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Water Energy Nexus in City and Hinterlands: Multi-Regional Physical Input-Output Analysis for Hong Kong and South China

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Abstract

Most cities import energy and water from their hinterlands. Both the nexus in a city and that between the city and its hinterlands should be considered for comprehensive management of water and energy. To examine the water-energy nexus associated with the city embedded in the hinterland, a city-hinterland water-energy mixed-unit input-output methodology is proposed to model the effects of growth under different water and energy production and consumption scenarios based on the growth of the demands for water and energy resources from the city. This study presents a demonstration of the water-energy mixed-unit input-output approach by analyzing Hong Kong and its associated hinterland in mainland China. A Sankey diagram and several indicators have been presented to illustrate the water–energy nexus in 2015, as well as the nexus for future city growth and the nexus incorporating the water and energy infrastructures planned in Hong Kong. Several indicators in the results compare the interaction between water and energy systems and the dependence on hinterland for different scenarios in Hong Kong. The modeling outcomes show that the current water infrastructures might be able to meet the demand for water treatment in 2050. The indicators obtained from this study suggest that all types of water for energy and energy for water will increase by 7.8%–9%.

Keywords: water–energy nexus, city, hinterland, input–output analysis, Sankey diagram

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1. Introduction

Anthropogenic metabolism of water requires significant amounts of energy. Approximately 7% of the commercial energy generated worldwide is used for the anthropogenic water cycle, including the processes of water supply, distribution, and wastewater treatment [1]. Cities are in need of water and energy because of high population density and various economic activities. To meet this demand, infrastructure is built in and outside of cities to supply water and energy. The infrastructure for water and energy makes the system of anthropogenic water and energy flows highly interconnected. Majority of the demand for water is met by the hinterlands. Pumping water from a distant source is a very energy-intensive activity. The different types of energy imported from outside the city also have diverse levels of embodied water footprints [2,3]. Well-structured frameworks are required to analyze the complex system of the water-energy nexus, not only within the city but also between the city and the hinterland.

The water-energy system is complex and dynamic [4]. Changes in certain factors, such as climate, energy price, technologies, and population, impact the balance of supply and demand in a city. When one of the factors changes, most of the activities relevant to the water or energy flows may change owing to their complex interactions for urban activities. To examine a city’s resilience regarding the supply and demand balance for water and energy, integrated models that can reflect the effects of changes in the environmental, economic, and social factors on entire systems [1,5] are required. So far, the majority of studies on the water-energy nexus have focused on specific sets of water or energy facilities [6]. Only a minority of research studies have examined the underlying complex interactions between water and energy in urban water systems [7]. In recent years, increasing number of studies are developing models to capture a holistic view of the water–energy nexus system at different scales and over different scopes.

The analysis of water-energy nexus systems involves explicit description and modeling of the complicated links between water and energy systems. Sankey diagrams have been used as static models to illustrate the systems of water–energy nexus. The interwoven flows of water and energy can be examined quickly with their corresponding magnitudes represented by the thickness of arrows in the diagrams. Sankey diagrams for water–energy nexus can be found in several national or regional studies [4,8,9]. To design resilient and efficient water–energy systems in a city, decision makers would need tools to analyze and compare the balance of systems based on different development scenarios which adopt different designs or under various environmental and socio–economic stresses. More specifically, the tools should be able to model water uses, water technologies, and water resources in an integrated manner [10]. Similarly, the energy implications should be analyzed. Several integrated modeling approaches have been employed in water–energy nexus studies, including the dynamic equilibrium model, data envelopment analysis, and input–output analysis [11].

Studies employing the models based on input–output analysis (IOA) are dominant in the literature working on integrated systems models for water–energy nexus. Table 1 lists the IOA based studies from 2013 to 2017. Only a few studies implemented the analysis at city level, and most of them take Beijing as the study area. There are two widely used IOA approaches, the approach with monetary units and the one with physical units. The IOA using more than one kind of units is called mixed–unit input–output (MUIO) analysis. Hawkins et al. created the MUIO model by augmenting economic input-output model with material flow model [20,21]. MUIO models feature the capability to tack material flows more explicitly than the conventional monetary IOA. Hawkins' MUIO models can estimate the changes in the concerned material flows throughout the economy as well as the changes in the transaction of other material and services in the monetary unit in response to the change in any monetary or material demand.

Although the direct linkages of water-energy nexus are the physical flows of water and energy, the mainstream IOA studies for the water–energy nexus adopt monetary–based approach to estimate the physical linkages based on monetary flows. This is because monetary input–output tables are already compiled by the government and contain rich information regarding indirect linkages due to the transaction of non–water and non–energy products. The way to account for physical flows lies in the linear correlation of each sector's monetary output with associated energy and water flows. The water and energy intensities or coefficients are widely used in monetary studies. Recent studies have demonstrated that monetary IOA is powerful to characterize the interaction between sectors of water and energy services and the sectors simply consuming water and energy at national scale. Water footprint and cumulative energy use of a sector can be estimated by summing up the direct and indirect linkages through the Leontief model [18]. However, the approach based on monetary IOA involves several sources of uncertainty that the bottom-up inventory approach can address.

Table 1. Comparison of literature using input – output analysis based method for water–energy nexus.

Studies	Scope	Linkage analysis	Physical flows	Nexus Illustration
Fang and Chen, 2017 [6]	City (Beijing)	30 sectors monetary IO table based on 2007 data	Estimation based on energy and water coefficients	Backward and forward linkages of sectors
Wang et al, 2017 [12]	State (China)	30 regions multi–regional IO table	Estimation based on energy and water intensities	Embodied water–energy flows among regions within China
Wang et al, 2017 [13]	City (Beijing)	8 sector monetary IO table based on 2012 data	Estimation based on energy and water intensities	Hybrid water and energy
Duan and Chen, 2017 [14]	State (China)	Mixed–unit IO table with 30 monetary sectors 2 water physical sectors based on 2010 data	Estimation based on water coefficients	Pair–wise comparison of energy–water nexus due to the trade between 14 economies
Sherwood et al., 2017 [15]	382 Counties in the U.S.	428 sectors national IO table based on 2002 data	FAO* and EIO–LCA data, not accounting for regional differences	Ranking of counties' food, energy and water requirements
Wang and Chen, 2016 [2]	Province and cities (Beijing–Tianjin–Hebei)	30 sectors multi–regional input–output table based on 2007 data	Estimation based on energy and water intensities	Hybrid water and hybrid energy flows
Duan and Chen, 2016 [16]	City (Beijing)	Mixed–unit IO table with 30 monetary sectors 2 water physical sectors based on 2010 data	Water use coefficients for monetary sectors is based on National census data	Not included
Chen and Chen, 2016 [17]	City (Beijing)	8 sectors monetary IO table based on 2008 data	Estimation based on energy and water intensities	Water nexus model and energy nexus model
Liu et al., 2016 [9]	Global and regional level	Energy for water	Data from FAO & AQUASTAT and energy intensities	Diagram of energy for water
Okadera et al., 2015 [18]	Province (Liaoning in China)	36 sectors regional input–output table based on 2002 data	Water footprint based on water intensities of sectors	Not included
Qin et al., 2015 [8]	State (China)	Water from sources through energy processing processes to sinks	Data from various sources	Diagrams of energy flows and water for energy
Fulton and Cooley, 2015 [3]	State (California)	Not included	Estimation based on Energy related water footprint factor	Energy flow diagram
Feng et al., 2014 [19]	State (China)	135 sectors monetary IO table based on 2007 data	US Department of Energy's water for hydropower estimation and China Energy Statistical Yearbook	Map of regional electricity fuel mix and degree of water stress
Curmi et al, 2013 [4]	State (California)	Flows of water from source to services	Based on rich available data	Sankey for water only

*FAO is the abbreviation for the Food and Agriculture Organization of the United Nations

For applications in planning future urban water–energy systems, the analyses and modeling based on monetary–IO based approach are associated with several kinds of uncertainty [21]. First, sectors' water and energy coefficients on which the physical flows of IOA studies are based may not reflect the advancement of technology and infrastructure.

Second, the compilation of IO tables usually takes few years, which limits the availability of timely analysis. Thus, in the related literature, all monetary–IO method–based studies can only obtain the IO tables to represent the economy of more than five years before the publication, even up to 15 years, while the economic structure might have changed significantly by the time the audience reads the article. Third, the IO tables are aggregated at different levels. Usually, all types of energy facilities are aggregated in one sector, so are the water facilities. Thus, it might be difficult for regional IO based studies to detail the flows associated with the actual water and energy facilities in a city. Forth, most of regional or city level IO tables are derived from a national IO table through the allocation of national flows and updated to include the input coefficients based on regional economic statistics. The estimation of regional flows also causes uncertainty [22,23].

The bottom–up approach that surveyed the physical flows of water–energy nexus might elaborate on more details at city level and avoid the uncertainties of monetary IO based methods. Few studies analyze city level water–energy nexus with the linkage of physical inputs and outputs. A study based on Beijing compiled a MUIO table that has water production sector and distribution sector using physical units [16]. The linkage associated with the rest of 30 sectors are still based on the monetary flows. The aggregated physical sectors provide little information about the energy and water infrastructure in a city. To make IOA based model a tool for real application at the city level for water and energy planning and management, the sectors of the IO table should be customized to depict the specific processes in city and its hinterlands. Linkage analysis between relevant water–energy processes would be more reliable if models can use the data of surveyed local flows. However, the availability of local data and lack of a general method to compile physical flows based on IO tables make it a challenge to implement city level analysis based on physical IOA.

To demonstrate the feasibility and practicability of analyzing city level water–energy nexus based on physical flows, this article introduced the method, as well as the results and implications derived from a Hong Kong case study. Facing the need to plan the city's water and energy systems for the future, this study aims to characterize the flows and direct linkages of the water–energy nexus in a city and between its hinterland with the explicit elaboration of the relevant processes in the water and energy systems. In this paper, the Materials and Methods section introduces *a two–region water–energy mixed–unit input–output (WEMUIO) table and model* which enables modeling the effects of changing end–uses on water–energy systems. The Results section presents two Sankey diagrams to illustrate the two–region water–energy nexus system of Hong Kong and its hinterland for 2015 and 2050. Also, the influences of city's modifications of current and commissioning of new infrastructures are examined in the scenario analyses. Several water and energy indicators are used to quantify the energy used by the water system, water used by the energy systems, and the dependence on the resources purchased from the hinterland.

2. Materials and Methods

An accounting framework has been proposed to reflect the energy and water flow systems in both a city and its hinterlands. Each flow system contains the key processes from supply to demand. Moreover, the flows of the water–energy nexus are included in the accounting framework. Based on the relationships between the inputs and outputs for all processes, the IOA is employed to model the manner in which changes in demand and water–energy infrastructures affect resource efficiency and safety. The data describing the current situation of Hong Kong and its hinterlands in the Guangdong province located at the south of China was compiled.

2.1 Mixed–unit input–output analysis for the water–energy nexus

The accounting framework proposed herein for the water–energy nexus of an urban region and its hinterlands is a kind of multi–regional physical input–output table combining water flows and energy flows. Using input–output analysis framework, the changes in city's water and energy systems can be modeled as responses to the changes in demands or linkage between water and energy activities. As the framework illustrated in Fig. 1, a two–region water–energy mixed–unit input–output (WEMUIO) table records the annual flows of water and energy systems from sources through transformation and uses to sinks in a city and the nexus between water and energy system. The WEMUIO model is an adaptation and real implementation of the water–energy–food framework suggested by Karnib [24]. The adaptation is an expansion of hinterland sectors and elaborates on end–uses constituting the final demands. In contrast to other mainstream IOA methods in literature, the WEMUIO framework estimates the linkages of water and energy systems through a bottom-up inventory of physical flows rather than the outputs of sectors of monetary input-output tables. The linkage of water and energy systems is based on the bottom–up inventory of physical flows.

The two regions represent a city and the hinterland that offers the city water or energy. The upper left window–shaped quadrant consists of four rectangles, which record the water flows among relevant water sectors. The upper left rectangle represents the array of water flows in the city. The upper right rectangle represents the flows from the city to the hinterland. The lower left one indicates the water flows from the hinterland to the city. The lower right one represents the flows within the hinterland. The rest of the window–shaped quadrants in the WEMUIO table consist of similar sub–tables to describe the flows in the city, hinterland, and those between the city and the hinterland. In the upper left quadrant, the volume of water flow is measured in physical units such as million cubic meters (MCM). The quadrant on the upper right of the WEMUIO table also measures water flow by volume.

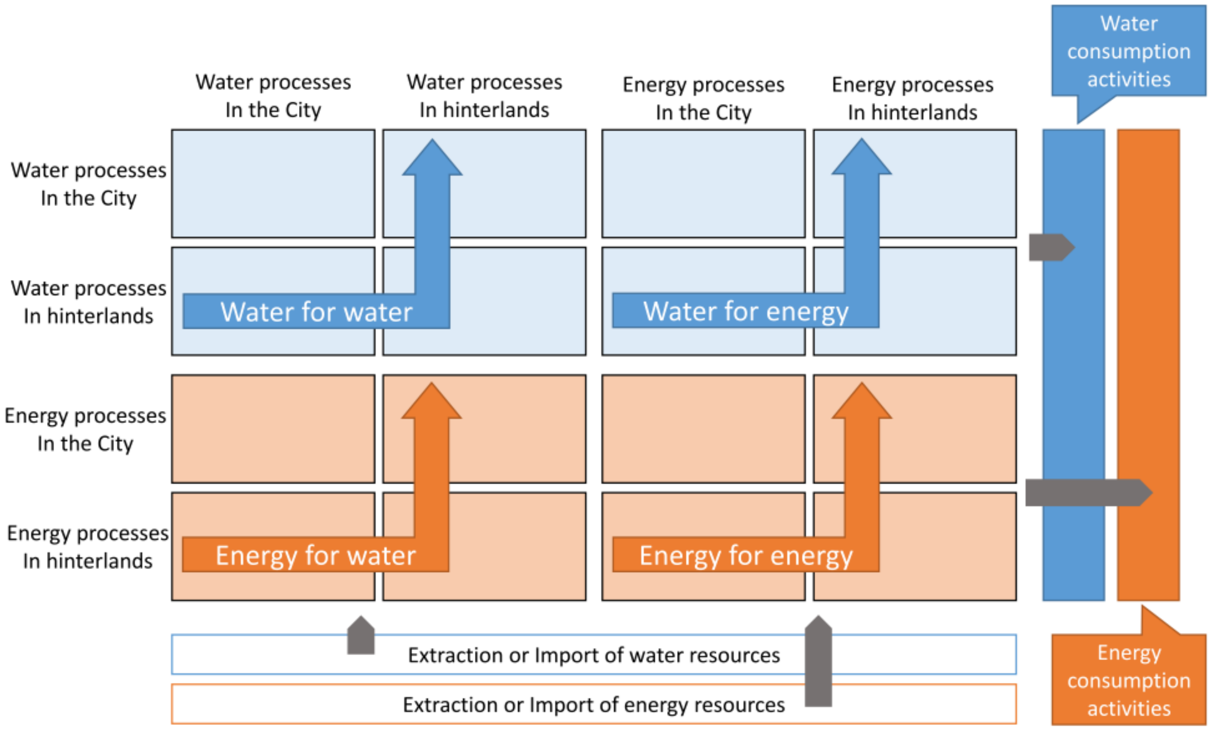

Figure 1. The framework of the two–region water–energy mixed unit input–output table.

The upper right quadrant elaborates on the water flows required by the energy systems. For example, the quantity of water used for power generation is specified in this quadrant. Similarly, the lower left quadrant elaborates on the energy flows required by the water system. For instance, the amount of electricity consumed for potable water supply and wastewater treatment are recorded in this quadrant. The lower right quadrant accounts for the energy flow in the energy sector, including energy supply, transformation, and consumption. The measurement for energy flows is based on unit for energy, such as terajoule (TJ). The water and energy sectors were selected for the design of the framework based on a review of the literature on comprehensive water–energy nexus systems [1,25,26]. Then, the processes not existing in the city can be excluded when designing the WEMUIO table.

The two vertical bars to the right of the four quadrants serve as final demand vectors in the input–output tables. The end–uses of water and energy are represented by the sectors in the two bars. The two horizontal bars underneath the four quadrants function similarly to the primary inputs in the input–output tables. The extraction of water resources or energy carriers from nature by the sectors is specified here. Moreover, the water and energy imported from places other than the hinterlands included in the WEMUIO table should be included under the primary input of the WEMUIO table. The final demand and the primary input arrays of the WEMUIO table allow for modeling end–uses as the drivers of energy and water service activities, and the demands for water and energy resources.

The water–energy nexus can be modeled by applying input–output analysis using the data structured in the proposed framework. The flows of the water–energy nexus can be represented in a tabulated form $\boldsymbol{Z}^*$ that concatenates the sub–matrices of the four quadrants, as expressed by Eq. (1). The superscript w indicates that the source or the destination of the flow is the water system. The superscript e refers to the energy system.

$$\boldsymbol{Z}^* = \begin{bmatrix} \boldsymbol{Z}^{w,w} & \boldsymbol{Z}^{w,e} \\ \boldsymbol{Z}^{e,w} & \boldsymbol{Z}^{e,e} \end{bmatrix} \tag{1}$$

$\boldsymbol{Z}^{w,w}$: Matrix of flows between sectors of water system

$\boldsymbol{Z}^{w,e}$: Matrix of flows from sectors of water system to those of energy system

$\boldsymbol{Z}^{e,w}$: Matrix of flows from sectors of energy system to those of water system

$\boldsymbol{Z}^{e,e}$: Matrix of flows between sectors of energy system

The vector $\boldsymbol{Y}^*$ is the summation of the final demands across end–use sectors of water and energy. The calculation is expressed by Eq. (2), in which m is the number of water end–use sectors; n is the number of energy end–use sectors, l is the number of all sectors in the water–energy nexus system, which is equivalent to the size of the matrix $\boldsymbol{Z}^*$.

$$\boldsymbol{Y}^* = \boldsymbol{Y}^w + \boldsymbol{Y}^e = \begin{bmatrix} \sum_{\boldsymbol{j=1}}^{\boldsymbol{m}} y_{1,j}^w \\ \vdots \\ \sum_{\boldsymbol{j=1}}^{\boldsymbol{m}} y_{l,j}^w \end{bmatrix} + \begin{bmatrix} \sum_{\boldsymbol{j=m+1}}^{\boldsymbol{m+n}} y_{1,j}^e \\ \vdots \\ \sum_{\boldsymbol{j=1}}^{\boldsymbol{m}} y_{l,j}^e \end{bmatrix} \tag{2}$$

Similar to the general input–output analysis, the output vector $\boldsymbol{X}^{*}$ of l sectors is the sum of intermediate flows among the water and energy systems and the flows to end–use sectors, as expressed by Eq. (3). The calculations of input coefficients follows Eq. (4), where $\boldsymbol{X}^{*\boldsymbol{diag}}$ represents the diagonalization matrix of the vector $\boldsymbol{X}^{*}$. By applying the Leontief model, the flow changes in the water–energy nexus systems $\boldsymbol{Z}^{*\prime}$ in response to changes in the end–uses of water and energy, as well as technological changes, can be estimated, as in Eq. (5), wherein the superscript $'$ indicates that the matrix or the vector is adjusted for analyzing a given scenario.

$$\boldsymbol{X}^{*} = \begin{bmatrix} \sum_{\boldsymbol{j=1}}^{\boldsymbol{l}} z_{1,j}^{*} \\ \vdots \\ \sum_{\boldsymbol{j=1}}^{\boldsymbol{l}} z_{l,j}^{*} \end{bmatrix} + \boldsymbol{Y}^{*} \tag{3}$$

$$\boldsymbol{A}^{*} = \boldsymbol{Z}^{*} \times (\boldsymbol{X}^{*\boldsymbol{diag}})^{\boldsymbol{-1}} \tag{4}$$

$$\boldsymbol{Z}^{*\prime} = (\boldsymbol{I} - \boldsymbol{A}^{*\prime})^{\boldsymbol{-1}} \times \boldsymbol{Y}^{*\prime\boldsymbol{diag}} \tag{5}$$

The model allows for estimation of the environmental impacts of water and energy systems, as long as the inventory of impacts of each water and energy sector is available. As the method used in environmentally extended input–output analysis, the intensity of the direct impact of each sector q_j^k is calculated using Eq. (6), where Q_j^k is the impact of sector j in a given year of inventory. The superscript k refers to the different impact categories being considered. For instance, the extraction of raw water, fossil fuels, emissions of GHGs, and discharge of water pollution can be the impact categories for WEMUIO modeling. The impacts across all water and energy sectors can be estimated using Eq. (7) [6,16].

$$q_j^k = \frac{Q_j^k}{x_j} \tag{6}$$

$$\boldsymbol{E^k} = \boldsymbol{q} \cdot \boldsymbol{X}^{*\prime} = \boldsymbol{q} \cdot (\boldsymbol{I} - \boldsymbol{A}^{*\prime})^{\boldsymbol{-1}} \times \boldsymbol{Y}^{*\prime} \tag{7}$$

2.2 Study area and scenarios for demonstration

The case study for demonstrating the features of the WEMUIO table is based on Hong

Kong which is a special administrative region of China. Among cities with populations greater than seven million worldwide, Hong Kong has the sixth highest population density [27]. The growing population and economic activities have increased the demands for water and energy. However, Hong Kong relies heavily on imported energy and freshwater, especially from the Guangdong province of China.

To meet the growing demands, Hong Kong needs more infrastructure for water and energy supply, as well as facilities for water reuse and recovery of energy. Hong Kong is a leading city for seawater toilet flushing, with coverage higher than 70%, which reduces the need for freshwater. In 2015, 77% of the city's freshwater supply came from the Dongjiang river in Guangdong; owing to the long–distance pumping involved in this supply system, the associated energy consumption is high. Water use in Hong Kong causes environmental impacts in Guangdong due to the additional energy use and freshwater collection infrastructure. The proposed method can reveal the potential pressures of supplying additional water and energy from the hinterlands to meet the city's demands. The Results section, holistically illustrates Hong Kong's water and energy flows and the water–energy nexus system.

In the face of the growing water and energy demands, Hong Kong has been developing resilient strategies and infrastructures for its water and energy systems. The potential future changes in the water and energy systems were considered in the models to evaluate their possible benefits and impacts. It was expected that the method might provide insights for determining which infrastructure or strategy should be put in place first for providing a more resilient and sustainable water energy service to a city and its hinterlands. The scenarios for modeling future water–energy nexus systems are listed as follows:

1. 10.6% population growth in 2050 and associated changes in water and energy consumption activities.
2. Commission of a desalination plant that can serve 10^8 cubic meters of water per year.
3. Energy recovery from wastewater, including biogas and sludge incinerator.
4. Water reclamation in one sewage treatment plant with tertiary treatment.

2.3 Data integration

To demonstrate the applicability of the proposed method, WEMUIO tables for Hong Kong and its hinterland Guangdong province were compiled. The data on water and energy flows were collected from reports prepared by government organizations and energy corporations:

- Water Supply Department: Water supply and consumption [28]
- Drainage Service Department: Wastewater treatment and water reuse [29]
- Electrical & Mechanical Services Department: Energy end–use [30]
- Census and Statistics Department: Hong Kong energy statistics [31]
- CLP Power Hong Kong Limited: Power generation and water for power generation [32]
- HK Electric Investments Limited: Power generation and water for power generation [33]
- Hong Kong and China Gas Company Limited: Gas supply and water for gas supply [34]

In the Hong Kong case study, the sectors of the WEMUIO table were selected according to the relevant sectors specified in the reports or data provided by the organizations and companies mentioned above. Table 2 lists the sectors of the water and the energy systems. Table 3 contains the end–use sectors of water and energy. The selection of the end–use sectors for the final demands of this case study is based on the most detailed description of the activities associated with water or energy flows in the reports of Hong Kong Water Supply Department, Drainage Service Department, Electrical & Mechanical Services Department, and the report of Hong Kong energy statistics [28-31]. The detailed classification of final demand sectors allows for modeling how the change in specific demand can drive the changes in the entire water-energy nexus systems. Moreover, a part of the water and energy sectors in Guangdong was included for illustrating the import of water and energy from the hinterland. The export of energy to the hinterland is included in the case study as well. Full life cycles of water and energy were considered. To ensure that the entire flow system is driven by end–uses, we modified the general alignment of flow entries in the input–output table. The entire WEMUIO table is placed in the supplementary material.

Table 2. Intermediate sectors of water and energy systems in the proposed Hong Kong model.

Sectors of water systems	**Sectors of energy systems**
HK* Freshwater supply	HK Imported coal
HK Seawater supply	HK Imported oil
HK Potable & reclaimed water supply	HK Imported gas

HK Desalination (Tseung Kwan O)	HK Domestic bioenergy
HK Seawater consumption	HK Power generation
HK Water reclamation	HK All power consumption
HK Wastewater treatment	HK Power system loss
HK Water leakage	HK Unleaded motor gasoline, kerosene, gas oil, diesel oil and naphtha use
HK Residential	HK Gas manufacture
HK Industrial	HK Residential
HK Service & trades	HK Industrial
HK Toilet	HK Service & trades
GD** Freshwater supply	GD Power generation
	GD All power consumption

* HK refers to the sectors in Hong Kong

** GD refers to the sectors within Guangdong, the hinterland of Hong Kong

In the general input–output table, one flow of wastewater into the wastewater treatment sector has entries at the intersection of the row of the corresponding water end–use and the column of wastewater treatment. Such a depiction may lead to confusion, with the water end–uses appearing to be driven by wastewater treatment in the Leontief model. Because the actual situation is that the volume of wastewater treated is driven by the amount of water used in end–uses, the row and column index of the entries of the flows to wastewater treatment were swapped. Thus, in the WEMUIO tables, these flows seem to be directed from wastewater treatment to different end–uses.

Table 3. Final demand sectors of water and energy systems in the proposed Hong Kong model.

Sectors of water end–uses	**Sectors of energy end–uses**
Residential	Cooking
Industrial	Air Conditioning
Service & Trades	Hot Water & Refrigeration
Toilet	Lighting
Government	Refrigeration
Construction & Shipping	Office Equipment
	Industrial Process/Equipment
	Others

	Street Lighting
	Transport Air
	Transport Road
	Transport Sea

Another feature of the WEMUIO table is that the residential, industrial, and service & trade sectors were considered as endogenous. This feature allows for more detailed elaboration on the end–uses of energy in the final demand sub–table. As shown in Table 3, cooking, air conditioning, lighting, and other energy end–uses determine the overall energy consumption of the three endogenous consumption sectors. A few sectors have both water and energy outputs; for example, wastewater treatment can recover energy from wastewater and reclaim water for non–potable uses. Hydropower stations as part of the freshwater supply system also generate water and electricity. Among all the flows from the water sectors that record the flow volume of water in the WEMUIO table, the sector generating electricity using the potential energy of water and the wastewater treatment sectors record the quantity of energy as well.

3. Results

3.1 HK nexus in 2015

The water–energy nexus of Hong Kong for 2015 was inventoried considering its interconnection with Guangdong province. Moreover, the water–energy nexus of 2050 based on the projected water and energy demands was modeled. The results are presented in Sankey diagrams for illustrating the complex water and energy systems in the city and its hinterlands.

Fig. 2 shows the water–energy nexus of Hong Kong in 2015. For the water systems, roughly 79% of the freshwater is imported from the Guangdong province. To reduce the demand for potable water, Hong Kong supplies treated seawater to cover up to 71% of the water demand for toilet flushing. The amounts of energy used for water supply in Hong Kong are 429 TJ for potable water and 378 TJ for seawater. In other words, 0.59% of the power generated in Hong Kong is used for water supply. This energy for water does not include the energy used to extract water from the source, i.e., the catchment of Dongjiang in Guangdong province. Since the data are limited, the energy required to lift upstream water by 46 meters in a gravity–fed water supply system was estimated. Assuming 60% pump efficiency, the electricity required for supplying water from Guangdong to Hong Kong is at least 576 TJ, which is higher than the power consumed by the water supply section in Hong Kong.

In terms of water consumption, most of the supplied water is consumed by the residential and the service & trade sectors. Only one–tenth of the potable water supply is used by the industrial sector. The portfolio of water consumption reflects the industrial structure of Hong Kong, in which the service and trade sectors dominate, accounting for at least 90% of Hong Kong’s GDP. Agriculture is excluded from this study because of the minimal amount of farming activities and farmlands in Hong Kong.

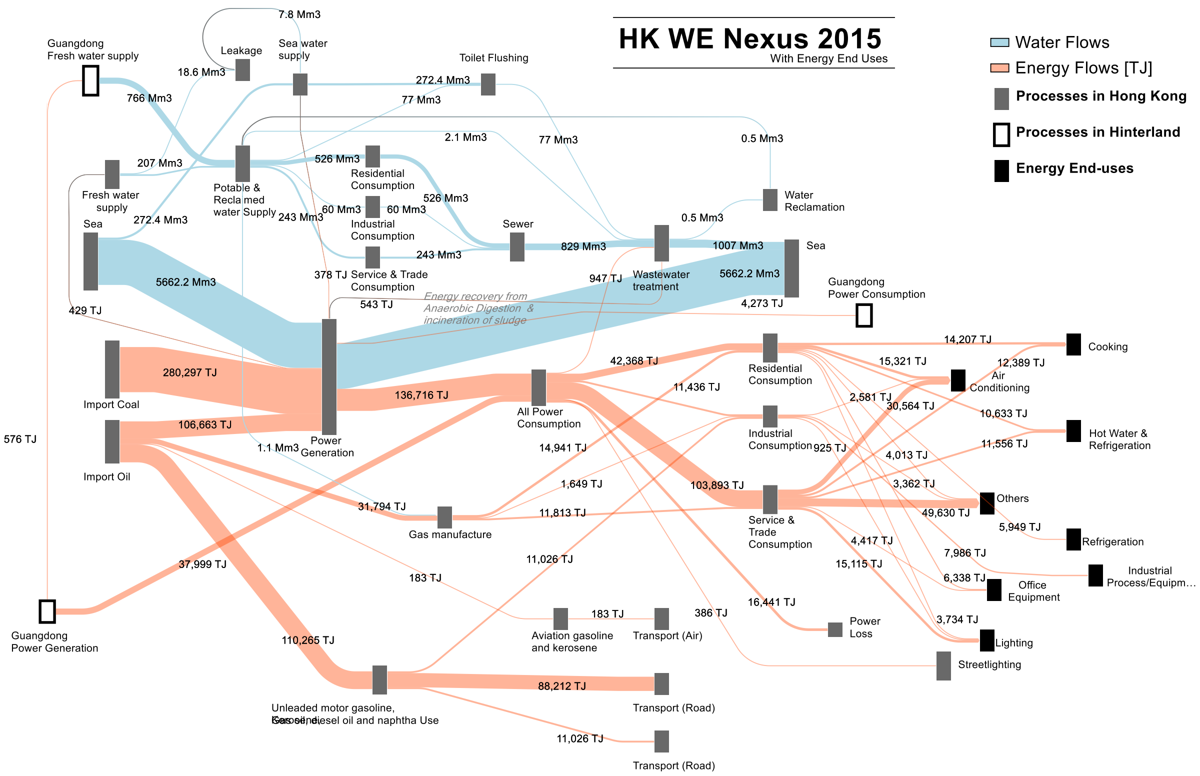

Fig 2. Hong Kong’s water–energy nexus with its hinterland.

Wastewater collection and treatment is an energy–intensive activity in Hong Kong. In 2015, electricity equivalent to 947 TJ was used for wastewater management, which is more than the energy used by the water supply system. The Drainage Service Department in Hong Kong has invested in energy recovery from wastewater. The biogas harvested from four wastewater treatment plants generated 107 TJ of electricity in 2015. A sludge incineration facility, namely T–Park, can generate 365 TJ per year from 43,800 tons of dry sludge.

By applying advanced technology, Hong Kong reclaimed 0.53 MCM of water from urban sewage. The reclaimed water is used for factory cleaning, garden irrigation, toilet flushing, and dilution in chemical processes. Hong Kong has created a plan for increasing water reuse. The capacity to reclaim wastewater might reach 21 MCM by 2022. In addition, Hong Kong is exploring a strategy to facilitate the introduction of greywater recycling and rainwater harvesting systems in new large–scale building projects. Data about decentralized water supply systems in Hong Kong are limited. Only one study has evaluated the energy efficiency of a greywater system in a 35–story residential building in Hong Kong [35].

The energy system is shown in the lower part of Fig. 2. The major energy throughputs are electricity from coal and oil–fired power plants, liquid petroleum gas (LPG), and oil products. Owing to insufficient power generation, Hong Kong imports electricity from mainland China to meet 21.7% of its power demand. Most of this electricity is consumed by the commercial sector, which used 2.44 times as much electricity as the residential sector. The system loss of electricity is 14,941 TJ, which is more than the demand of the industrial sector (11,436 TJ). The industrial sector in Hong Kong consumes considerably less electricity than the commercial and residential sectors; nonetheless, it dominates the consumption of oil products, including gas oil, diesel oil, and naphtha. The natural gas consumption is similar to that of electricity.

The water used for energy in Hong Kong has several links. The power stations withdrew 5662 MCM of seawater for power generation and returned it to the sea. This quantity is more than ten times the quantity of residential consumption. The coal–fired power plants in Hong Kong with an installed capacity of 6608 MW dominate the use of water for power generation among all types of power stations, including gas–fired and diesel–fired power stations. Hong Kong manufactures gas from imported oil products. The gas manufacturer used 1.1 MCM of water in 2015. Since there are no energy extraction activities and oil refinery industry in Hong Kong, this study only shows major water–energy nexus in Hong Kong. The end–uses of water and energy co–consumption are not within the scope of this study.

Our inventory of the water–energy nexus contains detailed information on the end–uses in three major sectors. Excluding the other unknown end–use types, air conditioning is the main driver of electricity in the residential sector and the service & trade sector. The second largest driver of electricity use in the service & trade sector is lighting. The power used for indoor lighting in the service & trade sectors is 51 times higher than the power used for street lighting. Cooking, too, results in significant energy consumption, and this can be ascribed to cooking at home and in restaurants. The major energy type used for cooking is natural gas or LPG and electricity, in that order. Electricity consumption covers only 23.8 % and 32.3% energy use in the residential and the trade & service sectors, respectively. The industrial sector uses energy mostly for the operation of processes and equipment. The amounts of energy used for office equipment, hot water, and refrigeration are shown in Fig. 3. The elaborately illustrated flows of energy end–uses provide the knowledge required to develop energy–saving strategies and technologies.

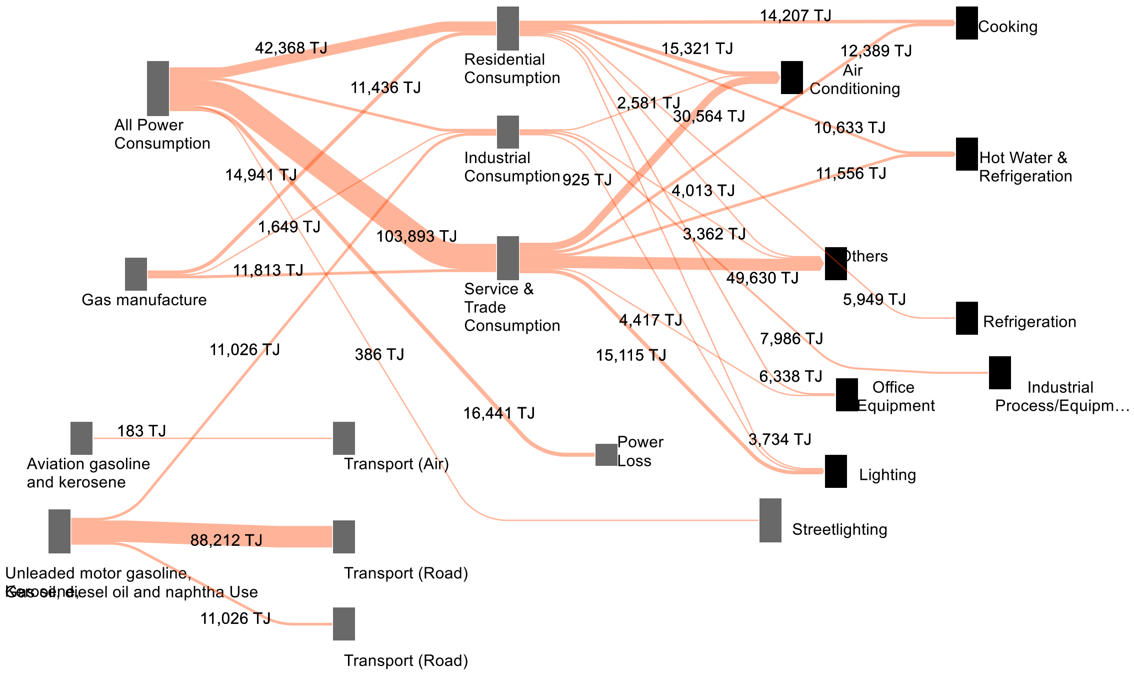

Fig. 3. End–uses of energy in Hong Kong, an extract of Fig. 2.

3.2 Pressure of population growth in 2050

Population growth leads to increased demand both for water and energy. By using the proposed WEMUIO method, the incremental pressure on the water and the energy systems was estimated. According to a projection by the HK government, the population in 2050 will be 10.57% higher than that of 2015 [31]. Assuming the same level of consumption per capita, the water required by the residential sector, service & trade sector, and toilet flushing would increase by 10.57%, as would the energy demand of the corresponding sectors. The results are shown in Fig. 4 and listed in Tables 4 and 5.

In the future, water services in Hong Kong will need to be expanded. The demand for potable water in 2050 is projected to increase to 91 MCM. If the water from local yield can reach an annual average of 295 MCM, then 768 MCM would be required to be imported from Guangdong, which is 2 MCM higher than the water purchased from Guangdong in 2015. The government of Guangdong province just capped annual freshwater extraction from Dongjiang at 10,664 MCM. The competition for Dongjiang's water resources among Hong Kong, Shenzhen, and other cities will intensify in the future. The annual volume of treatment of the existing water supply and wastewater treatment infrastructure will need to be increased by 5% and 9%, respectively.

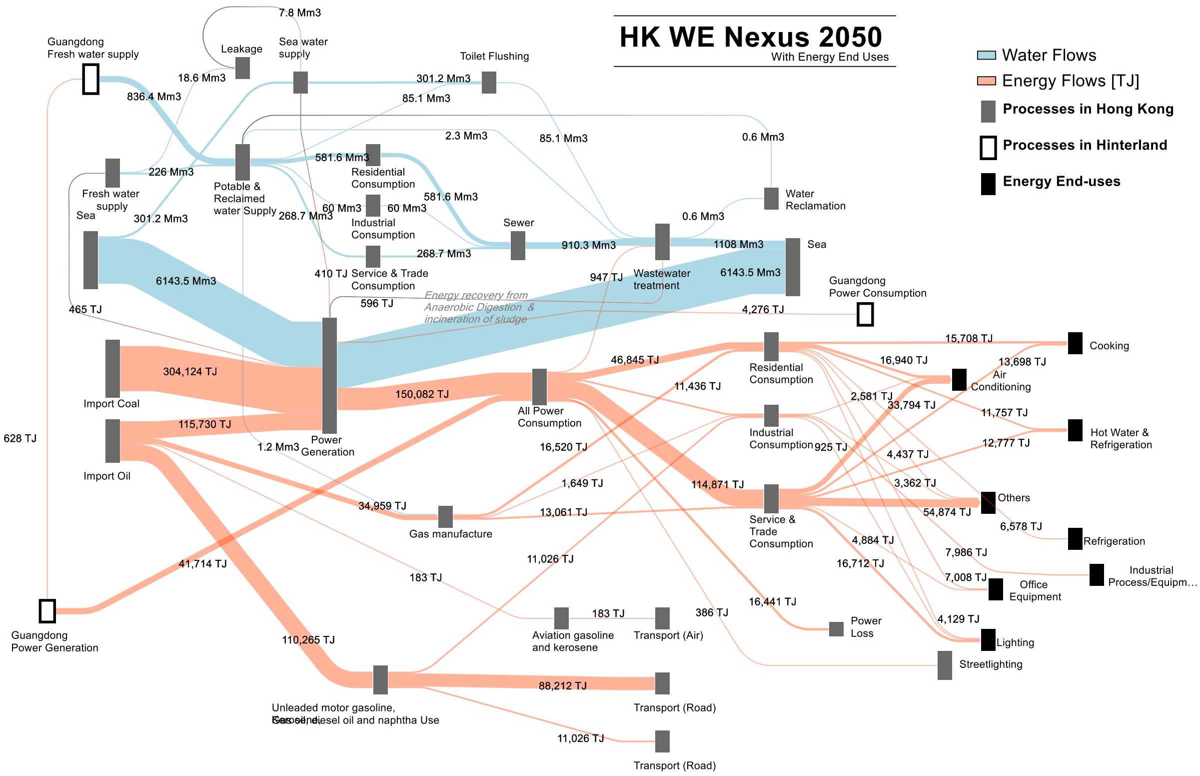

Fig 4. Projected water–energy nexus by 2050 based on population growth.

Table 4. Increasing demand for water services

	Availability / Capability	**Water service in 2015**	**Water service in 2050**	**Difference %**
Water resources				
Supply of potable water (MCM)		974	1063	8.42%
From natural catchment (MCM)	295	207	295	29.83%
From Dongjiang (MCM)	1100	766	768	0.26%
Water infrastructure				
Water treatment works (MCM)	1832	1740	1831	5.00%

Wastewater treatment works (MCM)	1837	1007	1107	9.02%

The estimated WEMUIO table facilitates the prediction of the water–energy nexus for the population in 2050. As shown in Table 5, all types of water for energy and energy for water will increase by 7.8%–9%. The power stations in Hong Kong use seawater for power generation. Therefore, the increasing demand for electricity has minor impact on the freshwater supply. The energy for water will increase in both Hong Kong and the hinterland Guangdong. In Hong Kong the increased demand for water will originate from increased energy needs for water conveyance, potable water treatment, and wastewater treatment; in Guangdong, more source water will be lifted to the aqueduct for satisfying Hong Kong's water consumption.

Table 5. Indicators of the water–energy nexus in Hong Kong and Hinterland

	WE nexus in 2015	**WE nexus in 2050**	**Difference %**
Water for Energy (MCM)			
All	5,663	6,145	7.84%
Freshwater	1.12	1.23	9.05%
Seawater	5,662	6,144	7.83%
Energy for Water (TJ)			
All	2,328	2,543	8.47%
Hong Kong	1,752	1,914	8.48%
Guangdong	576	628	8.42%

3.3 Improvements in water and energy systems

Many cities are changing their water system frameworks [36]. To meet future societal needs, Hong Kong has several infrastructure plans to ensure safe and efficient supply of water and energy in the future. The operational parameters of these water energy facilities have been incorporated into the scenario analysis based on the WEMUIO table. Thus, several indicators of the water–energy nexus systems can be examined. Four scenarios for four infrastructures to be built or upgraded were analyzed. The processes and the associated water and energy flows are illustrated in Fig. 5.

Scenario 1: Desalination plant at Tseung Kwan O, 270,000 cubic meters per day [28].

Scenario 2: Hydropower generation plant at Tuen Mun, 3,000,000 kWh/year [28].

Scenario 3: Water reclamation and greywater recycling through Shek Wu Hui and other sewage treatment works, 2.1 MCM/year [29].

Scenario 4: T–Park sludge treatment facility at Tuen Mun, power capacity of 2 terawatts [37].

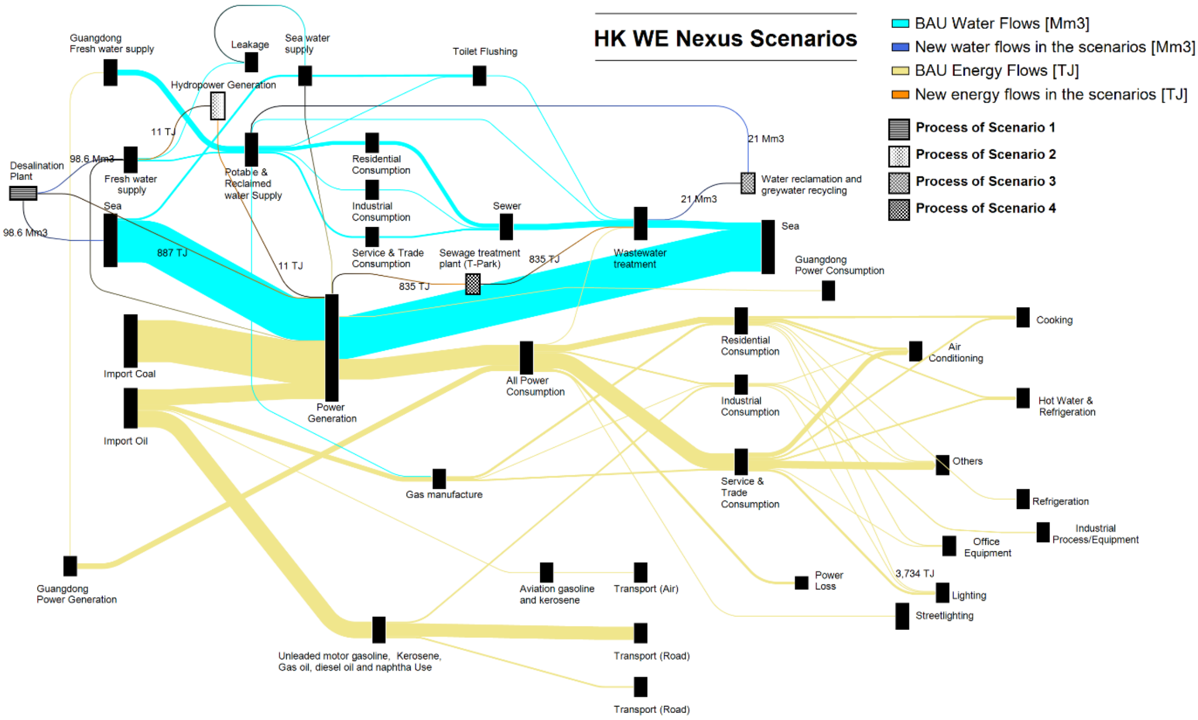

Fig 5. Processes and the associated water and energy flows of the four scenarios.

In the first scenario, a new reverse osmosis desalination plant would be built in Hong Kong. When the two–stage construction of the plant is finished, the domestic supply of potable water could increase to 6,267 MCM per year. In other words, reliance on the freshwater from Guangdong would decrease from 78.68% to 68.56%. The risk of competition with other cities needing water from Dongjiang could thus be reduced. The second scenario represents that a hydropower generation plant is going to contribute 10 TJ per year of electricity, equivalent to 1.84 % of the domestic energy from the water systems. The actual power generated depends on the water level of the upstream reservoir at Tuen Mun Water Treatment Work. To obtain more green energy, Hong Kong is installing additional floating solar PV panels on the surface of reservoirs.

The third scenario reflects the potential to reclaim water from sewage treatment works (STWs) using advanced tertiary treatment processes. The Shek Wu Hui STWs will provide 21

MCM of freshwater per year for non–potable uses. The water recycling rate of Hong Kong would increase from 0.015% to 0.584%. The energy for tertiary treatment is not included in this study because of the low water recycling rate and the lack of real site data. The fourth scenario includes the additional energy recovered from the sludge resulting from sewage treatment. Currently, the facility treats 1200 tons each day. If more sludge was to be delivered to Tuen Mun and the facility was to run at its full capacity of 2000 tons per day, the energy from water will increase by 53.8%, equivalent to the 0.08% of domestic power generation in Hong Kong.

The scenario analysis based on our approach can gain information of the implications for planning future water and energy systems. Looking at the results in Table 6, the desalination process will intensify the energy for water systems from 2,329 to 3,216 TJ. The price and carbon footprint of water supply would increase significantly. On the other hand, Hong Kong would recover energy from the sludge of sewage works. The energy from water will grow from 543 to 835 TJ when the sludge incinerator runs at its full capacity of 2000 tons per day. However, this part cannot compensate the energy demand of the desalination plant. In scenario 3, current plan to increase power supply from reservoirs has a negligible contribution to the total electricity demand. Similarly, the scheme to reclaim water reflected in the Scenario 3 has little contribution to the total water demand. Hong Kong needs more significant progress in increasing the water recycling rate, so as to alleviate the pressure on competing for the water from Dongjiang. Hong Kong has land limitation for the implementation of renewable energy options such as solar and wind farms. Thus, pervasive energy reduction in the major end–used sectors, as shown by the thick flows in Fig. 3, might lead to significant reduction in power demand.

Table 6. Comparison of scenarios to improve water and energy supply

	BAU **2015 Nexus**	**Scenario 1** **Desalination**	**Scenario 2** **Hydropower Generation Plant**	**Scenario 3** **Water Reclamation**	**Scenario 4** **Sludge Treatment Facility**
Water for Energy (MCM)	5,663	5,663	5,663	5,663	5,663
Energy for Water (TJ)	2,329	3,216*	2,329	2,329	2,329
Domestic Water Supply (MCM)	6,168	6,267*	6,168	6,168	6,168
Domestic Electricity Supply (TJ)	387,503	387,503	387,513*	387,503	387,795*

Water Recycling Rate %	0.015%	0.015%	0.015%	0.584%*	0.015%
Energy from Water (TJ)	543	543	553*	543	835*

Note: the calculated indicators with * are those different from the BAU 2015 scenario.

4. Discussion

This study demonstrates the feasibility and practicability of analyzing city level water–energy nexus based on physical flows of water and energy. The model based on the method of input–output analysis allows for illustrating the effect of end–uses as driving forces on the activities across the water and energy systems in a city. As distinct from using the monetary input–output table with environmentally extended accounts, including direct water and energy consumption across sectors, WEMUIO approach can avoid the uncertainty due to aggregation sectors, conversion of physical units to monetary units, and downscale or allocation of national physical accounts to the city level. The data used in the Sankey diagram figures and the model for scenarios were based on exact flows between the activities associated with relevant water and energy flows in Hong Kong. The flows between Hong Kong and the hinterland Guangdong were included as well. In this way, a systematic and holistic picture of the city–level water–energy nexus with exact water and energy flows can be presented for urban water and energy resource management.

4.1 Implications for water and energy management

For urban water and energy management, several implications can be drawn from the analyses based on the two–region WEMUIO table and modelling. First, the flows can be used to draw a Sankey diagram. When a city needs to plan for water and energy infrastructure in the future, a quantitative–based decision can be made based on the wide flows in the diagram, which represent the major supplies of and demands for water and energy. The flows of energy for the water system and the water required for the energy system can elucidate the potential impact of feedback effects between the water and energy systems, such as the increased energy demand due to an increase in the amount of water subjected to desalination treatment. Second, the effects of adding new facilities to the existing infrastructure can be examined by adding the flows into the corresponding entries of the WEMUIO table. The performance indicators, such as the water for energy and energy for water, can be calculated easily by summing up the entries in the corresponding areas of the WEMUIO table. Third, the two–region systems depicted in the table can reveal the dependence of the city on the water and energy from the hinterland. In the Hong Kong case study, it was estimated that the energy for conveying water from

Dongjiang to Hong Kong is significant. Plans to improve domestic water supply can help reduce the level of competition for water with other cities in Guangdong province to a certain extent.

4.2 Comparison of city–level studies

Beijing is the focus of several water–energy studies. One study estimated that the electricity for water chain in Beijing consumed 14.2% of its locally produced electricity in 2009 [38]. In Hong Kong, the water chain in 2015 consumed 1.46% of its locally produced electricity, including the energy for the conveyance of water from Dongjiang. The crowded housing in Hong Kong and the toilet flushing using seawater can reduce the energy to transport freshwater and sewage. Venkatesh et al. (2014) compared four cities' energy efficiency of water systems by measuring power consumption per cubic meter of water [39]. As shown in Table 7, the energy efficiency of Hong Kong's water treatment and distribution is higher than that of Toronto and Oslo, but lower than that of Turin and Nantes. The energy efficiency for wastewater collection and treatment in Hong Kong is only better than Toronto. The composition of sewage and the technology adopted for wastewater treatment make the difference. Most of the sewage in Hong Kong is treated with chemically enhanced primary treatments.

Table 7. Energy efficiencies of different cities' water utilities in kWh/m^3

City	Raw water supply	Water treatment and distribution	Wastewater collection and treatment
Toronto	0.09	0.52+0.41	0.132+0.144
Oslo	0.03	0.41+0.31	0.129+0.132
Turin	Not available	0.37+0.29	0.06+0.94
Nantes	Not available	0.28+0.16	0.03+0.87
Hong Kong	0.21*	0.547 [28]	0.2716 [29]

* The gravity–fed water supply system of Dongjiang lifts upstream water by 46 meters.

4.3 Limitations of the WEMUIO table

The proposed approach has a few limitations. The data requirements for generating a WEMUIO table might be time– and effort–intensive. Many cities in the world do not have publicly available detailed water and energy statistics as Hong Kong does. Additional survey efforts would be required for compiling a comprehensive WEMUIO table. As in the case of most water–nexus studies, this case study lacks information regarding the nexus among end–uses. For example, cooking and water heating consume both water and energy. Additional surveys might be required to integrate this part into a WEMUIO table.

4.4 Outline for future research

Future studies can broaden the fields of application in several ways. Studies based on monetary input–output analysis can access the indirect effect (e.g. identifying related economic impacts) in contrast to our model, which focuses on the direct impacts across water and energy systems. Developing a hybrid model that integrates the physical flow systems of water and energy with the economic system manifested in monetary flows will provide more insights from the viewpoint of managing the water–energy nexus. The number of studies incorporating the system of agriculture and food into the water–energy nexus is increasing. With sufficient information about the food system, a water–energy–food nexus version of the mixed–unit input–output model can be built. In this way, the water and energy for food production and the potential to recover energy from agricultural and food wastes can be explored.

5. Conclusions

In this study, a city level water–energy nexus was analyzed with consideration of the flows between the city of Hong Kong and its hinterland, namely Guangdong province in South China. The characterization of flows and linkages were presented through a Sankey diagram and indicators for 2015. The results show that the Guangdong province provided the majority of freshwater, about 79%, for Hong Kong in 2015. Regarding the power supply, 21% of the Hong Kong's electricity demand was met by the purchase of power from the hinterland as well. In addition, the diagram provides an unprecedentedly detailed elaboration of energy end–uses, such as electricity, gas, and oil for lighting, air conditioning, cooking, and transport in the residential, industrial, and service & trade sectors. Drawing upon this detailed end–use information, this study modeled how population growth will change the water and energy flows across the entire system in 2050.

Regarding the novelty of this research, a mixed–unit input–output table measuring the linkages based on physical water flows and energy flows was created. To the best of our knowledge, this is the first city level water–energy nexus study based on detailed physical water and energy flows. Several types of uncertainty associated with the monetary input–output analysis based studies in the literature is avoided through the method presented in this study. Furthermore, the demand for water and energy from the hinterland can be predicted as a response to changes in demands from different end–uses in Hong Kong.

The proposed method enables the evaluation for city's different scenarios for future planning. Hong Kong's plans for future water systems were analyzed, including adding desalination plants, water reclamation at sewage treatment plants, sewage treatment plant to recover energy and a hydropower station at a reservoir. The planned capacity for desalination could cut the import of freshwater from the hinterland by 10%. This plan could, in turn, reduce competition for Dongjiang's water resources among Hong Kong, Shenzhen, and other cities in the future. The energy recovered from the sewage treatment plants can add about 0.08% to the existing power supply. The energy saved in the end–uses by different sectors may relieve the pressure of purchasing water and fossil fuels from the hinterland.

The water–energy mixed–unit input–output table can be applied to other cities that are facing water scarcity and a transition towards higher energy system efficiency. Future works can further incorporate the systems of agriculture and food into the proposed framework. In this way, the holistic linkages of the water–energy–food nexus can be illustrated to urban planners. Research using environmentally extended input–output analysis can be expanded to the physical flow systems of water–energy mixed–unit input–output table to create a hybrid system. Thus, both the direct and indirect impacts of demands on specific processes in the city's water and energy systems can be quantified explicitly.

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