Interference and correlation between water, energy, and food due to the issue of scarcity and security of natural resources become more prominent (Qasemipour and Abbasi, 2019); In fact, the link between water, energy, and food is a vision of sustainable development that seeks to strike a balance between different goals, including the interests and needs of people and the environment (Hoff et al., 2019).

5. Conclusion

As the demand for water, energy, and food increases in the coming decades, the pressure on these three sectors will increase, and the importance of the link between water, energy, and food will become even more apparent. Given the importance of this issue, the present study aims to provide a conceptual model of water-energy-food interconnection, an attempt to develop the growing literature of this interconnection in Iran. Also, as an application of the mentioned interconnection, the economic productivity index of water-energy-food was calculated for Iran, the study of which shows that ups and downs have accompanied the mentioned productivity. In 2010 this index reached its lowest point. After this year, policies to reform the consumption pattern and the targeted implementation of subsidies, water, and energy efficiency in the agricultural sector have been accompanied by a positive trend.

It should be noted that attention to stakeholders' goals in these three key areas, in decisions and policies by decision-makers and trustees in these areas is essential. In this regard, institutional development for policy and discourse of the various sectors involved is the proposed strategy to achieve a common consensus and basis. The Ministries of Energy, Agriculture, Industry, Mines, and Trade play a key role in this case.

Coordination between the three departments of the Deputy for Planning and Economic, the Deputy for Water Affairs, and the Deputy for Electricity and Energy Affairs of the Ministry of Energy and their involvement in the Strategic and Integrated Planning Office are to formulate development plans organize the relevant affairs. And also, soil quality strategies are needed to improve water efficiency and regulate water consumption in the agricultural sector. Monitoring of food production and supervision of the country's industries should also be considered to make optimal use of the country's energy and water resources. The development of the country's industries based on environmental economics and clean goods is also effective. The Islamic Consultative Assembly has a very important role in achieving sustainable development by formulating upstream laws in industrial development, use of energy and water resources, coordination between responsible bodies, and determining the role of each institution.

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.

References

Aboelnga, H.T., Ribbe, L., Frechen, F.B., Saghir, J., 2019. Urban water security: definition and assessment framework. Resources 8 (4), 178.

Ahmad, S., Tahar, R.M., Muhammad-Sukki, F., Munir, A.B., Rahim, R.A., 2016. Application of system dynamics approach in electricity sector modelling: A review. Renew. Sust. Energ. Rev. 56, 29–37.

Artioli, F., Acuto, M., McArthur, J., 2017. The water-energy-food nexus: an integration agenda and implications for urban governance. Polit. Geogr. 61, 215–223.

Ashraf, A., Majd, A., Troubitsyna, E., 2017. Towards a realtime, collision-free motion coordination and navigation system for a UAV fleet. In: Proceedings of the Fifth European Conference on the Engineering of Computer-Based Systems, pp. 1–9. August.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Yumkella, K.K., 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. Energy Policy 39 (12), 7896–7906.

Belmonte, B.A., Benjamin, M.F.D., Tan, R.R., 2017. Biochar systems in the water-energy-food nexus: the emerging role of process systems engineering. Curr. Opin. Chem. Eng. 18, 32–37.

Biggs, E.M., Bruce, E., Boruff, B., Duncan, J.M., Horsley, J., Pauli, N., Imanari, Y., 2015. Sustainable development and the water–energy–food nexus: A perspective on livelihoods. Environ. Sci. Pol. 54, 389–397.

Bogardi, J.J., Dudgeon, D., Lawford, R., Flinkerbusch, E., Meyn, A., Pahl-Wostl, C., Vörösmarty, C., 2012. Water security for a planet under pressure: interconnected challenges of a changing world call for sustainable solutions. Curr. Opin. Environ. Sustain. 4 (1), 35–43.

Cai, X., Wallington, K., Shafiee-Jood, M., Marston, L., 2018. Understanding and managing the food-energy-water nexus–opportunities for water resources research. Adv. Water Resour. 111, 259–273.

Centeral Bank of the Islamic Republic of Iran (CBI), 2021. Economic Database, Tehran/Iran. https://www.cbi.ir/section/1372.aspx.

DeNooyer, T.A., Peschel, J.M., Zhang, Z., Stillwell, A.S., 2016. Integrating water resources and power generation: the energy–water nexus in Illinois. Appl. Energy 162, 363–371.

El Zein, A., Shelnutt, K.P., Colby, S., Vilaro, M.J., Zhou, W., Greene, G., Mathews, A.E., 2019. Prevalence and correlates of food insecurity among US college students: a multi-institutional study. BMC Public Health 19 (1), 1–12.

El-Gafy, I., 2017. Water–food–energy nexus index: analysis of water–energy–food nexus of crop's production system applying the indicators approach. Appl Water Sci 7 (6), 2857–2868.

Endo, A., Tsurita, I., Burnett, K., Orencio, P.M., 2017. A review of the current state of research on the water, energy, and food nexus. J. Hydrol. 11, 20–30.

Esfandiari-Baiat, M., Barzegar, Z., Yousefi, L., Maheshwari, B., 2014. Urbanisation and its effects on water, food security and energy needs in Iran: A case study of city of shiraz. In: The Security of Water, Food, Energy and Liveability of Cities. Springer, Dordrecht, pp. 101–112.

Fang, K., Heijungs, R., de Snoo, G.R., 2014. Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: overview of a footprint family. Ecol. Indic. 36, 508–518.

Fontes, C.H.D.O., Freires, F.G.M., 2018. Sustainable and renewable energy supply chain: A system dynamics overview. Renew. Sust. Energ. Rev. 82, 247–259.

Georgiadis, P., Vlachos, D., Iakovou, E., 2005. A system dynamics modeling framework for the strategic supply chain management of food chains. J. Food Eng. 70 (3), 351–364.

Gohari, A., Mirchi, A., Madani, K., 2017. System dynamics evaluation of climate change adaptation strategies for water resources management in Central Iran. Water Resour. Manag. 31 (5), 1413–1434.

Hagemann, N., Kirschke, S., 2017. Key issues of interdisciplinary nexus governance analyses: lessons learned from research on integrated water resources management. Resources 6 (1), 9.

Hang, M.Y.L.P., Martinez-Hernandez, E., Leach, M., Yang, A., 2016. Designing integrated local production systems: a study on the food-energy-water nexus. J. Clean. Prod. 135, 1065–1084.

Hjorth, P., Bagheri, A., 2006. Navigating towards sustainable development: A system dynamics approach. Futures 38 (1), 74–92.

Hoff, H., Alrahaife, S.A., El Hajj, R., Lohr, K., Mengoub, F.E., Farajalla, N., Ulrich, A., 2019. A nexus approach for the MENA region—from concept to knowledge to action. Front. Environ. Sci. 7, 48.

Jalilov, S.M., Keskinen, M., Varis, O., Amer, S., Ward, F.A., 2016. Managing the water–energy–food nexus: gains and losses from new water development in Amu Darya River basin. J. Hydrol. 539, 648–661.

Javadinejad, S., Ostad-Ali-Askari, K., Eslamian, S., 2019. Application of multi-index decision analysis to management scenarios considering climate change prediction in the Zayandeh Rud River basin. Water Conserv. Sci. Eng. 4 (1), 53–70.

Karimi, P., Qureshi, A.S., Bahramloo, R., Molden, D., 2012. Reducing carbon emissions through improved irrigation and groundwater management: A case study from Iran. Agric. Water Manag. 108, 52–60.

Kumar, M.D., Sivamohan, M.V.K., Narayanamoorthy, A., 2012. The food security challenge of the food-land-water nexus in India. Food Secur. 4 (4), 539–556.

Leopold, A., 2016. Energy related system dynamic models: a literature review. CEJOR 24 (1), 231–261.

Liu, L., Hejazi, M., Patel, P., Kyle, P., Davies, E., Zhou, Y., Edmonds, J., 2015. Water demands for electricity generation in the US: modeling different scenarios for the water–energy nexus. Technol. Forecast. Soc. Chang. 94, 318–334.

Madani, K., 2014. Water management in Iran: what is causing the looming crisis? J. Environ. Stud. Sci. 4 (4), 315–328.

Madani, K., Khatami, S., 2015. Water for energy: inconsistent assessment standards and inability to judge properly. Curr. Sustain. Renew. Energy Rep. 2 (1), 10–16.

Madani, K., Shafiee-Jood, M., 2020. Socio-hydrology: a new understanding to unite or a new science to divide? Water 12 (7), 1941.

Madani, K., AghaKouchak, A., Mirchi, A., 2016. Iran's socioeconomic drought: challenges of a water-bankrupt nation. Iran. Stud. 49 (6), 997–1016.

Mirchi, A., Madani, K., Watkins, D., Ahmad, S., 2012. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resour. Manag. 26 (9), 2421–2442.

Mirzaei, A., Saghafian, B., Mirchi, A., Madani, K., 2019. The groundwater–energy–food nexus in Iran's agricultural sector: implications for water security. Water 11 (9), 1835.

Naderi, M.M., Mirchi, A., Bavani, A.R.M., Goharian, E., Madani, K., 2021. System dynamics simulation of regional water supply and demand using a food-energy-water nexus approach: application to Qazvin plain, Iran. J. Environ. Manag. 280, 111843.

Nasresfahani, A., Bagheri Moghaddam, N., 2021. A comparative study of energy security strategies and policies of selected countries and lessons learned for Iran. Rahyaft 31 (81), 73–90.

Nhamo, L., Mpandeli, S., Senzanje, A., Liphadzi, S., Naidoo, D., Modi, A.T., Mabhaudhi, T., 2021. Transitioning toward sustainable development through the water–energy–food nexus. In: Sustaining Tomorrow via Innovative Engineering, pp. 311–332.

Norouzi, N., 2022. Regulating Sustainable Economics: A Legal and Policy Analysis in the Light of the United Nations Sustainable Development Goals. *Handbook of Research on Changing Dynamics in Responsible and Sustainable Business in the Post-COVID-19 Era*. IGI Global, pp. 266–287.

Norouzi, N., Fani, M., Talebi, S., 2022. Green tax as a path to greener economy: A game theory approach on energy and final goods in Iran. Renew. Sust. Energ. Rev. 156, 111968.

Norouzi, N., Kalantari, G., 2020. The sun food-water-energy nexus governance model a case study for Iran. Water-Energy Nexus 3, 72–80.

Pahl-Wostl, C., 2019. Governance of the water-energy-food security nexus: A multi-level coordination challenge. Environ. Sci. Pol. 92, 356–367.

Qasemipour, E., Abbasi, A., 2019. Virtual water flow and water footprint assessment of an arid region: A case study of South Khorasan province, Iran. Water 11 (9), 1755.

Ringler, C., Bhaduri, A., Lawford, R., 2013. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5 (6), 617–624.

Sadeghi, S.H., Moghadam, E.S., 2021. Integrated watershed management vis-a-vis water–energy–food Nexus. In: The Water–Energy–Food Nexus. Springer, Singapore, pp. 69–96.

Sanders, K.T., Masri, S.F., 2016. The energy-water agriculture nexus: the past, present and future of holistic resource management via remote sensing technologies. J. Clean. Prod. 117, 73–88.

Saray, M.H., Baubekova, A., Gohari, A., Eslamian, S.S., Haghighi, A.T., 2022. Optimization of Water-Energy-Food Nexus considering CO2 emissions from cropland: A case study in northwest Iran. Appl. Energy 307, 118236.

Scanlon, B.R., Ruddell, B.L., Reed, P.M., Hook, R.I., Zheng, C., Tidwell, V.C., Siebert, S., 2017. The food-energy-water nexus: transforming science for society. Water Resour. Res. 53 (5), 3550–3556.

Shimbar, A., Ebrahimi, S.B., 2020. Political risk and valuation of renewable energy investments in developing countries. Renew. Energy 145, 1325–1333.

Simonovic, S.P., 2002. World water dynamics: global modeling of water resources. J. Environ. Manag. 66 (3), 249–267.

Stillwell, A.S., Hoppock, D.C., Webber, M.E., 2010. Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus. Sustainability 2 (4), 945–962.

Wa'el, A.H., Memon, F.A., Savic, D.A., 2017. An integrated model to evaluate water-energy-food nexus at a household scale. Environ. Model. Softw. 93, 366–380.

White, D.J., Hubacek, K., Feng, K., Sun, L., Meng, B., 2018. The water-energy-food Nexus in East Asia: A tele-connected value chain analysis using inter-regional input-output analysis. Appl. Energy 210, 550–567.

Winz, I., Brierley, G., Trowsdale, S., 2009. The use of system dynamics simulation in water resources management. Water Resour. Manag. 23 (7), 1301–1323.

World Economic Forum (WEF), 2018. Global Risks 2018. World Economic Forum, Cologne/Geneva. www.fao.org.

Wu, L., Elshorbagy, A., Pande, S., Zhuo, L., 2021. Trade-offs and synergies in the water-energy-food nexus: the case of Saskatchewan, Canada. Resour. Conserv. Recycl. 164, 105192.

Xiao, R., He, X., Zhang, Y., Ferreira, V.G., Chang, L., 2015. Monitoring groundwater variations from satellite gravimetry and hydrological models: A comparison with in-situ measurements in the mid-Atlantic region of the United States. Remote Sens. 7 (1), 686–703.

Xu, Y., Szmerekovsky, J., 2017. System dynamic modeling of energy savings in the US food industry. J. Clean. Prod. 165, 13–26.

Zera'at Kish, S.Y., Kamaei, Z., 2017. Factors affecting food security of rural farming households in Kohkiluyeh and Boyer-Ahmad Province of Iran. J. Food Technol. Nutr. 14 (2), 77–86.

Zhang, X., Vesselinov, V.V., 2016. Energy-water nexus: balancing the tradeoffs between two-level decision makers. Appl. Energy 183, 77–87.