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Integrated modeling approach for optimal management of water, energy and food security nexus

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ABSTRACT

Water, energy and food (WEF) are inextricably interrelated. Effective planning and management of limited WEF resources to meet current and future socioeconomic demands for sustainable development is challenging. WEF production/delivery may also produce environmental impacts; as a result, green-house-gas emission control will impact WEF nexus management as well. Nexus management for WEF security necessitates integrated tools for predictive analysis that are capable of identifying the tradeoffs among various sectors, generating cost-effective planning and management strategies and policies. To address these needs, we have developed an integrated model analysis framework and tool called WEFO. WEFO provides a multi-period socioeconomic model for predicting how to satisfy WEF demands based on model inputs representing productions costs, socioeconomic demands, and environmental controls. WEFO is applied to quantitatively analyze the interrelationships and trade-offs among system components including energy supply, electricity generation, water supply-demand, food production as well as mitigation of environmental impacts. WEFO is demonstrated to solve a hypothetical nexus management problem consistent with real-world management scenarios. Model parameters are analyzed using global sensitivity analysis and their effects on total system cost are quantified. The obtained results demonstrate how these types of analyses can be helpful for decision-makers and stakeholders to make cost-effective decisions for optimal WEF management.

1. Introduction

Water, energy and food are critical resources for meeting the socioeconomic demands and sustainable worldwide economic development. They are inextricably interrelated; each of them significantly depends on others (Bazilian et al., 2011; Gold and Webber, 2015; Dubreuil et al., 2013; USDOE 2014). Water plays an important role in almost every stage of energy development, including extraction, production and processing of fossil fuels, electricity generation, and treatment of wastes from energy-related activities (Bazilian et al., 2011; USDOE 2014; Hoff, 2011; Mo et al., 2014; Fulton and Cooley, 2015; Perrone et al., 2011; Bartos and Chester, 2014; Pereira-Cardenal et al., 2016). In the US, about 90% of the electricity was produced by thermoelectric power plants, where significant quantities of water are withdrawn and consumed for cooling purposes (Ackerman and Fisher, 2013; Copeland, 2014; Zhang and Vesselinov, 2016). Water is needed for food production, mainly for irrigation and processing of crops. Agricultural production is the largest consumer of water globally, accounting for about 90% of global freshwater consumption in the past century (USDOE 2014; Hoff, 2011; Khan and Hanjra, 2009; Shiklomanov, 2000). Energy is needed to pump, collect, treat, and distribute water; at the same time, energy is crucial in food production and processing for mechanization, land preparation, fertilizer production and application, irrigation, packaging, processing and storage of food (USDOE 2014; Hoff, 2011; Canning et al., 2010; Zhou et al., 2013; Mo et al., 2010); about 30% of the global energy consumptions are from food production and supply (FAO 2011). The interdependent relationships of these three critical resources are termed as water-energy-food (WEF) nexus. The nexus concept has garnered more and more attention in the past several years (Zhang and Vesselinov, 2016; Hellegers et al., 2008; World Economic Forum 2011). With the rapid increase of the world population, demands for WEF resources increase significantly (FAO 2014). It is estimated that world population will increase by 50% by 2050 (Lazarus, 2010). The associated increase in demand for food has resulted in, and will continue to cause, increasing stresses on both energy and fresh water resources. This will substantially exacerbate the water and energy shortage at different scales, locally, regionally, nationally as well as internationally. It is challenging to effectively plan and make optimal use of limited WEF resources to meet current and future

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socioeconomic demands for sustainable development (Bazilian et al., 2011; FAO 2014; Howells et al., 2013).

Major energy sources are nonrenewable (e.g., coal and natural gas), and their uses also produce Greenhouse Gases (GHG) - predominantly CO_2 - into the atmosphere that are consequently impacting the global climate (IPCC 2007; Zhang et al., 2014; Zhang and Huang, 2013). For examples, thermoelectric power plants generate significant quantities of GHGs; agriculture contributes about 30% of the global anthropogenic GHG emissions worldwide (FAO 2003). Greater demand for food requires more energy consumption (for irrigation as well as fertilizer production and application) and water (consequently consuming more energy for pumping, delivering, and treating water), leading to more GHG emissions (Schlesinger, 1999; Smith et al., 2007). Control of GHG emissions is crucial for mitigating the impacts of climate change. It is also desirable that GHG emission control be incorporated into the WEF nexus management.

The processes representing the integrated WEF system are complicated and dynamic, because not only each of the three sectors does affect one-another at various spatial and temporal scales, but also numerous economic, social, political, technological, and environmental factors are involved (USDOE 2014; Hoff, 2011). Nexus management aiming to provide WEF security necessitates integrated approaches and/or tools for analysis that are capable of identifying the tradeoffs among various sectors, generating cost-effective planning and management strategies and policies. The outcomes of these analyses will be applied to inform decision-makers and stakeholders in practical decision scenarios. The WEF nexus management analyses should be able to answer a series of critical questions, such as “what are optimal strategies for managing water, energy and food simultaneously?”, “how will polices and management strategies within a sector affect the other sectors?”, and “how will GHG mitigation measures affect energy supply, food production and water consumption?” (Hoff, 2011). Those are the core tasks of the WEF nexus management. Optimal WEF allocation and use cannot be accomplished without integrating considerations from all three sectors and acknowledging interrelationships (FAO 2011; FAO 2014).

Model-based approaches are effective tools for supporting such planning problems and quantitatively analyzing the inseparable relationships among WEF resources, and facilitating robust decision-making facing the complex WEF system. Previously, many studies have been reported in the research areas of WEF nexus. Most of them focused on a single sector such as water resources management, energy systems management or agricultural production planning, or two sectors such as water-energy nexus, or specific issues such as socioeconomic impacts of water uses, or conceptual descriptions of the WEF nexus management (Zhang and Vesselinov, 2016; FAO 2011; Hu et al., 2011; Hightower and Pierce, 2008; Nilsson and Mårtensson, 2003; Li et al., 2011; Chung et al., 2004; AlQattan et al., 2015; Lall and Mays, 1981; Rasul and Sharma, 2015). For example, Lall and Mays (1981) proposed a mathematical programming model for managing water and energy resources. Lotfi and Ghaderi (2012) formulated a fuzzy possibilistic mixed integer programming model for mid-term electric power planning in deregulated markets. Dubreuil et al. (2013) designed a water module in the world energy system model TIAM-FR to assess the linkages between energy and water. There is a lack of an integrated nexus modeling system which is capable of incorporating all of the three sectors and associated environmental impacts into a general framework, and quantitatively studying the complex interactions to optimize the WEF nexus management strategies from a whole-system perspective (Howells et al., 2013; Biggs et al., 2015).

The objective of this study is to develop an integrated model analysis framework and tool called WEFO capable of addressing the trade-offs and supporting decisions of the nexus management of WEF resources. WEFO can make predictions about multi-period WEF production costs based on availability of WEF resources, socioeconomic demands, and GHG emission controls. The interrelationships and trade-offs among WEF production and mitigation of environmental impacts are quantitatively analyzed. The applicability of WEFO is demonstrated in a hypothetical nexus management problem consistent with real-world management scenarios. The results demonstrate how these types of analyses can be helpful for decision-makers and stakeholders to make cost-effective strategies for optimally managing constrained WEF resources to meet the current and future socioeconomic demands.

2. Methodology development

A multi-period socioeconomic model, called WEFO (Water, Energy and Food security nexus Optimization model), is developed. The interactions represented in WEFO model between the WEF components as well as existing socioeconomic and environmental constraints are illustrated in Fig. 1. The decision variables of the WEFO model are (1) the amounts of available energy supplies of coal and natural gas, (2) the power plant capacity to generate electricity, (3) quantities of groundwater and surface water needed for food production, (4) quantities of groundwater, surface water and recycled water needed for electricity generation, and (5) socioeconomic demands on WEF production during a series of sequential planning periods. The management objective of the WEFO model is to minimize the total system cost; the total cost is a sum of energy supply, water supply, electricity generation, food production, and CO_2 emission mitigation costs.

In the text below, we list all the parameters implemented in the WEFO model. Key decision variables applied in the WEF optimization processes are:

ES_{jt} energy supply j in planning period t (PJ);
X_{jt} electricity generation from a power plant using energy supply j in planning period t (PJ);
GW_t^F groundwater quantity supplied to food production in planning period t (gal);
SW_t^F surface water quantity supplied to food production in planning period t (gal);
GW_{jt}^e quantity of groundwater supplied to the power plant j in planning period t (gal);
SW_{jt}^e quantity of surface water supplied to the power plant j in planning period t (gal);
RW_{jt}^e quantity of recycled water supplied to the power plant j in planning period t (gal); and
FO_t quantity of produced food in planning period t (tonne).

In the parameter list above, the suffixes identify:

j type of energy supply and the power plant that uses a given energy supply;
t the sequential planning time periods, where a planning period is defined as a period for planning water, energy and food nexus management.

The management objective is to minimize the total costs defined as

$$min\ f = a + b + c + d + e,$$

where:

a: costs of energy supply for electricity generation;
b: costs of electricity generation;
c: costs of water supply;
d: costs of food production;
e: costs of CO_2 emission abatement.

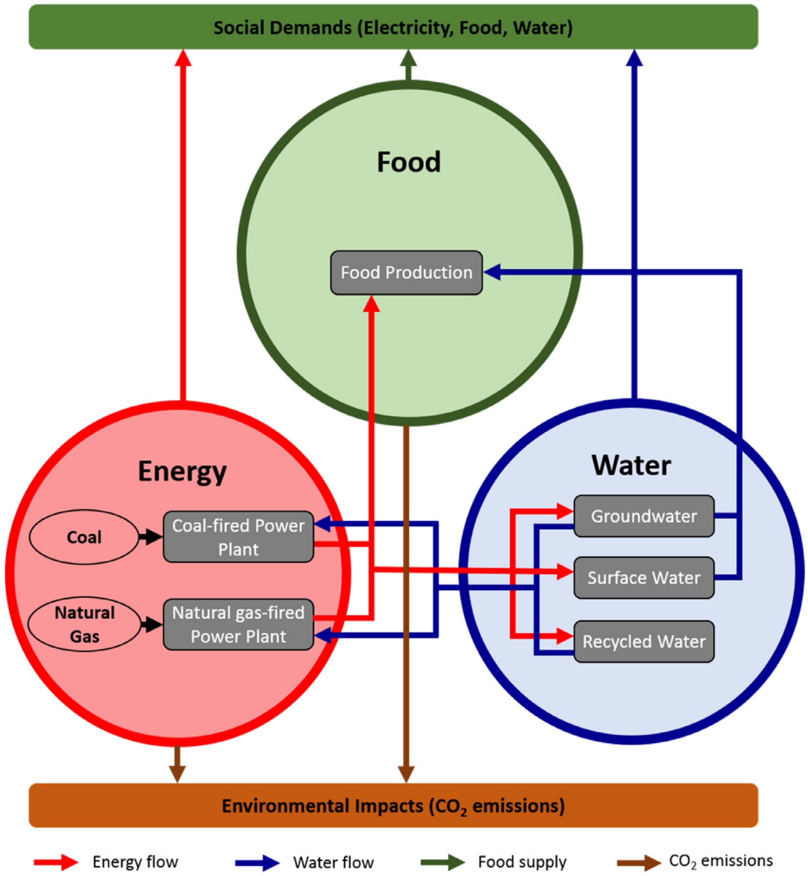

Fig. 1. A schematic representation of the interactions in the WEFO model related to optimal management of water, energy and food security nexus. The colored arrows represent the flow of the system components.

The costs of energy supply for electricity generation, a, are defined as

$$a = \sum_{j=1}^{m}\sum_{t=1}^{k} ES_{jt} ESC_{jt}$$

where ESC_{jt} are average costs for energy supply j in planning period t (million $/PJ), m is number of energy supply and the power plant, k is number of planning period. In general, there are no limitations for various parameters applied in this model. For example, the number of power plants or planning periods can be any integer greater than 0.

The costs of electricity generation, b, are defined as:

$$b = \sum_{j=1}^{m} FC_j + \sum_{j=1}^{m}\sum_{t=1}^{k} X_{jt} PC_{jt}$$

where FC_j are fixed costs for the power plant j (million $), and PC_{jt} are average operational costs for electricity generation in the power plant j in planning period t (million $/PJ).

The costs of water supply for electricity generation and food production, c, are:

$$c = \sum_{t=1}^{k} \left(GW_t^F CGW_t^F + SW_t^F CSW_t^F \right) + \sum_{j=1}^{m}\sum_{t=1}^{k} \left(GW_{jt}^e CGW_{jt}^e + SW_{jt}^e CSW_{jt}^e + RW_{jt}^e CRW_{jt}^e \right)$$

where CGW_t^F are costs of groundwater supplied to food production in planning period t ($/gal), CSW_t^F are costs of surface water supplied to food production in planning period t ($/gal), CGW_{jt}^e are costs of groundwater supplied to the power plant j in planning period t ($/gal), CSW_{jt}^e are costs of surface water supplied to the power plant j in planning period t ($/gal), and CRW_{jt}^e are costs of recycled water supplied to the power plant j in planning period t ($/gal).

The food production costs, d, are:

$$d = \sum_{t=1}^{k} CFO_t FO_t$$

where CFO_t are unit costs of food production in planning period t (million $/tonne).

The costs for CO_2 emission abatement, e, are:

$$e = \sum_{j=1}^{m}\sum_{t=1}^{k} CEA_t CC_{jt} X_{jt} + \sum_{t=1}^{k} CFA_t FO_t FF_t$$

where CEA_t are costs of CO_2 emission abatement for electricity generation in planning period t ($/kg), CFA_t are costs of CO_2 emission abatement for food production in planning period t ($/tonne), CC_{jt} are units of CO_2 emission per unit of electricity generation in planning period t (million kg/PJ), and FF_t are unit CO_2 emission per unit of food production in planning period t (tonne/tonne).

The management problem in WEFO is further characterized by the following management constraints:

(1) Mass balance of fossil fuels:

The generated electricity in each power plant in each planning period should not be larger than the energy-supplyconverted amounts.

$$X_{jt} \cdot FE_{jt} \leq ES_{jt}, \forall j, t$$

where FE_{jt} are unit of energy carrier per unit of electricity generation for conversion technology j in period t (PJ/PJ).

(2) Fossil energy availability constraints:

The supplied fossil fuels such as coal and natural gas should not be larger than their availability over the planning periods.

$$ES_{jt} \leq AV_{jt}, \forall j, t$$

where AV_{jt} are availability of energy supply j in planning period t (PJ).

(3) Energy demand for food production:

The consumed energy for food production should not be larger than maximum allowable electricity for food production.

$$ER_t^F \cdot FO_t \leq AER_{tmax}^F, \forall t$$

where AER_{tmax}^F is the maximum available electricity for food production in planning period t (PJ), and ER_t^F are unit energy demand for food production in planning period t (PJ/tonne).

(4) Energy demand for water collection, treatment and delivery:

The consumed electricity for water collection, treatment and delivery should not be larger than maximum allowable quantity.

$$ER_t^w \cdot \left(GW_t^F + SW_t^F + \sum_{j=1}^{m} \left(GW_{jt}^e + SW_{jt}^e + RW_{jt}^e \right) \right) \leq AER_{tmax}^w, \forall t$$

where AER_{tmax}^w is the maximum available energy (or electricity) for water collection, treatment and delivery in planning period t (PJ), and ER_t^w is the unit energy demand for water collection, treatment and delivery in planning period t (PJ/gal).

(5) Electricity demand constraints:

The generated electricity from the power plants should be able to meet the socioeconomic demands of electricity after supplying for food production and water collection, treatment and delivery.

$$\sum_{j=1}^{m} X_{jt} - ER_t^F \cdot FO_t - ER_t^w \cdot \left(GW_t^F + SW_t^F + \sum_{j=1}^{m} \left(GW_{jt}^e + SW_{jt}^e + RW_{jt}^e \right) \right) \geq D_t^e, \ \forall t$$

where D_t^e are socioeconomic demands of electricity in planning period t (PJ).

(6) Water demand constraints for food production:

The supplied water should meet the water requirements for food production.

$$(1 - \delta)\left(GW_t^F + SW_t^F \right) \geq WF_t \cdot FO_t, \forall t$$

where δ is loss factor of water delivery to the food subsystem, GW_t^F is the groundwater supplied for food production in planning period t (gal), SW_t^F is the surface water supplied for food production in planning period t (gal), and WF_t is the unit water consumption per unit of food production in planning period t (gal/tonne).

(7) Water demand constraints for electricity generation:

The water requirements for electricity generation should be met.

$$\left(1 - \mu_j\right) \cdot \left(GW_{jt}^e + SW_{jt}^e + RW_{jt}^e \right) \geq \alpha_j \cdot X_{jt}, \forall j, t$$

where μ_j is loss factor of water delivery to the power plant j, and α_j are unit water demand per unit of electricity generation in the power plant j (gal/GWh).

(8) Water resources availability constraints:

Supplied groundwater cannot exceed the maximum available groundwater quantity (safe yield) in planning period t.

$$GW_t^F + \sum_{j=1}^{m} GW_{jt}^e \leq SY_t, \forall t$$

Supplied surface water cannot exceed the maximum available surface water quantity.

$$SW_t^F + \sum_{j=1}^{m} SW_{jt}^e \leq ASW_t, \forall t$$

Supplied recycled water cannot exceed the maximum available recycled water quantity.

$$\sum_{j=1}^{m} RW_{jt}^e \leq ARW_t, \forall t$$

where SY_t is maximum available groundwater safe yield (gal), ASW_t is maximum available surface water quantity (gal), and ARW_t is maximum available recycled water quantity (gal).

(9) Food demand constraints:

The produced food should meet the socioeconomic demands of food.

$$FO_t \geq D_t^F, \forall t$$

where D_t^F is food demand in planning period t (tonne).

(10) CO_2 emission control constraints:

The generated CO_2 amounts should not be larger than the maximum allowable CO_2 emissions during the planning periods.

$$\sum_{j=1}^{m} \sum_{t=1}^{k} X_{jt} CC_{jt} \left(1 - \emptyset_{jt}\right) + \sum_{t=1}^{k} FO_t FF_t \leq TMCC$$

where $\emptyset_{jt}$ is average efficiency for CO_2 abatement in the power plant j in planning period t, and $TMCC$ is maximum allowable CO_2 emission during the time periods (million tonnes).

(11) In addition, we have the following constraints defining non-negativity of the decision variables:

$$X_{jt} \geq 0, \forall j, t$$

$$ES_{jt} \geq 0, \forall j, t$$

$$FO_t \geq 0, \forall t$$

$$GW_t^F \geq 0, \forall t$$

$$SW_t^F \geq 0, \forall t$$

$$GW_{jt}^e \geq 0, \forall j, t$$

$$SW_{jt}^e \geq 0, \forall j, t$$

$$RW_{jt}^e \geq 0, \forall j, t$$

All these elements of the management problem (goal, constraints and variables) are applied to create the WEFO model. The WEFO model is based on linear mathematical programming, and is coded in Julia, a high-level, dynamic high-performance programming language for technical computing (julialang.org). WEFO predictions are obtained by a simplex algorithm to achieve the optimal solutions (Dantzig, 1998); the computational time for every model run is less than 1 s on an Intel(R) Core(TM) i5-4310U 2.00 GHz CPU with 16GB of memory.

It is important to note that, in practice, some of the WEFO parameters listed above are variable instead of fixed. For example, cost-related parameters, socioeconomic demands of electricity and food, the maximum available water quantity, and the maximum allowable CO_2 emissions can fluctuate within certain ranges that can be represented as probability distributions; in the simplest case, the probability distribution can be uniform within predefined limits. To evaluate the impacts of this uncertainty, we have performed sensitivity analyses where the WEFO parameters are varied within predefined uniform ranges. In order to identify the most sensitive parameters and their effects on the modeling outputs, global sensitivity analysis is employed (Sobol', 2001) as implemented in the code MADS (mads.lanl.gov). The effects of variations of the parameters on the total system cost are evaluated.

3. Application

3.1. Overview of the synthetic example system

The proposed WEFO model is used to solve a synthetic example WEF system to demonstrate its applicability. The system that we study includes two thermoelectric (coal- and natural gas-fired) power plants to generate electricity. The WEFO planning is performed over three sequential five-year time periods. Electricity generation requires water provided from three different sources: groundwater, surface water and recycled water. The generated electricity is used not only within the WEF system itself (i.e. to deliver water to the power plants and for food production), but also for meeting socioeconomic demands. For food production and processing, both water (recycled water source is not considered due to human-health safety issues) and energy (in the form of electricity in this study) are required. In addition, GHGs are emitted by the electricity and food production. The problem under consideration is how to plan the energy and water supplies, the electricity generation, and the food production to achieve the minimum total system cost with consideration of a GHG emission control. A schematic representation of the subsystems in the WEFO model and their interconnections is presented in Fig. 1.

Our study system presented here is consistent with real-world management scenarios. The information used in this study is culled from published literature and government reports (Bazilian et al., 2011; USDOE 2014; Zhang and Vesselinov, 2016; FAO 2014; Lazarus, 2010; Smith et al., 2007; Hu et al., 2011; EIA 2015; Zhu and Huang, 2011; Li et al., 2010; Diehl and Harris, 2010; B.R. Scanlon et al., 2013; Wang et al., 2015; Stillwell et al., 2011; EIA 2015; B.R. Scanlon et al., 2013; Institution of Mechanical Engineers 2013; Woods et al., 2010; West and Marland, 2002). Table 1 shows all cost-related parameters in the WEFO model, including average energy and water supply costs, average operational costs for electricity generation, costs for food production, and abatement of CO_2 emission associated with electricity generation and food production. The costs related to energy and water supply, electricity generation, food production and abatement of CO_2 emissions are assumed to increase over the three periods. The fixed costs for electricity generation in the coal-fired and natural gas-fired power plants are \$65 and \$75 million, respectively. The parameters related to resource constraints are presented in Table 2, including electricity and food demands, energy availability, and maximum water availability. Socioeconomic demands for electricity and food over the planning horizon are projected to increase over time, attributed to increasing population and urbanization. Electricity demands are assumed to be 105, 115 and 126 PJ, respectively, and food demands are 67,000, 71,000, and 75,000, respectively during the three planning periods (as shown in Table 2). The availability of energy including coal and natural gas will decrease over the planning periods, assuming increasing stresses on energy supplies. The maximum available quantity of groundwater, surface water and recycled water will decrease over the planning periods due to the increasing competition for the limited water resources as well as changing climatic conditions, while the water supply costs will increase. The unit water demands per unit of electricity generation in the coal-fired and natural gas-fired power plants are estimated to be 0.33 and 0.44 gal/KWh, respectively (Diehl and Harris, 2010; B.R. Scanlon et al., 2013; Wang et al., 2015; Stillwell et al., 2011). The unit water consumptions per unit of food production over the planning horizon are estimated to be 659×10^3, 676×10^3, and 694×10^3 gal/tonne, respectively for the three-planning periods (Institution of Mechanical Engineers 2013). The loss factors involved in delivering water to the coal-fired and natural gas-fired power plants are 10% and 15%, respectively; the loss factor involved in delivering water for food production is 15%. Table 3 shows additional constants and constraints of the WEFO model. The unit CO_2 emissions per unit of electricity generation in the coal-fired power plant during the first, second and third periods are 261.03, 254.89, and 247.08 million kg/PJ, respectively, while those for the natural gas-fired power plant are 152.58, 149.98, and 146.19 million kg/PJ (EIA 2015). The average efficiencies for CO_2 abatement in the coal-fired and natural gas-fired power plants over the three planning periods are assumed to be constant and equal to 80% and 85%, respectively. The unit CO_2 emission per unit of food production during the three planning periods is also assumed to be constant (0.48 tonne/tonne) (West and Marland, 2002).

All the parameters listed in Tables 1 and 2 are uncertain due to lack of knowledge about the future socioeconomic conditions of the processes within the WEFO system model. The model parameter uncertainties can be represented with probability distributions representing prior expectations. To demonstrate how uncertainties can be characterized in the WEFO model, we have assumed uncertainty ranges for the model parameters as listed in Tables 1 and 2. These uncertainties are assumed to be represented by uniform probability distributions within acceptable minimum/maximum limits. The uncertainty ranges are used in global sensitivity analyses of the WEFO model parameters discussed below.

3.2. Results analyses

Figs. 2 and 3 show the optimal WEFO solutions for the energy and water subsystem based on the expected values of the model parameters (called the base-case scenario hereafter). The optimal food production is 67,000, 71,000 and 75,000 tonnes during the three planning periods, which are equal to socioeconomic food demands shown in Table 2. As the electricity demands increase, the optimized electricity generation during the three planning periods is 105.98, 116.14, and 127.27 PJ, respectively, which slightly exceeds socioeconomic electricity demands (105, 115, and 126 PJ in Table 2). That is because the additional electricity is required for food production as well as water collection, treatment and delivery. Coal with lower supply costs should be the main energy source over the planning horizon. In the latter two periods, more natural gas should be utilized. The ratio of natural gas to the total supplied energy will increase from 13% in period 1 to 26% in period 2, and 28% in period 3, reflecting the stricter environmental constraints.

Table 1
Unit cost for energy and water supplies, electricity generation, food production and CO_2 abatement; the table lists the assumed values for the best estimates and the minimum/maximum of the uniform uncertainty ranges associated with each model parameter in parentheses.

	Sequential Five-year Time Periods, k		
	$k=1$	$k=2$	$k=3$
Average operational costs for coal supplies (million $/PJ)	2.86(2.3, 3.2)	3.07(2.5, 3.5)	3.22(2.6, 3.6)
Average operational costs for natural gas supplies (million $/PJ)	4.73(4.1, 5.1)	4.98(4.2, 5.5)	5.26(4.5, 5.8)
Average operational costs for electricity generation in the coal-fired power plant (million $/PJ)	0.16(0.1, 0.3)	0.18(0.1, 0.3)	0.22(0.2, 0.3)
Average operational costs for electricity generation in the natural gas-fired power plant (million $/PJ)	0.52(0.4, 0.7)	0.55(0.4, 0.7)	0.58(0.4, 0.7)
Unit costs of food production ($/tonne)	149.5(135.0, 165.0)	165.5(150.0, 180.0)	180.0(165.0, 195.0)
Costs of CO_2 emission abatement for electricity generation ($/million kg)	12,600(11,400, 13,000)	14,500(13,100, 14,900)	16,200(15,200, 16,800)
Costs of CO_2 emission abatement for food production ($/tonne)	10.8(9.0, 13.0)	11.9(9.5, 14.5)	13.1(10.0, 16.0)
Groundwater supply costs for food production ($/10^3 gal)	1.96(1.6, 2.6)	2.42(1.9, 2.9)	2.83(2.5, 3.5)
Surface water supply costs for food production ($/10^3 gal)	2.23(1.6, 2.8)	2.56(2.1, 3.1)	3.38(2.9, 3.9)
Groundwater supply costs for electricity generation ($/10^3 gal)			
Coal-fired power plant	2.07(1.6, 2.6)	2.49(1.9, 2.9)	2.98(2.2, 3.5)
Natural gas-fired power plant	1.75(1.2, 2.5)	2.19(1.6, 2.8)	2.62(1.8, 3.0)
Surface water supply costs for electricity generation ($/10^3 gal)			
Coal-fired power plant	1.82(1.2, 2.8)	2.19(1.5, 3.0)	2.57(1.7, 3.2)
Natural gas-fired power plant	2.18(1.6, 2.8)	2.67(2.0, 3.3)	3.15(2.3, 3.6)
Recycled water supply costs for electricity generation ($/10^3 gal)			
Coal-fired power plant	4.15(3.6, 4.9)	4.37(3.8, 5.2)	4.52(4.0, 5.5)
Natural gas-fired power plant	4.32(3.8, 4.9)	4.48(3.9, 5.2)	4.66(4.0, 5.2)

Table 2
Model parameters related to resource constraints; the table lists the assumed values for the best estimates and the minimum/maximum of the uniform uncertainty ranges associated with each model parameter in parentheses.

	Sequential five-year time periods, k		
	$k=1$	$k=2$	$k=3$
Electricity demand (PJ)	105(104, 106)	115(114, 116)	126(125, 127)
Food demand (tonne)	67,000(66,900, 67,100)	71,000(70,900, 71,100)	75,000(74,900, 75,100)
Availability of coal (PJ)	285(282, 286)	265(262, 267)	240(237, 241)
Availability of natural gas (PJ)	129(127, 132)	117(115, 119)	105(103, 109)
Maximum available groundwater safe yield (billion gal)	50(49, 51)	48(47, 49)	46(45, 47)
Maximum available surface water quantity (billion gal)	32(31, 33)	30(29, 31)	27(26, 28)
Maximum available recycled water quantity (billion gal)	30(29, 31)	27(26, 28)	24(23, 25)
Maximum allowable CO_2 emissions (million tonnes)	15.2(15.0, 15.4)		

Table 3
WEFO model constants and constraints.

	Sequential Five-year Time Periods, k		
	$k=1$	$k=2$	$k=3$
Unit energy demand for food production (10^{-6} PJ/tonne)	2.52	2.64	2.75
Unit energy demand for water collection, treatment and delivery (KWh/1000 gal)	3.56	3.79	3.91
Maximum available electricity for food production (PJ)	0.23	0.25	0.27
Maximum available electricity for water collection, treatment and delivery (PJ)	1.00	1.15	1.25
Unit of energy carrier per unit of electricity generation (PJ/PJ)			
Coal-fired power plant	3.2	3	2.8
Natural gas-fired power plant	2.6	2.4	2.3

Consequently, more electricity will be generated from the natural gas-fired power plant (increase from 16.92 PJ in period 1 to 35.34 PJ in period 2 and 41.56 PJ in period 3).

It is important to note that in this case food production will consume more water resources than electricity generation. Recycled water will not be used for food production (an assumption based on safety issues). Groundwater is mainly applied for food production except for a small portion delivered to the natural gas-fired power plant in periods 1 and 2. In the last two periods, the ratio of groundwater to total supplied water for food production will decrease from 92% in period 1 to 76% and 75%, respectively. This is because the reduction of the maximum available groundwater will result in varying water use patterns for food production. The electricity generation mainly consumes surface water due to its relatively low costs. In periods 1 and 2, water supplied to the coal-fired power plant will be only from surface-water sources; all of the water supplied to the natural gas-fired power plant will be groundwater. The quantity of groundwater supplied to the natural gas-fired power plant will increase from 2.43 billion gallons in period 1 to 5.09 billion gallons in period 2, while that of surface water supplied to the coal-fired power plant will decrease from 9.08 billion gallons in period 1 to 8.24 billion gallons in period 2. In period 3, water supplied to the natural gas-fired power plant will include both surface water and recycled water, while all of water supplied to the coal-fired power plant will continue to be from surface water sources only. This is because all of the available groundwater in period 3 will be used for food production; after meeting the water demands for food production, surface water will be preferably supplied to the coal-fired power plant due to its relatively low supply costs; the rest of surface water is not

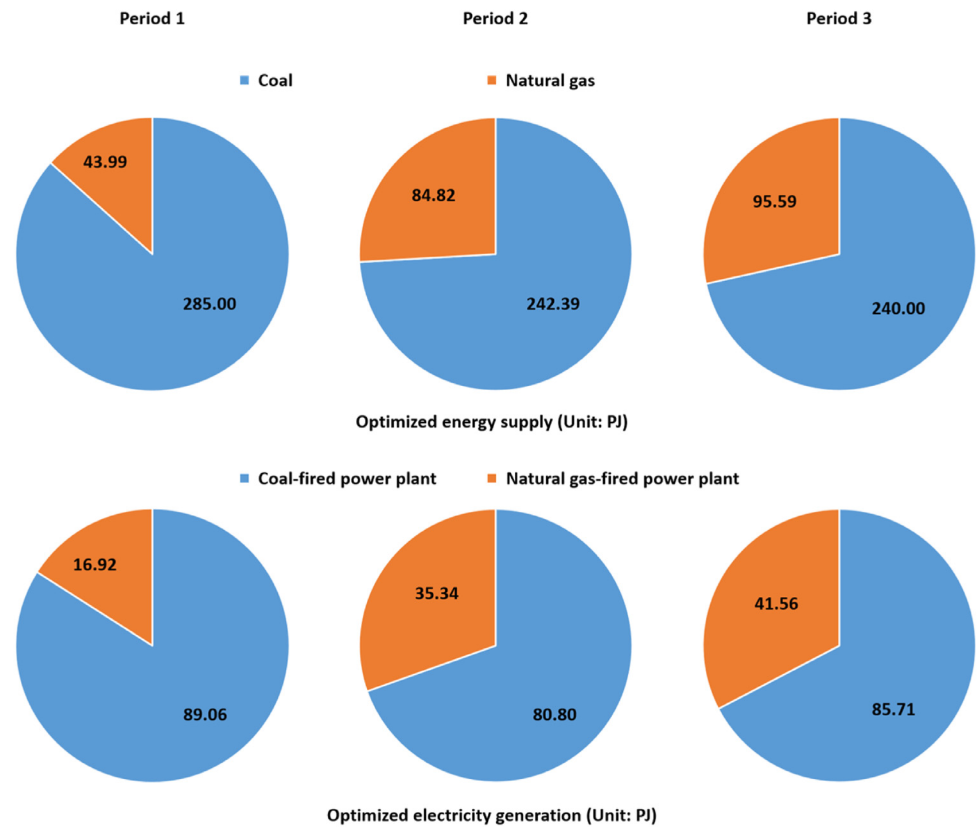

Fig. 2. Optimized energy supplies and electricity generation in three five-year time periods for the base-case scenario.

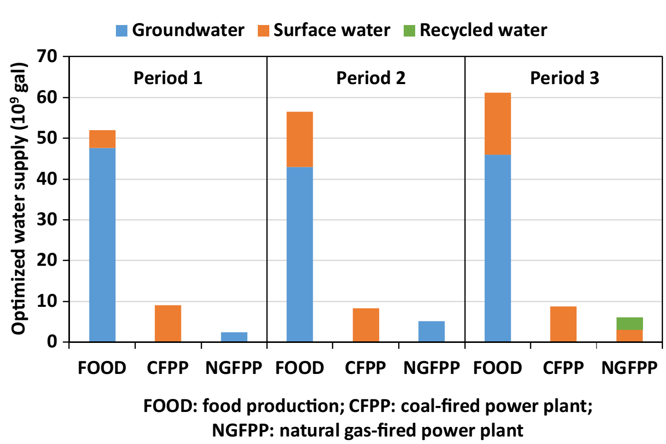

Fig. 3. Optimized quantity of supplied water for food production and electricity generation for the base-case scenario.

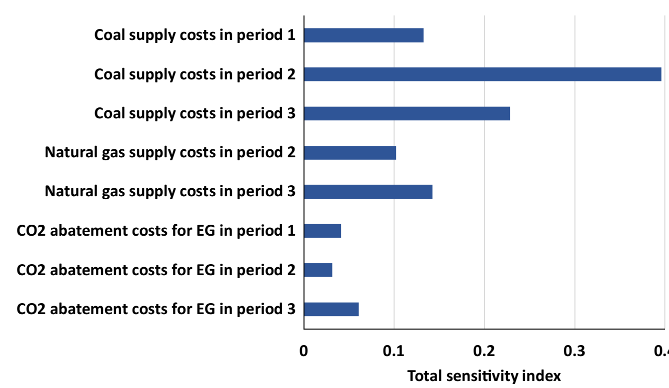

Fig. 4. Global sensitivity analysis results related to the total system cost; the figure presents the total sensitivity indices for the most sensitive model parameters in the WEFO model (EG: electricity generation).

sufficient for the natural gas-fired power plant so that recycled water will be used.

The total system cost under the base-case scenario will be \$5.40 billion, among which the main contributions are from energy supply with \$3.47 billion and CO_2 emission abatement with \$1.14 billion, and the remaining costs are relatively small: electricity generation, water supply, and food production with \$0.24, \$0.52, and \$0.03 billion, respectively.

Global sensitivity analysis is conducted for analyzing the most sensitive parameters in the WEFO model. Sobol's global sensitivity analysis (eFAST) (Saltelli et al., 1999) is performed using the code MADS (Model Analysis & Decision Support; mads.lanl.gov). The sensitivity analysis is applied to evaluate the impact of uncertainties in the model parameters on the total system cost. Within the specified uncertainty ranges, the most sensitive model parameters are the coal supply costs during the three planning periods and the natural gas supply costs during period 3. The sensitivity analysis results are presented in Fig. 4; the figure shows the total sensitivity indices for the most sensitive model parameters (Saltelli et al., 1999). These conclusions are also evidenced in Fig. 5, where the effects of unit costs for energy supply, electricity generation, food production, CO_2 abatement and water supply on the total system cost are analyzed. The energy-supply costs have the largest impact on the total system cost when compared to all the cost-related parameters. The impacts of the food production costs and the operational costs of electricity generation on the total system cost are much smaller. That means that reducing the energy

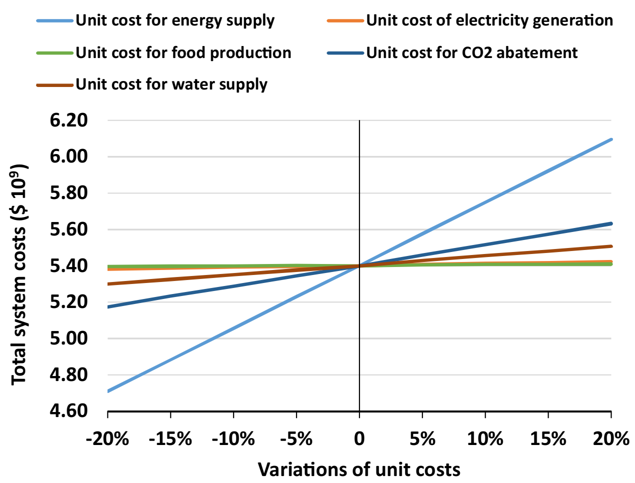

Fig. 5. Effects of unit costs for energy supply, electricity generation, food production, CO_2 abatement and water supply on the total system cost.

supply costs will have the greatest potential to lower the total system cost.

In practice, the resource constraints in the WEFO model may vary, such as socioeconomic demands of electricity and food, maximum allowable CO_2 emissions, and maximum available water (e.g. groundwater, surface- and recycled water) quantity. Their sensitivities are also analyzed using Sobol's global sensitivity analysis, as shown in Fig. 6. The electricity demand and the maximum allowable CO_2 emission levels are the most sensitive model parameters. For example, compared to the base-case scenario, if electricity-demand levels in the three periods are decreased to 95, 105, and 116 PJ, respectively, the total system cost will be decreased to $4.93 billion. As expected, the higher the electricity-demand level, the higher the total system cost; as discussed above, the energy supply costs are the main portion of the total system cost.

The allowable CO_2 emission levels are constrained mainly by management policies, and they can be changed over time depending on the political and socioeconomic demands. Generally, looser constraints on CO_2 emissions (e.g. an increase in the maximum allowable CO_2 emissions) will result in a decreased total system cost, as shown in Fig. 7. This is because under stricter constraints, more electricity will be generated from the natural gas-fired power plant since the natural gas has a low unit CO_2 emission rate; however, using more natural gas will also mean higher total system cost due to its relatively high supply and operational costs of the natural gas-fired power plant. In order to meet the requirements of CO_2 emission control, clean energy with a low CO_2 emission rate should be encouraged, even though this is leading to a higher total system cost. Using more coal can lower the total system cost, but results in more CO_2 emissions. Therefore, tradeoffs between environmental impacts and economic consideration are present and these depend on the management policies. Appropriate adjustment of the structure of energy supply and electricity generation is important to harmonize the economic development and environmental protection. However, loosened constraints on CO_2 emissions will not always lead to a reduced total system cost. Based on analyses of the WEFO model, when maximum allowable CO_2 emissions reach a certain level, the constraints on the CO_2 emission control will have no impact further on the total system cost (meaning the total system cost will not continue to reduce). This result demonstrates the importance of the management policies related to GHG emissions on the socioeconomic and environmental impacts.

The impacts of food demand and maximum available water quantity are relatively small compared to the electricity demand and the maximum allowable CO_2 emission levels. For example, if the food demands in the three periods will increase by 10%, the total system cost will slightly increase from $5.40 to $5.47 billion. This is because high food demands will result in the increase in energy supplies, electricity generation and associated water uses, leading to increased total system cost. Patterns of energy supply, electricity generation and water supply will also vary. The maximum water availabilities including groundwater, surface- and recycled water can significantly vary depending on the meteorological, climatic, hydrological, geographical and political conditions. If the available water (from the three types of water resources considered here) decreases by 10%, the total system cost will slightly increase to $5.42 billion. Changes in water availability will also change the relative distribution of the three water resources between the consumers in the WEFO system. If water resources are sufficient, food production and electricity generation will use more water with lower supply costs (e.g. groundwater for food production, and groundwater and surface water for electricity generation), leading to a reduction in the total system cost. Reasonable planning for water resource usage and seeking alternative water sources are also critical for integrated WEF nexus management for not only alleviating the stresses on water resources, but also enhancing the ability to respond to climate change.

3.3. Discussion

The aim of this study is to develop an integrated model analysis framework called WEFO to support WEF nexus management by promoting allocation of WEF resources and mitigating environmental impacts. The WEFO model is capable of addressing complex interrelationships among WEF components from a holistic perspective. Tradeoffs among economic objective, resources constraints and environmental protection are effectively quantified. As a multi-period optimization model, WEFO has the capability to account for temporal features of the WEF systems, and generate cost-effective strategies and polices for optimizing WEF production/delivery and mitigating associated environmental impacts (i.e. GHG emissions). Although only two types of energy supplies (coal and natural gas) are considered in the case study, the WEFO model can include more types by specifying additional decision variables, without changing the model's structure. Due to its high efficiency in computation and implementation, WEFO is suitable for large-scale practical applications at regional and national scales. Decision makers can easily develop their own site-specific applications depending on their preferences and purposes.

The WEFO model has various limitations. In general, a WEF system can be highly complicated, and the WEFO model is not providing an exhaustive representation of all the possible components and processes such as those related to social, cultural, territorial issues linked to WEF nexus management, as well as inequalities due to lack of access to WEF resources and security-related issues (Bazilian et al., 2011). Our goal in this study is to develop a decision analysis tool capable to address WEF-nexus issues at regional and national scales. As a result, only the most essential WEF elements including energy supply, water supply, food production, electricity generation, and CO_2 emission mitigation are incorporated into the WEFO model. WEFO only considers a few of the relationships between society and environment such as food production, water supply, and CO_2 emission control; issues related to other types of WEF resources withdrawals and emissions as well as impacts on ecosystems are not addressed. Energy demands for water and food subsystems are simplified using unit energy demand for water collection, treatment and delivery, and food production, respectively; water demands for electricity and food production are simplified using unit water consumption per unit of electricity generation and food production, respectively, instead of

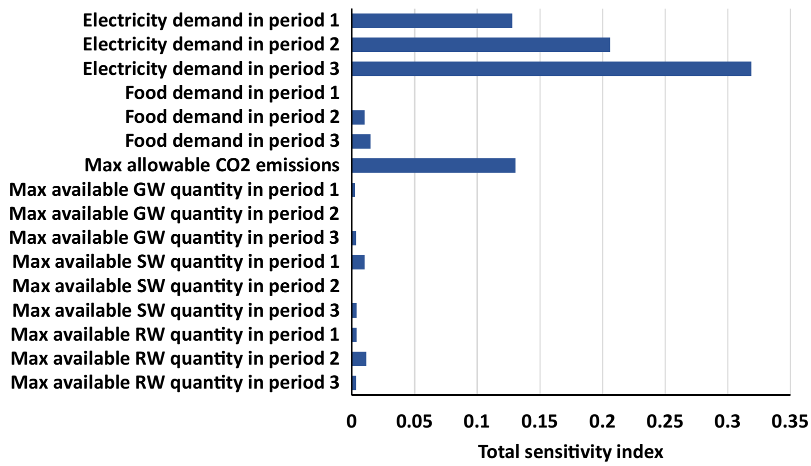

Fig. 6. Global sensitivity analysis of impact of resource constraints (listed also in Table 2) on the total system cost in the WEFO model (GW: groundwater; SW: surface water; RW: recycled water).

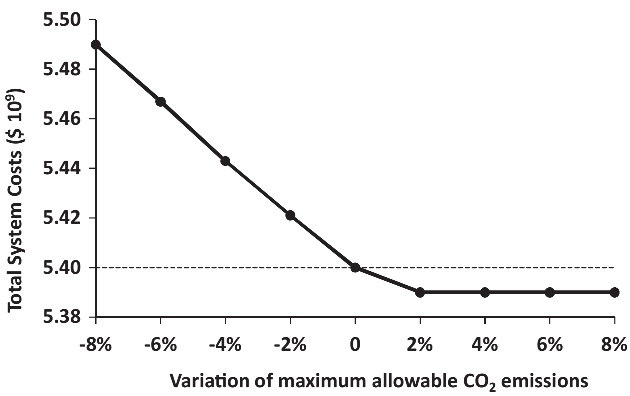

Fig. 7. Effects of maximum allowable CO_2 emission levels on the total system cost (0 means the existing level of 15.2 million tonnes; a positive/negative percentage represents an increase/decrease from the existing level).

direct measurements (Zhang and Vesselinov, 2016). Approximations were done for societal demands of electricity and food during the planning periods. In practice, future electricity and food demands can be accurately predicted based on simulation and/or stochastic models for better characterization of the practical WEF systems. WEFO accounts for temporal aspect of the WEF-nexus problem but does not take into account the spatial dimensions; the spatial characteristics of WEF systems may have important impacts on the generated decision strategies and policies but they are ignored in the WEFO model; this is also consistent with our goal to target WEF-nexus problems at regional and national scales. All the modeling parameters are assumed to be deterministic. Over the planning horizon, economic quantities such as costs of energy supply, water supply, electricity generation, food production, and CO_2 abatement are approximated to be constant values. In the future, various forms of uncertainties associated with the parameters and the model can be systematically analyzed using stochastic methods. Assessments of robustness of decisions against uncertainties are also frequently desired for the WEF nexus management and we plan to add these types of analyses in the WEFO model in the future as well. Climatic factors are not directly incorporated into the WEFO model; climate change may significantly affect WEF resources, and consequently the generated WEF nexus management strategies. Incorporation of climate change into the WEFO model will help development of optimal WEF nexus management strategies and polices for climate adaptation and resilience planning in responding to changing climatic conditions. In real-world applications, site-specific information needs to be considered depending on local hydrological, glaciological, oceanological, climatological and geographical conditions, as well as the complex relationships among the WEF components (Bongio et al., 2016).

The WEFO analyses presented here are performed for a representative synthetic example problem that should be sufficient to demonstrate real-world applicability of the integrated WEFO framework. In the future, we plan to apply the WEFO framework for real-world case studies. For example, WEFO can be applied to analyze the WEF problems discussed in (Bazilian et al., 2011).

4. Conclusions

An integrated model analysis framework and tool called WEFO is developed to support the decisions of the water-energy-food nexus management. The multi-period WEFO model is a linear mathematical programming model, where various components of the nexus management are incorporated, including planning of energy supply, electricity generation, water supply and demand, food production and GHG emission control. The WEFO model is capable of simultaneously addressing interactions among the water, energy, and food subsystems, as well as their effects on the decision alternatives and strategies for supporting nexus management. The WEFO model is applied to a hypothetical nexus management problem consistent with real-world management scenarios. Optimal solutions are obtained for management of limited water resources, energy supplies, electricity generation, and food production for meeting the current and future demands of the society. Using the WEFO model, decision- and policy- makers may make corresponding alternatives for integrated WEF nexus management through adjustment of socioeconomic demands of electricity and food (for example, by promoting conservation efforts), availability of water resources and environmental impacts constraints. Trade-offs among economic objectives, resource constraints, and environmental protection (e.g., GHG emission control) should be considered in practical WEF nexus management. Analyses of the effects of parameter uncertainties indicated that high societal demands for electricity and food will result in a higher total system cost, while the increases of maximum available water quantity and maximum allowable CO_2 emissions will decrease the total system cost. The WEFO model is computationally efficient, enabling it to be applicable to large-scale water-energy-food nexus management problems. The results demonstrate how these types of analyses can be useful for decision-makers and stakeholders to quantify the trade-offs among complex interrelationships of water, energy and food subsystems, and to make informed decisions for integrated water-energy-food nexus management.

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