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Modeling the urban water-energy nexus: A case study of Xiamen, China

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ABSTRACT

A general framework for the analysis of the urban water-energy nexus (WEN) was proposed and a dynamic and quantitative WEN model was developed based on the Long-range Energy Alternatives Planning System (LEAP) and Water Evaluation and Planning (WEAP) tools. Using Xiamen, China, as a case study, eleven future scenarios were designed to explore the impacts of different factors, from both supply and demand sides, on urban WEN. Both water-related energy (WRE) and energy-related water (ERW) were studied to reveal the interconnected relationship between water and energy. We found that most WRE and ERW savings lie on the supply side, except for demand management scenarios, and most scenarios have larger trans-boundary effects than in-boundary effects due to the import of large quantities of energy and water. Industry structure adjustments (oriented toward energy or water savings) and energy-saving measures have better co-benefits in terms of energy and water savings than other measures. Promoting electric vehicles increases electricity imports and related trans-boundary ERW. Such effects should be considered before importing resources from outside city boundaries. Developing high-tech industries might also increase energy or water burdens. Finally, the boundaries of urban WEN research were discussed to promote additional comparable studies.

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1. Introduction

Energy is required for the supply, use, and disposal of water (Mo et al., 2014). For example, an estimated 19% of California's electricity usage goes toward supplying water (CEC, 2006) and about 2–3% of Ontario's energy usage goes toward pumping and treating water for urban residents and industry in the municipal water sector (Harrison, 2007). Conversely, water is needed for energy exploitation and power generation. Freshwater withdrawn for power generation accounted for 41% of all freshwater withdrawals in 2005 in the U.S.(Kenny et al., 2009) Understanding the interactions and interdependence between water and energy, known as the water-energy nexus (WEN), can promote the integration of resource management practices across sectors and geographic regions. However, due to a lack of attention toward WEN, traditional independent and isolated resource management practices have caused problems. For example, water diversion projects have been applied to meet local water demands but have resulted in increased energy consumption (Khan et al., 2017). In addition, the energy sector is constrained by water scarcity in many regions (King et al., 2008), an example of which is that China is developing water-intensive coal-fired thermal power plants in its arid northwest regions (Zhang et al., 2014). WEN has been recognized as a key challenge around the world (Schnoor, 2011). Meeting future water needs depends on energy supply, and energy security depends on future water availability. Currently, 54% of the world's population lives in urban areas, with a 2.5-billion-person increase expected by 2050, primarily in Asia and Africa (UN, 2014). In China, 56.10% of the population lived in cities in 2015 and the urban population could reach 1 billion within the next two decades (Bai et al., 2014). Rapid urbanization in the future will put tremendous pressure on the environment and resources (Bai et al., 2017; McPhearson, 2016), including energy and water, and impact resident lifestyles, industry, and municipal policies, among others (O'Neill et al., 2017). Thus, it is important to explore the urban WEN in terms of complex

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future economic and social conditions in Chinese cities.

Recent research has shown the increasing importance of WEN in future planning and strategic policies worldwide (IEA, 2012). WEN studies have been conducted at an increasing variety of scales, including production (Gleick and Cooley, 2009), household (Gerbens-Leenes, 2016), community (Perrone et al., 2011), city (Zhou et al., 2013), province, nation (Fthenakis and Kim, 2010), region, and even global (Holland et al., 2015). However, most of these studies have addressed specific sectors and approach WEN from a "one-way" perspective (Gu et al., 2016): either energy-related water (ERW), such as in biofuels production (Pacetti et al., 2015), shale gas production (Schnoor, 2011), coal power plants (Zhang et al., 2014), and the electricity system (Fthenakis and Kim, 2010), or water-related energy (WRE), such as in groundwater pumping (Jinxia et al., 2012), desalination, water treatment (Schnoor, 2011), and the whole water supply system (Kelly and Michael, 2012; Mo et al., 2014). In contrast, "two-way" synergistic studies, which consider both ERW and WRE, have rarely been conducted at different scales. Also, supply-side WEN is comparatively well-studied because of its obvious interactions, while demand-side WEN is less understood and has only recently started gaining attention from researchers. The most commonly used assessment methods for WEN research include process analysis (Fthenakis and Kim, 2010; Kelly and Michael, 2012), life cycle assessment (LCA) (Pacetti et al., 2015), and input-output analysis (IO) (Wang et al., 2017). In addition, some dynamic approaches which aim to predict future scenarios and inform management decisions have been developed based on systems-analysis and mathematical models, including system dynamics (SD) (Zhou et al., 2013), computable general equilibrium models (CGE), modified energy models (Khan et al., 2017) (like MARKAL/TIMES, MESSAGE, and PRIMA) or modified water models (Suárez et al., 2014) (like AQUATOOL). A popular method for assessing WEN is to take an already-existing energy (or water) model and modify it to evaluate ERW (or WRE) (Khan et al., 2017). Other studies have integrated the Long-range Energy Alternatives Planning System (LEAP) and Water Evaluation and Planning (WEAP) tools to create an improved and superior platform for evaluating national or regional WEN (Howells et al., 2013). Even with its flexible framework and data requirements, the fully coupled LEAP-WEAP model was seldom applied on a city scale.

In this paper, we present a dynamic, quantitative, synergistic framework for WEN modeling at the urban scale based on the LEAP and WEAP models, which can facilitate tailored WEN analyses representing detailed local conditions. Using the city of Xiamen as a case study, we analyzed the current pattern of water-energy nexus. Also, a scenario analysis was applied to examine the cross-sectoral impacts of different policy choices in the future, including changes in industry structure, water and energy conservation, and water and energy supply alternatives. The objectives of our study are to (1) explore the broader WEN issues from a "two-way" synergistic perspective rather than a "one-way" perspective, (2) analyze complex urban WEN systems from both supply and demand sides, (3) provide decision makers with a better understanding of the interrelationships and tradeoffs between urban water and energy. Moreover, the integrated methods employed in this paper can be used to reveal a broader set of multiple relationships between water and energy and to highlight decision-making challenges in other cities.

2. Methods

2.1. Analysis framework

A general framework for analyzing urban WEN is proposed in Fig. 1, which includes both WRE consumption and ERW withdrawal. The framework contains both the supply and demand sides of energy and water systems, as well as the links between the two systems. In terms of geographic boundary, the energy (or water) demand of a city is met by both in-boundary and trans-boundary resource supplies, and trans-boundary energy (or water) supplies result in indirect water (or energy) use outside the city. In this paper, WRE includes direct energy use for water from inside the city and indirect energy use for water imported from outside the city boundary. ERW includes water used for energy production from sources inside the city and indirect use of water imported from outside the city. Both energy and water systems include five end-use demands: household, commerce, manufacturing, transportation, and agriculture. In addition, the energy system also includes the energy demand for water supply, treatment, and disposal, while the water system also includes cooling water for thermal power generation and industrial boilers. Two types of WEN are considered in this paper: (1) the "interactive link" represents the use of one resource to produce another resource's services, such as energy for water treatment and water for thermal power cooling, and mainly occurs on the supply side; (2) the "connected link" represents water and energy resources that are connected in devices whose final purpose is to provide other services, such as water heating and clothes washing, and mainly occurs on the demand side. Except for the ways of classification mentioned above (boundary, sector, interactive/connected link), WRE and ERW can also be categorized by process (Table 1). The former includes energy for water supply & disposal process and energy for water use process, while the latter includes water for energy supply & conversion process and water for energy use process.

2.2. Water-energy nexus (WEN) modeling

The urban WEN model is built based on the WEAP and LEAP tools (Fig. 1), including simulations of water and energy systems and the interactions between them. The model structure is shown in Fig. 1. LEAP and WEAP were developed by the Stockholm Environment Institute for energy and water planning, respectively, and are based on the mass balance principle and scenario analysis. They are widely used around the world because of their strong calculation capacities and flexible accounting frameworks, which can be adjusted based on available data (Khan et al., 2017; Lin et al., 2018). The basic modeling structures of the two tools are similar: LEAP consists of three modules (resource, transformation, and energy demand) as does WEAP (water supply, water demand, and water quality). And the calculation mechanism of the two tools is also similar to each other. Energy demand module is the core of LEAP tool, in which, the energy demand of a certain sector is calculated as the product of activity level and corresponding energy intensity. The energy resource and transformation module calculate the primary energy required for energy users and energy conversion, the latter of which is the function of the heat or electricity generation and the conversion efficiency. The core of WEAP tool, water demand module also calculates the water demand by activity level and water intensity, while the water supply amount and water disposal would be simulated in the other two modules.

The main links between water and energy incorporated into the model are listed in Table 1. Water is used by energy utilities (such as for thermal power and boiler cooling) and other sectors, including households, agriculture, manufacturing, and commerce). Energy demands, inside and outside geographic boundaries, were modeled for water utilities, wastewater treatment, and other sectors (household, agriculture, manufacturing,

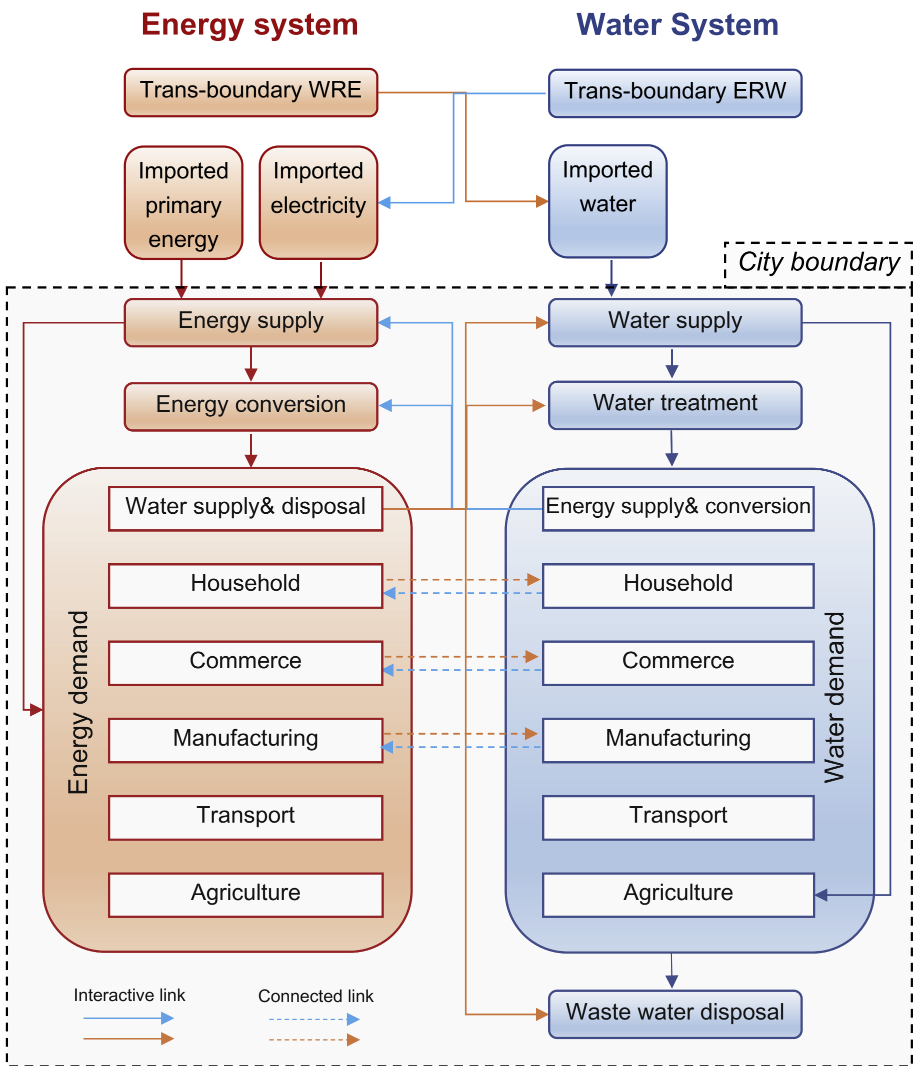

Fig. 1. Urban WEN analysis framework and model structure.

Table 1
Links between urban water and energy systems.

Process	Sector	Detailed processes
Water-related energy consumption (WRE)		
Energy for water supply & disposal	Water supply	Electricity for water withdrawal, conveyance, treatment, distribution, and waste water disposal
Energy for water use	Household	Energy for water heating, cooking, washing machine, etc.
	Commerce	Energy for water heating, washing machine, etc.
	Manufacturing	Energy for industrial heat supply, product washing, etc.
Energy-related water withdrawal (ERW)		
Water for energy supply & conversion	Power generation	Cooling water for electricity generation, water for steam production
Water for energy use	Household	Water used for water heating, cooking, washing machine, etc.
	Commerce	Water used for water heating, washing machine, etc.
	Manufacturing	Water for industrial heat supply, product washing, etc.

transportation, and commerce). The integrated model can pass data on specific linking variables between LEAP and WEAP, and it connects the water and energy models to match their supply and demand sides automatically (SEI, 2012). Moreover, LEAP and WEAP also share some common key assumptions about social and economic backgrounds, such as population and GDP.

3. Study case

3.1. Study area

Xiamen is a coastal city located in Fujian Province, southeast China (Fig. 2) covering 166.38 km^2 and is characterized by a

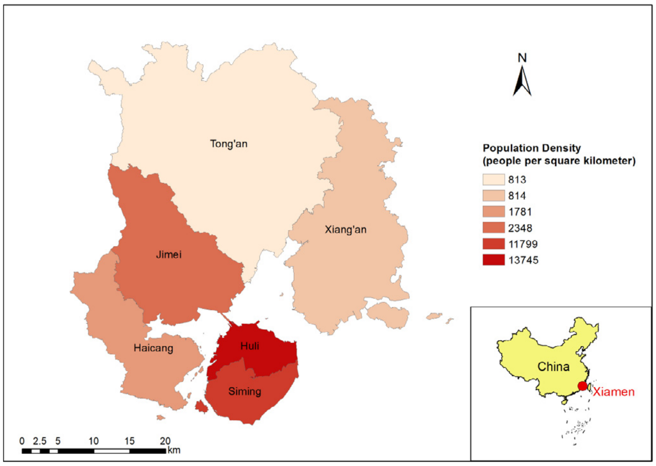

Fig. 2. Map of Xiamen city.

monsoonal humid subtropical climate. Xiamen was designated a special economic zone in 1980, and it has experienced rapid social and economic development since then. The population of the city increased from 2.05 million in 2000 to 3.86 million in 2015, and the GDP increased from 50 billion RMB to 347 billion RMB during the same period. Moreover, population and GDP are projected to reach 6.57 million and 1079 billion RMB, respectively, by 2030. As the city grows rapidly, it requires more energy and water. However, Xiamen faces increasing conflicts between final demands and local supplies of both energy and water. Xiamen consumed 1406 tce of energy in 2015, most of which was imported from outside the city. Regarding water, about 60% of Xiamen's total water resources were provided by diversion from another basin. Hence, it is important to study the WEN of Xiamen, as it relies so much on energy import and water diversion.

3.2. WEN-Xiamen model

According to the methodology detailed above, the WEN model for Xiamen (WEN-Xiamen) was developed for the period from 2015 to 2030. The basic assumptions for key variables are shown in Table 2 (XMCUP, 2017). The energy demands of different sectors are estimated as a function of population, GDP, water transport distance, ground water depth, the volume of water used, the volume of wastewater treatment, and corresponding energy intensities. The data used to estimate energy demands are obtained from the local statistical bureau, electricity power bureau, development and reform commission, transportation bureau, and related enterprises. In terms of energy supply, power generation in Xiamen includes thermal power plants (coal power plants and natural gas plants) and other plants like hydropower and solar power. Currently, only about 25% of the electricity in Xiamen is generated locally, while the remaining supply is imported (XDRC, 2016).

The water used by energy utilities is calculated as the function of the electricity generated and the related water intensity, while the water used by other sectors is calculated as a function of population, GDP and area, and water intensities based on historical data contained in local databases and annual reports. Water supply is linked to water demand by distribution rules, which are mainly determined by the priorities of the demand sectors and supply points. Local surface water is assumed to be the preferred choice over groundwater and imported water. The capacity of water deliverability is estimated based on historical data and future planning (XBWR, 2001–2016).

3.3. Scenario design

Scenario analysis was used in the WEN-Xiamen model to project future water and energy use. Eleven scenarios were designed to explore the impacts of different factors on water and energy use in Xiamen from both supply and demand sides, as shown in Table 3. The parameters of the different scenarios were assumed based on historical database, local planning, government documents, and literature reviews, and the planning of local government has the highest priority since it may provide more reliable guidance for water and energy management in the studied city. With respect to energy supply, we consider scenarios in which natural gas power generation increased and renewable power generation is maximized; for energy demand, we consider energy conservation and increased use of electric vehicles; for water supply, we consider imported versus locally sourced water supplies; for water demand, we consider water conservation; for both energy and water demand, we consider adjustments to industry structures that achieve energy savings, water savings, and an increased proportion of high-tech industries.

4. Results

4.1. WEN of base year

The Sankey diagram of water and energy flows of Xiamen in 2015 is shown in Fig. 3. In terms of energy consumption, the manufacturing sector used 41.20% of total energy, followed by transportation (30.97%), commerce (13.81%), and household (11.54%) sectors. The water supply (including imported water supply), water treatment, and agriculture sectors accounted for a combined total of only 2.47% of energy. In terms of water withdrawal, the power generation sector (including imported electricity generation) was the largest consumer of water, accounting for 58.21% of the total, followed by the household (13.13%), manufacturing (12.23%), agriculture (8.79%), and commerce (7.64%) sectors. Overall, manufacturing is a notable sector in terms of both energy and water use.

In the WEN system, WRE accounts for 4.25% of total energy consumption (0.59 Mtce), while ERW accounts for 68.42% of total water withdrawal (890 million m^3) in Xiamen. From a process-

Table 2
Basic assumptions for key variables in the WEN-Xiamen model.

Key variables		2015	2020	2025	2030
Population (million)		3.86	4.92	5.82	6.57
Household size (people/household)		3.1069	3.1125	3.1135	3.1100
GDP[a] (billion Yuan)		347	549	775	1002
Proportion of three industries (%)	Primary industry	0.7	0.5	0.4	0.3
	Secondary industry	43.5	39.5	37.1	34.7
	Tertiary industry	55.8	60.0	62.5	65.0

Note: a. Adjusted for future years based on 2015 GDP.

Table 3
Scenario design used in the WEN-Xiamen model.

Classification	Full name of scenarios	Abbreviation	Main assumptions
For comparison	Business-as-usual	BAU	No changes in policies or regulations that would affect water and energy use.
Energy supply	Power generation: increasing natural gas	PGN	The capacity of natural gas power plants increases from 786 MW in 2015 to 1296 MW in 2025 by reducing coal usage, and no increase after 2025.
	Power generation: maximizing renewable energy	PGR	Solar power generation capacity increases from 9.7 MW in 2015 to 183.3 MW in 2030; hydro power increases from 10.7 MW to 15.7 MW; and wind power increases from 0 MW to 800 MW.
Energy demand	Energy saving	ES	Energy efficiencies are improved by 5%–15% over BAU levels by 2030 in different sectors.
	Electric vehicles used widely	EV	Electric bus use increases from 0% of total transportation in 2015 to 10% in 2030, electric taxi use increases from 10% to 50%, and private electric cars increase from 0% to 30%.
Water supply	Water resources: imported water first	WI	Proportion of water diversion increases from 61.6% in 2015 to 76.7% in 2030, compared to the BAU level of 70.5%.
	Water resources: local water first	WL	Proportion of water sourced locally increases from 38.2% in 2015 to 50.1% in 2030 by using reclaimed water and sea water desalination.
Water demand	Water saving	WS	Improvements in water conservation technologies and management decrease water use intensities by 10–25% in different sectors by 2030, compared to BAU.
Water & energy demands	Industry structure adjustment: energy saving oriented	ISE	Share of energy-intensive industries is decreased to 3% from the BAU level of 25%.
	Industry structure adjustment: water saving oriented	ISW	Share of water-intensive industries is decreased to 2% from the BAU level of 27%.
	Industry structure adjustment: high-tech industries oriented	ISH	Share of high-tech industries (like manufacturing of pharmaceutical products, machinery and equipment, transportation equipment, computers, optical products, and electrical equipment) is increased to 80% from the BAU level of 67%.

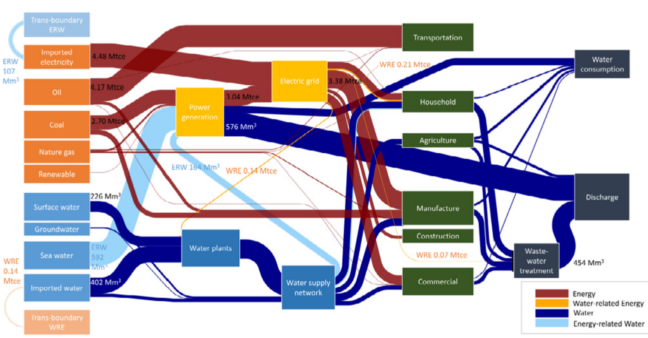

Fig. 3. Sankey diagram of water and energy flows of Xiamen 2015.

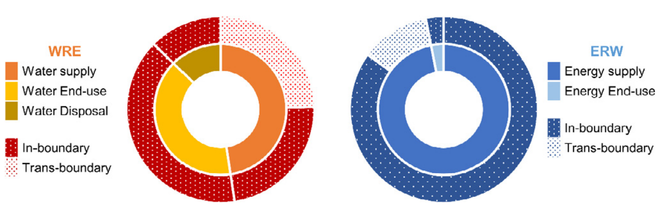

Fig. 4. Structure of water-related energy consumption (WRE) and energy-related water withdrawal (ERW) in 2015.

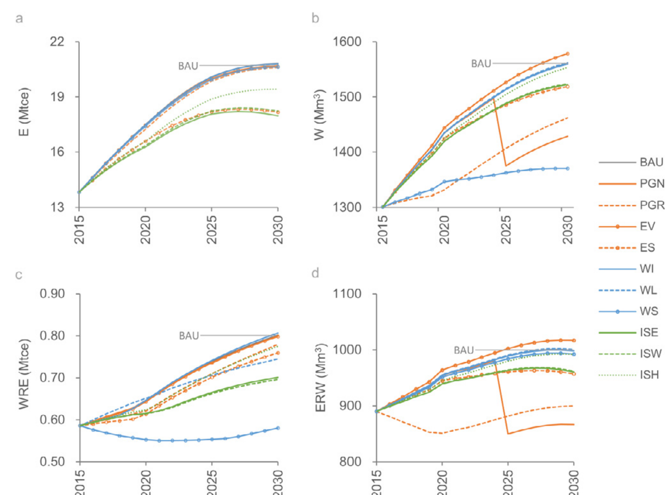

Fig. 5. Overall trends in total energy consumption (E), total water withdrawal (W), water-related energy consumption (WRE), and energy-related water withdrawal (ERW) under different scenarios
Note: BAU is "business-as-usual"; PGN and PGR are power generation using increased sources of natural gas and maximizing renewable energy, respectively; ES and WS are energy savings and water savings, respectively; WI and WL are imported water and water sourced locally, respectively; ISE, ISW, and ISH are industry structure adjustments oriented toward energy savings, water savings, and increasing the proportion of high-tech industries, respectively; and EV is increased use of electric vehicles.

based perspective, water end-use and water supply contributed most to WRE in the base year (46% and 45%, respectively) (Fig. 4). The majority of WRE, 76.92%, was used inside the city boundary. Energy supply was the largest contributor to ERW in the energy chain (96.92%) in 2015. And similar to WRE, most of ERW (88.03%) was also used inside the city boundary.

4.2. Overall trend of water-energy nexus under different scenarios

Eleven scenarios were simulated by the WEN-Xiamen model. Fig. 5 shows the results of total energy consumption by the urban energy system (E), total water withdrawal by the urban water system (W), WRE consumption and ERW withdrawal. In the BAU scenario, E and W are projected to increase 1.51 and 1.20-fold, respectively, from 2015 to 2030. There is an upward trend in E in all scenarios (Fig. 5a), but the growth rate slows down after 2025. The industry structure adjustment scenarios (ISE, ISW, and ISH) and energy-saving scenario (ES) have more energy-saving potentials than the others. W shows an upward trend similar to that of E in most scenarios except for PGN (Fig. 5b). Under the PGN scenario, W would be expected to plunge in 2025 if coal power generation capacities are replaced by natural gas power generation, which has a much smaller cooling water intensity. In 2030, the PGN, PGR, and WS scenarios show more water-saving effects than the others. All scenarios except WS show increasing WRE consumption trends from 2015 to 2030 (Fig. 5c). The WS scenario has the largest WRE saving effect, followed by ISE and ISW. All scenarios except PGN and

PGR show increasing ERW withdrawal trends from 2015 to 2030 (Fig. 5d). PGN and PGR exert the largest effects on ERW savings, followed by EV, ISE, and ISW.

It is worth mentioning that the EV scenario results in higher W and ERW withdrawal than the BAU scenario due to increased electricity imports, which require additional cooling water. The ISH scenario has less of a saving effect on E, W, WRE, and ERW than the other two industry structure adjustment scenarios (ISE and ISW), because Xiamen's high-tech industry is either water-intensive (such as in the manufacture of pharmaceutical products) or relatively energy-intensive (such as in the manufacture of electrical equipment).

4.3. Identifying the WRE-saving and ERW-saving effects of different scenarios

The potential reductions in WRE consumption and ERW withdrawal by 2030 under different scenarios, as compared to the BAU scenario, from both a process perspective and a boundary perspective are shown in Fig. 6. The potential savings in WRE consumption under most scenarios lies in the water supply stage, except under the ES scenarios (Fig. 6a). This is because the supply side is driven by demand, so a decrease in water demand leads to a decrease in supplied water and the WRE of water supply. In terms of geographic boundary (Fig. 6b), more WRE savings occur outside the city under the water supply scenarios (WI and WL) and the industry structure adjustment scenarios (ISE, ISW, and ISH). Most scenarios lead to large potential ERW withdrawal savings on the supply side, except for the WS scenario, because energy demand management affects water supply (Fig. 6c). In terms of geographic boundary (Fig. 6d), most scenarios overwhelmingly lead to potential ERW savings outside the city due to a large proportion of imported electricity, except in local energy supply scenarios (PGN and PGR). Overall, most potential savings in WRE and ERW lie on the supply side, except for in the demand management scenarios (ES and WS), and most scenarios have larger trans-boundary effects than in-boundary effects due to the import of large quantities of energy and water. It's notable that WRE is projected to increase under the WI scenario and that the EV scenario is projected to increase ERW outside the city.

4.4. Trade-offs and co-benefits of different scenarios

The interactions among potential savings in E, W, WRE consumption, and ERW withdrawal under different scenarios by 2030, compared to the BAU scenario, are shown in Fig. 7. For comparison, the values are standardized by the maximum value of each category of resource-saving effects. Only two industry adjustment scenarios (ISE and ISW) and the ES scenario have weak co-benefits in terms of E and W savings (Fig. 7a). Other scenarios tend to have one main savings effect: the ISH scenario mainly saves energy, while the energy supply scenarios (PGR and PGN) and the WS scenario mainly save water. The WI and WL water supply scenarios have little effect on energy and water savings. Only two industry adjustment scenarios (ISE and ISW) and the ES scenario have strong synergistic effects on WRE consumption and ERW withdrawal

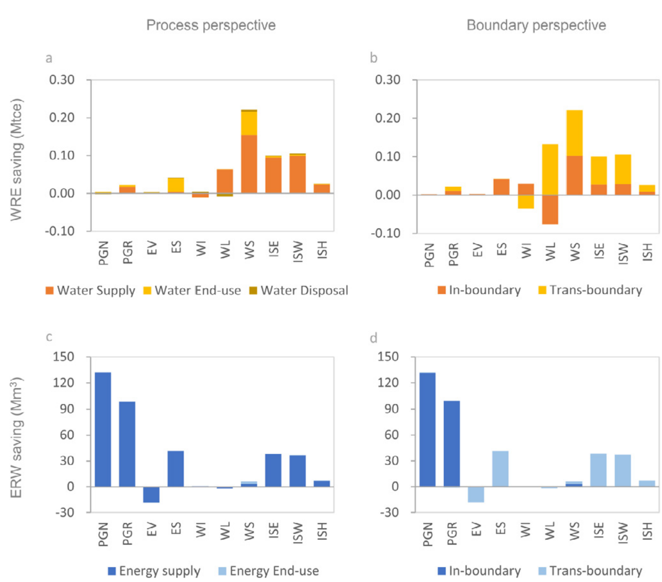

Fig. 6. Savings of total energy consumption (E), total water withdrawal (W), water-related energy consumption (WRE), and energy-related water withdrawal (ERW) under different scenarios by 2030 compared with the Business-as-usual (BAU) scenario, both in-boundary and trans-boundary

Note: PGN and PGR are power generation using increased sources of natural gas and maximizing renewable energy, respectively; ES and WS are energy savings and water savings, respectively; WI and WL are imported water and water sourced locally, respectively; ISE, ISW, and ISH are industry structure adjustments oriented toward energy savings, water savings, and increasing the proportion of high-tech industries, respectively; and EV is increased use of electric vehicles.

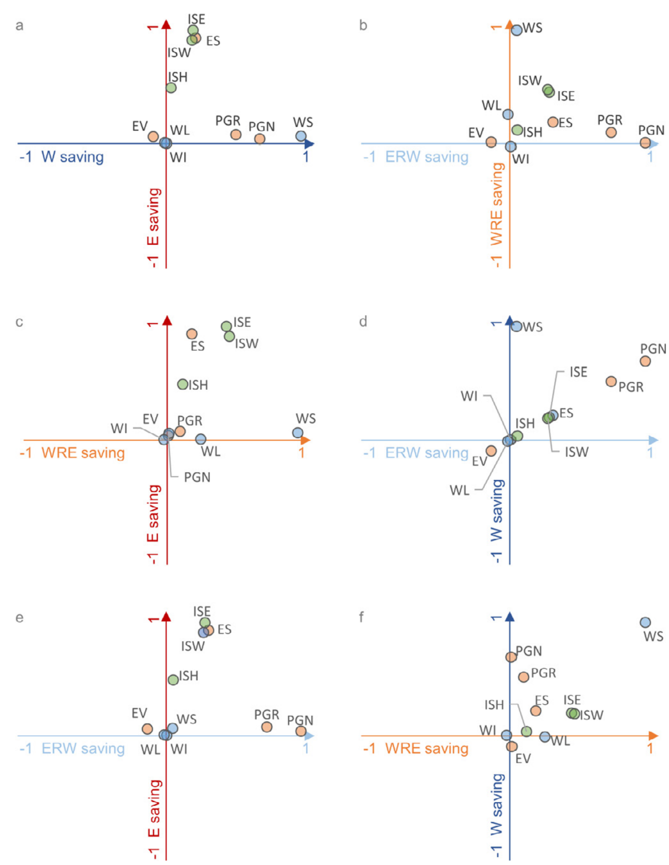

Fig. 7. The trade-offs and co-benefits of potential savings in total energy consumption (E), total water withdrawal (W), water-related energy consumption (WRE), and energy-related water withdrawal (ERW) under different scenarios. The values are standardized by the maximum value of each category of resource-saving effects.

Note: PGN and PGR are power generation using increased sources of natural gas and maximizing renewable energy, respectively; ES and WS are energy savings and water savings, respectively; WI and WL are imported water and water sourced locally, respectively; ISE, ISW, and ISH are industry structure adjustments oriented toward energy savings, water savings, and increasing the proportion of high-tech industries, respectively; and EV is increased use of electric vehicles.

savings (Fig. 7b). The energy supply scenarios (PGR and PGN) mainly have ERW savings effects, while the WS, WL, and ISH scenarios mainly have saving effects on WRE. The WS scenario has little effect on E savings but has a large effect on WRE savings (Fig. 7a and b). The EV scenario has little effect on either E or WRE savings, but increases ERW withdrawal, which in turn increases W.

Most scenarios, except for the water supply and saving scenarios (WL, WI, and WS), produce simultaneous savings benefits in both E and WRE (Fig. 7c). In these latter scenarios, this suggests that WRE savings do not result in E savings. Most scenarios, except for WS, produced savings in both E and ERW (Fig. 7d). As discussed above, some water management strategies, such as WS, produce remarkable WRE savings, but they only have a slight impact on E. In contrast, some energy management strategies, such as PGR and PGN, produce significant effects on ERW and W. The reason for this difference is that WRE accounts for only 2.81–4.18% of E in 2030, while the proportion of ERW to W ranges from 60.68 to 72.43%. This suggests that scenarios that achieve energy savings have a greater impact on W than scenarios that achieve water savings have on E.

The demand-side management scenarios have different co-benefits for E and ERW savings, while the supply-side management scenarios (PGN, PGR, WI, and WL) tend to have little effect on energy savings (Fig. 7e). The demand-side management scenarios show diverse synergistic effects on W and WRE savings (Fig. 7e).

Fig. 8. Overall trends in WRE and ERW structures under different scenarios. The figure shows the base year 2015 and projected values for 2030 under the different scenarios. *Note: PGN and PGR are power generation using increased sources of natural gas and maximizing renewable energy, respectively; ES and WS are energy savings and water savings, respectively; WI and WL are imported water and water sourced locally, respectively; ISE, ISW, and ISH are industry structure adjustments oriented toward energy savings, water savings, and increasing the proportion of high-tech industries, respectively; and EV is increased use of electric vehicles.*

5. Discussion

5.1. Research boundaries

Cities are characterized by concentrated resource consumption, a large proportion of trans-boundary resource consumption, and the environmental impacts related to these activities (Ramaswami et al., 2012). In Xiamen, trans-boundary WRE and ERW accounted for 23.08% and 11.97% of total WRE and ERW in 2015, respectively. To identify different impacts, calculations of urban carbon footprint consider three categories (Lin et al., 2013): Scope 1 includes emissions emanating directly from inside city boundaries, Scope 2 includes indirect emissions from power sourced outside the city boundaries, Scope 3 includes other indirect and embodied emissions that occur outside the city boundary. Similar to such carbon accounting scopes, the WRE can be evaluated by considering three scopes: Scope 1 includes direct energy use for water inside a city, Scope 2 includes indirect energy use for importation of water from outside city boundaries, and Scope 3 includes other indirect and embodied energy used for water, such as the embodied energy for water infrastructures (Kahrl and Roland-Holst, 2008). The ERW can also be evaluated in a similar way: Scope 1 includes direct water use for energy inside a city, Scope 2 includes indirect water use for importation of electricity from outside a city, and Scope 3 includes other indirect and embodied sources of water used for energy, such as the water used in oil and gas production outside a city. In this paper, only Scope 1 and Scope 2 were calculated for WRE and ERW, but calculations of all three scopes may provide a better understanding of WEN.

Using this categorization process, energy and water use processes are divided into supply and end-use stages, plus an additional disposal stage for water. Water for energy supply and energy for water supply or disposal are typically included in WEN research (Kelly and Michael, 2012; Li et al., 2016), while little attention has been paid to end-use processes. However, the end-use stage is non-negligible and it has been reported that more than 90% of energy for water is consumed in the end-use stage in Dutch households (Gerbens-Leenes, 2016). In Xiamen, the end-use stage accounts for 39.80% of total WRE (Fig. 8), while the proportion of ERW withdrawal is much lower (3.08%). WEN is broken down into two types, an "interactive link" and "connected link," as defined in Section 2.1, which are based on service purpose (Kyle et al., 2016).

The former represents using water or energy to produce another resource's service, such as water withdrawn for energy production (like cooling water for electricity generation). Another example is the energy consumed for direct water service processes (abstraction, treatment, distribution, wastewater collection, and treatment), in which water is the final product. The latter, the "connected link," represents the processes in which energy and water are connected in some devices, but the final purpose of the energy and water is to provide other services like clothes washing. The "interactive link" mainly occurs during the supply stage, while the "connected link" coincides with the relationship of water and energy during the consumption stage.

Another issue to consider is which water sources should be included in WEN research. First, the differences between withdrawn and consumed water resources must be distinguished. Generally, withdrawn water includes water taken from its source and used for certain purpose, while consumed water includes water that is permanently removed from its source due to evaporation, transpiration, or incorporation into products (Vickers, 1999). This study only considered withdrawn water due to data availability, although some studies on water for energy have evaluated both (Peer and Sanders, 2016; Sattler et al., 2012). The second issue in water calculations is whether sea water should be included. The final decision depends on the energy intensity of various water source mix solutions, with sea water an undoubtedly important and energy-intensive water source (due to desalination) in some cities which will become increasingly important in the future. Water-scarce coastal cities like Xiamen must rely on either water diversion or local unconventional water resources (e.g. seawater desalination) to meet its water demands, which are the WI and WL scenarios described in this study, respectively. Our results show that the WL scenario requires 7.68% less WRE than the WI scenario in Xiamen by 2030.

Table 4
Best practices for achieving different management objectives.

	In-boundary & Trans-boundary		In-boundary	
	WRE saving	ERW saving	WRE saving	ERW saving
Supply side	PGR + PGN + WL	PGN + PGR + WI	PGR + PGN + WI	PGN + PGR + WI
Demand side	ES + WS + ISW + EV	ES + WS + ISE	ES + WS + ISW + EV	ES + WS

5.2. Best practices and policy implications

Eleven different scenarios were designed to analyze the impacts of different factors on the WEN of Xiamen, China, from both supply-side and demand-side management perspectives (Table 3). Here, the best practices to achieve specific management objectives are proposed for Xiamen's WEN (Table 4). To minimize WRE, the best combination of practices includes: further development of renewable energy and natural gas production, increased use of local water resources, energy savings, water savings, increased use of electric vehicles, and adjustments to the structure of water-saving oriented industries. When the objective is to minimize ERW, we recommend increasing the use of imported water and adjustments to the structure of energy-saving oriented industries. In addition, different combinations of practices are recommended when only in-boundary resource consumption is considered.

From the energy supply-side management perspective, developing local renewable energy and replacing coal plants with natural gas facilities can save both WRE and ERW, but especially ERW. Regardless of the energy and water benefits of renewable energy development, it is difficult to develop large-scale local renewable energies in Xiamen due to geographical conditions and land resource constraints (Lin et al., 2018). For example, Xiamen has little space available for wind energy development and can only develop solar energy on a limited number of building roofs, despite the city's relative abundance of solar radiation. The relatively high price of natural gas also presents a barrier to natural gas development; as a result, the proportion of natural gas use in Xiamen was only 5.54% in 2015, compared with the world average of 23.85%. From the water supply-side management perspective, developing local water resources will save more WRE than importing water into Xiamen. However, importing water would become a better option only when considering the in-boundary impacts. Increased water imports in Xiamen would shift the local water burden and related energy burden to adjacent areas in Fujian Province.

From the energy demand-side management perspective, energy-saving measures provide co-benefits in terms of both WRE and ERW savings. However, promoting electric vehicles requires more ERW because of increased electricity use, which is mostly imported from outside the city. Shifting Xiamen's local energy burden, as well as its related water burden, to Fujian Province would be an acceptable choice because Fujian has a relatively large supply of energy and water. In contrast, in water-scarce Northern China, the development of electric vehicles requires careful consideration because it would create a resource transfer problem in the form of increased electricity and related water use. From the water demand-side management perspective, energy-saving measures have a large effect on WRE, both in-boundary and trans-boundary.

From both energy and water demand-side management perspectives, adjustments to the structure of the manufacturing industry have a large impact on energy and water savings, because energy and water consumption are driven by economic activities, especially resource-intensive production activities. Adjustments to industry structures that are designed to save energy and water have positive synergistic effects on WRE and ERW conservation, but only a small effect is produced by adjustments to high-tech industries in Xiamen since high-tech industries tend to be energy- or water-intensive. These energy and water effects may be in-boundary or trans-boundary, so an industry's local resource needs and potential for external resource transfer should also be considered when planning future urban industrial developments.

Overall, because cities are heavy downstream consumers of resources, demand-side management considerations should be emphasized in urban WEN research and management. Moreover, water and energy resources, as well as their nexus, are perpetually influenced and driven by the demand side.

6. Conclusions

In this paper, a fully-coupled model for urban water-energy nexus is built based on LEAP and WEAP tools, and scenario analysis is applied to explore the impacts of different related measurements in the future from both supply and demand sides. Both water-related energy (WRE) and energy-related water (ERW), rather than only one aspect in previous studies, are examined to provide a better understanding of interaction and feedbacks between water and energy.

The case study of Xiamen suggests that WRE saving and ERW saving lies more on supply side rather than demand side except for demand management scenarios. In terms of geographic boundary, most scenarios have larger trans-boundary WRE or ERW saving effects than in-boundary saving effects due to much imported energy and water. Regarding energy or water saving effect, there are prominent co-benefits in energy and water saving oriented industrial structure scenarios, and in energy saving scenario. Developing electric vehicles might require more ERW and developing high-tech industries might increase energy or water demand. The trade-offs and co-benefits of the scenarios were also analyzed, which shows that the choice of management measures varies with the management objectives, either WRE minimizing or ERW minimizing. Thus, we developed a set of best practice based on the results of scenario analysis.

To promote more comparable researches, research boundaries, including research scopes, processes, water types and sources should be paid more attention in future study. Despite that the LEAP-WEAP method is flexible in data requirement and modeling framework, it is relatively weak in feedback simulation compared to System Dynamic model. Research uncertainties mainly come from intensity parameters (water for energy or energy for water), which are drawn from literature or estimated based on engineering reports. The proposed approach can comprehensively reveal urban water and energy relationships, and address future energy and water challenges simultaneously.

Declarations of interest

None.

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