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Energy-water nexus: Balancing the tradeoffs between two-level decision makers

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HIGHLIGHTS

- A bi-level decision model for energy-water nexus is proposed.
- The upper level decision demands are satisfied first.
- Tradeoffs between the two-level decision-makers' demands are effectively quantified.
- Optimal overall satisfaction of energy-water nexus management is achieved.

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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.

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].

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Nomenclature

$\varnothing_{jt}$	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

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.