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Water, energy, and food nexus: review of global implementation and simulation model development

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Abstract

Water, energy, and food (WEF) have complex interconnections. Water is required to produce energy, while energy is needed for water extraction, treatment, and distribution. The food sector requires water and energy to produce food products, while fertilizer and pesticide from farmland have a negative impact on water quality; however, biomass is a potential alternative energy source. Understanding these interconnections will help determine the developmental framework that connects all of the elements. Some global regions have implemented a variety of sustainable management concepts to manage the natural resources, however, mainly for an individual resource. Furthermore, various computer models have been developed to estimate the interdependency of each resource and to quantify future requirements of WEF; the limitations of current models have opened opportunities for development through the addition of components and features such as feedback analysis, optimization, and visualization. We reviewed the literature to determine the present state of the WEF nexus, especially its global implementation and simulation model. We concluded that the involvement of stakeholders, integration of policies, and development of a nexus simulation model are required for successful implementation of the WEF nexus, which is an emerging issue for a sustainable resources' management.

Keywords: Review study; Simulation model; Stakeholders' involvement; Sustainable development; Water, energy, and food (WEF) nexus

Introduction

Water, energy, and food scarcity

As reported by the United Nations, the number of people suffering from water, energy, and food (WEF) scarcity is high. It reported that 748 million people still lack access to drinking water, and 2.5 billion do not have access to sanitation facilities. Moreover, 1.3 billion people still have no

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access to electricity, especially in sub-Saharan Africa and East Asia (WWAP, 2015). In 2012, the Food and Agricultural Organization of the United Nations (FAO) reported that almost 870 million people were undernourished, and the number is growing in Africa (FAO, 2012). The report from United Nations World Water Assessment Programme (WWAP, 2015) also mentioned that the world population is growing by 80 million people per year, which will increase the world population to 9.1 billion by 2050. This population growth will increase the demand for WEF.

The other features that affect resource sustainability are urbanization and climate change. To date, about 54% of the world population is living in urban areas (United Nations, 2014), resulting in the need for more resources including energy, water, and food. Another effect of urbanization is the increasing number of buildings and transportation activities, which contribute up to 80% of global greenhouse gas (GHG) emissions (Heinonen & Junnila, 2011). Meanwhile, climate change affects water availability due to the reduction of glaciers, changes in rainfall patterns, and frequent occurrence of extreme events (for example, droughts and floods) (Hoff, 2011).

The challenge regarding the WEF nexus is the establishment of a sustainable development plan that addresses all needs without producing a shortage of natural resources. At the beginning, the awareness of natural resource sustainability focused on water, which is a primary human consumption product. However, once the energy demand (for example, gasoline and electricity) increased, the focus broadened to include the energy sector. The issue of food security was the last component (of the WEF nexus) to be acknowledged. The interconnections among WEF are considered in the concept of integrated water resources' management (IWRM). Currently, IWRM has been implemented in several countries in order to balance water allocation for energy (hydropower) and food (irrigation) demand. In practice, the IWRM considers water as the primary component, while energy and food are the dependent components (FAO, 2014). The concept puts each element as a separate individual sector (Bach *et al.*, 2012); hence, it is difficult to accommodate the broader integration by adding other sectors or institutions, or enlarging the scales (Hoff, 2011). The WEF nexus concept has emerged as an answer to focus and integrate all sectors with the same priority in a single framework.

The WEF nexus consists of three main elements: water, energy, and food (agriculture). Within the WEF nexus concept, all elements connect and affect each other. A change in supply or demand of any element of this nexus will affect the other element(s). The interconnection is usually drawn as three circles representing the three elements, and six arrows representing the connections between the elements. The scheme can be further extended by adding external elements, such as climate change, environment, or governance (Bazilian *et al.*, 2011; Hoff, 2011; Mohtar & Daher, 2012). The common scheme representing the WEF nexus is shown in Figure 1.

Introducing the WEF nexus

Water resources can be divided into conventional and non-conventional resources. The conventional resources include surface water, rainfall, and groundwater, while non-conventional resources consist of desalinated water, wastewater, and drainage water. Further, the available water sources also could be categorized as green, blue, and grey water. Green water is the rainfall water contained in the soil for plants and ecosystems; blue water is the pooled water in lakes, reservoirs, rivers, and aquifers for human usage; and grey water is the household wastewater (except the black water) that could be treated, and reclaimed (Hoff, 2011).

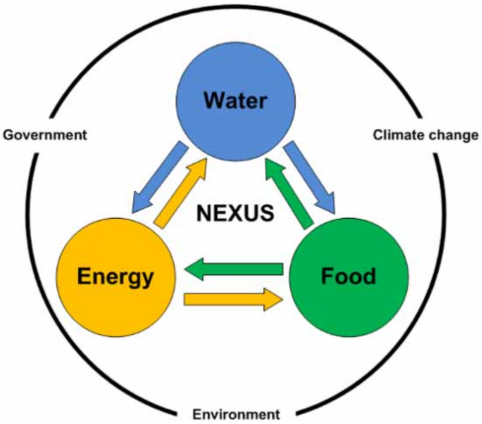

Fig. 1. WEF nexus schematic diagram.

The energy component usually refers to electricity and transportation fuel. Currently, electricity is the main energy source supporting human activities. Electricity is generated in power plants and is produced using methods such as hydropower, thermal power, or nuclear fusion. Recently, renewable energy sources from the wind and solar systems have become alternatives since they consume less water and are eco-friendly. Meanwhile, most transportation energy is derived from crude oil obtained from mining processes. The challenge in energy development is to improve the efficiency during production and consumption processes. High production efficiency will reduce the amount of water consumed during production, while high consumption efficiency will reduce the amount of actual energy needed to provide a service. Bach *et al.* (2012) suggested the three energy policies of 'long, legal, and loud' for sustainable development of energy. Development should address the 'long-term' by considering future demand and supply; it must have a 'legal' framework and allow for coherent implementation; and it must be 'loudly' broadcast to all sectors in order to produce renewable and efficient energy.

Food security is a serious global issue. The FAO defined food security as a condition in which all people can access sufficient, safe, and nutritious food (FAO, 2014). This condition considers the sufficient production and balanced distribution of food products for all people in the area of interest.

The consideration of natural resource sustainability has been discussed in the book *The Limits to Growth* written by Meadows in 1972, and in a report written by Grenon and Lapillonne in 1976. These authors predicted the interactions of population, food, industry, pollution, and non-renewable natural resources (Turner, 2008). The idea of these interactions was ignored for several decades and then re-emerged at an international conference in 2011, the Bonn 2011 Nexus Conference entitled 'The Water, Energy, and Food Security Nexus Solutions for the Green Economy'. The conference was initiated for the global consideration of WEF security. Following the Bonn 2011 Nexus Conference, more discussion forums and conferences were held to strengthen the global consideration of the WEF nexus. The last such dialogue was the Nexus 2014: Water, Food, Climate, and Energy Conference. At this meeting, the delegations agreed that the world is a single complex system, in which all the parts constantly interact, and a set of basic values need to be followed to address the system as a whole at global, regional, national, and local levels (Dodds & Bartram, 2014).

However, as a new concept, the WEF nexus still has many inadequacies to overcome. The knowledge gap, such as insufficient knowledge of connections, non-uniform regulations, inconsistent monitoring, lack of databases of resources' demand and supply, unbalanced distribution, and the indistinct capability to face the increasing demand are the obstacles to developing and implementing the WEF nexus (Hoff, 2011; Hanlon *et al.*, 2013). Improvement in common practices through increases in productivity; reuse of waste; public stimulation using economic incentives; creation of coherence among governance, institutions, and policies; and increased capacity and awareness are all required to address the obstacles impeding the realization of the WEF nexus (Hoff, 2011).

Objectives and review outline

Nowadays, hundreds of studies related to the WEF nexus exist and are easily accessed through the internet. Those studies mainly discuss the introduction or definition of the WEF nexus, potential implementation in practice, related policy development, computer model development and implementation, etc. Focusing on the global implementation and computer model development, the authors found more than 200 published studies. After a quick review of the main discussion for each paper, the authors finally narrowed down the number to 50 papers to be studied in-depth and used as references in this review paper.

In particular, this paper attempts to assess the global implementation of the nexus concept and the development of a computer simulation model to help the decision-making and policy-making processes. This paper reviews: (1) the concept of the interconnections between WEF including the involvement of external factors (next section); (2) the implementation of the resources' management concept in several representative countries (third section); and (3) the existing computer simulation model and opportunities for further development (fourth section); and finally it identifies prospects for future research. Through an understanding of the problem and development opportunity of the WEF nexus, our final goal is to draw attention to the next phase of the nexus for achieving WEF security and sustainable development through the collaboration of all sectors, governances, economies, and infrastructures.

Interconnections of WEF

WEF are inevitably linked with each other; that is, water needs energy for distribution, while energy needs water for production. Both water and energy are used in food production, while agricultural products supply bioenergy but have negative impacts on water quality. The following sections describe the details of each interconnection and introduce the outer elements that potentially affect the WEF nexus.

Water for energy

Flowing water is the main source of electricity generation in hydropower plants; if it is boiled and transformed to steam, it becomes the source of thermal power. Water is also used as a cooling material in thermal power plants. The volume of consumed water for producing a unit of energy is termed *water intensity* and is expressed in units of m^3/MWh. In a thermal power plant, the water intensity is calculated from the volume of water consumed and lost during the cooling process, while the intensity for a hydropower plant is commonly measured by the amount of evaporation in the reservoir because the water only passes through the turbine without being consumed (Lamberton *et al.*, 2010). Biofuel from agriculture as an alternative energy source does not always consume less water than conventional methods. The production of one litre of ethanol from irrigated corn consumes 190 to 2,260 litres of water, while a litre of biodiesel produced from soybeans consumes 9,040 litres of water. The water intensity for generating energy from different sources is summarized in Table 1 based on Lamberton *et al.* (2010) and Desai (2013).

Water for food

Irrigation in the agriculture sector is the most water-intensive of all industries, consuming 70% of all global water (Hoff, 2011; Mohtar & Daher, 2012; FAO, 2014). The amount of water contained in food products is termed *virtual water* or *water footprint*. Figure 2 shows a diagram presenting the clear and detailed differences between virtual water and water footprint, as adapted from Velázquez *et al.* (2011).

Table 1. Water intensity for energy production (Lamberton *et al.*, 2010; Desai, 2013).

Energy process	Units[a]	Average water intensity
Hydropower	Gal/MWh	1,430 (variable)
Thermal power		
Geothermal	Gal/MWh	2,900
Nuclear	Gal/MWh	400–720
Coal	Gal/MWh	200–480 (390)
Biomass	Gal/MWh	390
Natural gas	Gal/MWh	100–180 (140)
Solar (photovoltaic)[b]	Gal/MWh	30
Wind[b]	Gal/MWh	1
Crude oil production	Gal. water/Gal. crude oil	350

[a] 1 gallon = 3.7854 litres.

[b] The water in solar and wind power plants is only used for cleaning the panel or blade.

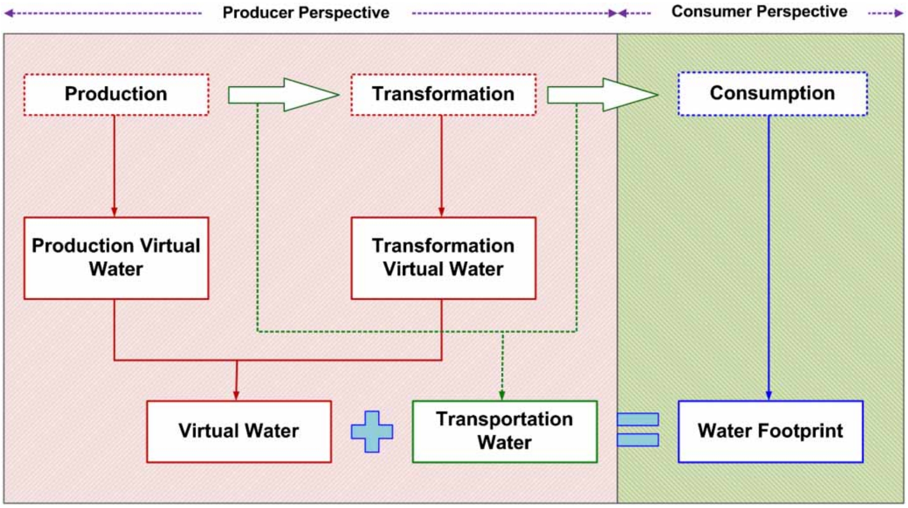

Fig. 2. Global processes of virtual water and water footprint calculation (Velázquez *et al.*, 2011).

Based on the figure, *virtual water* is defined as the amount of water used to produce and transform raw foodstuffs into food products (producer viewpoint), while the *water footprint* is the amount of virtual water plus the water used to deliver the product to the consumer (consumer viewpoint) (Velázquez *et al.*, 2011). In Figure 2 it is clear that the water footprint represents all amounts of water that consist of a single unit of food that is consumed by the consumer.

In the agricultural system, water is mainly used for irrigation and mostly originates from rainfall. During the dry season, water is supplied from surface water or groundwater sources through canals and pipelines. The water footprints of vegetables and meat products were summarized by Mekonnen & Hoekstra (2010) as shown in Table 2. According to this data, meat products consume more water than do vegetable products.

Energy for water

Energy is required for extraction, conveyance, treatment, and distribution of water to the end-user. Generally, the main energy type in these processes is electricity, and the unit consumption rate is stated as *energy intensity*. Summarized from Hoff (2011), and Mohtar & Daher (2012), the energy intensity to produce one cubic metre of clean water is listed in Table 3. The production processes of

Table 2. Global average of water footprints (Mekonnen & Hoekstra, 2010).

	Water footprint per tonne (m^3/tonne)				Water footprint per unit of nutritional value		
Food item	Green water	Blue water	Grey water	Total	Calorie (litre/kcal)	Protein (litre/g protein)	Fat (litre/g fat)
Vegetables	194	43	85	322	1.34	26	154
Starchy roots	327	16	43	387	0.47	31	226
Fruits	726	147	89	962	2.09	180	348
Cereals	1,232	228	184	1,644	0.51	21	112
Oil crops	2,023	220	121	2,364	0.81	16	11
Nuts	7,016	1,367	680	9,063	3.63	139	47
Milk	863	86	72	1,020	1.82	31	33
Eggs	2,592	244	429	3,265	2.29	29	33
Chicken meat	3,545	313	467	4,325	3.00	34	43
Butter	4,695	465	393	5,553	0.72	0	6.4
Pig meat	4,907	459	622	5,988	2.15	57	23
Sheep/goat meat	8,253	457	53	8,763	4.25	63	54
Bovine meat	14,414	550	451	15,415	10.19	112	153

Table 3. Energy intensity of clean water production (Hoff, 2011; Mohtar & Daher, 2012).

Source of water	Energy intensity
Lake or river	0.37 kWh/m^3
Groundwater	0.48 kWh/m^3
Wastewater treatment	0.62–0.87 kWh/m^3
Wastewater reuse	1–2.5 kWh/m^3
Seawater	2.58–8.5 kWh/m^3

non-conventional water sources usually require more energy to produce than the conventional sources. Meanwhile, the amount of energy needed for groundwater extraction varies depending on the aquifer depth, pumping volume, and types of pump, while the amount of energy required for desalination depends on the technologies applied. In practice, the total amount of energy needed for distribution must also consider leakage, which reduces the efficiency and increases the energy consumption.

In a wastewater treatment process, energy is needed for collecting raw wastewater, treating it in a treatment plant, and redistributing it to end-users. The amount of energy needed for wastewater treatment depends primarily on the quality of inflow (raw wastewater) and outflow (reclaimed water). Cooley & Wilkinson (2012) summarized the amount of energy required for recycling wastewater in the United States depending on the technologies and end-users, as shown in Table 4.

Energy for food

The energy consumption for food production can be categorized as direct and indirect consumption. Direct energy consumption is the amount of energy directly used in agricultural production such as fuel consumption of machinery and electricity for pumps, while indirect consumption is for producing the equipment used in agricultural practices such as fertilizer, herbicide, or machinery (Jackson, 2010). The units for describing the amount of energy used in farm operations (production, formulation, storage, and distribution) vary depending on the type of energy usage, taking such forms as volume (litre), weight (kg), calories (kcal), joules, or electricity (kWh). Most agricultural operations involve energy combustion that produces CO_2 or other GHG emissions. Thus, Lal (2004) suggested converting these various units into kg carbon equivalent (CE) to quantify carbon emission as a single unit. Table 5 shows the equivalent energy used in food production, summarized from Canakci *et al.* (2005) and Jackson (2010). Canakci *et al.* (2005) estimated the equivalent energy to produce crops and vegetables in the Antalya region in Turkey, while Jackson (2010) summarized the data from Australia. Both studies reported similar equivalent energy amounts, which were subsequently converted to CE units.

Table 4. Energy intensity of wastewater treatment (Cooley & Wilkinson, 2012).

Technologies	Energy intensity (kWh/MG)	End user
Conventional tertiary treatment		
Anthracite coal bed filtration, demineralization, chlorination	982	Irrigation, industrial use
Flocculation, direct filtration, UV/advanced oxidation	1,500	Irrigation, industrial use
Clarification, media filtration, chlorination	1,619	Irrigation, industrial & commercial
Anthracite coal bed filtration, UV	1,703	Irrigation, industrial use
Rapid mix, flocculation, media filtration, & UV	1,800	Irrigation
Membrane treatment		
Coagulation, flocculation, clarification, UF, RO, UV/advanced oxidation	3,220	Agriculture, industrial use
MF, RO, UV/advanced oxidation	3,680	Groundwater recharge
MF, RO, UV/advanced oxidation	3,926	Seawater intrusion barrier
UF, RO, UV	4,050	Industrial use
MF, RO	4,674	Industrial use
MF, RO	8,300	High-quality industrial use

Table 5. Energy and CE at food production (Lal, 2004; Canakci *et al.*, 2005; Jackson, 2010).

Energy input	Unit	Energy equivalent (MJ/unit)	Energy equivalent (kWh/unit)	Carbon equivalent (kg CE/unit)
Human power	hour	1.96–2.3		–
Fuel				
Diesel	litre	38.6	10.7	0.94
Liquid petroleum gas (LPG)	kg fuel	27.0	7.5	0.63
Electricity	kWh	11.9	3.3	0.00725
Fertilizer				
Nitrogen	kg	66.1	18.4	1.3
Phosphorous	kg	12.4	3.4	0.2
Potassium	kg	11.2	3.1	0.15
Lime	kg	0.6	0.2	0.16
Pesticide	kg/ha	199.0	55.3	–
Fungicide	kg/ha	92.0	25.6	3.9
Herbicide	kg/ha	240.0	66.7	6.3
Insecticide	kg/ha	200.0	55.6	5.1

Acceleration of GHG emission has degraded soil and environmental conditions. Careful assessments, such as integrated nutrient and pest management and enhancing water and energy efficiency in farm operations, are needed to reduce carbon emission and energy consumption (Lal, 2004). An approach to increasing such efficiency is grouping or sectoring the intake systems for water and energy distribution. A case study in Spain showed that this approach could reduce energy consumption by 36.4% (Jiménez-Bello *et al.*, 2010).

Another linkage between energy and food is seen in food price. Global energy prices, especially crude oil, affect food prices because many farm operations are dependent on crude oil (Bazilian *et al.*, 2011; Hoff, 2011). The relationship between global crude oil and food products' prices is shown in Figure 3, adapted from Ajanovic (2011).

Food for water

Slightly different from other interconnections, food products have no benefit to the water component except that some vegetation can be utilized as a natural water filter in a water treatment process. The obvious relationship between food and water is untreated food waste and excessive uses of fertilizer that become water pollutants. In the United States, as an example, 27% of edible food is wasted (Cuéllar & Webber, 2010), and less than 3% is recycled (Buzby *et al.*, 2011). Without proper management, food waste can reduce the availability of clean water and fertile soil. Furthermore, the increasing food demand has accelerated land intensification and farmland expansion. Land intensification increases groundwater extraction and the use of fertilizer and pesticide. The chemical residues from fertilizers and pesticides can infiltrate the soil or discharge to waterways, producing rapid deterioration in water quality. Meanwhile, expansion of a new agricultural area will degrade soil fertility, change the run-off characteristics, and influence groundwater recharge (Hoff, 2011).

Although it is not related to food products, willow vegetation can be used as a filter in wastewater treatment plants. Such treatment systems have already been implemented in Sweden and Poland,

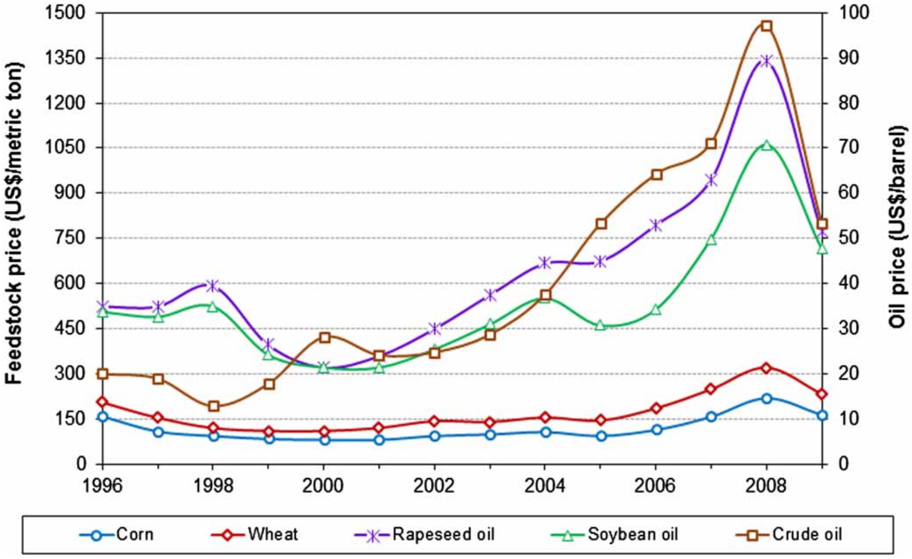

Fig. 3. Crude oil and feedstock prices for 1996–2009 (Ajanovic, 2011).

where they reduced the energy consumption in wastewater treatment (Perttu & Kowalik, 1997; Elowson, 1999). However, due to some limitations, such as a need for a large-scale area for implementation and lack of harmonization between policies and agriculture, the development and implementation of this technology are still in their early stages (Börjesson & Berndes, 2006).

Food for energy

The consideration of environment-friendly energy has triggered the development of bioenergy. Because it is produced from natural ingredients, bioenergy has many benefits for the environment since it is water-soluble, non-toxic, and biodegradable. In addition, bioenergy enhances social economy by reducing pollution, increasing farmland value, and reducing oil prices (Shi *et al*., 2009). There are several types of bioenergy category according to the energy product. Biofuel (or bioethanol) and biodiesel are liquid forms of bioenergy that are used as a transportation fuel to replace petroleum and diesel fuel. Biogas is a gaseous bioenergy produced from biomass through a gasification process (Yuan *et al*., 2008). Among these types of bioenergy, the most commonly produced and consumed are biofuel and biodiesel, as the alternative energy of transportation fuels. These types of bioenergy are already used by developed countries in order to reduce their dependence on petroleum (Mohtar & Daher, 2012). Bioenergy can be produced from agricultural crops (corn, sugar cane, wheat, or soybean) or food waste. The agricultural crops are usually used to produce biofuel and biodiesel, while food waste is mainly utilized to produce the biogas used to supply the gas for cooking or heating. Presently, global bioenergy production is still concentrated on biofuel ethanol and biodiesel, producing annually about 35.8 Mtoe (million tonnes of oil equivalent), while biogas production is 16.4 Mtoe per year (Smyth *et al*., 2010).

The products of biofuel could be categorized as a first- and second-generation of biofuel. The first-generation biofuel is usually made from feedstock crops (for example, sugar, starch (maize), or vegetable oil), which are easy to grow using conventional technologies. Second-generation biofuel is produced using novel materials (cellulose) and advanced technologies (Smyth *et al.*, 2010). The first-generation biofuel usually produces less energy than conventional petroleum but consumes more water (to produce one litre of biofuel, almost 1,000 litres of water are consumed). Moreover, the unsustainable development of biofuel threatens food supply security, in amount and price. Second-generation biofuel consumes less water and produces more energy than the first generation; however, it cannot be easily implemented due to a high production cost.

Environment and climate change

The environment is an external element of the WEF nexus, sometimes referred to in terms of ecology or ecosystem. It is clear that over-exploitation of natural resources can damage the environment, which requires water and energy for rehabilitation. Climate change is also known to affect temperature and rainfall patterns. The increasing temperature of the earth – known as global warming – leads to accelerating drying of arid land, reduced glacier water storage, and increased seawater level.

The temperature also affects steam turbine efficiency in electricity generation. Steam turbines generate electricity by creating steam to circulate a turbine, and high efficiency is obtained when the temperature of the inlet is higher than the temperature of the outlet. The inlet temperature usually depends on the steam temperature, while the outlet temperature depends on the cooling water or environment. A higher environmental temperature results in an increased need for water to cool the turbine and reach a low temperature at the outlet (Lamberton *et al.*, 2010). Extreme temperatures may result in increased use of air conditioning or heating systems, which consume more energy to operate and produce more carbon emission as a residue that accelerates climate change.

Water is the most vulnerable element affected by climate change. Climate change affects the rainfall pattern and increases the frequency and intensity of extreme events such as flood and drought (Hoff, 2011). Statistical data from the United Nations International Strategy for Disaster Reduction revealed that the number of extreme natural disasters has increased significantly during the last decade, and the trend is expected to continue to increase in the future (UNISDR, 2012). Furthermore, variations in water availability and rainfall pattern also affect the water supply for hydropower and irrigation (World Economic Forum, 2011). Climate change will interrupt the stable water supply for irrigation, and unexpected floods and droughts threaten food crop productivity, especially crops grown in rain-fed irrigation systems.

The variations in rainfall pattern, intensity, duration, and frequency also affect the availability of water sources. Rainfall with higher intensity and frequency but with shorter duration produces a large amount of surface run-off and does not contribute to the groundwater aquifer. This surface run-off can cause floods in the rainy season and drought in the dry season because less water is stored in groundwater as the base flows into the river. Furthermore, the decrement of stream flow reduces the amount of reliable surface water, which threatens water security and the environment (OECD, 2015).

Involvement of stakeholders and policymakers

For a long time, the sustainability of natural resources and the environment was mainly discussed by engineers and environmentalists, without the participation of policymakers or stakeholders. This situation creates a large gap of knowledge between engineers and stakeholders with regard to the sustainable development of resources. To date, the management of resources needs involvement and interaction from stakeholders and policymakers in order to develop a new policy concept related to the sustainability of WEF at local, national, and international levels (FAO, 2014). The adjustment of policy instruments by considering the WEF nexus can minimize and prevent conflicts between sectors, such as conflicts over water use for hydropower plants versus irrigation; agricultural land for food crops versus biofuel crops; and development projects versus environmental sustainability (McCornick *et al*., 2008). Such policy instruments can manage regulations, direct provisions by governments, encourage the public and private sectors to participate in the chosen policies, and create and manage the market to support green and sustainable development (Bizikova *et al*., 2013). Hellegers *et al*. (2008) suggested a revision of the present policy by adopting WEF interactions, encouraging the development and promotion of new technologies, expanding biofuel production, creating stimuli in the agricultural sector to maintain food security, and bridging the conflict between water development projects and environment sustainability. In future, stakeholders are expected to take part by creating integrated policies and plans, generating guidelines for economic incentives, establishing a collaboration forum of countries or science groups, and encouraging the public to actively participate in realizing the WEF nexus. Furthermore, the WEF nexus does not only manage the resources in a region or country, but it also raises opportunities for a trade between regions. Hence, it requires the participation of stakeholders to conduct international collaboration. Finally, the nexus governance should have a continuous innovation, political support, constant monitoring, and transparent governance principles to achieve sustainable development and reduce competition or conflicts (Bhaduri *et al*., 2015).

Global implementation practices

The WEF nexus is an emerging concept to enhance the sustainable management of WEF resources. This concept has been studied in several regions of the world but it is not yet fully implemented in policy and infrastructure development practices. The following sections introduce the WEF resources' management practices that have been conducted in several countries in the world. The introduced practices are using the nexus concept and can be extended effectively for development and implementation of the complete WEF nexus in the future.

Water allocation model in Sri Lanka and Indonesia

Sri Lanka is an island country in the Indian Ocean with more than 20 million people. Presently, 75% of the population has access to safe potable water, and 81% has access to electricity. However, the demand keeps increasing due to population growth. The main supply of electricity in this country is the hydropower plant, resulting in a conflict between clean water supply and water for energy. The conflict has involved several national agencies with separate authorities for generating and distributing electricity, supply of water for irrigation, and supply of clean water. Accommodating the differences among these interests, the government imposed the Mahaweli Development Programme, a water resources' development programme to manage water for irrigation, residential or industry, and hydropower (Manthrithilake & Liyanagama, 2012). Using this programme, the government has simulated and optimized water allocation in all Sri Lanka basin areas. The model covers seven basins, including eighteen reservoirs, nineteen major irrigation schemes, and thirteen hydropower stations. The model simulates and optimizes the allocation of water demand under the priorities of human needs, food production, environment, hydropower, and industry. Based on this model, the complexity of water management beyond multi-stakeholders can be wisely managed in Sri Lanka.

Similar to Sri Lanka, Indonesia has a conflict of water allocation for irrigation, clean water supply, and hydropower in river basin management. One of the country's large, long, and complex river basins is the Citarum River Basin located in West Java Province, which covers an area of 12,000 km^2 and 14 cities with different land use development and activities. The Indonesian government implemented the IWRM scheme by creating a river management institution to manage and control the quantity and quality of water along the river. Cooperating with other national institutions, such as electricity distributors, reservoir operators, irrigation organizations, and clean water distributors, they developed short- and long-term water management plans to maintain water sustainability.

Along the Citarum River, three cascade reservoirs of Saguling Reservoir, Cirata Reservoir, and Djuanda Reservoir are located. These three reservoirs generate 1,400 MW of electricity to supply Java and Bali. In particular, the Djuanda Reservoir supplies water for 4,200 km^2 of irrigation area and 80% of the municipal use in the Jakarta area (around 7.68 million citizens) (Hadihardaja *et al.*, 2013). A recent study showed that only 59% of the total 12.95×10^9 m^3 water per annum could be managed due to the capacity of reservoirs and inflow fluctuation over the year (Idrus *et al.*, 2013). To optimize the usage of available water, the operator relies on a computer model to estimate the annual flow fluctuation and optimize reservoir operation.

These similar conflicts in both countries represent a common issue that occurs in large-scale and long-term water management. Using an approach and computer model based on the IWRM, in which water is a primary element to generate energy and irrigate agriculture, both countries efficiently managed the conflict and maintained water sustainability. In future, the WEF nexus could advance IWRM by putting WEF on the same priority level to ensure the resources' security.

Implementation of a computer model to manage the food supply in Qatar

The State of Qatar faces a challenge in fulfilling the food demand for 1.9 million people. The primary obstacles to increasing agricultural production are the extremely high temperature and lack of water and fertile soil. Currently, the government of Qatar imports 90% of its food products from other countries in order to fulfill the food necessity while aiming to become a food self-sufficient country by 2023 (Mohtar & Daher, 2014). To reach this goal, the Qatar Environment and Energy Research Institute (QEERI) developed a computer simulation model, called WEF Nexus 2.0, to calculate and predict the requirements of water, energy, land, and carbon emission for food production and importation. Based on available resources and technologies in 2010, to increase food production by 25%, it was predicted to require 206% more water, 382% more land, and 200% additional energy and GHG emissions (Mohtar & Daher, 2014). Recently, the government used this model to create and simulate several scenarios in order to achieve food security by optimizing food production and import or trade. Using this model, stakeholders in Qatar can obtain an optimal scenario for fulfilling its food demand with minimum water, energy, and cost, while considering the sustainability of natural resources and the environment.

Management of WEF consumption in the United States

The United States is one of the largest consumers of energy and water in the world, representing 25% of the global electricity and petroleum consumption and almost 10% of the global water usage, most of which is used for thermoelectric cooling (Maupin *et al.*, 2014). The consideration of sustainable water and energy has been included in the US Energy Policy Act since 2005; this Act addresses the usage of energy related to the provision of adequate water supplies, and vice versa (Lamberton *et al.*, 2010). The US Department of Energy evaluates the annual usage of water and energy in the USA and reports it using a Sankey diagram (USDOE, 2014). This diagram could be used as an evaluation tool in water and energy supply management. In water management, the practice of Prior Appropriation Doctrine and Riparian Doctrine has been implemented to systemize water usages in the USA. The Prior Appropriation Doctrine legislates that people with the earlier priority date have priority to use the water over others with later priority dates. The Riparian Doctrine authorizes people who own land that physically contacts the water sources (river, stream, lake, etc.) to have an equal right to use the water from that source (EERC, 2005). Most of the states in the western part of the USA apply the Prior Appropriation Doctrine due to the lack of water, while states in eastern USA more typically apply the Riparian Doctrine. Recently, some states have modified or combined both doctrines to adapt to the increased population and water demand.

In addition, the USA also consumes a significant amount of food. In 2011, the average daily food consumption was 2,729 grams per person, which is 30% higher than the world average (National Geographic Magazine, 2015). About 15.7% of energy is used to produce this amount of food, although almost 27% of edible food is wasted (Cuéllar & Webber, 2010). Hence, the US government has encouraged the consumption of locally produced food in order to reduce energy and transportation costs. They are also promoting a non-meat-based diet programme (since meat-based products involve more water and energy for production), the consumption of organic food (to reduce chemical herbicides), and wise storage and cooking of food to minimize food waste (Center for Sustainable Systems, 2014).

The inclusion of the water and energy nexus in the policy, and the implementation of water doctrine in practice show the efforts of the US government to maintain sustainable development. Meanwhile, the encouragement to consume more local food and following a dietary programme are policies to promote food saving and food waste reduction. All these programmes already consider the sustainability of resources, and it would be more controllable if managed in one big programme.

Development of the WEF nexus in Europe

The trans-boundary rivers programme has promoted international river management among countries in Europe for many years. The International Commission for the Protection of the Rhine, the International Commission for the protection of the Danube River, and the Commission for the Protection of the Meuse are the international commissions established to monitor the water quality and quantity along the named rivers. Although these commissions do not have authority to ensure sufficient water quality and quantity for all countries along these rivers, this monitoring system does ensure the sustainability of the river basin. These commissions can potentially become a benchmark for further collaboration in energy and food production and trade to secure the resources' management.

Currently, European countries face an energy dilemma. They still import natural gas from central Asia and crude oil from OPEC countries, accounting for 53% of total consumed energy. Hence, European countries are increasingly using alternative energy sources such as biodiesel and biofuel for transportation energy. This effort has made the EU one of the top-five producers and consumers of biodiesel in the world. On the other hand, the high production of biodiesel has threatened the environment and agricultural sector of the EU and has resulted in negative social issues (for example, land use change, food price increase, etc.). In order to prevent the rapid growth of biofuel production and environmental degradation, the European countries have introduced policies to limit the use of biofuel for transportation and to trigger the development of more efficient vehicles. Moreover, the EU has restricted the conversion of farmland from food supply to bioenergy supply and has promoted environmentally friendly farming practices in an attempt to achieve sustainability (Smyth *et al.*, 2010). This could be a suitable approach to prevent the conflict of providing agricultural commodities for food supply and bioenergy production.

Research into the WEF nexus has already been established at a number of institutions, including the Stockholm International Water Institute and the Stockholm Environment Institute. These institutions are attempting to expand the implementation of the WEF nexus in developing countries in Africa, central Asia, and Latin America.

Consideration of GHG emissions in Australia

The Australian government also considers GHG emissions in the WEF nexus dialogue. The consideration of GHG emissions is another approach to expanding the relationship between water, energy, food, and the environment. The rapid growth of urbanization and electric appliance usage in the country is expected to increase the energy demand by 250% by 2030 (Kenway, 2013). The government plans to reduce the consumption of water, energy, and the emission of GHGs by 2030. To reach this goal, they have developed a mathematical model to simulate the usage of water and energy, and the level of GHG emissions at the household level. The Mathematical Material Flow Analysis (MMFA) model calculates the present water usage at the household level and further intends to explore the aspect of urban metabolism in order to understand the total water flow, energy consumption, and emission production in cities (Kenway *et al.*, 2013). Based on the findings from this simulation model, the Australian government plans to generate a systematic management policy to maintain the sustainability of water, energy, and GHG emission. The implementation of MMFA is further evidence that computer models could help stakeholders and policymakers create sufficient strategies and policies.

Introducing the WEF nexus to eliminate water and food scarcity in Africa

The main problem facing most countries in Africa is water scarcity. Particularly in the central region of Africa, water scarcity causes energy and food scarcity. In 2010, only 5% of the cultivated land in Africa was irrigated; less than 10% of the potential hydropower was developed; and only 58% of the population had access to safe drinking water (Foster & Briceño-Garmendia, 2010). Recently, some innovations, such as drip irrigation systems and wastewater reclaiming systems, were developed to address the water scarcity issue.

Africa has potential natural resources to develop, such as coal, solar photovoltaic, wind power, hydropower, biomass, and even wave and ocean current power (Banks & Schäffler, 2006). However, the lack of data and information regarding the natural resources hinders its development. In this situation, the WEF nexus could be a solution to solve the scarcity through sustainable development and natural resource trade-offs. In 2013, the International Union for Conservation of Nature and International Water Association held the first international workshop on the WEF nexus in Africa. This workshop discussed the problems, proposed solutions, identified challenges, and made action plans for implementing the WEF nexus in five river basins (namely, Lake Victoria, Niger, Orange-Senqu, Pangani, and Tana) in order to increase sustainability (IUCN & IWA, 2013).

WEF nexus assessment model

Existing model

Several computer models or tools, such as Impact Water, WESim, CLEW, Sankey diagram, multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM), WEF Nexus Tool 2.0, and ANEMI, have been developed to simulate the WEF nexus and estimate the resources' requirements considering various future scenarios. These models intend to help decision-makers and policymakers to develop appropriate resources' management policies. Among these existing models, only the last four are reviewed in this paper since these models show some advantages to being foundations for further development.

Sankey diagram. Recently, a nexus between water and energy has been presented using a Sankey diagram. A Sankey diagram presents the distribution and linkage of water and energy to map and visualize the source, destination, and quantity of flows in each stage of the water and energy supply chains (Hu *et al.*, 2012). The diagram represents the flow amount with different arrow widths, which intuitively visualizes the allocations and linkages among elements. This diagram has been applied to visualize the nexus between water and energy on a household scale in Australia (Kenway *et al.*, 2013), regional scale in Beijing, China (Hu *et al.*, 2012), and national scale in the USA (USDOE, 2014). The Sankey diagram is a decent visualization tool to describe the supplies and usage of resources in an intuitive manner. Although the Sankey diagram does not have the capability to do a simulation process, it has an opportunity to extend and adapt to visualize the WEF nexus.

MuSIASEM. The MuSIASEM is an innovative tool derived from the Bioeconomics and Complex System Theory in order to account for integrated quantitative information (Giampietro *et al.*, 2013). Based on the analysis of the metabolic pattern of energy in modern society, MuSIASEM was developed to simulate the WEF nexus by characterizing the metabolic patterns of WEF in connection with socio-economic and ecology variables. MuSIASEM can be used as a diagnostic tool to characterize the existing socio-economic and ecological system or as a simulation tool that is capable of determining the feasibility of various proposed system scenarios. The scheme operation is based on Georgescu-Roegen's flow-funds elements approach, which effectively presented an integrated approach to sustainability problems (Giampietro *et al.*, 2008). The MuSIASEM tool has simulated the WEF nexus in the Republic of Mauritius, in the Indian State of Punjab, and in South Africa with various scenarios and conditions (Giampietro *et al.*, 2013). The MuSIASEM is an applicative model at a global level and has been applied in several countries worldwide. However, the complexity of the model limits its utilization.

WEF Nexus Tool 2.0. The WEF Nexus Tool 2.0 was developed by the QEERI to calculate the required water, energy, land, financial support, and carbon production for food supply in Qatar. This application is a scenario-based tool that was developed to quantify the resources' requirement for nationwide food supply. The user has the ability to create scenarios by defining the three main inputs of food portfolio, water portfolio, and energy portfolio. Based on the inputs, the tool calculates the required water, local and imported energy consumption, land and financial requirements, and carbon emissions (Mohtar & Daher, 2014).

The model allows users to determine resource demand and calculate the sustainability index for each scenario. According to Mohtar & Daher (2014), this tool can be used to generate policy in a two-step process. The first step is to calculate the ratio between required and available resources in order to determine the sustainability index for each scenario. Using this sustainability index, the user can compare and analyse the resource requirements and sustainability of each scenario. The second step is to adopt a regulation or stakeholder assessment by modifying the scenario parameters to adapt to the possible national resource availability and allocation strategies. After the scenarios are satisfied, stakeholders can develop national strategies and policy preferences to achieve the optimum scenario. A limitation of this model is that the parameters are limited to the situation of Qatar and needs information on the specific site and characteristics of the study area. However, the concept of this model could be utilized as a base platform to develop a global model applicable to general cases.

ANEMI model. A new concept of 'Global Change' broadens the definition of climate change by adding human activities as the cause of environmental degradation. Hence, a decision-support model is needed to provide some normative regulations to control human activities. The first-generation ANEMI model (named after the Greek God) was developed as an integrated assessment model to model and simulate all involved elements, such as climate–carbon cycle, economy, land use, population, natural hydrological cycle, water demand, and water quality system (Davies & Simonovic, 2010). The model focused on learning the interconnections and feedback of each element. The first model, however, did not simulate the individual sectors in detail, neglecting some regional processes and seasonal effects. The second-generation model (ANEMI-2) was developed in 2011 to improve the capability of the previous model by including food production and enhancing the capability of optimizing the energy-economy element. In the new model, the population and food production calculations were adapted from the WORLD3 model, a system dynamics model developed in 1970, to simulate the interactions between population, industrial growth, food production, and limited resources (Akhtar *et al.*, 2013).

Both models were based on a system dynamics model that is capable of explicitly modelling the feedback between components, which makes it easy to trace their interactions (Davies & Simonovic, 2010). This capability means that system dynamics should become the main structure in developing the new model. The model was developed using the Ventana Simulation Environment (Vensim) software that has the capability to conceptualize, simulate, analyse, and optimize the system dynamics model (Vensim User's Guide, 2013). The usage of a user-defined causal-loop or stock-flow diagram makes the model easy to track for further evaluation and analysis.

Summary of the existing models. The evaluation in this section is not intended to compare the models 'face to face' because each model was developed for different purposes. Hence, the evaluation is focused on the strength of model to be adopted, and the weakness that can be improved in new models as summarized in Table 6. It should be noted that the existing models simulate the nexus in a one-way direction rather than fully investigate the feedbacks and interconnections of each element. Also, none of the models has an optimization module to optimally allocate the resources. Further improvements are needed for model development and will be discussed in the following section.

Table 6. Summary of existing nexus models.

Model	Year	Applied area	Summary
Sankey diagram	1898: (1st drawn) 2006: (1st computer application)	Australia, China, USA, etc.	The Sankey diagram is a decent visualization model to describe the usage of water and energy. The diagram represents the direction of flow in an arrow while the amount is represented by its thickness. However, it is only a visualization model, incapable of doing scenario simulation. Nowadays, mainly utilized to present the distribution of energy and water, it is not used to show the amount of energy and water used in the production of food. This visualization scheme could be very helpful to represent the distribution of WEF.
MuSIASEM	2013	Rep. of Mauritius, Punjab (India), and South Africa	Diagnostic or simulation model to analyse the WEF nexus by characterizing the metabolic patterns of WEF in connection with socio-economic and ecology variables based on Georgescu-Roegen's flow-funds elements. An applicative model, but also a complex model that can be understood only by limited users.
WEF Nexus Tool 2.0	2013	Qatar	Basically utilized to calculate the water and energy needed for food supply in Qatar. This application is a scenario-based tool that was developed to quantify the resources' requirement for nationwide food supply. The user has the ability to create scenarios by defining the food, water, and energy portfolio, while it results in the required water, local and imported energy consumption, land, and financial requirements, and carbon emissions. It is a user-friendly application and could be referred to the development of another simulation model.
ANEMI	2011	Canada	A system dynamics model for analysing the behaviour of the social-energy-economy-climate system. Developed using the Ventana Simulation Environment (Vensim) software, it has a user-friendly module to develop the model but limited flexibility in creating new scenarios. The implementation of a system dynamics model gives the advantage to model the linkage of nexus.

Opportunity for model development

The existing models reviewed in previous sections are representative examples of computer models to simulate any nexus, of which the results are used to develop policies and regulations for resource sustainability. However, the existing models have limitations, which offers opportunities for further development. Here, we have identified the potential features to pursue in future model development for WEF nexus simulation. Figure 4 summarizes the features of existing models and further development, while the details are explained in the following discussion.

- Develop feedback analysis

The present models commonly set a particular element as the main component and estimate the requirements of other elements to meet the demand of the main component without considering the feedback among the elements. WEF Nexus Tool 2.0 is a typical example, in which water and energy demands are estimated to supply food products. A future model should have the capability to simulate the feedback between elements in a single modelling framework.

- Revise the agricultural sector

Most of the models place the agricultural sector as a consumer of water and energy. However, agriculture also has a role in creating alternative energy through biofuel. On the other hand, farmland expansion causes land degradation, changes run-off patterns, and affects groundwater recharge. Moreover, land degradation and erosion add sediment in the downstream areas of rivers and reservoirs, which can reduce the water availability. Land degradation and erosion also affect water availability by altering surface run-off characteristics as land use changes. Various contributions of the agricultural sector should be considered in future applications.

- Include climate change

Climate change affects the environment, especially the availability of water resources. As long as water is the main element in the WEF nexus, changes in water characteristics will affect the other elements. Most of the present models simulate the WEF nexus without considering the impact of climate change. The challenge for future simulation models is to include climate-related changes, such as variations in temperature and rainfall pattern or intensity, in nexus simulation.

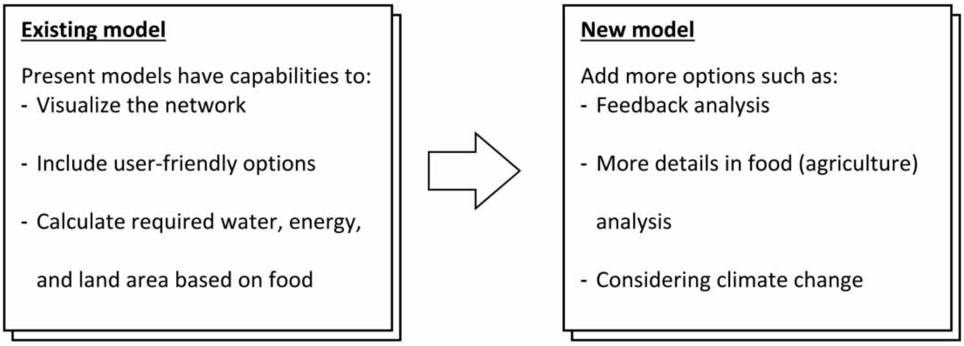

Fig. 4. Features of existing models and further development.

- Include government policies

Human activities contribute to environmental sustainability and climate change. Comprehensive government policies will guide human activities to consider environment and resources' sustainability and, eventually, improve the nexus. In a simulation model, these policies could act as the constraints on some actions in order to maintain sustainability. Thus, the model can aid in the decision-supporting process for governments to develop policies and regulations to maintain WEF sustainability.

- Optimization and visualization capabilities

Existing models calculate a number of needed resources to fulfil the population demand. Modelling options to optimize the allocation of resources in an economic and sustainable way will be beneficial for planning and managing the limited resources. In addition, visualizing the simulation results will promote more involvement of stakeholders in the nexus dialogue and will make the decision process more transparent to non-technical parties.

- Adopt an economic-engineering approach

The economic sector is rarely considered in existing models. In fact, the inclusion of the economic sector in the model could be an objective in the optimization framework for creating sustainable development scenarios. For example, the concept of benefit–cost ratio can be used as a feasibility index for proposed engineering scenarios.

Discussion

This review has presented an overview of the literature regarding the WEF nexus, mainly focusing on its global implementation and model development. According to the research, supplies of WEF are in a critical condition and cannot be analysed separately due to their interconnections. In addition to the interconnections between elements, it should be recognized that an element itself has internal connections, such as water for water, energy for energy, and food for food. For example, in the production of drinking water, water is withdrawn from a river or groundwater source; when generating electricity in a thermal power plant, coal is needed in the combustion process; and crops are consumed to raise livestock.

The fundamental concept of the WEF nexus has already been implemented in some countries and regions in the form of IWRM, trans-boundary river basin management, or other management systems to balance the water usage for multipurpose users. However, considering the growing popularity of environmental sustainability, a more integrated system is needed. The WEF nexus is believed to be a novel concept to achieve WEF security in balance. However, the idea is still at an early stage and not practically applied due to the difficulty of integrating the complex components in a single framework. Discussions are under way to improve existing governance and policy systems by adopting the WEF nexus. The improvement of existing governance includes a broad involvement and collaboration of planners and policymakers (financial, institutional, technical, and intellectual sectors) to build a responsible and supportive governance at local, national, and supranational level (Bhaduri *et al.*, 2015). On the policy side, Gain *et al.* (2015) suggested the integration of the existing policies of each sector, rather than creating a new exclusive policy. The integration and coordination should cover WEF along with climate and environment policies.

The first step in collaboration is to help the policy planners gain a better understanding of the WEF nexus concept. The complex linkages between nexus elements encouraged researchers to develop a simulation model to assist the planners. The computer model also analyses the elements' linkages and quantifies the resources needed under various scenarios presuming future conditions. The WEF Nexus Tool 2.0 and MuSIASEM are two computer models that have attempted to calculate the amounts of WEF consumption as a basis to establish policies or strategies in fulfilling the population demand. However, the limitations of each model demonstrate the need to develop an advanced model for improved simulation, calculation, and optimization analysis as a decision-supporting tool.

Concluding this review paper, the continued development of the WEF nexus has two main goals. The first is to incorporate all sectors by including planners and policymakers of each sector in the decision-making process. The collaboration with stakeholders could help increase community awareness through policies and economic incentives. The second goal is the development of a decision-support system based on computer tools that simulate and quantify the WEF interactions. Using the computer model, sustainable development plans can be created, evaluated, and optimized.

The WEF nexus is a vexing problem to face our planet. WEF planners, policymakers, and engineers have to stop working in isolation, and create integrated policy and infrastructure solutions to ensure the resources' security in the future.

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