LA-UR-16-23511 (Accepted Manuscript)

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To be published in: Applied Energy

DOI to publisher's version: 10.1016/j.apenergy.2016.08.156

Energy-Water Nexus: Balancing the Tradeoffs between Two-Level Decision Makers

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Abstract:

Energy-water nexus has substantially increased importance in the recent years. Synergistic approaches based on systems-analysis and mathematical models are critical for helping decision makers better understand the interrelationships and tradeoffs between energy and water. In energy-water nexus management, various decision makers with different goals and preferences, which are often conflicting, are involved. These decision makers may have different controlling power over the management objectives and the decisions. They make decisions sequentially from the upper level to the lower level, challenging decision making in energy-water nexus. In order to address such planning issues, a bi-level decision model is developed, which improves upon the existing studies by integration of bi-level programming into energy-water nexus management. The developed model represents a methodological contribution to the challenge of sequential decision-making in energy-water nexus through provision of an integrated modeling framework/tool. An interactive fuzzy optimization methodology is introduced to seek a satisfactory solution to meet the overall satisfaction of the two-level decision makers. The tradeoffs between the two-level decision makers in energy-water nexus management are effectively addressed and quantified. Application of the proposed model to a synthetic example problem has demonstrated its applicability in practical energy-water nexus management. Optimal solutions for electricity generation, fuel supply, water supply including groundwater, surface water and recycled water, capacity expansion of the power plants, and GHG emission control are generated. These analyses are capable of helping decision makers or stakeholders adjust their tolerances to make informed decisions to achieve the overall satisfaction of energy-water nexus management where bi-level sequential decision making process is involved.

Keywords:

Energy-water nexus, two-level decision making, tradeoff, GHG emission control

1. Introduction

Fossil-fuel power plants are the main source of electricity in the U.S., where around 90% of the national electricity is generated by thermoelectric power plants [1–4]. In thermoelectricity production, a large number of water is withdrawn and consumed, mainly for cooling purposes; at the same time, in order to pump, collect, treat and distribute water, energy is demanded [5–9]. With rapid increase of worldwide population, societal demands of energy and water are significantly increasing [7]. It is estimated that energy consumption worldwide will increase by 50% by 2030 [10]. This will substantially exacerbate the crises of energy and water shortages in the world, especially in some energy- and/or water- scarce regions and countries. The integrated approach, termed as energy-water nexus, is thus desired to study the inseparable relationships between energy and water, which has substantially increased importance in the past years [6,11–16]. A comprehensive literature review of the progresses in energy-water nexus can be found in [17–20].

In energy-water nexus management, various issues need to be addressed jointly, such as energy and water resources allocation, capacity expansion planning for the power plants, and environmental impacts (i.e. greenhouse gas emission control). The decision analyses should account for multi-objective, dynamic, and multi-period characteristics. A large number of factors may affect the future of energy-water nexus, including water resources and energy availabilities, societal demands of energy and water, environmental impacts control decisions. However, most of the existing energy and water management policies are independent from one another, and energy-water nexus decision making is fragmented [6,14,21], which have hindered sustainable development of energy and water resources in an integrated way. Separate management of energy and water systems could lead to ineffectiveness of the generated management decisions and strategies.

Synergistic approaches based on systems-analysis and mathematical models are critical for helping decision makers better understand the interrelationships and tradeoffs between energy and water, and integrate their connections to make informed decisions and rational policies across complex energy-water nexus systems [6,11]. Energy-water nexus management involves various decision makers with different goals and preferences, which are often conflicting. These decision makers may have different controlling power over the management objectives and the decisions. They make decisions sequentially from the upper level to the lower level. One of such examples is that energy-development decision maker wants to maximize the total generated electricity to meet the ever-increasing societal demands of electricity, which is a prioritized task, while whole-system decision maker hopes to seek a minimized total system cost. That means that the objective and the decisions of the decision maker in a higher decision level need to be preferably met, and the decision maker in a lower decision level must follow the higher-level decision maker's decisions, but at the same time the upper-level decision maker's decisions are affected by the lower-level decisions [22]. Such a management problem is formulated as a bi-level programming problem [23]. The decision making process in a bi-level programming problem is in a hierarchical order, where each decision maker at two hierarchical levels independently controls a set of decision variables, and their decisions are affected by each other [24,25]. Bi-level programming is different from multi-objective programming (MOP) although both of them have multiple objectives to be optimized. In MOP, multiple objectives are optimized simultaneously (at the same level), while in bi-level programming, optimization of multiple objectives are performed from the upper- to the lower- level. Clearly, bi-level programming provides an effective means of prioritizing the goals of decision maker who are more important in the decision making processes, and addressing the tradeoffs between decision makers in various decision-making levels.

Recently, some researchers have begun to attempt to optimize the energy and water nexus from various perspectives. For examples, Bazilian et al. [8] discussed the energy, water and food nexus from the integrated modeling perspective. Chen et al. [26] proposed a Western China Sustainable Energy Development Model to project energy and water consumptions in China. Davies et al. [27] estimated water withdrawals and consumptions for electricity generation by incorporating water demands into an integrated energy, agriculture, and climate change assessment model called GCAM (Global Change Assessment Model). As the extensions of the work of Davies et al. [27], Hejazi et al. [28] analyzed six socioeconomic scenarios for agriculture, energy, industrial and municipal sectors, and Liu et al. [29] projected state-level water demands associated with electricity generation in USA under different scenarios. Dubreuil et al [9] extended an energy optimization model (TIAM-FR) by incorporating a water module to evaluate the opportunities of water reuse and non-conventional water resources in the Middle East region. Huang et al. [30] integrated a water module into an energy system model (China TIMES model) to assess the impacts of carbon and water constraints on electricity generation in China. Lubega and Farid [31] developed an engineered systems model to optimize the energy and water systems from an engineering systems perspective, including electricity generation, engineered water supply, and wastewater management. Nanduri et al. [32] advanced a Markov decision process model to investigate the energy-water-climate-change nexus. Santhosh et al. [33,34] developed an economic dispatch for co-optimizing power and water from the supply side of energy-water nexus, where production costs are minimized. Yang and Chen [35] analyzed water consumption for electricity generation and energy cost for water in the wind power generation system in China, based on life cycle analysis and network environ analysis. Wanjiru and Xia [36] optimized the lawn irrigation scheduling for energy and water savings. Welsch et al. [37] modeled the connections among climate, energy, water and land-use. Although these research efforts are helpful for integrally addressing the energy and water issues, they cannot deal with the emerging challenges in energy-water nexus optimization, such as sequential decision-making involving multiple decision makers with different decision-making levels. There is a lack of effective tools to quantify the tradeoffs between the two-level decision makers in energy-water nexus.

The objective of this study is to develop a bi-level decision model, called BEWM (Bi-level Decision Model for Energy-Water Nexus Management) for providing effective decision supports for energy-water nexus management. It incorporates fuel supply planning, water resources management, electricity generation, capacity expansion of the power plants, and greenhouse gas (GHG) emission control into a general framework. The proposed BEWM model represents a methodological contribution to the challenge of sequential decision-making in energy-water nexus through development of an integrated modeling framework/tool. Tradeoffs between the two-level decision makers in energy-water nexus are effectively addressed and quantified. The generated management alternative scenarios will provide cost-effective decision supports to help improve the understanding of energy-water linkages, and to make informed decisions for not only cost savings of energy and water, but also optimal planning of energy development. The developed model is applied to a hypothetical energy-water nexus planning problem involving two-level decision makers for demonstrating its applicability in practice.

2. BEWM: Bi-Level Decision Model for Energy-Water Nexus Management

2.1. Model Development

A bi-level decision model for energy-water nexus management, called BEWM, is proposed. It involves the two-level including the upper-level and lower-level decision makers, as shown in Figure 1. The upper-level decision maker, also referred as an energy-development decision maker, sets a goal to maximize the total electricity production in the power plants for meeting the societal demands of electricity. The lower-level decision maker, referred as a whole-system decision maker, is focusing more on cost control and wants to minimize the total system cost. The two goals of the two-level decision makers are conflicting; increasing the total electricity generation will lead to an increase of the total system cost. The two-level decision makers make decisions sequentially, from the upper-level to the lower-level. Decision variables for representing the quantity of electricity generation from the power plants in each planning period are determined by the upper-level decision maker, while those for fuel supply, water supply, and capacity expansion of the power plants are controlled by the lower-level decision maker. The two-level decisions are subject to a series of energy- and water- related constraints, such as mass balance of fossil fuel, fossil fuel availability, societal demands of electricity, power plant capacity expansion, energy demand for water subsystem, water demand for energy subsystem, availability of water resources including groundwater, surface water and recycled water, CO_2 emission control, and technical constraints.

The problem under consideration is how to plan and manage the bi-level energy-water nexus system in order to satisfy the two goals of the two-level decision makers sequentially and achieve the optimal plans for electricity generation, capacity expansion of the power plants, fuel and water supplies.

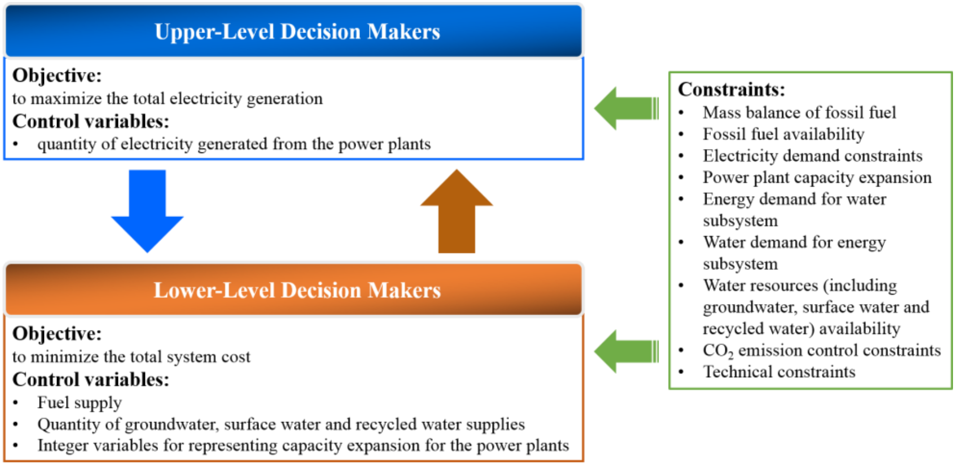

Figure 1 Bi-level decision-making process for energy-water nexus management; note that the constraints are the same for upper- and lower-level decision makers

The BEWM model is formulated as follows:

Upper-Level:

The management objective of the upper-level decision maker in energy-water nexus is to maximize the total generated electricity from the power plants.

$$\max f_U = \sum_{j=1}^{2} \sum_{t=1}^{3} X_{jt} \quad (1)$$

where f_U is the objective function of the upper-level decision maker, X_{jt} is the generated electricity from the power plant *j* in the planning period *t* (PJ), *j* is index for the power plants (*j* = 1: coal-fired power plant; *j* = 2: natural gas-fired power plant), and *t* is index for the planning periods (*t* = 1, 2, 3). Decision variables of X_{jt} are controlled by the upper-level decision maker.

Lower-Level:

The management objective of the lower-level decision maker is to minimize the total system cost, including fossil fuel supply costs, fixed and operational costs for electricity generation, capital costs for capacity expansions of the power plants, delivery costs of water including groundwater, surface water and recycled water for electricity generation, and CO_2 emission abatement costs.

$$\min f_L = \sum_{i=1}^{2}\sum_{t=1}^{3} ES_{it}ESC_{it} + \sum_{j=1}^{2} FC_j + \sum_{j=1}^{2}\sum_{t=1}^{3} X_{jt}PC_{jt} + \sum_{j=1}^{2}\sum_{m=1}^{3}\sum_{t=1}^{3} IC_{jt}EC_{jmt}Y_{jmt} + \sum_{j=1}^{2}\sum_{t=1}^{3}\left(CGW_{jt}GW_{jt} + CSW_{jt}SW_{jt} + CRW_{jt}RW_{jt}\right) + \sum_{j=1}^{2}\sum_{t=1}^{3} CEA_tCC_{jt}X_{jt} \quad (2)$$

where *i* is index for fossil fuel (*i* = 1: coal; *i* = 2: natural gas), *m* is index for capacity expansion options in the power plants (*m* = 1, 2, 3), f_L is the objective function of the lower-level decision maker, ES_{it} is fossil fuel supply *i* in the planning period *t* (PJ), ESC_{it} is the average cost for fossil fuel supply *i* in the planning period *t* (million $/PJ), FC_j defines the fixed costs for electricity generation in the power plant *j* (million $), PC_{jt} is the average operational cost for electricity generation in the power plant *j* in the planning period *t* (million $/PJ), IC_{jt} is capital cost for capacity expansion of the power plant *j* by option *m* at the start of the planning period *t* (million $/GW), EC_{jmt} is expanded capacity of the power plant *j* with option *m* at the beginning of the planning period *t* (GW), Y_{jmt} is integer variable (1 or 0) for representing capacity expansion in the power plant *j* with option *m* at the beginning of the planning period *t* (1: expanded; 0: not expanded), GW_{jt} is quantity of groundwater supplied to the power plant *j* in the planning period *t* (gal; 1 gal = 0.0037854 m^3), SW_{jt} is quantity of surface water supplied to the power plant *j* in the planning period *t* (gal), RW_{jt} is quantity of recycled water supplied to the power plant *j* in the planning period *t* (gal), CGW_{jt} is cost of groundwater supplied to the power plant *j* in the planning period *t* ($/gal), CSW_{jt} is cost of surface water supplied to the power plant *j* in the planning period *t* ($/gal), CRW_{jt} is cost of recycled water supplied to the power plant *j* in the planning period *t* ($/gal), CEA_t is unit abatement cost of CO_2 emissions from electricity generation in the planning period *t* ($/Gg), and CC_{jt} is unit CO_2 emission per unit of electricity generation in the power plant *j* in the planning period *t* (Gg/PJ). Decision variables of ES_{it}, Y_{jmt}, GW_{jt}, SW_{jt} and RW_{jt} are controlled by the lower-level decision maker, based on the given X_{jt} from the upper-level decision maker.

The constraints for the bi-level energy-water nexus system include:

(a) Mass balance of coal and natural gas:

$$X_{jt} \cdot FE_{jt} \le ES_{jt}, \forall j, t \quad (3)$$

where FE_{jt} is unit energy carrier per unit of electricity generation in the power plant *j* in the planning period *t* (PJ/PJ).

(b) Fossil fuel availability constraints:

$$ES_{jt} \le AVE_{jt}, \forall j, t \quad (4)$$

where AVE_{jt} is availability of fossil fuel *j* in the planning period *t* (PJ).

(c) Electricity demand constraints:

$$\sum_{j=1}^{2} X_{jt} - \sum_{j=1}^{2} ER_t \cdot \left(GW_{jt} + SW_{jt} + RW_{jt}\right) \ge D_t, \forall t \quad (5)$$

where ER_t is unit energy demand for water collection, treatment and delivery in the planning period *t* (PJ/gal), and D_t defines the societal demands of electricity in the planning period *t* (PJ).

(d) Capacity expansion of the power plants constraints:

$$X_{jt} \leq CF_{jt}\left(RC_j + \sum_{m=1}^{3}\sum_{t'=1}^{t} EC_{jmt'}Y_{jmt'}\right), \forall j, t \quad (6)$$

where CF_{jt} is unit electricity production per unit of capacity of the power plant *j* in the planning period *t* (PJ/GW), and RC_j is residual capacity of the power plant *j* (GW).

(e) Energy demand for water collection, treatment and delivery:
Energy demand for collecting, treating and delivering water to the power plants should not be larger than the maximum available energy (in the form of electricity) pre-specified by the decision maker.

$$\sum_{j=1}^{2} ER_t \cdot \left(GW_{jt} + SW_{jt} + RW_{jt}\right) \leq AER_{tmax}, \forall t \quad (7)$$

where AER_{tmax} is the maximum available energy (in the form of electricity) for water collection, treatment and delivery in the planning period *t* (PJ).

(f) Water demand for electricity generation:
The supplied water resources including groundwater, surface water and recycled water should meet the water demands for electricity generation in the power plants.

$$\left(1-\beta_j\right) \cdot \left(GW_{jt} + SW_{jt} + RW_{jt}\right) \geq WR_j \cdot X_{jt}, \forall j, t \quad (8)$$

where β_j is a loss factor of delivering water to the power plant *j*, and WR_j is unit water demand per unit of electricity generation in the power plant *j* (gal/PJ).

(g) Water resources availability constraints:
The supplied groundwater, surface water and recycled water to the power plants in each planning period should not be larger than their availabilities, respectively.

$$\sum_{j=1}^{2} GW_{jt} \leq SY_t, \forall t \quad (9)$$

$$\sum_{j=1}^{2} SW_{jt} \leq ASW_t, \forall t \quad (10)$$

$$\sum_{j=1}^{2} RW_{jt} \leq ARW_t, \forall t \quad (11)$$

where SY_t is safe yield of groundwater in the planning period *t* (gal), ASW_t is surface water availability in the planning period *t* (gal), and ARW_t is recycled water availability in the planning period t (gal).

(h) CO_2 emission control constraints:

$$\sum_{j=1}^{2}\sum_{t=1}^{3} X_{jt}CC_{jt}\left(1-\emptyset_{jt}\right) \leq TMCC \tag{12}$$

where $\emptyset_{jt}$ is the average efficiency for CO_2 abatement in the power plant j in the planning period t, and $TMCC$ is the maximum allowable CO_2 emissions over the planning horizon (Gg).

(i) Technical constraints:

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

$ES_{it} \geq 0, \forall i, t$

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

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

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

$$\sum_{m=1}^{3} Y_{jmt} \leq 1, \forall j, t$$

(The capacity of each power plant can only be expanded once at the beginning of each planning period.) (13)

$Y_{jmt} = 1 \; or \; 1, \forall j, m, t$

2.2. Solution method for BEWM model

The BEWM model can be reformulated to be a general bi-level programming form as follows [23,38,39]:

Upper-Level Management Objective:

$$\underset{X}{Max}\, f_U(X,Y) \;=\; aX + bY \tag{14}$$

where a and b are constants, X and Y are vectors of decision (or control) variables, and f_U is the objective function of the upper-level decision maker. The vectors X and Y are controlled by the upper-level and lower-level decision makers, respectively.

Lower-Level Management Objective:

$$\underset{Y}{Min}\, f_L(X,Y) \;=\; cX + dY \tag{15}$$

Subject to:

$$A_1X + A_2Y \leq B \tag{16}$$

$$X, Y \geq 0 \tag{17}$$

where c and d are constants, B is a vector of constants, A_1 and A_2 are matrices of constants, f_L is the objective function of the lower-level decision maker, and f_U and f_L are linear objective functions [23,38,39].

An interactive fuzzy approach of [23] is introduced to solve the above bi-level programming problem. Its basic idea is that the two-level decision makers need to make compromises to find the solutions for meeting the overall satisfaction of the bi-level system since it is impractical or impossible to achieve their individual optima simultaneously [23,25,39,40]. The upper level decision maker sets his/her goal and decisions and asks the lower-level decision maker to follow them, otherwise the decisions of the lower-level decision maker may be rejected. The lower-level decision maker can only seek his/her optimal solutions through fully integrating the upper-level decision maker's decisions into his/her decision-making process, but he/she may communicate his/her results to the upper-level decision maker to make adjustments of the goal and preferences until a satisfactory solution is obtained for integrally considering the overall benefits of the bi-level system [22,23,25,39,40]. First, the individual optimal solutions are obtained by solving two single-level models, where the upper-level model has the objective of (14) only and the constraints of (16) and (17), and the lower-level model has the objective of (15) only and the constraints of (16) and (17). The optimal solutions of the upper-level model are assumed to be (X^U, Y^U) and f_U^*, and those of the lower-level model are assumed to be (X^L, Y^L) and f_L^*. If the solutions of (X^U, Y^U) and (X^L, Y^L) are same, they are the optimal solutions of the original bi-level programming problem. Generally, these two sets of solutions are different, reflecting the conflicting management objectives of the two-level decision makers. The two-level decision makers need to make compromises in finding the optimal solutions for meeting their two objectives. Since the vector X is controlled by the upper-level decision maker, for given X^U, it is generally impossible for the lower-level decision maker to find his/her individual optimal solutions under such strict conditions. Thus, the upper-level decision maker allows X to fluctuate within a certain range of $[X^U - p_1, X^U + p_2]$, where p_1 and p_2 are the lower- and upper-bound tolerances specified by the upper-level decision maker, and the most preferred value is X^U, which is reflected in Figure 2 [23,39].

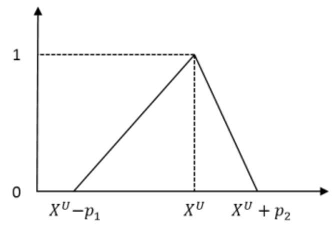

Figure 2 Lower- and upper-bound tolerances specified by the upper-level decision maker

The fuzzy membership function of X^U can be elicited as follows [41,42]:

$$\mu_X(\mathrm{X}) = \begin{cases} \dfrac{X - X^U + p_1}{p_1}, & if\ X^U - p_1 \leq X \leq X^U; \\ \dfrac{X^U + p_2 - X}{p_2}, & if\ X^U < X \leq X^U + p_2; \\ 0, & if\ X < X^U - p_1, \text{or } X > X^U + p_2 \end{cases} \quad (18)$$

In addition, the upper-level decision maker needs to specify the tolerances of his/her goal so that the lower-level decision maker follows them to find his/her optimal solutions. Based on the obtained individual optima of (X^U,Y^U), f_U^*, (X^L,Y^L), and f_L^*, we can obtain $f_U' = f_U(X^L,Y^L)$, and $f_L' = f_L(X^U,Y^U)$. Since the upper-level decision problem is a maximization problem, the upper-level decision maker may think all $f_U \geq f_U^*$ are absolutely acceptable, all $f_U \leq f_U'$ are absolutely unacceptable, and all $f_U' \leq f_U \leq f_U^*$ are linearly increasing [23,39]. The fuzzy membership function of the upper-level objective is assumed to be as follows [23,39]:

$$\mu_{f_U}(f_U) = \begin{cases} 1, & if\ f_U > f_U^*; \\ \dfrac{f_U - f_U'}{f_U^* - f_U'}, & if\ f_U' \leq f_U \leq f_U^*; \\ 0, & if\ f_U < f_U'; \end{cases} \tag{19}$$

Similarly, the lower-level decision maker specifies the tolerances of his/her goal, and the membership function for the lower-level objective (a minimization problem) can be established as follows [23,39]:

$$\mu_{f_L}(f_L) = \begin{cases} 1, & if\ f_L < f_L^*; \\ \dfrac{f_L' - f_L}{f_L' - f_L^*}, & if\ f_L^* \leq f_L \leq f_L'; \\ 0, & if\ f_L > f_L'; \end{cases} \tag{20}$$

Finally, a fuzzy max-min operator λ is introduced to aggregate an overall satisfaction to satisfy the decision variables X of the upper-level decision maker and the decision goals of the two-level decision makers simultaneously [23,25,39,40,43]:

Max λ

Subject to

$$\begin{aligned} & A_1X + A_2Y \leq B \\ & \mu_X(X) \geq \lambda \\ & \mu_{f_U}(f_U) \geq \lambda \\ & \mu_{f_L}(f_L) \geq \lambda \\ & X, Y \geq 0 \\ & 0 \leq \lambda \leq 1 \end{aligned} \tag{21}$$

The above model can also be represented as:

Max λ

Subject to

$$\begin{aligned} & A_1X + A_2Y \leq B \\ & \frac{X - X^U + p_1}{p_1} \geq \lambda \\ & \frac{X^U + p_2 - X}{p_2} \geq \lambda \\ & \frac{f_U - f_U'}{f_U^* - f_U'} \geq \lambda \end{aligned} \tag{22}$$

$$\frac{f_L' - f_L}{f_L' - f_L^*} \geq \lambda$$
$$X, Y \geq 0$$
$$0 \leq \lambda \leq 1$$

By solving the above model, we can obtain the optimal solutions of the bi-level programming problem: f_U^{opt}, f_L^{opt}, and (X^{opt}, Y^{opt}). If the upper-level decision maker is satisfied with the obtained results, a satisfactory solution is reached; otherwise the upper-level decision maker can adjust the tolerances of the objective and the control variables until a satisfactory solution is reached [23,39]. The BEWM model is coded in Julia which is a high-performance programming language for scientific and numerical computing (julialang.org), and is tested on an Intel(R) Core(TM) i5-4310U 2.00 GHz CPU with 16 GB of memory. The execution of a single optimization analysis takes about less than one second.

3. Case Study

3.1. Problems Statement

A synthetic bi-level energy-water nexus system is presented to demonstrate the applicability of the developed BEWM model, where the relevant data and information are derived from published literature and reports [2,4,6,8,12,14,21,29,44–49]. Two kinds of fossil fuels, coal and natural gas, are supplied to the two thermoelectric power plants, respectively. Most of the generated electricity from the power plants is distributed to meet societal demands of electricity, and a portion is used for water subsystem for pumping, treating, collecting and transporting water. A large number of GHGs are produced from the uses of non-renewable coal and natural gas, and controlling of GHG emissions is considered in the BEWM model. The 15-year planning horizon is divided into three equal planning periods, each of which is 5 years. Table 1 presents the parameters related to energy subsystem. The average costs for fossil fuel supplies and operational costs for electricity generation are expected to increase over time. Availability of fossil fuel is expected to decrease over time due to the competition of limited energy resources. As the population increases, the existing capacities of the two power plants cannot meet the increasing societal demands of electricity, and their capacity expansions are considered over the planning horizon. Each of the power plants has three options for capacity expansion with different increments (shown in Table 1), but can only be expanded once with only one option in each of the three planning periods. Fixed costs for electricity generation in coal-fired and natural gas-fired power plants are \$55 and \$65 million, respectively. The existing capacities of coal-fired and natural gas-fired power plants are 0.9 and 0.5 GW, respectively.

Model input parameters related to water subsystem are listed in Table 2. Recycled water has the highest supply costs due to the highest treatment requirements. The available water resources including groundwater, surface water and recycled water are expected to decrease over time because of the competition from multiple water-intensive end-users and the effects of climate change. Loss factors of delivering water to coal-fired and natural gas-fired power plants are estimated to be 10% and 15%, respectively. Unit water demands for electricity generation in coal-fired and natural gas-fired power plants are 91.74×10^6 and 122.32×10^6 gal/PJ, respectively [2,4,14,21,45].

Table 3 shows the model parameters related to GHG emission control. The allowable GHG emissions from electricity generation in the two power plants are limited to a pre-specified level over the planning horizon.

Table 1 Model input parameters related to energy subsystem

	Planning Period *t*		
	t = 1	*t* = 2	*t* = 3
Average cost for fossil fuel supply (million $/PJ)			
Coal	2.65	2.89	3.16
Natural gas	4.58	4.86	5.12
Average operational cost for electricity generation in the power plants (million $/PJ)			
Coal-fired power plant	0.20	0.22	0.24
Natural gas-fired power plant	0.46	0.49	0.52
Capital cost for capacity option of the power plants (million $/GW)			
Coal-fired power plant	700	660	620
Natural gas-fired power plant	550	500	450
Capacity expansion options for coal-fired power plant (GW)			
Option 1	0.26	0.26	0.26
Option 2	0.31	0.31	0.31
Option 3	0.36	0.36	0.36
Capacity expansion options for natural gas-fired power plant (GW)			
Option 1	0.09	0.09	0.09
Option 2	0.14	0.14	0.14
Option 3	0.19	0.19	0.19
Unit energy carrier per unit of electricity generation (PJ/PJ)			
Coal-fired power plant	3.1	2.9	2.7
Natural gas-fired power plant	2.5	2.3	2.1
Unit electricity production per unit of capacity for the power plants (PJ/GW)			
Coal-fired power plant	85	90	95
Natural gas-fired power plant	75	80	85
Societal demands of electricity (PJ)	142	155	163
Availability of coal (PJ)	319	306	295
Availability of natural gas (PJ)	237	224	212
Unit energy demand for water subsystem (J/gal)	13068	13752	14256
Maximum available energy (in the form of electricity) for water subsystem (PJ)	1.15	1.20	1.25

Table 2 Model input parameters related to water subsystem

	Planning Period *t*		
	t = 1	*t* = 2	*t* = 3
Cost of groundwater supply ($/1000 gal) (1 gal = 0.003785 m^3)			
Coal-fired power plant	1.78	2.03	2.47

Natural gas-fired power plant	2.21	2.62	3.12
Cost of surface water supply ($/1000 gal)			
Coal-fired power plant	2.06	2.55	2.93
Natural gas-fired power plant	1.80	2.14	2.55
Cost of recycled water supply ($/1000 gal)			
Coal-fired power plant	3.89	4.05	4.31
Natural gas-fired power plant	4.02	4.18	4.37
Safe yield of groundwater (10^9 gal)	8.6	8.2	7.8
Surface water availability (10^9 gal)	9.8	9.5	9.2
Recycled water availability (10^9 gal)	8.1	7.8	7.5

Table 3 Model input parameters related to GHG emission control

	Planning Period *t*		
	t = 1	*t* = 2	*t* = 3
Unit CO_2 emission per unit of electricity generation (Gg/PJ) [46]			
Coal-fired power plant	261.03	254.89	247.08
Natural gas-fired power plant	152.58	149.98	146.19
Cost of CO_2 emission abatement for electricity generation ($/Gg)	13200	14100	15800
Average efficiency for CO_2 abatement			
Coal-fired power plant	0.80	0.80	0.80
Natural gas-fired power plant	0.85	0.85	0.85
Maximum allowable CO_2 emissions (Gg)	19000		

3.2. Results Analyses

The individual optimal solutions for the upper-level and lower-level decision problems are first obtained by solving two single-level models: the upper-level model (with upper-level management objective only) and the lower-level model (with lower-level management objective only). Table 4 shows the optimized electricity generation from the two power plants. The optimal solutions for electricity generation from two single-level models are different, reflecting different goals and preferences of the two-level decision makers. The upper-level or energy-development decision maker aims maximized total electricity production, while the lower-level or whole-system decision maker wants to minimize the total system cost. The disagreements between the two-level decision makers lead to totally different plans for electricity generation. If the upper-level decision maker is in full control of the whole system, the optimal electricity generation in coal-fired power plant during the three planning periods will be 90.47, 84.86 and 105.00 PJ, respectively, and that in natural gas-fired power plant will be 51.75, 70.40 and 90.95 PJ, respectively. Based on such plans for electricity generation (controlled by the upper-level decision maker), it is impractical or impossible for the lower-level decision maker to find optimal solutions constrained by fossil fuel supplies, water supplies, and capacity expansion of the two power plants that produce a satisfactory (minimized) total system cost. As a result, the upper-level decision maker needs to make compromises by specifying the tolerances of electricity generation and the goal in order to obtain a satisfactory solution for meeting the goals of the two-level decision makers. That means that the quantity of electricity generation may fluctuate within the lower- and upper-bound tolerances specified by the upper-level decision maker, as shown in Table 4. In the bi-level energy-water nexus system, the produced electricity in coal-fired power plant over the planning horizon will be 91.74, 87.62, and 104.26 PJ, respectively, while that in natural gas-fired power plant will be 50.48, 67.63, and 87.32 PJ, respectively. Ratio of electricity generated from coal-fired power plant to the total electricity during all the three planning periods is 58.0%, which is slightly larger than that estimated for the upper-level model (56.8%), and less than that for the lower-level model (66.3%). Coal-fired power plant is the main source for electricity generation due to lower coal supply costs, lower operational costs of electricity generation, and relative high coal availability over the planning horizon.

Fuel supplies are positively correlated to electricity generation over the planning horizon. Figure 3 shows the optimized fuel supplies obtained from two single-level models and the bi-level model. The upper-level decision maker aims to maximize the total electricity generation, and as a result the optimized supplies of coal and natural gas are equal to their availabilities in each of the three planning periods. That means all the available coal and natural gas will be supplied to the power plants to generate the most electricity. The lower-level decision maker targets minimization of the total system cost; as a result, the natural gas use significantly decreases due to its relatively high supply costs. In bi-level analysis of the energy-water nexus, the optimized coal supplies will be less than that from each of single-level models, and optimized natural gas supplies will be larger than those from the lower-level model, but be less than those from the upper-level model. In the bi-level energy-water nexus system, natural gas supplies will increase from 126.2 PJ (30.7% of total fuel supplies) in period 1 to 155.55 PJ (38.0% of total fuel supplies) and 183.38 PJ (39.4% of total fuel supplies) in periods 2 and 3, respectively, while coal supplies during the three planning periods will be 284.38, 254.11, and 281.51 PJ, respectively. These reflect the compromises between economic objective and energy development of the two-level decision makers.

Individual optimal solutions for the two objectives of the two-level decision makers are obtained from two single-level models as shown in Table 5. Based on the obtained individual optimal solutions for the decision variables from two single-level models, the tolerances of the two objectives are determined by calculating $f_U' = f_U(X^L, Y^L)$, and $f_L' = f_L(X^U, Y^U)$. The fuzzy membership functions for the two objectives are elicited based on the equations of (19) and (20). By solving the model (22), the optimal solutions for the bi-level energy-water nexus system are obtained (Table 5). In the bi-level energy-water nexus system, the total electricity generation is 489.05 PJ, which is closer to that from the upper-level model (493.42 PJ), since electricity generation planning can only be optimized within the pre-specified tolerances by the upper-level decision maker. More electricity generation which is the upper-level decision maker's expectation necessitates more water uses and fuel supplies. As a result, the total system cost increases in the bi-level system ($7.03 billion) compared to the lower-level model ($6.40 billion). The two-level decision makers make compromises between their conflicting goals, with an overall satisfactory degree (λ) of 0.783. If the upper-level decision maker is willing to give more relaxation of the tolerances for the goal and the decision variables controlled by him/her, a higher overall satisfaction degree (a higher λ) will be obtained so that the two-level decision makers are more willing to accept the satisfactory solution. A stricter limitation of the tolerances for the goal and the decision variables will lead to a lower overall satisfaction degree, or even infeasible solutions for the two-level decision makers. Tradeoffs between the goals of the two level decision makers are effectively addressed and quantified. These analyses can help decision makers adjust their goals and preferences to make informed decisions to achieve the overall satisfaction of the bi-level energy-water nexus system.

Table 4 Solutions for electricity generation (unit: PJ)

Decision variables	Type of fossil fuel and the power plant	Planning period	Upper-level	Lower -level	Lower- and upper-bound tolerances (-, +)	Bi-level
X_{11}	Coal-fired power plant	1	90.47	98.6	(4.5, 6.0)	91.74
X_{12}	Coal-fired power plant	2	84.86	101.2	(8.8, 13.6)	87.62
X_{13}	Coal-fired power plant	3	105.00	105.47	(3.5, 4.5)	104.26
X_{21}	Natural gas-fired power plant	1	51.75	43.61	(9.1, 5.3)	50.48
X_{22}	Natural gas-fired power plant	2	70.40	54.05	(15.6, 7.9)	67.63
X_{23}	Natural gas-fired power plant	3	90.95	57.8	(17.2, 10.5)	87.32

Table 5 Optimal objectives and tolerances of the two-level decision makers

	f_U (PJ)	f_L (billion $)	λ
Max f_U (upper-level)	493.42 (f_U^*)	8.81 (f_L')	NA
Min f_L (lower-level)	460.73 (f_U')	6.40 (f_L^*)	NA
Bi-level	489.05 (f_U^{opt})	7.03 (f_L^{opt})	0.783

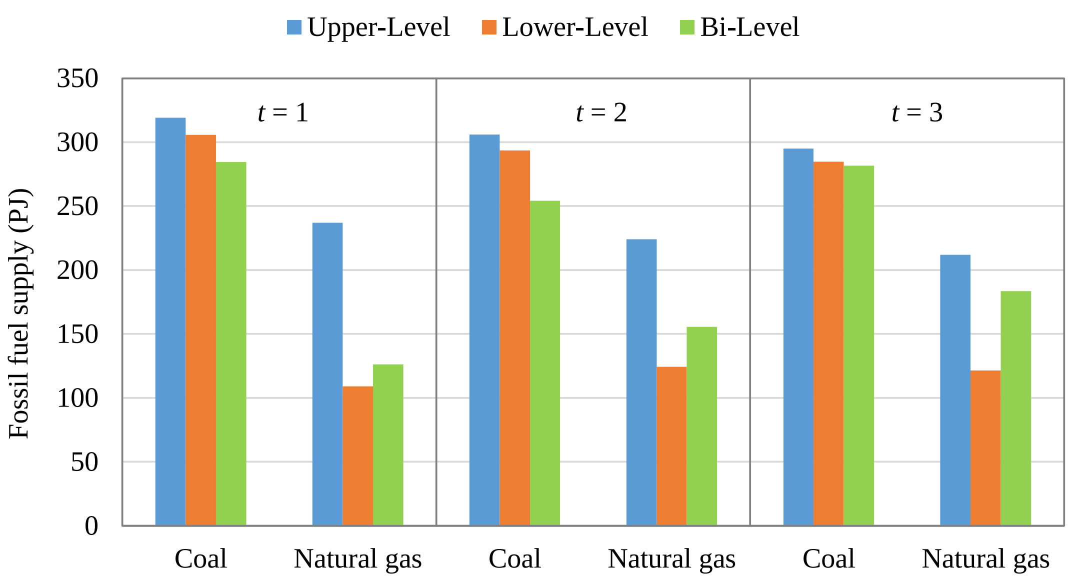

Figure 3 Optimized fossil fuel supply during the three planning periods

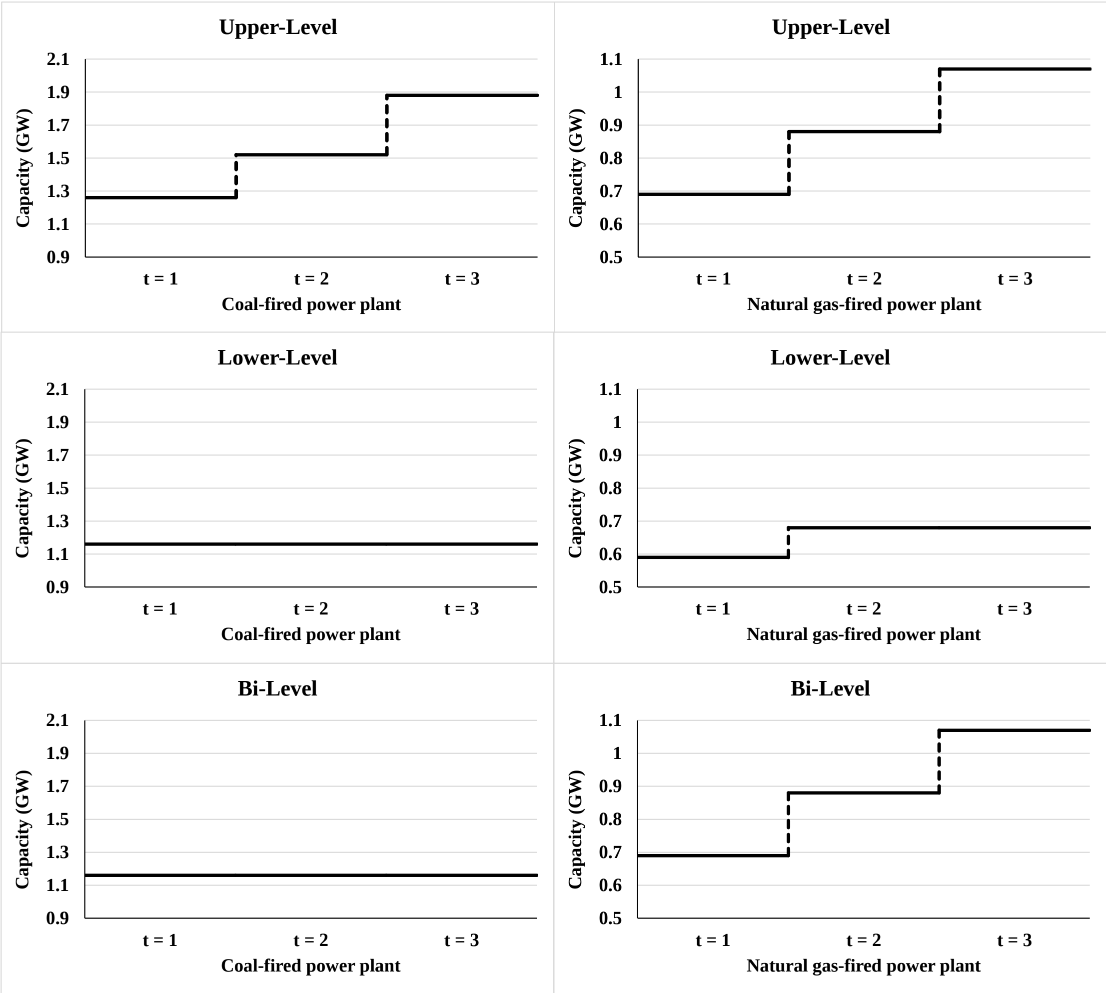

Figure 4 Optimized capacity expansion of the two power plants

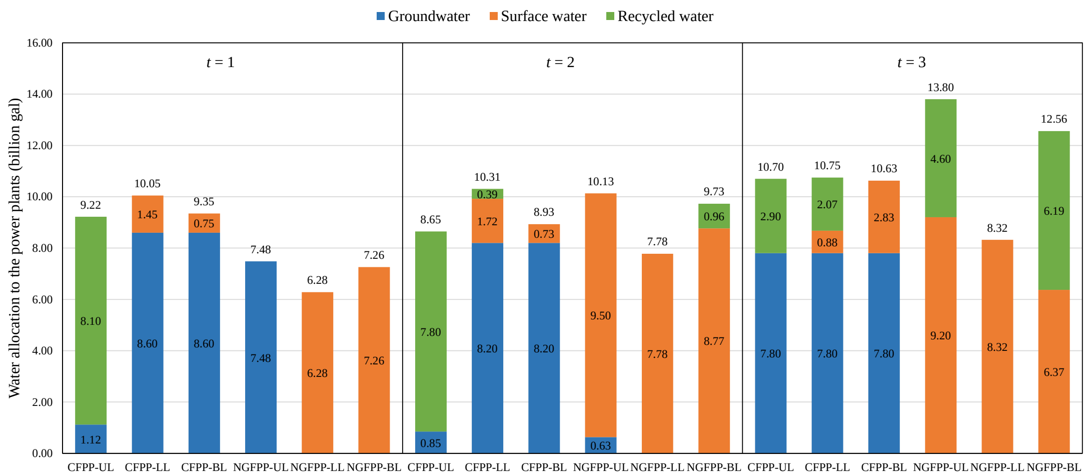

Figure 5 Optimized water allocation from the different models over the three planning periods (CFPP: coal-fired power plant; NGFPP: natural gas-fired power plant; UL: upper-level model; LL: lower-level model; BL: bi-level model)

Figure 4 shows the solutions for capacity expansion planning in the two power plants over the planning horizon. In the bi-level energy-water nexus, coal-fired power plant should only be expanded with an incremental electricity generation capacity of 0.26 GW at the beginning of the first planning period and no further expansions are needed in periods 2 and 3. Natural gas-fired power plant should have the capacity expansion of 0.19 GW at the beginning of each of the three planning periods due to relative lower capital costs for capacity expansion and less GHG emissions in natural gas-fired power plant. Such capacity expansions are the compromised results between the aggressive (more capacity expansions in the two power plants) upper-level decision maker and the conservative (less capacity expansions in the two power plants) lower-level decision maker as shown in Figure 4.

The optimized supplies of water resources including groundwater, surface water and recycled water to the two power plants during the three planning periods are shown in Figure 5. Among the three models, the bi-level model has moderate total water uses (by summing all water supplies to each power plant during each planning period), while the upper-level model has the most total water uses and the lower-level model has the least total water uses. This is consistent with the patterns of electricity generation in the power plants, where a higher electricity generation (in the upper-level model) requires more water uses. Water supply patterns from the three models are different over the planning horizon. In period 1, coal-fired power plant will mainly use recycled water in the upper-level model, while mainly groundwater in the bi-level and lower-level models; natural gas-fired power plant will totally use groundwater in the upper-level model, while totally surface water in the bi-level and lower-level models. In periods 2 and 3, the bi-level model will use more recycled water only in natural gas-fired power plant, while in the lower-level model recycled water is only supplied to coal-fired power plant, and in the upper-level model recycled water is used the most in the two power plants. In the upper-level model decision maker cares most on total electricity generation instead of types of water used; more water is used with more capacity expansions in the two power plants. In the lower-level model, in order to achieve the goal of a minimized total system cost, decision maker preferably uses water with lower supply costs and least capacity expansions in the two power plants; when recycled water is required, it is only delivered to coal-fired power plant due to relatively low supply costs to reduce the total system costs. The bi-level model reflects the compromises between the two objectives in the upper- and lower-level models; groundwater and surface water will be preferably used due to their relative lower supply costs; when the available groundwater and surface water will not be able to meet the increased water demands due to the most capacity expansions in natural gas-fired power plant (same to those in the upper-level model, shown in Figure 4), recycled water will only be supplied to natural gas-fired power plant in periods 2 and 3.

4. Discussions

The developed BEWM model represents an integrated modeling approach to sequentially co-optimize electricity generation, fuel supplies, water uses, GHG mitigation in energy-water nexus. It improves upon the existing studies by effectively addressing the two-level decision making process in energy-water nexus. Such an integrated approach is desirable for sequential decision making from top to down in energy-water nexus, but lacked in the previous studies. It provides a flexible framework to effectively address the priority level of decision makers in the sequential energy-water nexus optimization processes. By dynamic adjustment of tolerances of the upper-level decision maker, various decision scenarios can be obtained with the optimal decision plans for achieving overall satisfaction of the two-level decision makers. The BEWM model complements the existing studies by offering an efficient tool to balance the tradeoffs between the two-level decision makers. It will be helpful for decision makers to preferably consider the preferences and goals of the higher-level (i.e. the upper-level) decision maker, who have a stronger power in controlling the decisions. The BEWM model provides insight into the interrelationships between energy and water, and makes it possible to develop the policies and regulations at regional and national levels for integrated energy and water management from a nexus perspective. It can be used as a viable tool for supporting capacity expansion planning of the power plants to meet the ever-increasing electricity demands. The high computational efficiency of the BEWM model enables it to be suitable and applicable to large-scale real-world applications. In addition, the solution method presented in this study is easily extendable to deal with multi-level decision-making problems. The BEWM model is also advantageous over the multi-objective mixed integer linear programming by incorporating sequential decision making into energy-water nexus instead of considering multiple objectives at the same level. Although weights can be assigned to multiple objectives to address the preferences of different decision makers in a multi-objective mixed integer linear programming, they cannot reflect the nature of the sequential decision-making from top to down.

Although the BEWM model represents an advancement over the existing studies relating to energy-water nexus, it has some limitations. First, since the BEWM model aims to address energy-water nexus sequentially at regional and national levels, less attentions are paid to site- or watershed-specific information such as those related to each specific power plant, each electricity generation technology and associated water demand. Water demand for electricity generation in the modeling approach is specified by unit water use per unit of electricity generation, which does not distinguish between water withdrawals and consumption. Secondly, the current version of the BEWM model does not consider the impacts of uncertainties inherently existing in the modeling parameters and structure. Thirdly, no wastewater management is considered in the current version, while treatment, disposal or recycling of wastewater may significantly affect energy-water nexus optimization decisions. Finally, the BEWM model only considers simple environmental impacts such as GHG emissions from electricity generation.

In the future research, more detailed relationships between energy development and water withdrawals/consumption can be quantitatively addressed and incorporated into the developed modeling framework. More electricity generation types, renewable fuels, and non-conventional water resources can be incorporated into the modeling framework. The modeling parameters' uncertainties and their impacts on energy-water nexus can be also systematically quantified. A comprehensive environmental impacts assessment can be conducted to address various environmental concerns in the energy-water nexus systems, and advance best management practices to mitigation these impacts. The BEWM model can also be extended to three- or more- level decision making problems including more management objectives and more complicated decision-making processes.

5. Conclusions

A bi-level programming model called BEWM has been developed for supporting energy-water nexus management, where a sequential decision making process from top to down is supported. An interactive fuzzy approach is introduced to seek a satisfactory solution to meet the overall satisfaction of the two-level decision makers. Application of the BEWM model to a synthetic example problem has demonstrated its applicability in energy-water nexus management. The BEWM model is capable of effectively quantifying the tradeoffs between the two-level decision makers in energy-water nexus management. Optimal solutions for electricity generation, fuel supply, water supply including groundwater, surface water and recycled water, capacity expansion of the power plants, and GHG emission control are generated. These analyses are capable of helping decision makers or stakeholders adjust their tolerances to make informed decisions to achieve the overall satisfaction of energy-water nexus management where bi-level sequential decision making is involved. The BEWM model is computationally efficient and can be easily applicable to large-scale energy-water nexus management problems involving bi-level decision making. In the future research, improvements can be conducted to include more site-specific information and data, more detailed quantification of energy-water interrelationships, more comprehensive environmental impacts assessment, renewable energy and electricity generation, and non-conventional water resources into the modeling framework. The proposed method can be extended to multi-level decision making problems involving more decision-making levels and decision makers.

Acknowledgments

The work was supported by Director-funded Postdoctoral Fellowship at Los Alamos National Laboratory. The authors would like to thank the Editors and anonymous reviewers for their helpful comments and suggestions which substantially improved the quality of the manuscript.

Nomenclature

$\emptyset_{jt}$ the average efficiency for CO_2 abatement in the power plant *j* in the planning period *t*

AER_{tmax} the maximum available energy (in the form of electricity) for water collection, treatment and delivery in the planning period *t* (PJ)

ARW_t recycled water availability in the planning period *t* (gal)

ASW_t surface water availability in the planning period *t* (gal)

AVC_t availability of coal in the planning period *t* (PJ)

AVG_t availability of natural gas in the planning period *t* (PJ)

CC_{jt} unit CO_2 emission per unit of electricity generation in the power plant *j* in the planning period *t* (Gg/PJ)

CEA_t unit abatement cost of CO_2 emissions from electricity generation in the planning period *t* ($/Gg)

CF_{jt} unit electricity production per unit of capacity of the power plant *j* in the planning period *t* (PJ/GW)

CGW_{jt} cost of groundwater supplied to the power plant *j* in the planning period *t* ($/gal)

CRW_{jt} cost of recycled water supplied to the power plant *j* in the planning period *t* ($/gal)

CSW_{jt} cost of surface water supplied to the power plant *j* in the planning period *t* ($/gal)

D_t societal demands of electricity in the planning period *t* (PJ)

EC_{jmt} expanded capacity of the power plant *j* with option *m* at the beginning of the planning period *t* (GW)

ER_t unit energy demand for water collection, treatment and delivery in the planning period *t*

(PJ/gal)

ESC_{it} the average cost for fossil fuel supply *i* in the planning period *t* (million \$/PJ)

ES_{it} decision variables, representing fossil fuel supply *i* in the planning period *t* (PJ)

FC_j the fixed costs for electricity generation in the power plant *j* (million \$)

FE_{jt} unit energy carrier per unit of electricity generation in the power plant *j* in the planning period *t* (PJ/PJ)

GW_{jt} decision variables, representing quantity of groundwater supplied to the power plant *j* in the planning period *t* (gal)

IC_{jt} capital cost for capacity expansion of the power plant *j* by option *m* at the start of the planning period *t* (million \$/GW)

PC_{jt} the average operational cost for electricity generation in the power plant *j* in the planning period *t* (million \$/PJ)

RC_j residual capacity of the power plant *j* (GW)

RW_{jt} decision variables, representing quantity of recycled water supplied to the power plant *j* in the planning period *t* (gal)

SW_{jt} decision variables, representing quantity of surface water supplied to the power plant *j* in the planning period *t* (gal)

SY_t safe yield of groundwater in the planning period *t* (gal)

WR_j unit water demand per unit of electricity generation in the power plant *j* (gal/PJ)

X_{jt} decision variables, representing the generated electricity from the power plant *j* in the planning period *t* (PJ)

Y_{jmt} integer decision variables (1 or 0) for representing capacity expansion in the power plant *j* with option *m* at the beginning of the planning period *t* (1: expanded; 0: not expanded)

f_L the objective function of the lower-level decision maker

f_U the objective function of the upper-level decision maker

p_1 the lower-bound tolerances specified by the upper-level decision maker

p_2 the upper-bound tolerances specified by the upper-level decision maker

β_j a loss factor of delivering water to the power plant *j*

i index for fossil fuel (*i* = 1: coal; *i* = 2: natural gas)

j index for the power plants (*j* = 1: coal-fired power plant; *j* = 2: natural gas-fired power plant)

m index for capacity expansion options in the power plants (*m* = 1, 2, 3)

t index for the planning periods (*t* = 1, 2, 3)

λ an overall satisfaction degree for the decision variables of the upper-level decision maker and the decision goals of the two-level decision makers simultaneously

$TMCC$ the maximum allowable CO_2 emissions over the planning horizon (Gg)

X vectors of decision (or control) variables

Y vectors of decision (or control) variables

a constants

b constants

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