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Bi-Level Decision Making for Supporting Energy and Water Nexus

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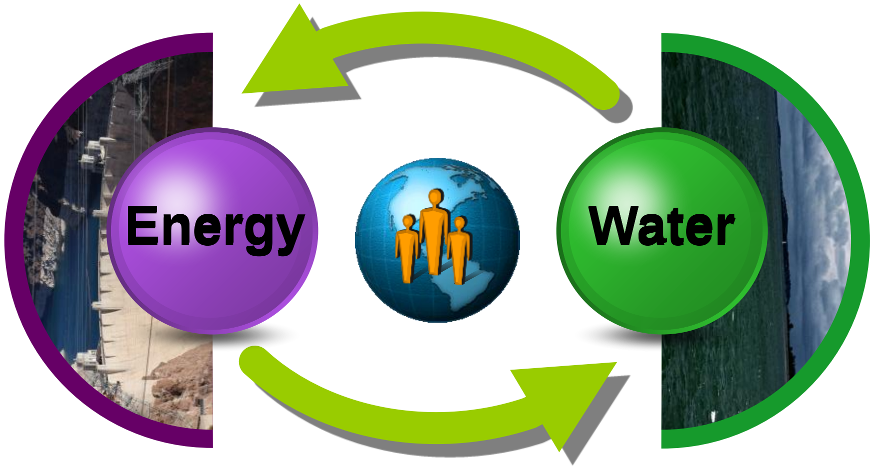
Background



- Energy-water nexus (EWN) ➔ inseparable relationships between the two critical resources
- Rapid worldwide population growth ➔ exacerbate the crises of energy and water shortages in the world
- A variety of crucial issues related to EWN: energy and water resources allocation, capacity expansion planning for the power plants, environmental impacts, etc.

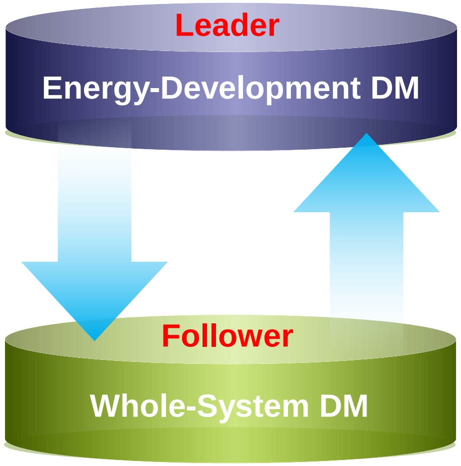
Separate and fragmented management of energy and water systems could lead to ineffectiveness of the generated management decisions and strategies

Problems

- Energy-water nexus management involves various decision makers (DMs) with different goals and preferences, which are often conflicting

- DMs may have different controlling power over the management objectives and the decisions ➔ make decisions sequentially from the upper level to the lower level

- Bi-level decision making ➔ different from multi-objective problems (at the same level)



Bi-Level System

We need effective tools to quantify the tradeoffs between the two-level decision makers in energy-water nexus

Research Objectives

- Formulate a bi-level decision model called BEWM (Bi-level Decision Model for Energy-Water Nexus Management)
- Address and quantify the trade-offs between the two-level decision makers in EWN
- Generate various scenarios to help improve the understanding of energy-water linkages and make informed decisions
- Demonstrate BEWM applicability through a hypothetical nexus management problem consistent with real-world management scenarios

BEWM: Bi-Level Decision Model for EWN Management

Upper-Level Decision Makers

Objective:
to maximize the total electricity generation

Control variables:
- quantity of electricity generated from the power plants

Lower-Level Decision Makers

Objective:
to minimize the total system cost

Control variables:
- Fuel supply
- Quantity of groundwater, surface water and recycled water supplies
- Integer variables for representing capacity expansion for the power plants

Constraints:
- Mass balance of fossil fuel
- Fossil fuel availability
- Electricity demand constraints
- Power plant capacity expansion
- Energy demand for water subsystem
- Water demand for energy subsystem
- Water resources (including groundwater, surface water and recycled water) availability
- CO_2 emission control constraints
- Technical constraints

Model Structure - BEWM

Objectives:

Upper-level: to maximize the total generated electricity from the power plants

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

Lower-level: to minimize the total system costs

$$\min f_L = \underbrace{\sum_{j=1}^{2}\sum_{t=1}^{3} ES_{it}ESC_{it}}_{\text{Fuel supply costs}} + \underbrace{\sum_{j=1}^{2} FC_j + \sum_{j=1}^{2}\sum_{t=1}^{3} X_{jt}PC_{jt}}_{\text{Fixed and operational costs}}$$

$$+ \underbrace{\sum_{j=1}^{2}\sum_{m=1}^{3}\sum_{t=1}^{3} IC_{jt}EC_{jmt}Y_{jmt}}_{\text{Capacity expansion costs}} + \underbrace{\sum_{j=1}^{2}\sum_{t=1}^{3} CEA_t CC_{jt} X_{jt}}_{CO_2 \text{ emission abatement costs}}$$

$$+ \underbrace{\sum_{j=1}^{2}\sum_{t=1}^{3}\left(CGW_{jt}GW_{jt} + CSW_{jt}SW_{jt} + CRW_{jt}RW_{jt}\right)}_{\text{Water supply costs}}$$

Model Variables

- Quantity of electricity generation (X_{jt})
- Quantity of fuel supply (ES_{it})
- Capacity expansion of the power plants (Y_{jmt})
- Supply of groundwater, surface water and recycled water (GW_{jt}, SW_{jt}, RW_{jt})

Model Constraints

- Mass balance of fossil fuels
- Fossil energy availability constraints
- Energy demand constraints
- Capacity expansion of the power plants
- Energy demand for water collection, treatment and delivery
- Water demand for electricity generation
- Water resources availability constraints (GW: groundwater, SW: surface water, RW: reclaimed water)
- CO_2 emission control constraints
- Technical constraints (i.e. non-negativity)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

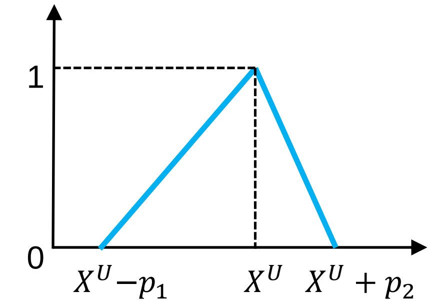
Solution Method

- **Interactive fuzzy approach**: two-level DMs make compromises to find the overall satisfactory solutions

Upper-level DM: sets upper-level goal, decisions, and the goal tolerances

A fuzzy max-min operator λ is applied to aggregate an overall satisfaction

Lower-level DM: can only follow upper-level inputs to seek optimal solutions, but may communicate to upper-level DM to make adjustments of the upper-level inputs



$$\text{Max } \lambda$$

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

$$\mu_X(X) = \begin{cases} \frac{X - X^U + p_1}{p_1}, & if\ X^U - p_1 \le X \le X^U; \\ \frac{X^U + p_2 - X}{p_2}, & if\ X^U < X \le X^U + p_2; \\ 0, & if\ X < X^U - p_1, \text{or } X > X^U + p_2 \end{cases}$$

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

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

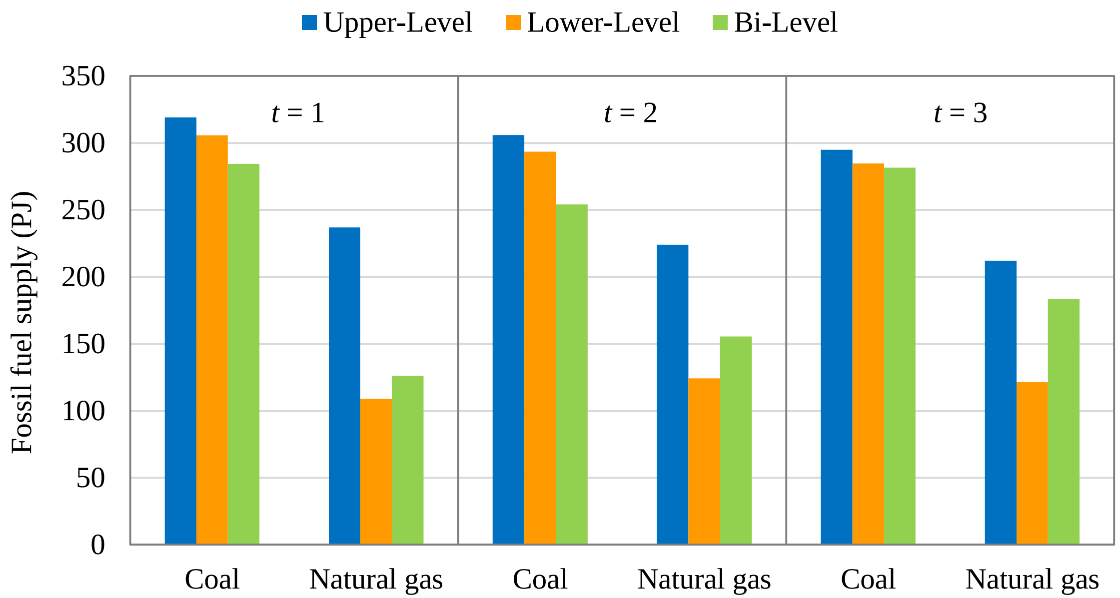
- Coded in Julia, a high-level, dynamic high-performance programming language for technical computing
- A part of the MADS (Model Analyses & Decision Support) framework (http://mads.lanl.gov)

Results Analysis … Optimized Electricity Generation

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

- Optimized quantity of electricity generation is controlled by upper-level DM
- Tolerances of electricity generation are specified by upper-level DM
- Coal-fired power plant ➔ main source for electricity generation

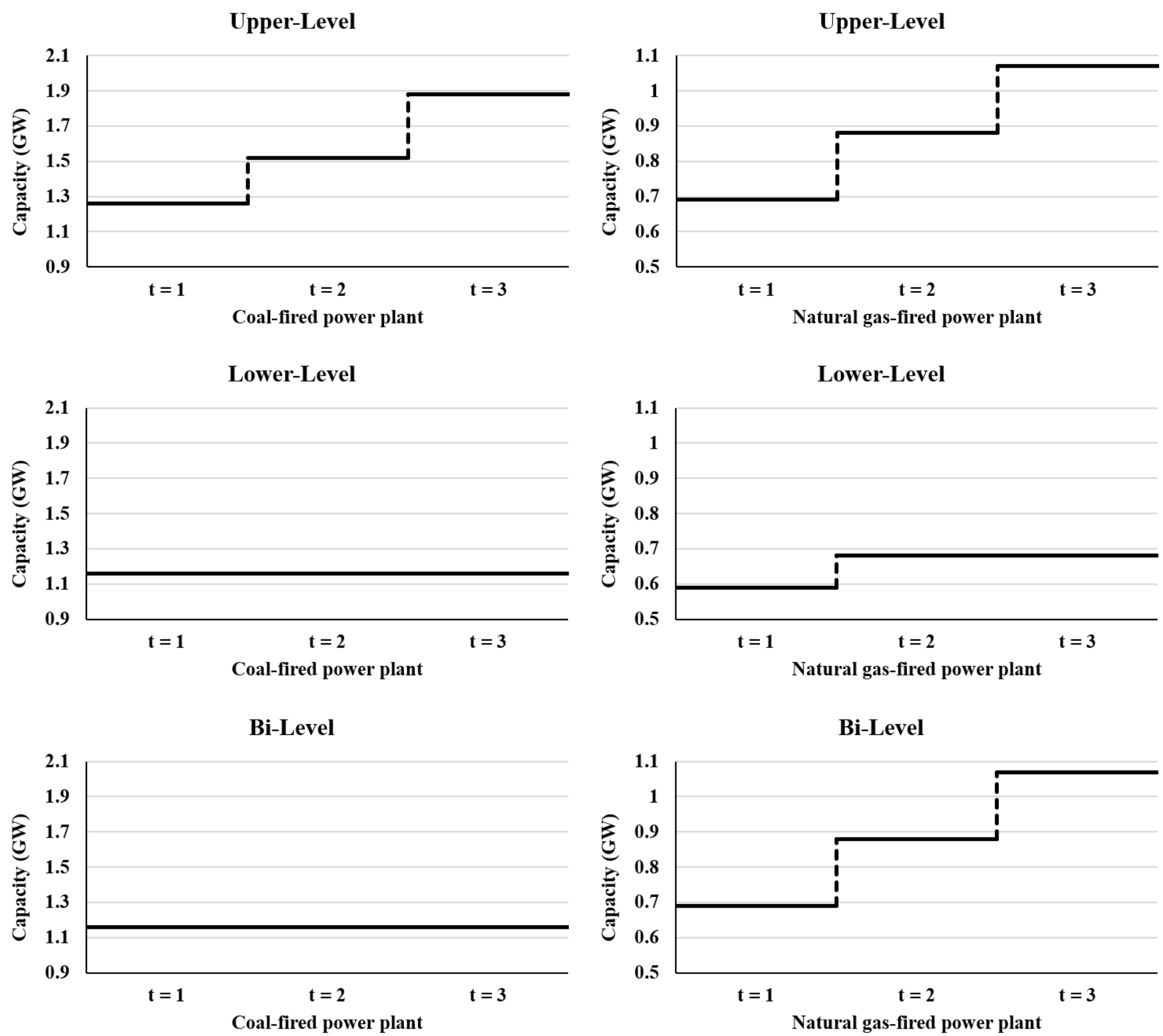
Results Analysis …. Optimized Fuel Supplies



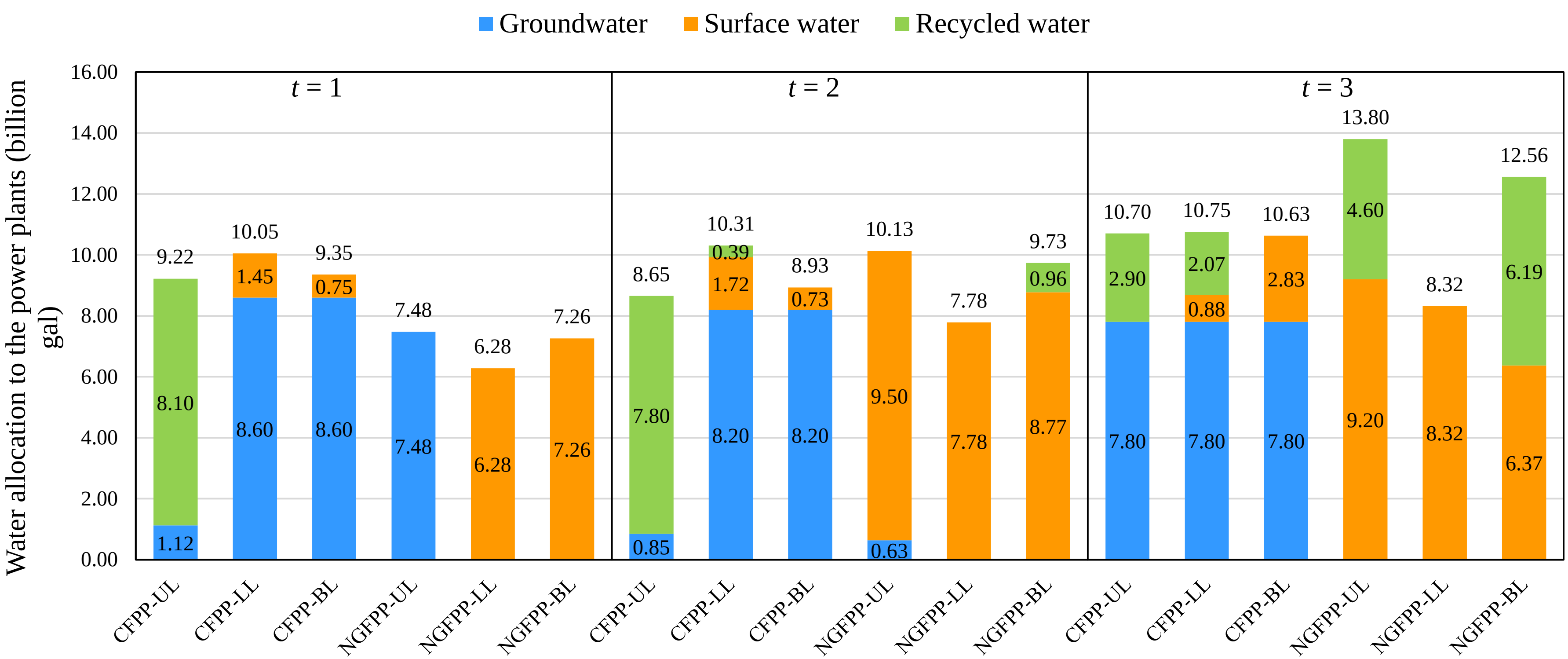
- **Upper-level DM only: optimized fuel supplies = their availabilities**
- **Lower-level DM only: natural gas use significantly decreases**
- **Bi-level analysis: optimized coal supplies will be least, and optimized natural gas supplies will be between lower- and upper-level models**

Compromises between economic objective and energy development of the two-level DMs

Results Analysis …. Capacity Expansion



Results Analysis …. Optimized Water Allocation



Water use:

- **Bi-level: moderate**
- **Upper-level: most**
- **Lower-level: least**

Bi-level reflects compromises between the two objectives in the two-level models

Objectives Analysis

	Upper-level (PJ)	Lower-level (billion $)	λ
Max (upper-level)	493.42	8.81	N/A
Min (lower-level)	460.73	6.40	N/A
Bi-level	489.05	7.03	0.783

- More relaxation of the tolerances ➔ a higher overall satisfaction degree (a higher λ) ➔ the two-level DMs are more willing to accept the satisfactory solution
- A stricter limitation of the tolerances ➔ a lower overall satisfaction degree, or even infeasible solutions
- Tradeoffs between the goals of the two level DMs are effectively quantified

These analyses can help DMs adjust their goals and preferences to make informed decisions to achieve the overall satisfaction of the bi-level EWN system

Summary

- A bi-level decision model called BEWM is developed for supporting energy-water nexus management.
- BEWM model provides a flexible framework to effectively address the priority levels of decision makers in the sequential top-down decision making process.
- 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.
- 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.
- BEWM model is computationally efficient and can be easily applicable to large-scale EWN management problems involving bi-level decision making.
- BEWM will be coupled with model-analyses tools such as MADS (http://mads.lanl.gov) to perform global sensitivity and uncertainty analyses related to model predictions and decision scenarios.

Thank you very much !

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