International Journal of Energy and Water Resources
https://doi.org/10.1007/s42108-019-00042-8

REVIEW ARTICLE

A review of the water–energy–food nexus measurement and management approach

F. M. Tashtoush[1,2] · W. K. Al-Zubari[2] · A. Shah[1,3]

Received: 26 August 2019 / Accepted: 12 October 2019

Abstract

Water, energy, and food are the fundamental resources for improving living conditions and sustainable development. Because substantial interdependencies and relationships exist among these three sectors, the word nexus between water–energy–food is being used to indicate the importance of managing them together and not in isolation. This paper reviews and analyzes the current status of water–energy–food nexus approach, which has attracted widespread attention in the past few years, with the aim to understand the nexus thinking and illustrate the methods and tools used in the nexus analysis. This is expected to help the policy makers and researchers to be better informed about the options for sustainable securing and managing these three resources. In addition, such integration between these three sectors will significantly help in achieving the goals of sustainable development, since the water–energy–food nexus is directly related to three goals 2, 6, and 7, which are, respectively, related to ensuring access to food, water, and sustainable energy for all.

Keywords Sustainable development · Sustainability · Nexus · Food, water, and energy security · Resource efficiency

Introduction

The three resources water, energy, and food are significant for sustaining life on earth, important for people well-being, and economic activities. Due to a number of variables, such as population growth, urbanization, rising incomes and consequent change in consumption patterns, and climate change, the demand on these three key sectors is continuously growing (Artioli et al. 2017; Misselhorn et al. 2012; Mortada et al. 2018). Availability of any one of these resources can be limited by constraints imposed or actions taken on the two other resources (Karnib 2018; Li et al. 2019a, b), and thus will be affecting their sustainability and securities. For example, production of agricultural food utilizes huge amounts of water and energy, accounting for more than 70% of freshwater and 30% of the worldwide used energy (FAO 2017). On the other side, water is important for processing of fossil fuels, generating energy, and cooling, while purification, pumping, distribution, and treatment of water require energy (Shang et al. 2018).

Several researchers studied the sustainability of the three resources focusing only on one sector, like water (Jiang et al. 2016) or food resources (Gephart et al. 2016) independently, but concluded the need for their coupling in an integrated framework. Understanding how these resources interact will be a major challenge for creating a sustainable future and quantifying the impact of one sector on the other two sectors is strongly recommended (Karnib 2018). Therefore, for managing the sustainability of these three essential sectors, there is a need to study them in an integrated way, because they are interrelated and interdependent among each other. Since 2011, in Bonn Conference, water, energy, and food interconnections have been mentioned as the "Water–Energy–Food (WEF) nexus" (Li et al. 2019a, b). The word "nexus" connotation is used to ensure improved long-term outcomes (solutions) for the three sectors (Mannan et al. 2018). Moreover, solutions of the nexus approach in contrast to individual WEF elements are expected to offer

✉ A. Shah
ashah@uob.edu.bh; afzals_qau@yahoo.com

1 Department of Environment and Sustainable Development, College of Science, University of Bahrain, 32038 Sakhir, Kingdom of Bahrain

2 Department of Natural Resources and Environment, College of Graduate Studies, Arabian Gulf University, 26671, Manama, Kingdom of Bahrain

3 Department of Chemistry, College of Science, University of Bahrain, 32038 Sakhir, Kingdom of Bahrain

Published online: 02 November 2019

more sustainable decisions to solve challenges of WEF interlinkages and trade-offs (Nie et al. 2019).

More importantly, the WEF nexus can also support achieving the sustainable development goals (SDGs) of 2030 UN agenda for sustainable development, because of its close relation to three SDGs: SDG2 "zero hunger", SDG6 "clean water and sanitation for all", and SDG7 "affordable and clean energy" (Mahlknecht and González-Bravo 2018). Because the SDGs are indivisibly connected with each other, the nexus integrated nature and perspective is crucially essential for promoting the integration not only between these three goals, but also across other goals by analyzing synergies and trade-offs between them, and, therefore, acts as a catalyst that improves implementation of the 2030 agenda.

Li et al. (2019a, b) indicated that studies on the WEF nexus in a holistic framework are still in their initial stages. However, many international institutions introduced the WEF nexus in a holistic framework (as discussed vide infra), but there is a lack in implementing these frameworks in the management of the natural resources or in policy formulation. It should also be noted that the interconnections and interdependencies are region- or country-specific. Therefore, there is no particular structure capturing all the tools required for providing a solid foundation for the WEF nexus analysis (Zhang et al. 2019). In general, the overall methodology of the WEF nexus management approach is performed in three steps (Nie et al. 2019): (1) overview characterization (identifying and quantifying the connectivity between food, water, and energy); (2) modeling the WEF nexus system; and (3) performing future management scenarios to help decision-making.

Overall, this study is significant in the sense that understanding, quantifying, and managing the crucial links between the three sectors in the nexus approach are an innovative solution to address the demands on these three primary sectors. Implementing a WEF nexus thinking and approach will be able to support the SDGs by ensuring integrated plans and policy settings, especially in countries that face problems of resource scarcity and environmental degradation. Presenting the WEF nexus is beneficial for the improvement of resource use efficiency and security achievement. Thus, the specific aim of this work is to conduct a review of the literatures on the WEF nexus addressing the following key questions: what are the challenges affecting water, energy, and food resources? What are the main linkages or relationships across the nexus sectors? What are the trends and advancements in the WEF nexus field research? What types of methods are used for quantifying and measuring the WEF nexus? Therefore, this study analyzes the WEF nexus peer-reviewed papers across the globe, and some international reports, covering the period from 2011 to May 2019, which were selected from several databases, e.g., Science Direct, Springer Link, and Google Scholar, using the keyword "nexus", "food", "energy", and "water" in the article title. The collected papers and reports in this review were then grouped to categories according to the nexus different domains and at various scales.

Challenges of water, energy, and food sectors

In the literature, a number of scholars emphasized that food, water, and energy resources around the world are already under considerable threat (Bazilian et al. 2011; Howells et al. 2013; WEF 2011a), and the demand for these resources is rapidly growing in the coming years (Hoff 2011). A warning in this regard was first given by Meadows et al. (1992); "If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next 100 years." The increase in demand is the outcome of rapid growth in population, unplanned urban development, globalization (e.g., by foreign investment and trade), technological development, conflicts, expanding middle-class lifestyles and consumption patterns, climate change and weather pattern transformation, and, most significantly, inefficient use of resources that caused their degradation and scarcity (FAO 2014; Hoff 2011; WEF 2011b; Bazilian et al. 2011). Forecasts indicate that demands for water will rise by more than 40% (USNIC 2012), energy demand will grow by 45% globally (IEA 2008), and annual global production of crops and livestock will need to be 35% higher in 2050 (FAO 2006). Due to the strong interdependence between these three sectors, the nexus interlinkages are expected to intensify in the future. There are several factors affecting the WEF nexus, which vary in significance depending on the specifics of countries or regions. In general, the literature indicates that there are three major driving forces to the three sectors/resources as discussed in the subsequent sections.

Accelerating socio-economic development

The world population is approximately growing at the rate of 83 million per year or 6 million people per month. It is projected to rise from 7 billion to more than 8 billion by 2030, and to more than 9 billion by 2050 (UNDESA 2015; UNDP 2006). This growth remains high especially in the least developed countries (LDCs) and countries where hunger and natural resource degradation are already widespread. Africa is predicted to be the largest contributor, followed by Asia (UNDESA 2015). Economic development is also putting more stress on the resources (European Union 2018), leading to irreversible ecosystem degradation, resource depletion, and thus threatening sustainable development (Chang et al. 2016; Hoff 2011). In the light of these facts and figures, it is believed that the most essential cause of change affecting the WEF nexus is population growth and economic development (Lawford et al. 2013).

Urbanization

Urbanization plays a greater role even more than the population growth, and has a bigger effect on production of energy than on production of food (Lawford et al. 2013). Globally for the first time, the urban population surpassed the rural population in 2007. It is assumed that the trend will proceed, so that by 2050, almost 70% of the population will live in cities (UNDESA 2014). While, in principle, services such as electricity and drinking water can be supplied more effectively in urban than in rural areas, living in cities encourages more consumption and resource demanding lifestyles and thereby increasing waste. This demographic prospect is increasing the pressures on the three resources together (OFID 2017). UNEP (2011) highlighted this demand for resources by stating that production of waste is more in urban areas due to greater population density and greater per capita consumption of resources relative to rural areas. Specifically, cities account for 75% of the energy consumption and emissions of 75% of greenhouse gases (GHGs). However, because these are centers of knowledge and economic prosperity, so compared to rural areas, there are more opportunities to improve resource efficiency and implement nexus approaches.

Climate change

Climate change further intensifies competition and trade-offs between the three resources and the challenge of meeting their increasing requirements (Bazilian et al. 2011; ESCWA 2015; Rasul 2016; Van-Vuuren et al. 2012). Because of the potential impacts of climate change manifested by temperature rise, more water and more energy will be needed for all sectors. In addition, the more severe and frequent extreme weather events can hit the areas that are important for food production (Beddington 2009). Moreover, climate change is affecting the energy sector by transitioning to energy supply alternatives of low GHGs' emissions, and this had expanded the use of biofuels (OFID 2017; Miralles-Wilhelm 2016). However, suitable adaptation to climate change demands efficient use of energy, water, and food resources to fight against vulnerability (OFID 2017).

History and development of the WEF nexus

The idea of WEF resource connectivity was known for decades. In 1983, the terminology of the nexus first appeared between food and energy, when the United Nations University (UNU) introduced a collection of food–energy nexus initiatives to recognize their significant interlinkages (Sachs and Silk 1990). In addition, the World Commission on Environment and Development report of 1987 "Our Common future" indicated the need for a more complete and comprehensive thinking about environment (Schmidt and Matthews 2018). However, the World Economic Forum (WEF) formally announced the three nexus pillars of food, water, and energy at their annual meeting in 2011 (WEF 2011b). In the same year, the Bonn International Conference "The Water, Energy and Food Security Nexus: Solutions for the Green Economy" arranged by the German Federal Government presented a visionary nexus method for achieving sustainability. This was the stepping stone to the UN Sustainable Development Conference (Rio + 20 summit), where the WEF nexus was first highlighted in the global agenda (Hoff 2011; Leck et al. 2015). A background paper "Understanding the Nexus" was introduced in the conference to demonstrate the direction of nexus approach and research in the sustainability context (Hoff 2011). Figure 1 represents the schematic illustration of the WEF nexus, where systems of energy, water, and food are inseparably related, and reliant on each other, highlighting the pressures and drivers that affect the concept, and the positive outcomes of the nexus integration.

Following the Bonn Conference, the global community focused on the WEF nexus. A growing number of

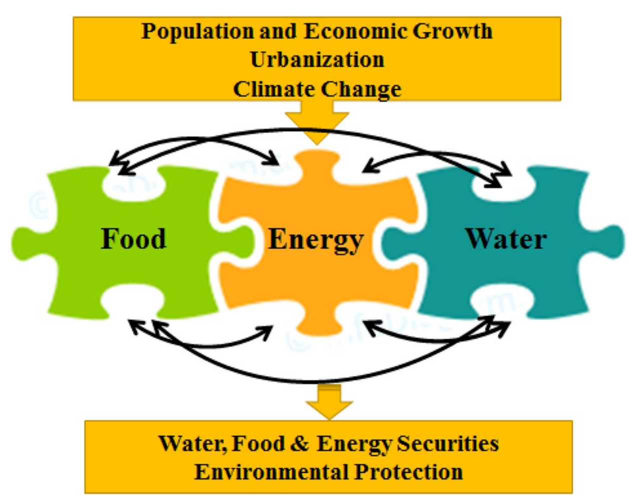


Fig. 1 Conceptual diagram of the WEF nexus, illustrating the linkages between the three components, the main drivers, and the outcomes of the nexus integration

development organizations across the world launched WEF nexus initiatives. One of the major initiatives is the German Federal Government establishing of the “WEF Security Nexus Resource Platform” in 2011 (Endo et al. 2017). In 2013, the UN Economic and Social Commission for Asia and the Pacific launched a paper “The Status of the Water–Food–Energy Nexus in Asia and the Pacific” (UN-ESCAP 2013). In addition, the Food and Agricultural Organization (FAO) prepared “The Innovative Accounting Framework for the WEF Nexus: Application of the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach to three case studies” (Giampietro et al. 2013). In 2015, the German Agency for International Cooperation (GIZ) together with the League of Arab States (LAS) and the Arabian Gulf University (AGU) prepared six policy briefs (available in both English and Arabic) on the WEF nexus in the Arab region (Al-Zubari 2016). These policy briefs are directed towards the ministers and senior management of the three sectors in the Arab countries, since this region represents an extreme case worldwide in terms of WEF securities (Al-Zubari 2013). In addition, ESCWA’s sixth water development report was on the WEF security nexus in the Arab region (ESCWA 2015). Currently, the nexus is the foundation of a host of many approaches addressing the global resources’ security challenges.

Ringler et al. (2013) mentioned that the notion of nexus thinking is associated with the integrated water resource management (IWRM) concept that formed the basis for the nexus approach. The 1992 Dublin statement on water and sustainable development and its four principles set the ground for the IWRM approach, and the sustainable development world summit set the goal of developing IWRM plans for all countries by 2005 (WWDR 2009). However, the IWRM is water oriented (Endo et al. 2017) and the formulation of IWRM strategies and plans failed to move the concept beyond the water box (ESCWA 2015). It is incomplete to treat water resource management discreetly, even within an IWRM structure, as all water decisions influence energy and food securities opportunities. As indicated earlier, the nexus existed under various forms for decades. Integrated natural resource management, IWRM, integrated energy system planning, sustainable agriculture, green economy, sustainable production and consumption frameworks, and sustainable development itself are all based on a nexus concept aimed at improving the management of natural resources and associated ecosystems. However, the nexus approach differs from the existing traditional integrated management approaches, (Miralles-Wilhelm 2016). The basic argument is that each approach examines only one sector, with no consistency of evaluation or possible scenarios for other sectors, and thereby, many studies recommended the need of reformulating these approaches for better meeting the demands among the sectors (Hoff 2011). Ideally, the nexus approach focuses on collaboration between sectors by encouraging resource use efficiency through minimizing trade-offs and maximizing the cross-sectoral benefits.

This review paper starts with figuring the content of the nexus collected papers, using qualitative data software to generate a word cloud that highlights the main issues related to the nexus. Figure 2 displays a graphical representation of the conceptual content of the WEF nexus approach. The word size is an indication of its appearance frequency inside the text, where the biggest is mentioned the most. As expected, the words “nexus”, “water”, “energy”, and “food” topped the list of the most frequent ones. However, the words water and energy are more repeated than “food”. In other words, the published research on the water and energy

Fig. 2 Top issues in the body of the WEF nexus papers

nexus is more than those including food. It can be noticed also that the nexus is greatly related to sustainable development. Other words like integrated, management, consumption, resources, economic, security, policy, and approach are also clearly seen in the word cloud.

Overview of the WEF nexus concept

Until now, there is no clear, commonly known definition to the WEF nexus (Endo et al. 2017; Roidt and Avellán 2019). However, according to the Merriam-Webster online dictionary and the Oxford dictionary of English, the "Nexus" is defined as "a connection, link or series of connections linking two or more things" or "a connected group or series" (see https://en.oxforddictionaries.com/definition/nexus and https://www.merriam-webster.com/dictionary/nexus). This means that the nexus thinking is seeking to overcome working in a traditional silos or sectoral mindset that hinders informational exchange and collaboration between different resources, in particular between the food, water, and energy sectors, since they are at the core of human requirements. On the contrary, the WEF nexus thinking and approach seeks for studying the important interlinkages and relations between the three resources and exploring their synergies and tradeoffs (Covarrubias 2019; Marker et al. 2018). Newell et al. (2011) reported that "system's performance cannot be optimized by optimizing the performance of its sub-systems taken in isolation from one another". This suggests that any sustainability improvement in one sector (e.g., water) relates to the other sectors (i.e., energy and food). Moreover, the FAO (2014) stated that "WEF Nexus has emerged as a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic and environmental goals".

The concept of the "nexus" has attracted considerable attraction as a holistic approach. The content of the nexus can be applied to several linkages, i.e., water–energy (Chen and Chen 2016; Dai et al. 2018; Liu et al. 2019; Marzooq et al. 2018), food–water (Mortada et al. 2018; Xu et al. 2019; Zeng et al. 2019), energy–food (Abdelradi and Serra 2015; Taghizadeh-Hesary et al. 2019), and WEF nexus (Hussien et al. 2017; Karnib 2018; Zhang et al. 2019). Furthermore, the literature indicates that many frameworks are used to address the nexus. While the WEF (2011a) has considered the nexus framework from a security perspective, other studies have incorporated the WEF nexus core with another element such as climate (Schmidt and Matthews 2018), ecosystem (Karabulut et al. 2018), land (Ringler et al. 2013), soil (Lal et al. 2017), and waste (Garcia et al. 2019). Both water–energy–land (WEL) nexus, outlined in the European Report on Development (EU 2012) and climate, land, energy, and water (CLEW) by the WEF (2011a) were introduced earlier in the same year 2011. These nexus frameworks and more others are clarified in ESCWA (ESCWA 2015).

Furthermore, the argument of resource centrality within the nexus increases its diversity. According to the WEF (2011a), water is the one that holds the web of resource use together and considered as the heart of the nexus (Hoff 2011; Swatuk and Cash 2018). On the other hand, Yillia (2016) justified that food is generally the third dimension of the WEF nexus for the reason that agriculture is a major human activity, the most visible in the complex web of interlinkages between the nexus dimensions. Similarly, the FAO sited food in the nexus center from the perspective of food security (FAO 2014). In addition, the international renewable energy agency (IRENA 2015) highlighted energy technologies as a massive profit among the three-pronged nexus approach. As a result, the WEF nexus approach normally depends on the perspective of the research.

WEF nexus within the context of sustainable development goals (SDGs)

It is worth noting that the WEF nexus can be usefully used to sustainable development debates and subsequent tracking of SDGs. For example, Karnib (2017a, b, c, d) addressed that there is a need for an integrated nexus approach to attain the SDGs. Specific to the 2030 agenda (UN General Assembly 2015), the three components of the WEF nexus are directly related to 3 of the 17 goals, which are aligned with the human rights (Mohtar and Lawford 2016; Saladini et al. 2018; ESCWA 2015):

- SDG2 "Zero Hunger", which seeks to "end hunger, achieve food security and improve nutrition and promote sustainable agriculture";
- SDG6 "Clean Water and Sanitation", which seeks to "ensure availability and sustainable management of water and sanitation for all"; and
- SDG7 "Affordable and Clean Energy", which seeks to "ensure access to affordable, reliable, sustainable and modern energy for all".

Integration within a nexus approach can also facilitate in achieving other goals, as: SDG1 "Zero poverty", SDG8 "Sustainable economic growth", SDG11 "Sustainable cities and communities", SDG12 "Sustainable consumption and production", SDG13 'Climate change", and SDGs14&15 "Conservation, protection, and sustainable use of marine and terrestrial resources and ecosystems" (Nhamo et al. 2018; Schlor et al. 2018a, b; Rasul 2016). Mohtar and Lawford (2016) highlighted this progress in 12 of the 17 SDGs linked to the sustainable resource utilization. Viewing the SDGs through the WEF lens makes it possible to explain the implications of other goals and manage the SDGs complexity, making the goals easier to communicate and to implement (OFID 2017; WWF-SA 2017). Thus, there is a need to adequately incorporate the WEF nexus thinking, since this can help in achieving the SDGs.

The WEF nexus interlinkages

Any nexus approach is a structured planning method that aims to capture the interdependency of resource use across all the three major sectors. The approach considers intricate linkages between energy, water, and food sectors. Some of these interactions are more important than the others. For example, water production does not need food and thereby the food for water nexus is negligible (Karnib 2017a). The following is a presentation of the main interlinkages in WEF nexus.

The water–energy nexus

Water is a key input to the value chain of energy production. The energy sector is regarded as the second biggest water user after the agriculture sector (Fig. 3). It accounts for about 44% of the total water withdrawals in industrialized countries (Collins et al. 2009). Water is used in a plethora of processes. Moreover, it is a significant element in many innovative technologies of energy production. Growing biofuels consume more water than fossil fuels (Hussey and Pittock 2012; IEA 2012).

On the other hand, energy is essential at all stages of the supply chain for water: in the extraction and allocation of water, wastewater treatment, and the heating of water for domestic and industrial uses (Wakeel et al. 2016). Moreover, the use of energy is more severe in the nonconventional water sources such as desalination (Wicaksono et al. 2017). Nevertheless, it is the main source of satisfying increasing water demands in many arid areas, especially in the GCC countries because of their energy capabilities and water scarcities, a trend that is projected to grow rapidly in the future (Al-Zubari 2017).

The food–water nexus

The close interlinkages between water and food are mainly characterized by the need for water and irrigation in agriculture (Gerbens-Leenes et al. 2009). Agriculture is undoubtedly the biggest consumer of the Earth's available freshwater, which accounts 70% of global withdrawals (FAO 2014), with Asia as the highest user. On the other side, water production does not require food, but food can indirectly affect water quality through the increased use of pesticides and fertilizers and the poor soil management practices associated with food production, leading to water contamination and soil degradation (OFID 2017; Olsson 2013).

Cereals are abundantly used in most of the countries (Frenken and Gillet 2012). Importing the food crops that are water intensive such as grains saves big volumes of water for the country purchasing this food. This concept of "virtual water" was first noticed in the 1990s, as a description of the conceptual amount of freshwater embedded in the traded products (Roth and Warner 2008). It is suggested as a good policy to rely on virtual water in the form of food imports for securing the food supply and saving the water resources for the water-scarce areas (Al-Saidi et al. 2016; Roth and Warner 2008).

The energy–food nexus

The modern global food sector is dependent on energy. Almost 30% of total energy is spent globally in the agricultural food supply chain (FAO 2012). FAO (2011) reported that energy is needed along the whole chain of food production (Fig. 4), and the global food sector represents around one-third of total global final energy demand. Energy is directly utilized in water pumping and production of fertilizers and agrochemicals (Chang et al. 2016; FAO 2012).

Cultivation of biomasses for energy production is the most obvious link between agricultural production and energy. In the latest years, in countries such as Argentina

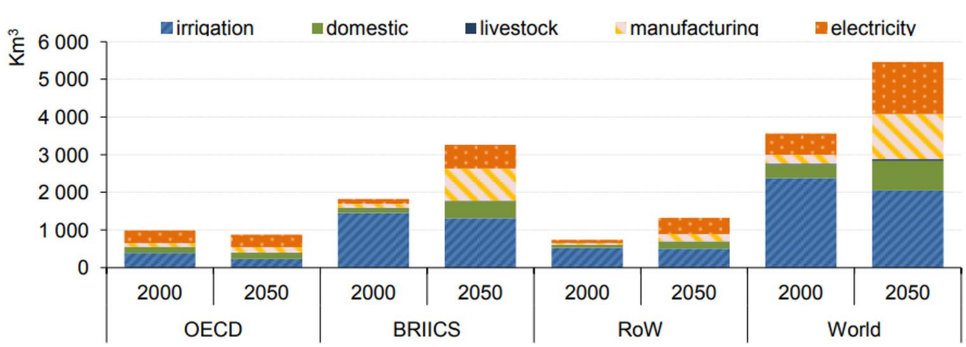


Fig. 3 Global water demand (OECD 2012). Note that OECD: 'Countries of the organization for Economic Cooperation and Development', BRIICS: 'Brazil, Russia, Indonesia, China and South Africa', RoW: 'Rest of the World'

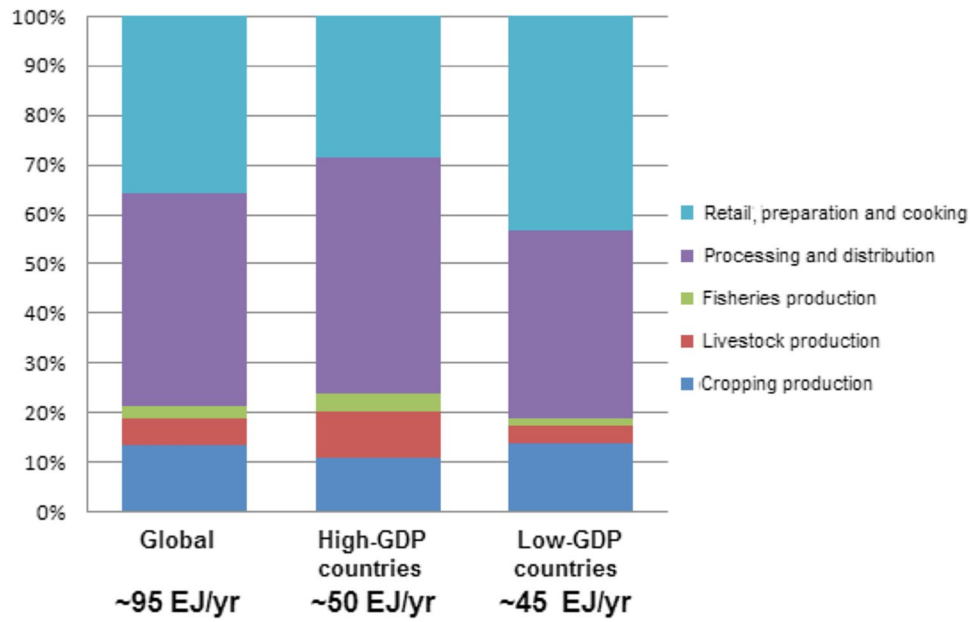


Fig. 4 Shares of energy consumption in the food sector (FAO 2011)

and Brazil, the use of biomass has risen considerably (Stephan et al. 2018). In particular, the world's production of biofuels has increased at an average annual rate of 15% (OFID 2017); the main drivers for this increasing trend for the use of biofuels as a clean energy source are supply security and climate change. A number of conflicts and trade-offs have generated from this increase in biofuel production (Chang et al. 2016; UNEP 2011). The primary conflict is the high requirement of water resources, as mentioned above. This has resulted in competition between food and energy crops for the use of water and agricultural land (Harvey and Pilgrim 2011). Although Chang et al. (2016) indicated that biofuels are promising to increase the energy supply and reduce the GHGs emissions, removing large areas of forest for the purpose of replacing them with other biofuel crops (e.g., maize or soya) is responsible for considerable amounts of carbon dioxide emissions and the destruction of whole ecosystems (Magoni 2017).

The nexus quantification approaches

In general, the overall methodology of the WEF nexus research and studies is performed in three main steps (Fig. 5): (1) characterization (identifying the relationships between the food, water, and energy sectors and their corresponding indicators, which is case-specific); (2) using indices or models for quantifying the WEF nexus system; and (3) application of models through management scenarios. Table 1 highlights some of the current tools and models that help to develop the WEF nexus approach.

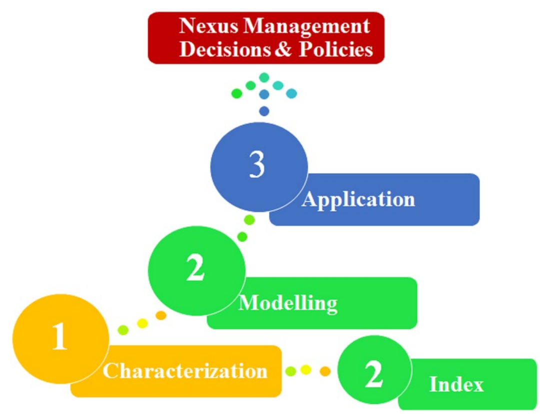


Fig. 5 General methodological framework for the WEF nexus quantitative studies

Characterization (the conceptual nexus)

Any quantification analysis for the WEF nexus starts with characterization stage that identifies interconnections between its three parts (Al-Ansari et al. 2015) and their quantitative values (inflows) or intensities, and determines the context of these interconnections. Figure 6 illustrates the major inflows within and between water, energy, and food systems. Preferably, these elements should be organized by following standard classifications, to promote the creation of quantitative records that are consistent, logical, and comparable as possible over time and across countries. Nevertheless, the environmental, social, economic, and institutional conditions and circumstances that impact strategies and policies of WEF management differ widely between countries. The composition of some WEF nexus accounts could,

Table 1 WEF nexus quantification methods

WEF methods	Examples of published papers
Characterization	Bazilian et al. (2011), Gulati et al. (2013), Rasul (2014), Saladini et al. (2018), Siddiqi and Anadon (2011)
WEF index	Abbott et al. (2017), El-Gafy et al. (2017), Kurian (2017), Mahlknecht and González-Bravo (2018), Moioli et al. (2018), Schlor et al. (2018a, b), Vito et al. (2017), Willis et al. (2016)
WEF tools	Howells et al. (2013), Flammini et al. (2014), Daher and Mohtar (2015)
WEF models	Amjath-Babu et al. (2019), Hussien et al. (2017), Karnib (2017a), Menegaki and Tiwari (2018), Momblanch et al. (2019), Tian et al. (2018)
Optimization models	Bieber et al. (2018), Jiang et al. (2016), Karnib (2017c), Li et al. (2019a, b), Mortada et al. (2018), Nie et al. (2019)
Life cycle assessment with the nexus models	Al-Ansari et al. (2015), Karabulut et al. (2018), Mannan et al. (2018), Laso et al. (2018)
Input–output analysis with the nexus models	Fang and Chen (2017), Karnib (2018), Nawab et al. (2019), Wang et al. (2019)

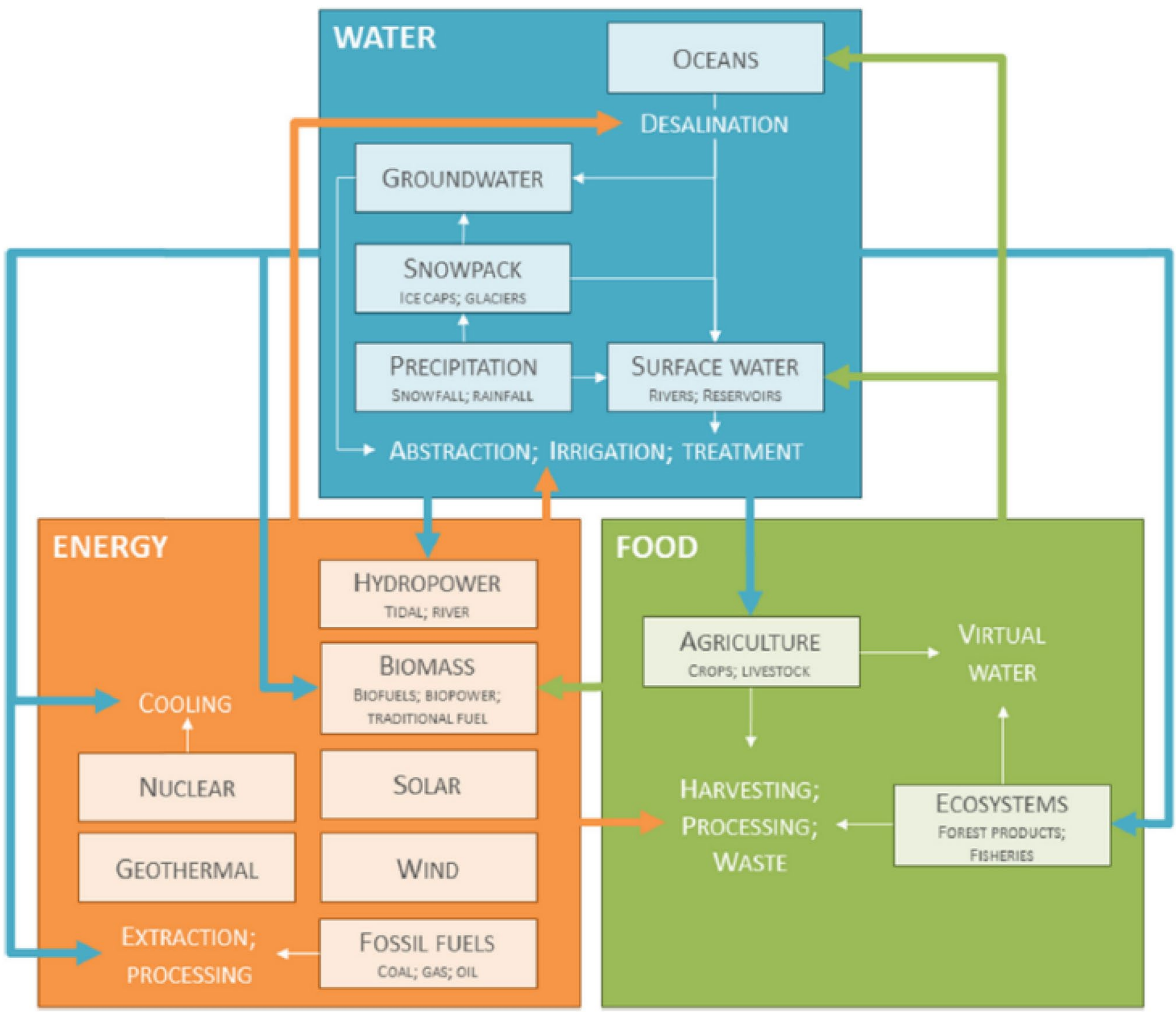


Fig. 6 The nexus system defines the major inflows within and between water, energy, and food sectors (Biggs et al. 2015)

therefore, differ depending on the particular WEF resource situations in every country. For example, Chang et al. (2016) characterized the nexus quantitatively at the national and global levels, thus providing fundamental parameter inputs for further modeling of the WEF nexus.

WEF index

Some assessment tools, such as CLEWS "Climate, land-use, energy and water strategies" (Howells et al. 2013), nexus assessment 1.0 (Flammini et al. 2014), and WEF nexus tool 2.0 (Daher and Mohtar 2015; Mohtar and Daher 2012) have been developed. Moreover, many efforts have been made to evaluate the performance of the WEF nexus by developing an integrated index, which usually captures the overall properties of nexus systems and presents characteristics of the three resources using multiple indicators (Endo et al. 2015). Yigitcanlar et al. (2015) stated that an index-based method not only helps to determine actions and policies for balancing environmental and growth concerns, but it also helps to assess comparison and bench-marking. For example, Mahlknecht and González-Bravo (2018) proposed a WEF nexus index to represent an overview on the existing state of the WEF nexus in 13 countries and sub-regions of the Latin America and the Caribbean. This index comprised of three key indicators: availability, access, and stability for each resource, based on the three SDGs: 2, 6, and 7. Parameters were presented as a percentage, with 100% as the best performance, and the WEF nexus index was calculated as an average for the nine indicators. Willis et al. (2016) developed the Pardee RAND WEF security index to provide a quantitative estimation of the WEF nexus. This index offers an online platform that can be accessed through a website (https://www.rand.org/t/TL165), which allows exploration and downloading of the data for the purpose of strategies assessment. Abbott et al. (2017) found that this WEF security index can affect the country's political and social stability Moreover, a nexus city index (Schlor et al. 2018a, b) was developed using a number of relevant indicators for 69 cities around the world, based on comprehensive UN database. The index aimed to assess the sustainability of the WEF nexus compares between regions and offers chances to cope with gaps and prosperity for the urban areas. The authors suggested to introduce more integrated indicators to obtain a more holistic picture of the nexus systems in a comprehensive manner (Schlor et al. 2018a, b).

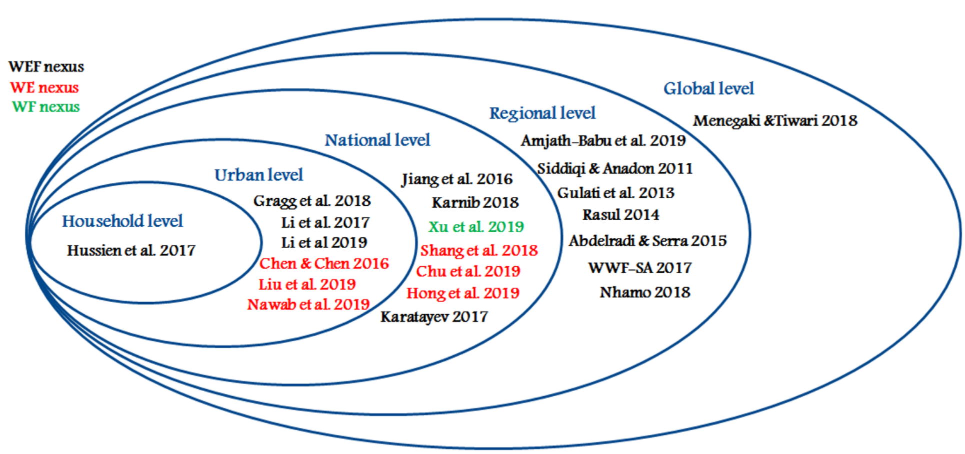
WEF models

Many researchers have attempted to develop more complicated models for quantifying the nexus, to provide more distinguished evaluation of the nexus connections, through simulation. This needs a framework that includes a solid model, reasonable algorithms, and a full data set. Moreover, these WEF nexus models can vary in scale from the local [household, institution, or city (urban)], national, regional, or global levels (Fig. 7).

In this regard, a number of studies have constructed frameworks to examine the WEF nexus for a group of countries, as a region of focus, but very few on the global level. The MENA region is among the driest regions worldwide, with constrained water and land resources. However, it is rich in energy resources and has two-thirds of the global oil reserves (IEA 2008). As a result, countries of this region are using desalination plants to fill the supply gap and meet the domestic, agricultural, and industrial needs. Siddiqi and Anadon (2011) attempted to quantify the water–energy nexus in five sub-regions in the MENA region. The findings revealed that water production and abstraction heavily depend on energy, while the energy sector has comparatively weak dependence on fresh water.

On the national level, Karnib (2017a) developed a simulation model to address the direct and indirect WEF nexus interconnections using a quantitative approach (the Q-nexus model), based on the input–output theory, i.e., quantifying the economic relationship between sectors,

Fig. 7 The variation in the scale of WEF nexus models/approaches



and quantitative balances. To place the model into practice and to approve its reliability, it was applied on Lebanon as a case study using data for the year 2012, to evaluate the nexus situation and the possible future scenarios. These scenarios consisted of a scenario of changing the resource demand (Karnib 2017a); and adopting efficient technologies polices (Karnib 2017b). Moreover, in Karnib (2017c), an integration framework by coupling the Q-nexus model simulator with an optimization framework was introduced, to find the best policy options that achieve the desired system outputs. The Q-nexus model demonstrated an ability to quantify the requirements of each resource, assess the impacts on availability and stress, and suggest that adverse effects in the combination scenario can be offset by the positive effects (Karnib 2018).

Fewer studies quantified the nexus at a household scale. The disaggregation of water, energy, and food into end-uses may help establishing the best management practice and identifying the improvement areas (i.e., reduction of consumption). Hussien et al. (2017) developed a bottom-up integrated model to capture the interactions between WEF at end-use level. Many variables were evaluated using the developed model such as the demand for each resource, the generated waste, and wastewater quantities, taking into consideration about 300 components including the impact of change in user behavior, diet, income, family size, and climate. The data for these parameters were collected using a survey for Duhok city in Iraq chosen as a case study. Then, Monte Carlo technique was used to analyze the model uncertainty. The model was validated by comparing the simulation results with the measured historical data. Finally, the model was applied as future scenarios called global scenario group scenarios (market force, fortress world, great transition, and policy reform) on the household demand for the WEF nexus. The results showed that the model values were close to the historical values, but not for the food consumption that was slightly higher than the historical data. They justified that the historical data were for Iraq, not the city Duhok (micro level), and the comparison at this way is not possible.

Recently, few studies have been reported on quantifying WEF nexus and managing the three resources through optimization. For example, Nie et al. (2019) proposed a novel three-step framework for effective integration WEF nexus-related data, models, and optimization methods. The methodology was based on step 1: superstructure design, step 2: data-driven modeling, and step 3: multi-objective optimization and assessment. Yucheng station in China was selected as a case study of the approach. Taking into consideration the interdependencies and competing interests among the three sectors, the framework was found to work effectively. The model addressed the best management for the nexus, providing actionable pathways to meet economic goals while reducing environmental concerns.

Li et al. (2019a, b) proposed a multi-objective nonlinear programming model for sustainable management of WEF nexus. The three-step methodology was: overview of the problem, modeling using intuitionistic fuzzy set theory to overcome uncertainties, followed by the application and testing. The authors found that the framework was effectively balancing the multiple required objectives between the nexus sectors.

Some approaches were conducted for only two elements of the nexus. For instance, Mortada et al. (2018) introduced an optimization model for achieving food and water securities. The model was considering the nexus through food and water security indicators. Three scenarios were tested on a hypothetical region to evaluate the model performance: resources abundance, land scarcity, and water scarcity extremes. The results showed the model sensitivity in shaping policies of water and agricultural sector, and its ability to be applied in real life conditions. However, many approaches highlighted the nexus through its three components.

Besides using the input–output theory in the nexus approach as in Karnib (2018), also life cycle analysis (LCA) is a methodology that can evaluate the environmental performance and potential impacts of systems throughout its entire life. The aim of using LCA tools in a nexus study is to translate the system outputs from different nexus representative processes into environmental scores (Al-Ansari et al. 2015) and to draw different environmental impact scenarios throughout all the life cycle stages of the resources that reduce the negative effects on the environment. For example, Al-Ansari et al. (2015) stated that the food system is playing a main role in the global warming.

The WEF nexus results can be presented in a spider or radar diagram that can be triple, pentagon, hexagon, or more, according to the number of indicators used in the nexus analysis approach, as generally seen in Fig. 8. From the diagram, for each indicator, the higher the distance from the origin of the axis, the higher the performance level for that indicator. This was performed in many articles results of WEF index (Vito et al. 2017), WEF models (Li et al. 2019a, b; Liu et al. 2019; Momblanch et al. 2019; Nie et al. 2019; Wang et al. 2019), WEF tools as (Flammini et al. 2014) or even for the WEF nexus characterization (Saladini et al. 2018), and conceptualization model (Gragg et al. 2018).

Conclusion

No security can be achieved for one of the three resources (water, energy, or food) without taking considerations to the other two resources. The WEF nexus is a concept of integration to ensure access to resources, where water, energy, and food are inextricably linked, and dependent on one another, and they have strong interactions with the environment and

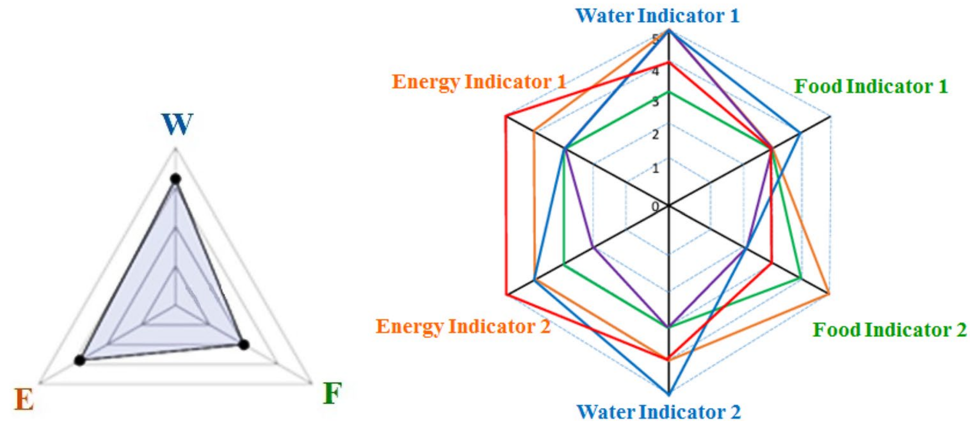


Fig. 8 The spider diagram

climate change. The importance of nexus approach, through identification of the interlinkages existing between the three components, is manifested in providing opportunities to explore appropriate alternatives and policies for increasing efficient use of resources, sustainable resource management, and minimizing the environmental impacts. In addition, WEF nexus can play a significant role toward better coordination between the key sectors. As such, developing methodologies that consider identifying synergies and tradeoffs between these sectors is highly emphasized.

From this review, it is clear that there is an increasing active research in the WEF nexus area and a considerable progress has been made on the different methods addressing and quantifying the WEF nexus in scientific literatures, which vary in their objectives and scales. However, to date, this area is somehow in its initial steps and it has not been widely implemented on the ground. The difficultly to identify the interconnections within and between sectors and the complexity of methods and models make it challenging to assess multiple systems in a cohesive manner. This review has also concluded that availability of data and reduction of uncertainties are considered challenges in WEF nexus models. Although as being said, no single approach is believed to fit to all conditions, for conducting an evaluation on the nexus numerous methods, there should be some common standards to be followed to avoid mismatches, minimize differences, and compare capacities, strengths, and weaknesses between existing approaches. A more detailed research focusing on the nexus modeling, identifying their strengths and weaknesses, is highly recommended.

Additionally, to convince the policy makers to adopt a WEF nexus thinking and approach, it is better that management scenarios are presented from an economic, environmental, i.e., GHGs emissions, and social perspectives, besides the resources use efficiencies. These three pillars of sustainable development need to be more explored in the nexus numerical modeling, as they are the basic for sustainably managing the resources for the benefit of humans, which cannot be achieved without the social dimension that is affected, for example, by technology choices and stakeholders involvement.

Acknowledgements The authors wish to thank all who assisted in conducting this work.

References

Abbott, M., Bazilian, M., Egel, D., & Willis, H. (2017). Examining the food–energy–water and conflict nexus. *Current Opinion in Chemical Engineering, 18,* 55–60.

Abdelradi, F., & Serra, T. (2015). Food–energy nexus in Europe: price volatility approach. *Energy Economics, 48,* 157–167.

Al-Ansari, T., Korre, A., Nie, Z., & Shah, N. (2015). Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus. *Sustainable Production Consumption, 2,* 52–66.

Al-Saidi, M., Birnbaum, D., Buriti, R., et al. (2016). Water resources vulnerability assessment of MENA countries considering energy and virtual water interactions. *Procedia Engineering, 145,* 900–907.

Al-Zubari, W. (2013). Water, energy, and food nexus in the Arab region. In: Paper presented at the Annual Conference of the Arab Forum for Environment and Development (AFED) "Sustainable Energy: Prospects, challenges, opportunities".

Al-Zubari, W. et al. (2016). WEF nexus policy briefs in the Arab region (1–6). GIZ and LAS publications. https://www.water-energy-food.org/resources/resources-detail/mena-policy-brief-series-the-wef-nexus-in-the-arab-region/. Accessed March 2019.

Al-Zubari, W. (2017). *Status of water in the Arab region (chapter 1): the water, energy, and food security nexus in the arab region. Water security in a new world*. Switzerland: Springer.

Amjath-Babu, T. S., Sharma, B., Brouwer, R., et al. (2019). Integrated modelling of the impacts of hydropower projects on the water–food–energy nexus in a transboundary Himalayan river basin. *Applied Energy, 239,* 494–503.

Artioli, F., Acuto, M., & McArthur, J. (2017). The water–energy–food nexus: an integration agenda and implications for urban governance. *Political Geography, 61,* 215–223.

Bazilian, M., Rogner, H., Howells, M., et al. (2011). Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy, 39*(12), 7896–7906.

Beddington, J. (2009). Food, energy, water and the climate: a perfect storm of global events. London, UK.

Bieber, N., Ker, H., Wang, X., et al. (2018). Sustainable planning of the energy–water–food nexus using decision making tools. *Energy Policy, 113,* 584–607.

Biggs, E. M., Bruce, E., Boruff, B., et al. (2015). Sustainable development and the water–energy–food nexus: a perspective on livelihoods. *Environmental Science & Policy Journal, 54,* 389–397.

Chang, Y., Li, G., Yao, Y., et al. (2016). Quantifying the water–energy–food nexus: current status and trends. *Energies, 9*(2), 65.

Chen, S., & Chen, B. (2016). Urban energy–water nexus: a network perspective. *Applied Energy, 184,* 905–914.

Chu, C., Ritter, W., & Sun, X. (2019). Spatial variances of water–energy nexus in China and its implications for provincial resource interdependence. *Energy Policy, 125,* 487–502.

Collins, R., Kristensen, P., & Thyssen, N. (2009). Water resources across Europe-confronting water scarcity and drought. European environment agency (EEA) report.

Covarrubias, M. (2019). The nexus between water, energy and food in cities: towards conceptualizing socio-material interconnections. *Sustainability Science, 14,* 277–287.

Daher, B. T., & Mohtar, R. H. (2015). Water–energy–food (WEF) nexus tool 2.0: guiding integrative resource planning and decision-making. *Water International, 40*(5–6), 748–771.

Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., et al. (2018). Water-energy nexus: a review of methods and tools for macro-assessment. *Applied Energy*, *210*, 393–408.

El-Gafy, I., Grigg, N., & Waskom, R. (2017). Water–food–energy: nexus and non-nexus approaches for optimal cropping pattern. *Water Resources Management, 31,* 4971–4980.

Endo, A., Burnett, K., Orencio, P., et al. (2015). Methods of the water–energy–food nexus. *Water, 7*(10), 5806–5830.

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. *Journal of Hydrology Regional Studies, 11,* 20–30.

ESCWA (United Nations Economic and Social Commission for Western Asia). (2015). Water development report 6: the water, energy and food security nexus in the Arab region. United Nations.

European Union (EU). (2012). European report on development 2011/2012—confronting scarcity: managing water, energy and land for inclusive and sustainable growth. https://www.erd-report.eu. Accessed March 2019.

European Union (EU). (2018). *Position paper on water, energy, food and ecosystems (WEFE) nexus and sustainable development goals (SDGs)*. Luxembourg: Publications Office of the European Union.

Fang, D., & Chen, B. (2017). Linkage analysis for the water–energy nexus of city. *Applied Energy, 189,* 770–779.

FAO (Food and Agriculture Organization of the United Nations). (2006). World agriculture: towards 2030/2050–global perspective studies unit, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations). (2011). Energy-smart: food for people and climate, issue paper, Rome. http://www.fao.org/docrep/014/i2454e/i2454e00.pdf. Accessed March 2019.

FAO (Food and Agriculture Organization of the United Nations). (2012). Energy-smart food at FAO: an overview, at a glance: the role of energy in food security and climate. United Nations Publications.

FAO (Food and Agriculture Organization of the United Nations). (2014). The water-energy-food nexus: a new approach in support of food security and sustainable agriculture, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations). (2017). The future of food and agriculture: trends and challenges.

Flammini, A., Puri, M., Pluschke, L., & Dubois, O. (2014). *Walking the nexus talk: assessing the water–energy–food nexus in the context of the sustainable energy for all initiative*. Rome: FAO publications.

Frenken, K., & Gillet, V. (2012). Irrigation water requirement and water withdrawal by country. FAO AQUASTAT reports.

Garcia, D. J., Lovett, B. M., & You, F. (2019). Considering agricultural wastes and ecosystem services in food–energy–water-waste nexus system design. *Journal of Cleaner Production, 228,* 941–955.

Gephart, J., Davis, K., Emery, K., et al. (2016). The environmental cost of subsistence: optimizing diets to minimize footprints. *Science of the Total Environment, 553,* 120–127.

Gerbens-Leenes, W., Hoekstra, A., & van der Meer, T. (2009). The water footprint of bioenergy. *PNAS, 106*(25), 10219–10223.

Giampietro, M., Aspinall, R., Bukkens, S., et al. (2013). *An innovative accounting framework for the food–energy–water nexus: application of the MuSIASEM approach to three case studies*. Rome: FAO publications.

Gragg, R., Anandhi, A., Jiru, M., & Usher, K. (2018). A conceptualization of the urban food–energy–water nexus sustainability paradigm: modeling from theory to practice. *Frontiers in Environmental Science, 133,* 1–14.

Gulati, M., Jacobs, I., Jooste, A., et al. (2013). The water–energy–food security nexus: challenges and opportunities for food security in South Africa. *Aquatic Procedia, 1,* 150–164.

Harvey, M., & Pilgrim, S. (2011). The new competition for land: food, energy, and climate change. *Food Policy, 36,* S40–S51.

Hoff, H. (2011). Understanding the nexus–background paper for the Bonn 2011 Conference: the water, energy and food security nexus; Stockholm Environment Institute. Stockholm, Sweden.

Hong, J., Zhong, X., Guo, S., et al. (2019). Water–energy nexus and its efficiency in China's construction industry: evidence from province-level data. *Sustainable Cities and Society, 48,* 101557.

Howells, M., Hermann, S., Welsch, M., et al. (2013). Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change, 3,* 621–626.

Hussey, K., & Pittock, J. (2012). The energy–water nexus: managing the links between energy and water for a sustainable future. *Ecology and Society, 17*(1), 31.

Hussien, W., Memon, F., & Savic, D. (2017). An integrated model to evaluate water–energy–food nexus at a household scale. *Environmental Modelling & Software, 93,* 366–380.

IEA (International Energy Agency). (2008). World energy outlook 2008. Paris, France.

IEA (International Energy Agency). (2012). Water for energy: is energy becoming a thirstier resource? (chapter 17) Excerpt from the world energy outlook 2012.

IRENA (International Renewable Energy Agency). (2015). Renewable energy in the water, energy and food nexus. Technical report.

Jiang, Y., Xu, X., Huo, Z., et al. (2016). Optimizing regional irrigation water use by integrating a two-level optimization model and an agro-hydrological model. *Agricultural Water Management, 178,* 76–88.

Karabulut, A., Crenna, E., Sala, S., & Udias, A. (2018). A proposal for integration of the ecosystem–water–food–land–energy (EWFLE) nexus concept into life cycle assessment: a synthesis matrix system for food security. *Journal of Cleaner Production, 172,* 3874–3889.

Karatayev, M., Rivotti, P., Mourão, S., et al. (2017). The water–energy–food nexus in Kazakhstan: challenges and opportunities. *Energy Procedia, 125,* 63–70.

Karnib, A. (2017a). A quantitative nexus approach to analyze the interlinkages across the sustainable development goals. *Journal of Sustainable Development, 10*(5), 173–180.

Karnib, A. (2017b). Quantitative assessment framework for water, energy and food nexus. *Computational Water, Energy, and Environmental Engineering, 6,* 11–23.

Karnib, A. (2017c). Evaluation of technology change effects on quantitative assessment of water, energy and food nexus. *Journal of Geoscience and Environment Protection, 5,* 1–13.

Karnib, A. (2017d). Water–energy–food nexus: a coupled simulation and optimization framework. *Journal of Geoscience and Environment Protection, 5,* 84–98.

Karnib, A. (2018). Bridging science and policy in water–energy–food nexus: using the Q-nexus model for informing policy making. *Water Resources Management, 32*(15), 4895–4909.

Kurian, M. (2017). The water–energy–food nexus trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environmental Science & Policy, 68,* 97–106.

Lal, R., Mohtar, R. H., Assi, A., et al. (2017). Soil as a basic nexus tool: soils at the center of the food–energy–water nexus. *Current Sustainable/Renewable Energy Reports, 4,* 117–129.

Laso, J., Margallo, M., García-Herrero, I., et al. (2018). Combined application of life cycle assessment and linear programming to evaluate food waste-to-food strategies: seeking for answers in the nexus approach. *Waste Management, 80,* 186–197.

Lawford, R., Bogardi, J., Marx, S., et al. (2013). Basin perspectives on the water–energy–food security nexus. *Current Opinion in Environmental Sustainability, 5,* 607–616.

Leck, H., Conway, D., Bradshaw, M., & Rees, J. (2015). Tracing the water–energy–food nexus. Description, theory and practice. *Geography Compass, 9*(8), 445–460.

Li, M., Fu, Q., Singh, V., et al. (2019a). An optimal modelling approach for managing agricultural water–energy–food nexus under uncertainty. *Science of the Total Environment, 651,* 1416–1434.

Li, M., Singh, V., Fu, Q., et al. (2019b). Optimization of agricultural water–food–energy nexus in a random environment: an integrated modelling approach. *Stochastic Environmental Research and Risk Assessment*. https://doi.org/10.1007/s00477-019-01672-4.

Li, G., Wang, Y., Huang, D., & Yang, H. (2017). Water–energy–food nexus in urban sustainable development: an agent-based model. *International Journal of Crowd Science, 1*(2), 121–132.

Liu, D., Zhang, J., Zeng, Y., Shen, Y. (2019). Modeling the physical nexus across water supply, wastewater management and hydropower generation sectors in river–reservoir systems. *Water, 11*(4), 822.

Magoni, M. (2017). *Energy systems and water and food nexus (chapter 16)*. Switzerland: Springer International Publishing.

Mahlknecht, J., & González-Bravo, R. (2018). Towards measuring the water–energy–food nexus: the case of Latin America and the Caribbean region. *Energy Procedia, 153,* 169–173.

Mannan, M., Al-Ansari, T., Mackey, H., et al. (2018). Quantifying the energy, water and food nexus: a review of the latest developments based on life-cycle assessment. *Journal of Cleaner Production, 193,* 300–314.

Marker, C., Venghaus, S., & Hake, J. (2018). Integrated governance for the food–energy–water nexus: the scope of action for institutional change. *Renewable and Sustainable Energy Reviews, 97,* 290–300.

Marzooq, M., Alsabbagh, M., & Al-Zubari, W. (2018). Energy consumption in the municipal water supply sector in the Kingdom of Bahrain. *Computational Water, Energy, and Environmental Engineering, 7,* 95–110.

Meadows, D. H., Meadows, D. L., & Randers, J. (1992). *Beyond the limits: confronting global collapse envisioning a sustainable future*. USA: Chelsea Green Pub.

Menegaki, A. N., & Tiwari, A. K. (2018). A global food–energy–water nexus with heterogeneity, non-stationarity and cross-sectional dependence. *Quality & Quantity, 52,* 2723–2755.

Miralles-Wilhelm, F. (2016). Development and application of integrative modeling tools in support of food-energy-water nexus planning—a research agenda. *Journal of Environmental Studies and Sciences, 6*(1), 3–10.

Misselhorn, A., Aggarwal, P., Ericksen, P., et al. (2012). A vision for attaining food security. *Current Opinion in Environmental Sustainability, 4*(1), 7–17.

Mohtar, R. H., & Daher, B. (2012). Water, energy, and food: the ultimate nexus, 2nd ed. *Encyclopedia of agricultural, food, and biological engineering*. Taylor & Francis.

Mohtar, R. H., & Lawford, R. (2016). Present and future of the water–energy–food nexus and the role of the community of practice. *Journal of Environmental Studies and Sciences, 6,* 192–199.

Moioli, E., Salvati, F., Chiesa, M., et al. (2018). Analysis of the current world biofuel production under a water–food–energy nexus perspective. *Advances in Water Resources, 121,* 22–31.

Momblanch, A., Papadimitriou, L., Jain, S., et al. (2019). Untangling the water–food–energy–environment nexus for global change adaptation in a complex Himalayan water resource system. *Science of the Total Environment, 655,* 35–47.

Mortada, S., Abou Najm, M., Yassine, A., et al. (2018). Towards sustainable water–food nexus: an optimization approach. *Journal of Cleaner Production, 178,* 408–418.

Nawab, A., Liu, G., Meng, F., et al. (2019). Urban energy–water nexus: spatial and inter-sectoral analysis in a multi-scale economy. *Ecological Modelling, 403,* 44–56.

Newell, B., Marsh, D. M., & Sharma, D. (2011). Enhancing the resilience of the Australian national electricity market: taking a systems approach in policy development. *Ecology and Society, 16*(2), 15.

Nhamo, L., Ndlela, B., Nhemachena, C., et al. (2018). The water–energy–food nexus: climate risks and opportunities in southern Africa. *Water, 10*(567), 1–18.

Nie, Y., Avraamidou, S., Xiao, X., et al. (2019). A food–energy–water nexus approach for land use optimization. *The Science of the Total Environment, 659,* 7–19.

OECD (Organization for Economic Co-operation and Development). (2012). *OECD environmental outlook to 2050*. Paris: OECD Publishing.

OFID (The OPEC Fund for International Development). (2017). *The energy–water–food nexus: managing key resources for sustainable development*. Vienna, Austria.

Olsson, G. (2013). Water, energy and food interactions—challenges and opportunities. *Frontiers of Environmental Science & Engineering, 7,* 787–793.

Rasul, G. (2014). Food, water, and energy security in south Asia: a nexus perspective from the Hindu Kush Himalayan region. *Environmental Science & Policy, 39,* 35–48.

Rasul, G. (2016). Managing the food, water, and energy nexus for achieving the sustainable development goals in south Asia. *Environmental Development, 18,* 14–25.

Ringler, C., Bhaduri, A., & Lawford, R. (2013). The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency. *Current Opinion in Environmental Sustainability, 5*(6), 617–624.

Roidt, M., & Avellán, T. (2019). Learning from integrated management approaches to implement the nexus. *Journal of Environmental Management, 237,* 609–616.

Roth, D., & Warner, J. (2008). Virtual water: virtuous impact? The unsteady state of virtual water. *Agriculture and Human Values, 25,* 257–270.

Sachs, L., & Silk, D. (1990). *Food and energy: strategies for sustainable development* (p. 90). Japan: United Nations University Press, Tokyo. http://archive.unu.edu/unupress/unupbooks/80757e/80757E00.htm. Accessed March 2019.

Saladini, F., Betti, G., Ferragina, E., et al. (2018). Linking the water–energy–food nexus and sustainable development indicators for the Mediterranean region. *Ecological Indicators, 91,* 689–697.

Schlor, H., Venghaus, S., & Hake, J. F. (2018a). An integrated assessment model for the German food–energy–water nexus. *Journal of Sustainable Development of Energy, Water and Environment Systems, 6,* 1–12.

Schlor, H., Venghaus, S., & Hake, J. F. (2018b). The FEW-nexus city index—measuring urban resilience. *Applied Energy, 210,* 382–392.

Schmidt, J., & Matthews, N. (2018). From state to system: financialization and the water–energy–food–climate nexus. *Geoforum, 91,* 151–159.

Shang, Y., Hei, P., Lu, S., et al. (2018). China's energy–water nexus: assessing water conservation synergies of the total coal consumption cap strategy until 2050. *Applied Energy, 210,* 643–660.

Siddiqi, A., & Anadon, L. D. (2011). The water–energy nexus in middle East and North Africa. *Energy Policy, 39,* 4529–4540.

Stephan, R., Mohtar, R., Daher, B., et al. (2018). Water–energy–food nexus: a platform for implementing the sustainable development goals. *Water International, 43,* 472–479.

Swatuk, L., & Cash, C. (2018). *Perspectives on the nexus (chapter 1): water, energy and food security in an era of climate change*, Political Economy Series (pp. 1–13). Water, Energy, Food and People Across the Global South.

Taghizadeh-Hesary, F., Rasoulinezhad, E., & Yoshino, N. (2019). Energy and food security: linkages through price volatility. *Energy Policy, 128,* 796–806.

Tian, H., Lu, C., Pan, S., et al. (2018). Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: from conceptual model to decision support system. *Current Opinion in Environmental Sustainability, 33,* 104–113.

UN General Assembly. (2015). Transforming our world: the 2030 agenda for sustainable development, A/RES/70/1. https://www.refworld.org/docid/57b6e3e44.html. Accessed October 2019.

UNDESA (United Nations, Department of Economic and Social Affairs). (2014). Population division, world urbanization prospects—the 2014 revision.

UNDESA (United Nations, Department of Economic and Social Affairs). (2015). Population division, world population prospects—the 2015 revision.

UNDP (United Nations Development Program). (2006). *World population projections, the 2006 revision*. New York: United Nations publications.

UNEP (United Nations Environment Program). (2011). Towards a green economy: pathways to sustainable development and poverty eradication—a synthesis for policy makers. Nairobi, Kenya.

UN-ESCAP (United Nations Economic and Social Commission for Asia and the Pacific). (2013). *The status of the water–food–energy nexus in Asia and the Pacific*. Bangkok: United Nations publications.

USNIC (United States National Intelligence Council). (2012). Global trends 2030: alternative worlds. Washington, DC, p. 137.

Van-Vuuren, D. P., Nakicenovic, N., Riahi, K., et al. (2012). An energy vision: the transformation towards sustainability—interconnected challenges and solutions. *Current Opinion in Environmental Sustainability, 4*(1), 18–34.

Vito, R., Portoghese, I., Pagano, A., et al. (2017). An index-based approach for the sustainability assessment of irrigation practice based on the water–energy–food nexus framework. *Advances in Water Resources, 110,* 423–436.

Wakeel, M., Chen, B., Hayat, T., et al. (2016). Energy consumption for water use cycles in different countries: a review. *Applied Energy, 178,* 868–885.

Wang, S., Fath, B., & Chen, B. (2019). Energy–water nexus under energy mix scenarios using input–output and ecological network analyses. *Applied Energy, 233–234,* 827–839.

WEF (World Economic Forum). (2011a). *Water security: the water–food–energy–climate nexus*. Washington: Island Press.

WEF (World Economic Forum). (2011b). Global Risks. (2011). *Sixth edition: an initiative of the risk response network*. Geneva, Switzerland: World Economic Forum. http://reports.weforum.org/wp-content/blogs.dir/1/mp/uploads/pages/files/global-risks-2011.pdf. Accessed October 2019.

Wicaksono, A., Jeong, G., & Kang, D. (2017). Water, energy, and food nexus: review of global implementation and simulation model development. *Water Policy, 19,* 440–462.

Willis, H. H., Groves, D. G., Ringel, J. S., et al. (2016). *Developing the pardee RAND food–energy–water security index: toward a global standardized, quantitative, and transparent resource assessment*. Santa Monica: RAND Corporation.

WWDR (World Water Development Report). (2009). WWDR 3: water in a changing world, world water assessment programme, earthscan, London, UK.

WWF-SA (World Wide Fund for Nature-South Africa). (2017). The food–energy–water nexus as a lens for delivering the UN's sustainable development goals in southern Africa. The Worldwide Fund for Nature, South Africa.

Xu, H., Tian, Z., He, X., et al. (2019). Future increases in irrigation water requirement challenge the water–food nexus in the northeast farming region of China. *Agricultural Water Management, 213,* 594–604.

Yigitcanlar, T., Dur, F., & Dizdaroglu, D. (2015). Towards prosperous sustainable cities: a multiscalar urban sustainability assessment approach. *Habitat International, 5,* 36–46.

Yillia, P. T. (2016). Water–energy–food nexus: framing the opportunities, challenges and synergies for implementing the SDGs. *Österreichische Wasser- Und Abfallwirtschaft, 68,* 86–98.

Zeng, X., Zhao, J., Wang, D., et al. (2019). Scenario analysis of a sustainable water–food nexus optimization with consideration of population-economy regulation in Beijing–Tianjin–Hebei region. *Journal of Cleaner Production, 228,* 927–940.

Zhang, P., Zhang, L., Chang, Y., et al. (2019). Food–energy–water (FEW) nexus for urban sustainability: a comprehensive review. *Resources, Conservation and Recycling, 142,* 215–224.