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Eco-efficiency Analysis of Non-Potable Water Systems in Domestic Buildings

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Abstract

Energy efficiency in water systems contributes significantly towards achieving sustainable water management. Decentralized anaerobic fluidized bed membrane bioreactor (AFMBR) systems with energy recovery have been proposed for greywater recycling in domestic buildings for non-potable uses, such as toilet flushing. This study developed an eco-efficiency analysis (EEA) framework with the integration of life-cycle assessment (LCA) and economic analysis for the evaluation of different water systems. Four water management scenarios including (1) freshwater flushing system, (2) seawater flushing system, (3) greywater flushing system adopting aerobic membrane bioreactor (MBR), and (4) greywater flushing system adopting AFMBR, were analyzed in a case study in Hong Kong. The EEA results reveal the AFMBR greywater reuse scenario to be the most eco-efficient option as the system is capable of energy recovery, recycling of water resource and reduction of sewage treatment loadings. This study has demonstrated that the EEA framework is an effective tool to guide water management towards sustainability and provides a basis for further research on the application of greywater recycling systems on a larger scale.

Keywords: *Eco-efficiency Analysis, Decentralized AFMBR, Greywater Reuse, Energy Recovery*

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Introduction

Anthropogenic activities are major contributors to intensifying water scarcity and uneven distribution of water resources around the globe. The World Economic Forum (2015) has listed the water crisis as the global risk of the most devastating impact. In 2015, 663 million people (approximately one-tenth of the world population) lacked access to safe drinking water, and 2.4 billion people lacked improved sanitary facilities (WHO & UNICEF, 2015). The vast majority of the population using substandard drinking water and unimproved sanitary facilities were in sub-Saharan Africa and Southern Asia, revealing the unbalanced distribution of water resources. In developing countries, population growth and rapid urbanization are major drivers for increasing water demand as the intense urban development activities are often coupled with escalating consumer demand and improving living standards (WWAP, 2014). Safe water resources are available in most of the developed countries, thus the water crisis is often not an immediate risk encountered in such regions, yet sustainable water management is still necessary for avoiding imprudent water resource exploitation and maintaining both the quantity and quality of the water supply (WWAP, 2014).

Traditional water management approaches generally aim at maintaining water supply with stable quantity and quality for water-related services and is demand-driven (Al-Jayyousi, 2003; Haasnoot, Middelkoop, van Beek, & van Deursen, 2011). Conventional water and wastewater treatment infrastructures are centralized and large-scale developments, as well as large energy consumers for many municipal governments. Water treatment utilities in the United States contribute to 30-40% of total energy demand, and thus are the largest consumers among the publicly owned utilities (US EPA, 2016). In the United States, drinking water and wastewater treatment systems account for approximately 2% of total energy consumption in the country and emit more than 45 million tons of greenhouse gases (GHGs) per year (US EPA, 2016). While in European Union (EU) countries, drinking water and wastewater treatment present net energy consumption of 34 and 88 kWh/y/person respectively, accounting for 7.6% of the overall energy consumption (EEA, 2014). To facilitate sustainability, unconventional derivatives for water and energy resources should be sought and sustainable water management approaches adopted in conjunction with changes in water utilization patterns, so that economically affordable, environmentally favourable, and socially acceptable resource utilization can be achieved.

Water and energy are both invaluable resources to maintain the well-being of humans, as well as the socio-economic development of the society. While conservation and sustainable management of both resources are gaining attention from the public, policy makers, and researchers, a novel perspective of "water-energy nexus" has been proposed in recent years, suggesting that water and energy resources are strongly interdependent (Schnoor, 2011; WWAP, 2014). The interlinkage between the resources could be reflected in the reality that energy transformation and utilization require water usage, and energy is required for water acquisition, transmission and treatment. Wakeel, Chen, Hayat, Alsaedi, & Ahmad (2016) reviewed the studies on energy consumptions of the different stages of the water sector in different countries, and suggested that the energy efficiency and the sustainability of the water sector could be improved by the integrated management of the energy and water resources. Studies have been conducted to investigate the correlation between water- and energy-saving policies so as to promote the formulation of more integrated policies (Gu, Teng, & Wang, 2014; Siddiqi & Anadon, 2011). The high organic content in wastewater stores a significant amount of energy, thus wastewater is now more commonly viewed as a source of energy (Frijns, Hofman, & Nederlof, 2013; Heidrich, Curtis, & Dolfing, 2011; Liu, Yu, Ng, & Stuckey, 2015; Silvestre, Fernández, & Bonmatí, 2015).

Regarding such characteristic of the wastewater, a notable number of studies have been conducted to evaluate the energy consumption and environmental performance of the centralized wastewater treatment plants (Corominas et al., 2013; Longo et al., 2016; Panepinto, Fiore, Zappone, Genon, & Meucci, 2016; Wakeel et al., 2016).

Greywater recycling and reuse offer notable potential for reducing sewage treatment loads and water supply costs, as well as alleviating the rising demand for freshwater supply, and therefore will become a core component in sustainable water management (Al-Jayyousi, 2003; Figueres, Rockstrom, & Tortajada, 2012). In contrast to blackwater, which is sewage collected from toilets and kitchen sinks, greywater includes the wastewater generated from showers, sinks (except kitchen sinks), bath and laundry, and accounts for 50-80% of total water consumption (Al-Jayyousi, 2003; Ghaitidak & Yadav, 2013; Jamrah, Al-Futaisi, Prathapar, & Harrasi, 2007). Greywater should be viewed as a stable and valuable source of water, energy, and cost savings through recycling for non-potable uses, such as toilet flushing, irrigation and car washing. Based on the close-looped concept, which states that water consumption follows certain cycles as in natural state (Figueres et al., 2012), a conceptual framework of greywater reuse for toilet flushing and landscaping has been proposed (Al-Jayyousi, 2003). Acceptable quality of treated greywater (Santos, Taveira-Pinto, Cheng, & Leite, 2012), sufficient greywater source for covering water consumption, and public acceptance of greywater reuse (Jamrah et al., 2007) have been investigated and the findings confirm the great potential for promoting greywater recycling systems.

In order to assist decision-making on water management, numerous studies have been conducted to evaluate the performance of greywater reuse systems. Most studies have focused on decentralized greywater recycling systems due to the low proportion of greywater flow relative to total water consumption (average greywater: consumption ratio = 0.6) (Ghaitidak & Yadav, 2013) and the significant resource and cost burdens for the collection and conveyance process (Al-Jayyousi, 2003; Ghaitidak & Yadav, 2013; T. P. Hendrickson et al., 2015). Previous research studies comparing the environmental performance of centralized and decentralized greywater reuse systems concluded that decentralized systems are more advantageous than a centralized system in terms of energy consumption and carbon emissions (T. P. Hendrickson et al., 2015; Matos, Pereira, Amorim, Bentes, & Briga-Sá, 2014). Some studies evaluated the economic aspect of the greywater reuse systems. Friedler & Hadari (2006) investigated the economic feasibility of the rotating biological contactor (RBC) and membrane bioreactor (MBR) greywater treatment systems, and found that the systems would be economically feasible when the building sizes reach seven and forty storeys respectively. In the decision-making model developed by Henriques & Louis (2011), economic and financial factors were considered for prioritizing the greywater reuse and drinking water supply systems. Few studies have considered a wider scope that include the impacts of greywater recycling on municipal sewer systems through a modelling approach. The applications of on-site greywater reuse systems decrease the velocity and quantity of the flow in sewer systems, but present only trivial impacts on the sizes of sewer pipes (R. Penn, Schütze, & Friedler, 2013). A multi-objective optimization model has been established to search for the optimal distribution of different types of greywater reuse in connection to existing sewer systems (Roni Penn, Friedler, & Ostfeld, 2013). The study results revealed that higher flow velocity enables the maximization of water savings while reducing treatment system costs and drinking water demand.

Notable efforts and contributions have been made in previous studies to evaluate the performance of greywater reuse systems, yet for the purpose of informing decision-makers and the public on the selection of sustainable water supply systems, there are some key shortcomings in the existing assessment frameworks. Firstly, only environmental or economic aspects and not both are evaluated in previous studies. Both aspects are important factors that directly influence the social acceptability of options, and evaluating only one of them is inadequate for supporting decision-making for sustainable water management. Secondly, detailed inventories of the evaluated systems studied in previous studies are not available. The absence of detailed environmental and economic inventories lowers the transparency of the LCA or economic analysis. The possibility of refining the developed frameworks for assessing greywater reuse systems is also hindered by the unavailability of the detailed inventory data used for evaluation.

In this study, an eco-efficiency analysis (EEA) was conducted to inform decision-making on greywater recycling with energy recovery for non-potable use, presenting three innovative features that significantly improve the comprehensiveness of the greywater management framework: (1) integration of the environmental and economic portfolios of the greywater systems to produce eco-efficiency scores; (2) detailed inventory backed up by full engineering system design, and; (3) consideration of freshwater supply as a substitute good to the greywater source. This study aims to assist decision-making in the selection of a sustainable water management approach with a focus on non-potable water supply in residential buildings. An inclusive eco-efficiency analysis (EEA) framework for greywater recycling systems was developed in this study. Detailed data inventories for environmental and economic analysis were built to serve as the foundation of the EEA. Eco-efficiency scores were obtained to serve as the final results for comparison between scenarios. This study also revealed the effects of freshwater price on the selection of water management options. The EEA framework developed in this study was demonstrated in the analysis of greywater recycling for toilet flushing in a residential building in

Hong Kong. The comprehensive framework was used to evaluate different greywater treatment technologies, including aerobic and anaerobic treatment, as well as freshwater and seawater supply scenarios. This framework can be applied widely for assessing water and greywater systems in other regions to assist decision-making in sustainable water management.

Description of the Case Study

Scope of Study

An anaerobic fluidized bed membrane bioreactor (AFMBR) system is proposed for treating greywater for non-potable use and recovering energy simultaneously. The AFMBR system is selected among various decentralized treatment options because the system is energy efficient, has low rate of sludge production and is effective for treating low-strength wastewater (Jaeho Bae, Shin, Lee, Kim, & McCarty, 2014; Kim et al., 2011; Shin, Kim, McCarty, Kim, & Bae, 2016). Application of the AFMBR greywater reuse system in a residential building in Hong Kong is evaluated under the EEA framework and compared with other three water supply systems in a mock case. The freshwater and seawater flushing scenarios are included for comparison because they are the existing systems in Hong Kong. Aerobic greywater treatment system is also analyzed and compared with the AFMBR system to feature the difference between aerobic and anaerobic systems. The environmental impacts and the economic costs of the construction and the operation phases of the scenarios are estimated and analyzed.

Background of Case Study

Due to the absence of natural lake and groundwater resources, the freshwater supply in Hong Kong mainly relies on the supply from Dongjiang River in mainland China and the rainwater from catchment (Research Office of Legislative Council Secretariat, 2015; WSD, 2014). The water consumption in Hong Kong was estimated to be 1.2 trillion cubic meters per year, with an average daily freshwater and flush water consumption of 0.13 and 0.09 cubic meter per capita (WSD, 2014, 2015). To conserve the precious freshwater resources, the city has been alleviating the rising demand for freshwater by introducing the seawater flushing system, which received international recognition for success in sustainable water management (CSB, 2004), since the 1950s. Currently about 80% of the population in Hong Kong is supplied with seawater for toilet flushing (WSD, 2016) while some inland areas in the New Territories are still using freshwater for flushing. The replacement with seawater has successfully saved more than 270 million cubic meters of potable water per year (Research Office of Legislative Council Secretariat, 2015; WSD, 2016).

The scenarios in this case study was set according to the actual conditions in a new town development project in the inland area in the New Territories in Hong Kong. A 35-storey residential building with 8 apartments per floor and 3 residents per apartment was studied (HK Housing Authority, 2016; LegCo, 2014). The daily freshwater and flush water consumption was assumed to be 130 and 83.8 liters per person respectively (LegCo, 2009; WSD, 2015). Four scenarios were defined in the case study (Figure 1). Greywater is defined as wastewater, except sewage from toilets and kitchen sinks, that could be recycled after appropriate treatment. The proportion of kitchen sink sewage was assumed to be 15% of the total water consumption (Butler & Memon, 2005). The background information and assumptions of the mock case are summarized in Supplementary Information (SI) Table 1 to Table 2.

Scenario 1 – Freshwater flushing

In Scenario 1 (S1), the total water consumption of the building is solely supplied by freshwater, which is the real situation in the remote areas in the New Territories in Hong Kong. Therefore, this scenario is considered the baseline scenario. Freshwater is supplied for toilet flushing and other uses. The ratio of potable water supply from Dongjiang River to local rainwater yield is 3:1 (Research Office of Legislative Council Secretariat, 2015). All the wastewater is collected through the sewer system and then transferred to the Sewage Treatment Works (STWs) for centralized treatment.

Scenario 2 – Seawater flushing

Seawater is supplied for toilet flushing in Scenario 2 (S2) after screening and chlorine disinfection (WSD, 2016). Water consumption for other purposes is supported by freshwater. The other settings for this scenario are the same as in Scenario 1.

Scenario 3 – Aerobic greywater reuse system

Greywater, which is wastewater excluding sewage from toilet flushing and the kitchen sink, is recycled for toilet flushing in Scenario 3 (S3). Supplemented with the recycled greywater, the demand for freshwater supply, as well as the sewage treatment loading, are reduced by approximately 40%. Greywater is collected separately from blackwater for decentralized treatment at the bottom of the building. The aerobic treatment system adopted in this scenario includes the aerobic membrane bioreactor (MBR) as the core treatment unit and a chlorine disinfection unit. The adoption of aerobic MBR for greywater reclamation has been studied and demonstrated to be a reliable technology in previous literatures (Abdel-Shafy, Al-Sulaiman, & Mansour, 2015; Hasar & Kinaci, 2004; Jefferson, Laine, Parsons, Stephenson, & Judd, 2000; Kishino, Ishida, Iwabu, & Nakano, 1996). The treated greywater is pumped up to the residents for use. The blackwater generated from the building is collected for centralized treatment in STWs.

Scenario 4 – Anaerobic greywater reuse system

Greywater is reclaimed for toilet flushing after treatment in an anaerobic fluidized bed membrane bioreactor (AFMBR) and chlorine disinfection unit in Scenario 4 (S4). The AFMBR is a reliable energy efficient treatment unit due to its low energy requirements compared to aerobic treatment systems, and its energy recovery capability through methane production (J. Bae, Yoo, Lee, & McCarty, 2013; Gao, Hu, Yao, Ren, & Wu, 2014; Kim et al., 2011; Ren, Ahn, & Logan, 2014). The substitution by biogas in electricity generation could reduce the consumption of conventional fossil fuels, thus is an advantageous feature of AFMBR-based systems in sustainable wastewater management (Bidart, Fröhling, & Schultmann, 2014). The fouling of the membrane could be alleviated through enhancing filtration with granular activated carbon (GAC), which can reduce the need for backwashing and maintenance (Gao et al., 2014; Kim et al., 2011). Other advantages of AFMBR include high effluent quality and low sludge production. The other settings for this scenario are the same as Scenario 3.

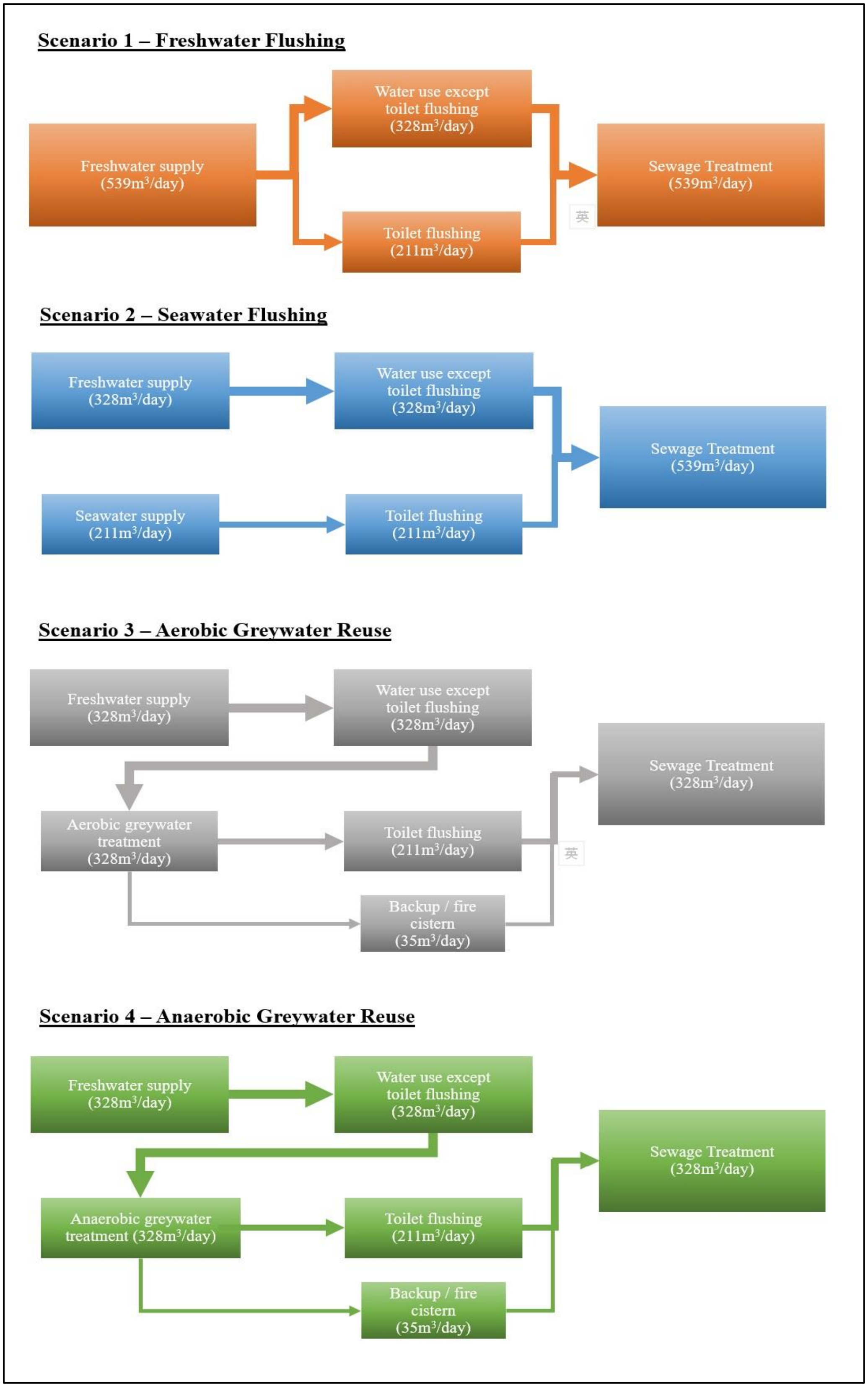

Figure 1 Water Management Scenarios for EEA

Engineering Design of Water System

This study focuses on the application of the different water systems on a practical level, thus the construction of pipelines, pumping systems, water tanks, and treatment units were included in the analysis. The engineering design of the water system for the case study was based on the standards stated in China National Standard: Code for Design of Building Water Supply and Drainage (China Engineering Construction Standardization Association, 2007). The parameters used for the design of the water supply and drainage systems are documented in SI Table 3. The water supply mode used in this case study adopted the pressure-boosting system, which is a common practice for water supply in high-rise buildings in Hong Kong. The system involves pumping the water from the sump tank to the roof tank. Then the building was divided into different water-pressure zones and water is supplied through the pressure reduction valves to different groups of apartments. Four sets of vertical freshwater pipeline were designed for the scenarios, each set covering the freshwater supply for six apartments on each floor. Four additional sets of seawater and greywater pipeline were designed for the seawater flushing and greywater flushing scenarios respectively. The SI Figure 1 shows the schematic design of one set of the pipelines. For the drainage systems, sewage from the households is collected through vertical drains and discharged into the public sewer system by gravity. The apartments on each floor were grouped into four drainage units, each unit covering six apartments. For scenarios 1 and 2, there are two sets of vertical drains: one set collects the sewage from the washing room and the other one collects sewage from the kitchen. As greywater excludes the sewage from toilets and kitchen sinks, an additional set of drains is required for the greywater reuse scenarios (scenario 3 and 4). The three sets of drains collect wastewater from: (i) the shower and washing basin in the washing room, and the washing machine; (ii) the toilet in the washing room, and; (iii) the kitchen sink. The wastewater collected by drain set (i), which is classified as greywater, is conveyed to the greywater treatment units at the bottom of the building. The treated greywater is pumped to the roof tank and distributed to the apartments for toilet flushing using a similar approach as for the freshwater supply. Details of the water systems designs are documented in the "Engineering water system designs" section in the SI.

Methodology

With the rising environmental awareness of policy-makers and the public, decision-support tools such as life-cycle assessment (LCA) have been widely used to assess the environmental performance of infrastructure projects or management strategies. However, the projects under assessment often involve economic investments, thus the economic performance should be considered and related to the environmental profile (Lorenzo-Toja et al., 2016; Saling et al., 2002). Early in 1992, the role of the economic market as a control to change decisions or actions has been discussed in the United Nations Conference on Environment and Development (Cope, 1993). To effectively facilitate sustainable development, the business costs and the environmental costs should be accounted for so that the market could serve as a driver to promote efficient resources consumption and waste minimization (Schmidheiny, 1992). The eco-efficiency analysis framework, which integrates the LCA and life-cycle costing (LCC), defined in the standard ISO 14045:2012 illustrates the principles for linking the environmental and economic aspects and provides guidelines for EEA at an operational level (ISO 14045, 2012).

Life-cycle assessment

Life-cycle assessment (LCA) is an approach for evaluating the environmental performance of a product or process from "cradle to grave", which includes the life-cycle phases of raw material acquisition, manufacturing, use and waste handling (ISO 14040, 2006; US EPA, 2006). The four main phases of conducting LCA are goal and scope definition, life-cycle inventory (LCI) analysis, life-cycle impact assessment (LCIA) and interpretation (ISO 14040, 2006; ISO 14044, 2006). Besides the traditional application on manufacturing processes, LCA has become more commonly applied on energy recovery from organic wastes, such as agricultural waste (Pierie et al., 2015; Tonini & Astrup, 2012) and food waste (Ebner, Babbitt, Winer, Hilton, & Williamson, 2014; Franchetti, 2013; Jin, Chen, Chen, & Yu, 2015). The LCA method has also been widely adopted in water, wastewater, and sludge management (Kalbar, Karmakar, & Asolekar, 2013; Lane, de Haas, & Lant, 2015; Opher & Friedler, 2016; Strauss & Wiedemann, 2000; Suh & Rousseaux, 2002; Yıldırım & Topkaya, 2012).

The two traditional approaches of LCA are process-based models and economic input-output (EIO) models. The process-based LCA models assess the series of processes involved in the scenarios under evaluation. The inputs and outputs of each process are identified and included in the life-cycle inventory. The advantage of such an approach is its high specificity and accuracy due to its use of primary data. Yet the process-based models also present drawbacks, including the exclusion of upstream processes outside the system boundary and the challenges encountered during collection of a huge volume of process-specific primary data (Rowley, Lundie, & Peters, 2009). Compared to the conventional process-based LCA, the EIO models enable a wider coverage of environmental impacts, especially those from upstream processes (C. Hendrickson, Horvath, Joshi, & Lave, 1998; Rowley et al., 2009). The EIO LCA models were developed based on an economic analysis methodology known as input-output analysis (IOA), in which the relationships between different production sectors in an economy are being studied. The limitations of EIO models include the inaccuracies induced by the assumptions of uniformity of prices and environmental emissions per unit price (Rowley et al., 2009). Wakeel et al. (2016) suggested that, besides the process-based (bottom-up) and input-output (top-down) LCAs, the hybrid approach is also a common methodology to assess the energy footprint and the environmental consequences of the water use cycles.

This study adopted a hybrid approach through the integration of the process-based and EIO LCA models. Two LCA tools were used to estimate the environmental impacts of the scenarios, namely the software SimaPro and the Economic Input-Output LCA (EIO-LCA) tool (Carnegie Mellon University (CMU), 2006). SimaPro is an internationally recognized tool for conducting LCAs and it was used in this study for quantifying the environmental impacts of the operation phase, which is comprised of a series of processes such as water pumping, water treatment, and electricity production. The EIO-LCA tool was used to estimate the emissions from the manufacturing of components such as pipes, pumps and water tanks, during the construction phase. The total life-cycle environmental impacts were evaluated and integrated using the ReCiPe Endpoint method (Goedkoop et al., 2009).

Life-cycle costing

The life-cycle costs of the water management scenarios were estimated in the life-cycle costing (LCC) analysis. Based on the engineering design of the plumbing and sewer systems, a detailed inventory of the components required for the construction phase of each scenario was built. The online cost estimation tool RSMeans and its up-to-date database were used for the LCC analysis (RSMeans, 2016). The operational costs associated with the purchase of freshwater, water treatment, electricity consumption, chemical requirements, and sludge treatment were also considered.

Eco-efficiency analysis

According to the definition by the World Business Council for Sustainable Development (WBCSD), eco-efficiency is "achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity" (WBCSD, 2000). The concept of eco-efficiency focuses not only on the environmental performance of an option, but also puts emphasis on the importance of considerations from a business perspective. On a practical level, the eco-efficiency of a certain process or product is evaluated in terms of the ratio between economic value added or service provided (outputs) and the environmental burdens produced (inputs) (Kicherer, Schaltegger, Tschochohei, & Pozo, 2007; Saling et al., 2002; WBCSD, 2000).

The methodology adopted in this study made modifications based on the Baden Aniline and Soda Factory (BASF) and the normalization EEA approaches described by Saling et al. (2002) and Kicherer et al. (2007) respectively. This method provides a means for integrating the environmental and economic performance of the alternatives and presenting the results in eco-efficiency (EE) scores to reveal the relative eco-efficiencies.

The environmental impact category indicators EI_i (i = 1, …, I) of the scenario n (n = 1, …, N) were estimated by the LCA tools. Normalization in the LCIA is a procedure to express the category indicators in relation to a set of well-defined reference data (de Bruijn, van Duin, & Huijbregts, 2002), such as the global or regional per capita environmental impact category indicators ($\frac{GREI_i}{Pop}$). Based on the policy targets or the social preference, weightings (w_i) could also be assigned to the impact categories to reveal their different importance. Thus, the total environmental impacts were estimated as the aggregated normalized and weighed impacts:

$$EP_n = \sum_{i=1}^{I} \frac{EI_{i,n}}{GREI_i} \cdot Pop \cdot w_i \qquad \text{------ Eq. (1)}$$

EP_n = total environmental impact of the scenario n

$EI_{i,n}$ = environmental impact in category i of the scenario n

$GREI_i$ = global/regional impact normalization reference indicator for impact category i

Pop = population of the region

w_i = weighting of impact in category i

For economic performance, the total life-cycle cost LC_n is estimated from the price (P_j) and the quantity requirements (Q_j) of the component j (j = 1, …, J).

$$LC_n = \sum_{j=1}^{J} P_{j,n} \cdot Q_{j,n} \quad \text{------Eq. (2)}$$

LC_n = total life-cycle cost of the scenario n

$P_{j,n}$ = price of the component j used for the scenario n

$Q_{j,n}$ = quantity of the component j used for the scenario n

The environmental and economic performances were integrated and presented on an EE portfolio graph to show the overall relative eco-efficiencies of the scenarios. The two aspects were first considered to be equally important as the sustainability concept suggests, yet the tool is capable of allowing the users to change the relative importance of the two aspects based on their own preferences. According to Kicherer et al. (2007) and Saling et al. (2002), the environmental impact portfolio position (y-coordinate) of scenario n is:

$$PP_{E,n} = \frac{EP_n}{(\sum EP)/N} \quad \text{------Eq. (3)}$$

$PP_{E,n}$ = environmental impact portfolio position of the scenario n

EP_n = total environmental impact of the scenario n

$\sum EP$ = summation of environmental impacts of all scenarios

N = number of scenarios

Similarly, the life-cycle cost impact portfolio position (x-coordinate) is:

$$PP_{C,n} = \frac{LC_n}{(\sum LC)/N} \quad \text{------Eq. (4)}$$

$PP_{C,n}$ = life-cycle cost impact portfolio position

LC_n = total life-cycle cost of the scenario n

$\sum LC$ = summation of the life-cycle costs of all scenarios

N = number of scenarios

In an eco-efficiency portfolio graph, the upper-right corner indicates the highest eco-efficiency, where both the environmental burden and the economic cost are minimal. The bottom-left corner, in contrast, indicates the lowest eco-efficiency. The y and x axes display the relative environmental and economic performances of the scenarios respectively, with the value 1 representing the average performance ($\sum EP\ /N$ and $\sum LC\ /N$). The distance between the options and the diagonal of the graph represents the respective eco-efficiency of the scenarios. Such graphical presentation enables clear and easy communication to the audience.

A term R_{EC}, which is defined as the ratio of regional or global significance of environmental impacts to that of the cost impacts, is used to reflect the relative importance of the two aspects (Kicherer et al., 2007). The R_{EC} ratio is defined as:

$$R_{EC} = \frac{EP_n}{LC_n} \quad \text{------Eq. (5)}$$

R_{EC} = ratio of significance of environmental impacts to cost impacts

EP_n = total environmental impact of the scenario n

LC_n = total life-cycle cost of the scenario n

The EEA tool in this study allows the adjustment of the R_{EC} ratio to reflect the emphasis of the decision-makers in their policy formulation. A ratio larger than 1 means that the environmental performance is more highly valued than the economic one, and vice versa. The portfolio positions, thus the results, can be adjusted in accordance with the R_{EC} ratio to the new positions (Kicherer et al., 2007):

$$PP'_{E,n} = \frac{(\sum PP_E)/N + [PP_{E,n} - (\sum PP_E)/N] \cdot \sqrt{R_{EC}}}{(\sum PP_E)/N} \quad \text{------Eq. (6)}$$

$$PP'_{C,n} = \frac{(\sum PP_C)/N + [PP_{C,n} - (\sum PP_C)/N] / \sqrt{R_{EC}}}{(\sum PP_C)/N} \quad \text{------Eq. (7)}$$

$PP'_{E.n}$ = adjusted environmental portfolio position of the scenario *n*

$PP'_{C.n}$ = adjusted cost portfolio position of the scenario *n*

PP_E = original environmental portfolio position of the scenario *n*

PP_C = original cost portfolio position of the scenario *n*

N = number of scenarios

R_{EC} = ratio of significance of environmental impacts to cost impacts

Data Inventory

The data source for this study includes documents issued by the Hong Kong Government, experimental results, the engineering designs of the systems, and previous literature. The data was used to build the life-cycle inventory on which the eco-efficiency analyses were based.

Table 1 Water flow in mock building

	S1	S2	S3	S4
Freshwater supply (m^3/d)	539	328	328	328
Seawater supply (m^3/d)	-	211	-	-
Greywater supply (m^3/d)	-	-	211	211
Sewage treatment (m^3/d)	539	539	328	328
Greywater treatment (m^3/d)	-	-	247	247

Table 1 shows the flow rate (m^3/day) of freshwater supply, seawater supply, greywater supply, sewage treatment, and greywater treatment of the four scenarios. In S3 and S4, all the greywater from the households (247 m^3/day) was collected for decentralized treatment at the bottom of the building, yet only the quantity needed for toilet flushing was pumped up for use. The extra amount of treated greywater (36 m^3/day) was stored as backup or used for other purposes, such as irrigation and floor cleaning. Based on the engineering design of the systems for the four scenarios, the material and operational requirements of each scenario were identified and listed in the inventories of construction and operation phases (Table 2 and Table 3).

Table 2 Inventory of construction phase

	S1	S2	S3	S4
Freshwater supply system	539 m^3/day - Roof tank - Sump tank - Plumbing - Pump	328 m^3/day - Roof tank - Sump tank - Plumbing - Pump	328 m^3/day - Roof tank - Sump tank - Plumbing - Pump	328 m^3/day - Roof tank - Sump tank - Plumbing - Pump
Seawater supply system	N.A.	211 m^3/day - Roof tank - Sump tank - Plumbing - Pump	N.A.	N.A.
Greywater supply system	N.A.	N.A.	211 m^3/day - Roof tank - Plumbing - Pump	211 m^3/day - Roof tank - Plumbing - Pump
Drainage collection system	539 m^3/day - 2 sets of sewers - 6 Septic tanks	539 m^3/day - 2 sets of sewers - 6 Septic tanks	328 m^3/day - 1 set - 2 sets of sewers - 4 Septic tanks	328 m^3/day - 1 set - 2 sets of sewers - 4 Septic tanks
Greywater treatment unit	N.A.	N.A.	247 m^3/day - 2 equalization basins - Aerobic MBR	247 m^3/day - 2 equalization basins - AFMBR - Adsorption unit

Table 3 Inventory of operation phase

	S1	S2	S3	S4

Purchase of Dongjiang water (m^3/d)	404	246	246	246
Treatment of freshwater from local yield (m^3/d)	135	82	82	82
Seawater treatment (m^3/d)	N.A.	211	N.A.	N.A.
Sewage treatment (m^3/d)	539	539	328	328
Sludge treatment (kg/d)	N.A.	N.A.	19	9
Water pumping (m^3/d)	539 (freshwater)	328 (freshwater) 211 (seawater)	328 (freshwater) 211 (greywater)	328 (freshwater) 211 (greywater)
Energy consumption of treatment unit (kWh/d)	N.A.	N.A.	128	19
Energy recovered (kWh/d)	N.A.	N.A.	N.A.	177
Chlorine dosage (kg/d)	N.A.	N.A.	1.2	1.2

More details of the system requirements are shown in the SI. The detailed cost information of the materials required for the construction phase is listed in SI Table 31 to Table 34. The parameters used for the operation costs estimation and the breakdowns of operation costs are listed in SI Table 35 to Table 54. The inventories of conventional air emissions and greenhouse gas emissions of the construction phase are presented in SI Table 59 to Table 66.

Results

Economic Analysis Results

The economic analysis results are shown in Figure 2. The total costs are estimated as the summation of the construction and the 20-year operation costs in net present values (NPV) (SI Table 55). The construction cost of S1 is the lowest, followed by S2 and S3, while that of S4 is the highest. The scenarios in ascending order of operation costs are S4, S2, S3 and S1. When considering both cost components, S2 and S4 has the lowest total cost and S1 presents the highest total cost.

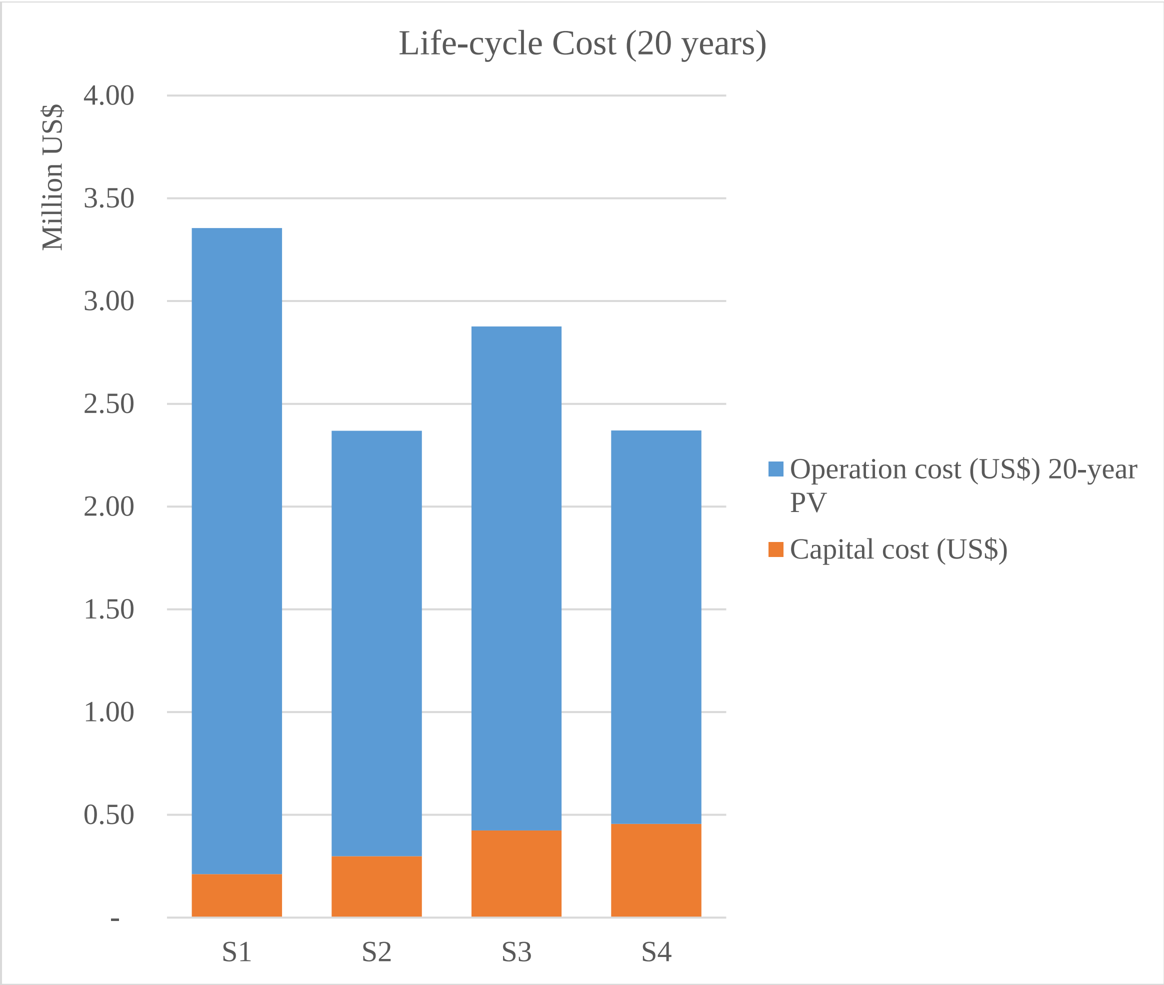

Figure 2 Economic analysis results

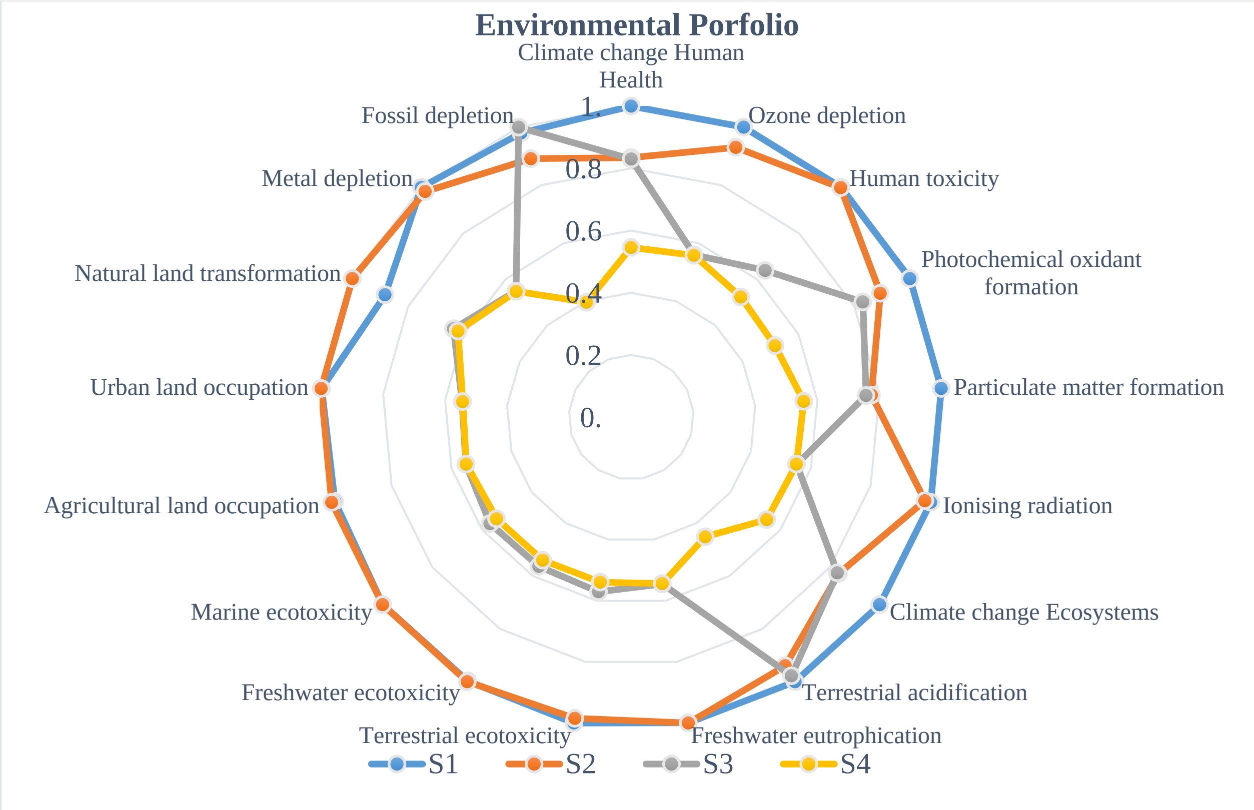

Figure 3 Environmental portfolio of scenarios

Life-cycle Assessment Results

The ReCiPe Endpoint method was adopted to conduct the environmental impact assessment of the scenarios in this study. The environmental emissions estimated based on experimental results, literature review, EIO-LCA and the Ecoinvent database were analysed using the SimaPro software and seventeen impact categories were assessed. The characterization and single score results of the construction and operation phases are presented in SI Table 67 to Table 70. Figure 3 shows the environmental portfolios of the scenarios, which reveal the relative performance of the scenarios in each impact category (SI Table 71). Within each category, the scores assigned to the scenarios range from 0 to 1. The scenario with the highest impact is assigned to score 1 and serves as the reference. The scores of other scenarios reveal their performance relative to the reference scenario. The scenario with an environmental portfolio closest to the centre, which is S4 in this case study, are the most environmentally favourable. The environmental portfolios also reveal that S1 and S2 generally perform less favourably in most of the impact categories.

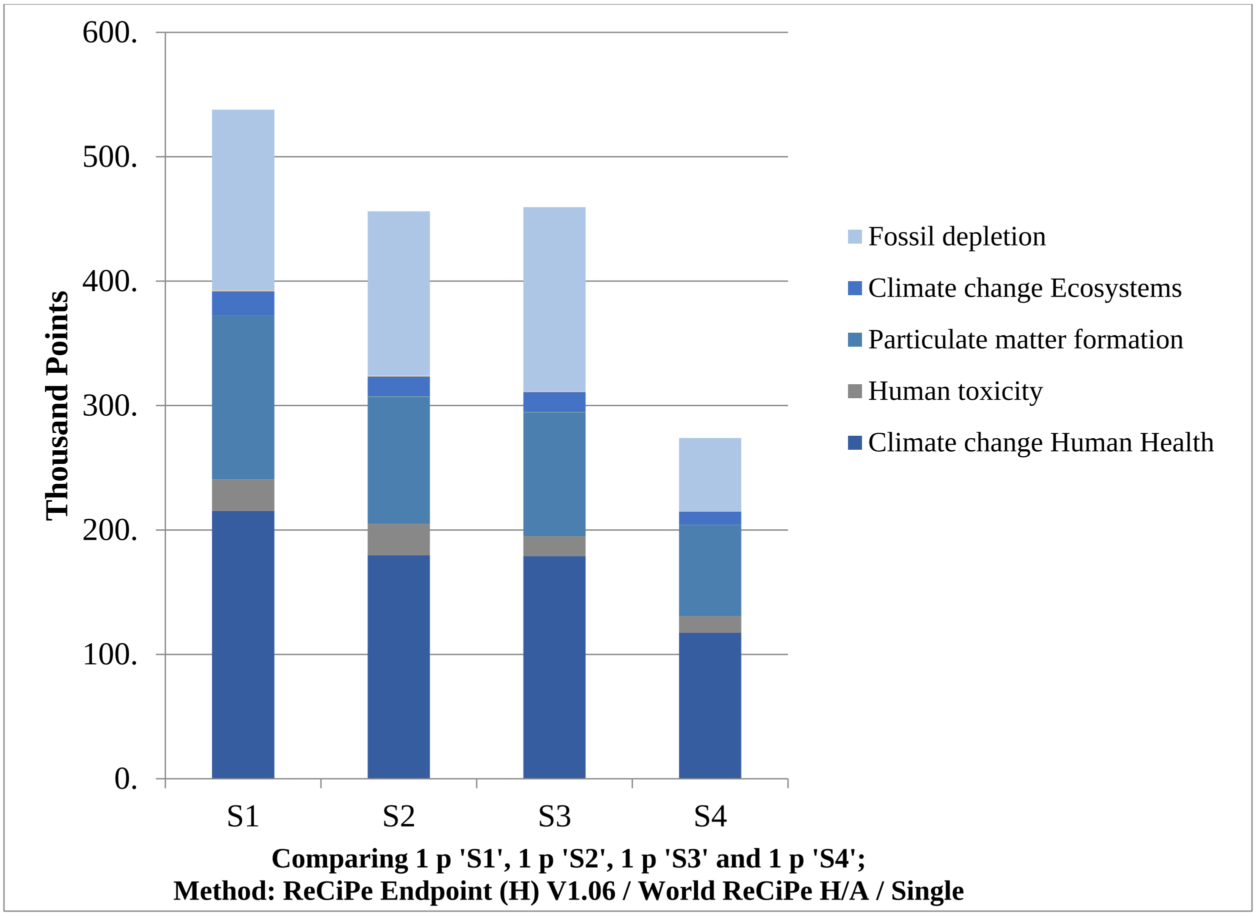

Figure 4 Life-cycle assessment results

The environmental portfolio only shows the relative performance of alternatives in different impact categories; the different magnitudes of their effects on the total environmental burden are not considered. Thus, a standard LCA has been conducted to evaluate the total environmental performance of the scenarios and the results are shown in Figure 4 (SI Table 72). As the environmental impacts are normalized against the world reference inventories using the ReCipe method, the LCA results of the different indicators are of the same unit (points) and, therefore, a single score for each scenario could be obtained. The graph presents the summation of the normalized environmental impacts of each scenario. S4 induced the least environmental impact, followed by S2, S3, and then S1. The top three impacts caused by the water systems in this case study are on "climate change human health", "freshwater ecotoxicity" and "fossil depletion".

Eco-efficiency Analysis Results

Assuming that the environmental and the economic implications are of equal importance and complimentary, the LCA and the economic analysis results were linked in the EEA (SI Table 73). The value 1 represents the average performance, and the vertical and the horizontal axes of the eco-efficiency portfolio show the relative environmental and economic performance of the scenarios respectively. With consideration of both aspects, the eco-efficiencies of the four water management scenarios in descending order are S4>S2>S3>S1 (Figure 5).

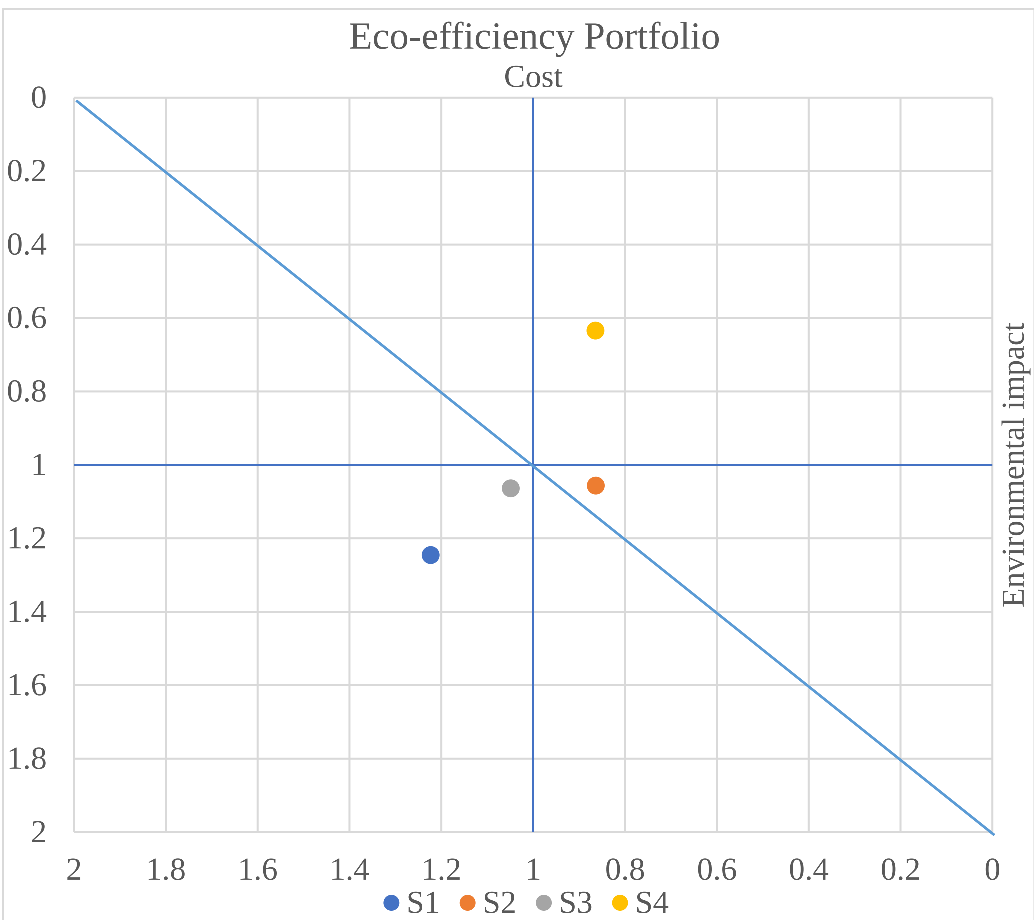

Figure 5 Eco-efficiency analysis results

Discussion

Economic Analysis

Different from the other three scenarios that require a separate seawater or greywater system, S1 only requires a single plumbing and tank system for conveying freshwater for all potable and non-potable uses. Thus, the material requirements and capital cost (US$211,000) could be the lowest among the scenarios. The plumbing design for the greywater systems is the same as the seawater system, yet the greywater treatment units have a notable impact on the capital cost. The costs of aerobic (US$177,000) and anaerobic greywater treatment units (US$222,000) were estimated to account for 42% and 48% of the total capital cost of S3 and S4 respectively.

For S2, S3 and S4, a proportion of freshwater demand is replaced with either seawater or treated greywater, with the potential to significantly lower freshwater cost. S4 has the lowest operation cost among the scenarios due to several reasons. Firstly, the greywater recycling strategy alleviates the freshwater demand of the scenario, so the expenditure on purchasing Dongjiang water and treatment of locally yielded freshwater could be reduced. Secondly, as the anaerobic greywater treatment by AFMBR has a low sludge production rate, the treatment cost for sludge produced on-site is lower compared to S3. Lastly and most importantly, energy could be recovered by the AFMBR through methane production, thus earnings could be made from electricity generation. Although the same amount of freshwater demand could be avoided, the aerobic greywater recycling scenario S3 has a higher operation cost than S2 and S4, mainly due to the aeration energy requirement (Lo, McAdam, & Judd, 2015). The relatively high sludge production rate in greywater treatment increases the sludge treatment cost of the scenario, yet the economic impact on the operation cost is trivial. The high operation cost of S1 is mainly attributed to the freshwater cost, more specifically the purchase of Dongjiang water. This study has taken a conservative estimation: the reduction of freshwater demand in S2, S3 and S4 is shared by proportion among the Dongjiang (75%) and the local supply (25%). If the greywater reuse, together with other sustainable water management strategies, could be applied on a large scale, the freshwater demand could be remarkably reduced and reliance on Dongjiang water could be lessened. As the price of Dongjiang water (US$1.11/$m^3$) is more than double the treatment cost of local freshwater (US$0.51/$m^3$), if 100% of the freshwater demand reduction is borne by the purchase of Dongjiang water, the costs of S2, S3 and S4 could be further decreased (Research Office of Legislative Council Secretariat, 2015).

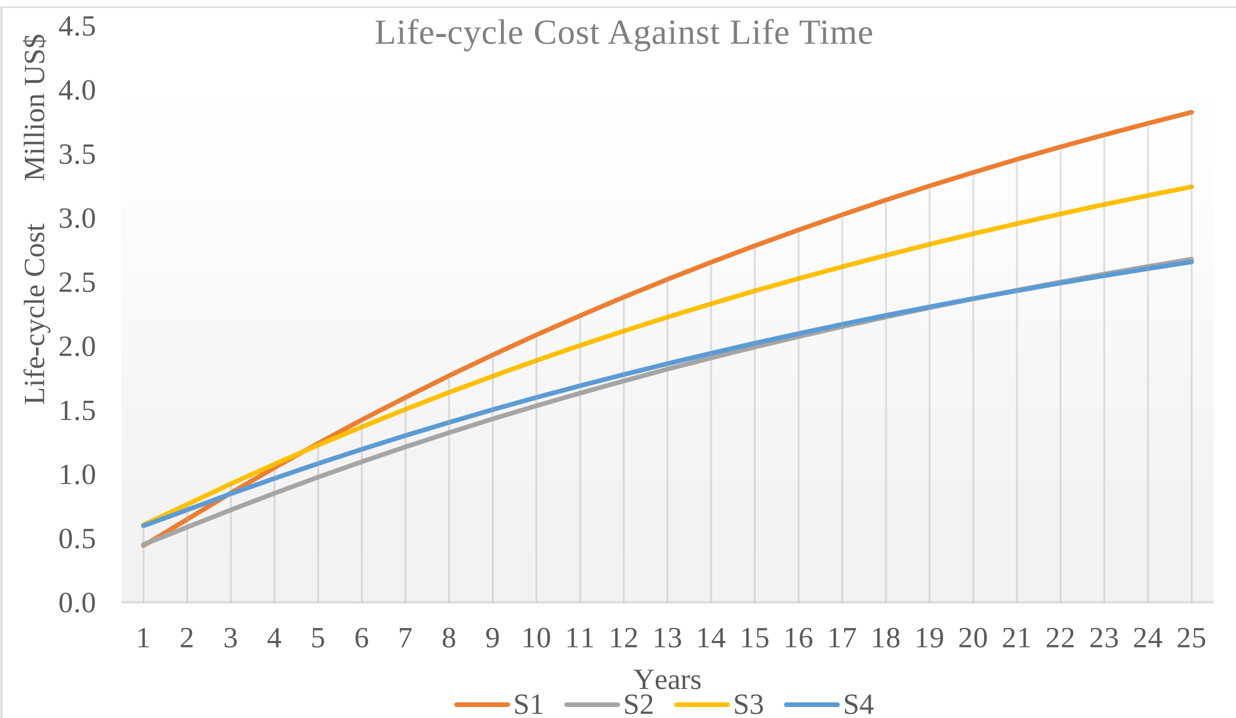

Figure 6 Life-cycle cost against life time

The capital cost was considered as a single investment during the first year of the time period in this study and the operation cost was an annual expenditure. The total life-cycle cost was calculated as the summation of the capital cost and the annual operation cost, and was presented in NPV. The time period of operation is a crucial factor in determining the most economically favorable option. Thus, this study also investigated the time factor in the economic analysis (SI Table 56). Figure 6 shows the change in total life-cycle cost according to the length of time period considered. In the first year of operation, the scenarios that adopted greywater recycling (S3 and S4) show less favorable economic performance at the total cost of US$600,000, which is US$150,000 more expensive than the other two scenarios. However, starting from the fifth year of operation, the freshwater scenario (S1) becomes the least economically favorable option. The anaerobic greywater reuse system is the most economically advantageous option when applied for 21 years or longer.

The purpose shared between the implementation of seawater flushing in Hong Kong and the proposal of greywater recycling system for toilet flushing is the alleviation of freshwater demand. Greywater and seawater could be regarded as substitute goods to freshwater, thus a rise in freshwater price could lead to an increased demand for the utilization of seawater or greywater, and vice versa. The influence of Dongjiang water price on the life-cycle costs of the scenarios was investigated (Figure 7 and Figure 8).

Figure 7 shows that when the Dongjiang water price is the same as the local freshwater treatment cost (US$0.51/$m^3$, equals to HK$4/m^3), the freshwater flushing option (S1) becomes economically competitive within a short period of operation (SI Table 57). The total life-cycle cost of S1 is the lowest among the water management alternatives in the first two years of operation. Seawater flushing is the most economical for operation periods ranging from 3 to 20 years. The case with the assumption of a doubled Dongjiang water price was also analysed (Figure 8). The high price of imported water caused the freshwater flushing option (S1) to be the least economically favourable for operation of more than 2 years (SI Table 58). For an operation period of 21 years or above, the most economically feasible option would be anaerobic greywater reuse (S4) no matter whether the change in imported water price is halved or doubled.

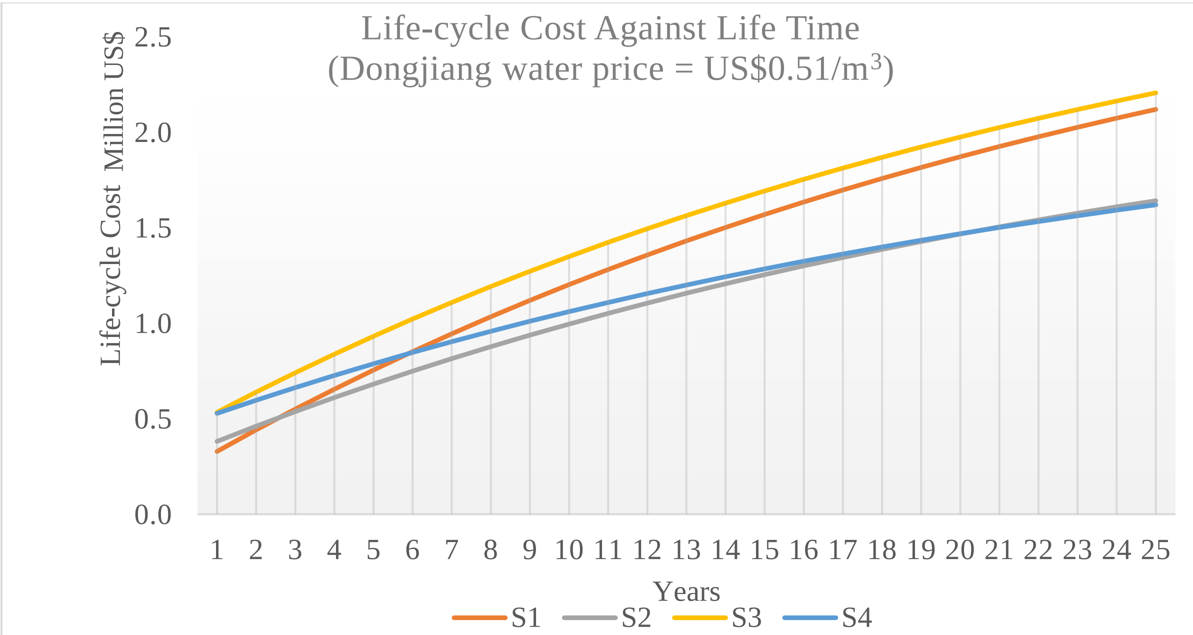

Figure 7 Life-cycle cost against life time (Dongjiang water price = US$0.51/$m^3$)

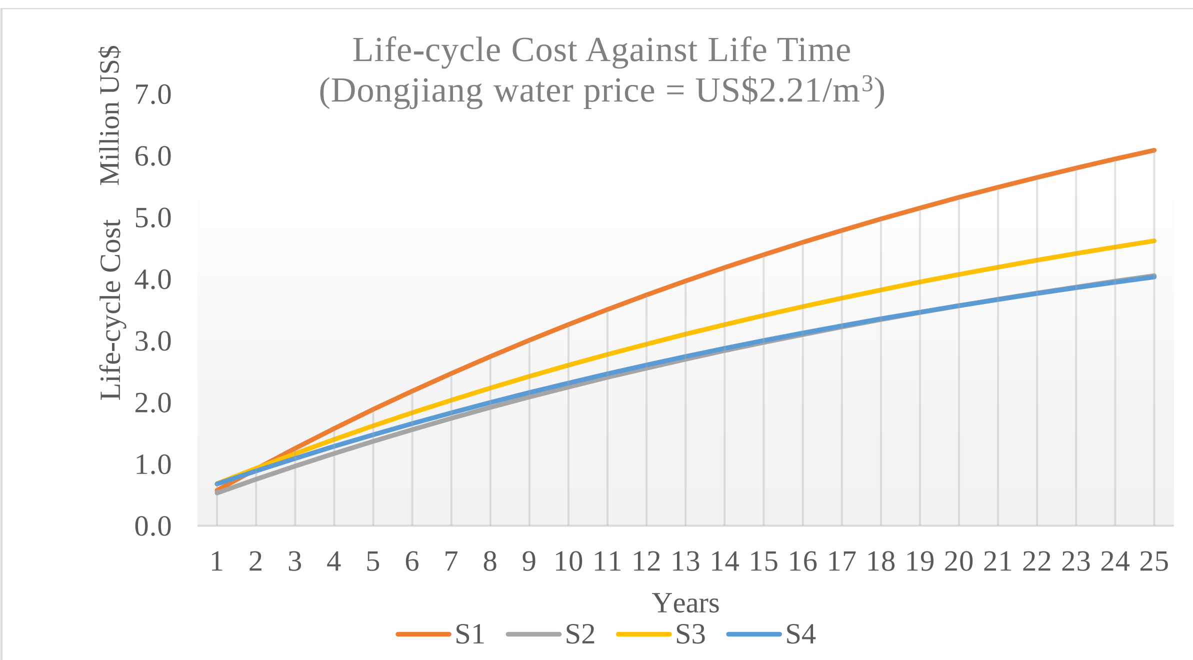

Figure 8 Life-cycle cost against life time (Dongjiang water price = US$2.21/$m^3$)

Environmental Impact Assessment

The environmental impacts of the construction and the operation phases were evaluated in the environmental impact assessment. For the construction phase, the environmental emissions in descending order are S4>S3>S2>S1 (Figure 9(a)).

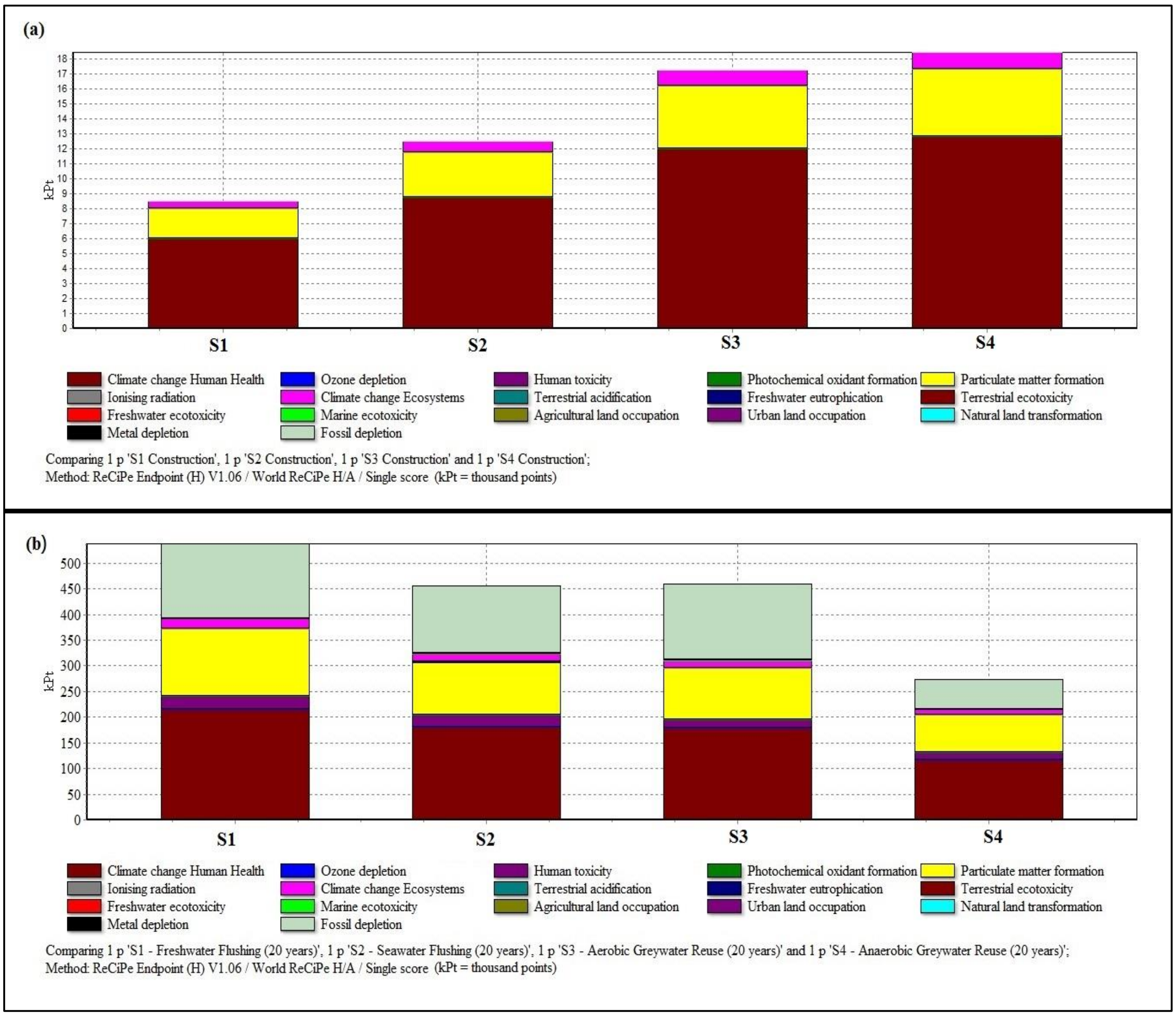

Figure 9 Life-cycle environmental impacts of (a) Construction and (b) Operation phases

The freshwater flushing scenario (S1) has the lowest environmental releases during the construction phase because it only requires a single plumbing system for water supply that covers toilet flushing and other water uses (Table 2). The water supply plumbing system for the other three scenarios are similar: one pipeline system for supporting general domestic water demand except toilet flushing, and one pipeline system for supplying either seawater or treated greywater for flushing. The higher environmental impacts of S3 and S4 relate to the material requirements of the greywater treatment units, which were mainly composed of the aerobic or anaerobic bioreactors, the adsorption unit, and the equalization basins.

In the operation phase, the S4 presented the lowest environmental impact, followed by S2 and S3, while S1 showed the highest impact (Figure 9(b)). There are three primary factors contributing to the environmental impacts associated with the operation phase, namely the drinking water purification, electricity production, and sewage treatment. Because of the high freshwater demand in S1, potable water treatment is the major cause of emissions in this scenario, contributing to 43.6% of the impact. In comparison to S1, the drinking water requirement in S2 is lower but the electricity consumption is higher due to the dual pumping systems for freshwater and seawater. Due to the recycling of greywater for non-potable uses, the sewage treatment loadings for S3 and S4 are lower than those for the other two scenarios. Both the greywater recycling scenarios require electricity for the operation of the on-site treatment units, yet the electricity consumption of S3 is higher than in S4. This difference derives from the energy-intensive aeration requirement for the aerobic greywater treatment unit in S3, as well as the energy recovery via methane production achieved by the anaerobic system in S4.

After integrating the environmental impact assessment results of the construction and operation phases with the ReCiPe method, S4 was revealed to be the most environmentally friendly scenario, followed by S2 and then S3, leaving S1 to be the least favorable option to the environment (Figure 4).

Eco-efficiency Analysis

The EEA results reveal S4 to be the most eco-efficient water management option, which coincides with the advantageous economic and environmental performances of the scenario as shown in the economic analysis and environmental impact assessment. Its ability to recover energy and water resources along with its ability to reduce freshwater demand and sewage treatment requirement are key features that favor the implementation of an anaerobic greywater reuse system. S2 is the second most eco-efficient scenario, followed by S3. Although the two scenarios performed similarly in terms of environmental impacts, S2 is more economical as it does not require the construction of the greywater treatment system and avoids some costly operation processes, such as aeration and disinfection. However, it should be noted that seawater flushing is not a common practice in the world and Hong Kong is one of the few regions that has adopted such a practice. Based on the EEA results, the seawater flushing option nonetheless remains the second-best strategy to be adopted in regions where a seawater system is technically feasible. For inland regions, an aerobic greywater reuse system could be a second favorable choice. A freshwater system is the least favorable option among the scenarios in terms of both the economic and environmental performance.

Sensitivity to R_{EC} Ratio

The sensitivity of the results to the R_{EC} ratio was tested as the relative importance of the environmental and economic performance may influence the final results of the eco-efficiency of the scenarios. Equal importance of the two aspects was first assumed in this study, and then two R_{EC} ratios, including 100 and 0.01, which represent high significance of the environmental and the economic influences respectively, were tested (Figure 10, SI Table 73). The denotations S1', S2', S3' and S4' represent the S1, S2, S3 and S4 with changed portfolio positions due to different R_{EC}

ratios used. The eco-efficiency portfolio positions of the scenarios change accordingly with different R_{EC} ratios, yet the anaerobic greywater recycling system remained the most favourable option and the sequence of the scenarios in terms of eco-efficiency remained unchanged in both situations. As a high R_{EC} ratio represents high importance placed on environmental performance, the difference in environmental profiles (Y-coordinates) of the scenarios were amplified when the R_{EC} ratio is 100 (Figure 10a). In contrast, the divergence between the economic profiles (X-coordinates) of the scenarios was enlarged when R_{EC} ratio is 0.01, which places much greater weight on the economic aspects than on environmental impact (Figure 10b). The results of the sensitivity test reveal that the anaerobic greywater reuse scenario (S4) remains the most efficiency option regardless of the R_{EC} ratio shifting from 0.01 to 100.

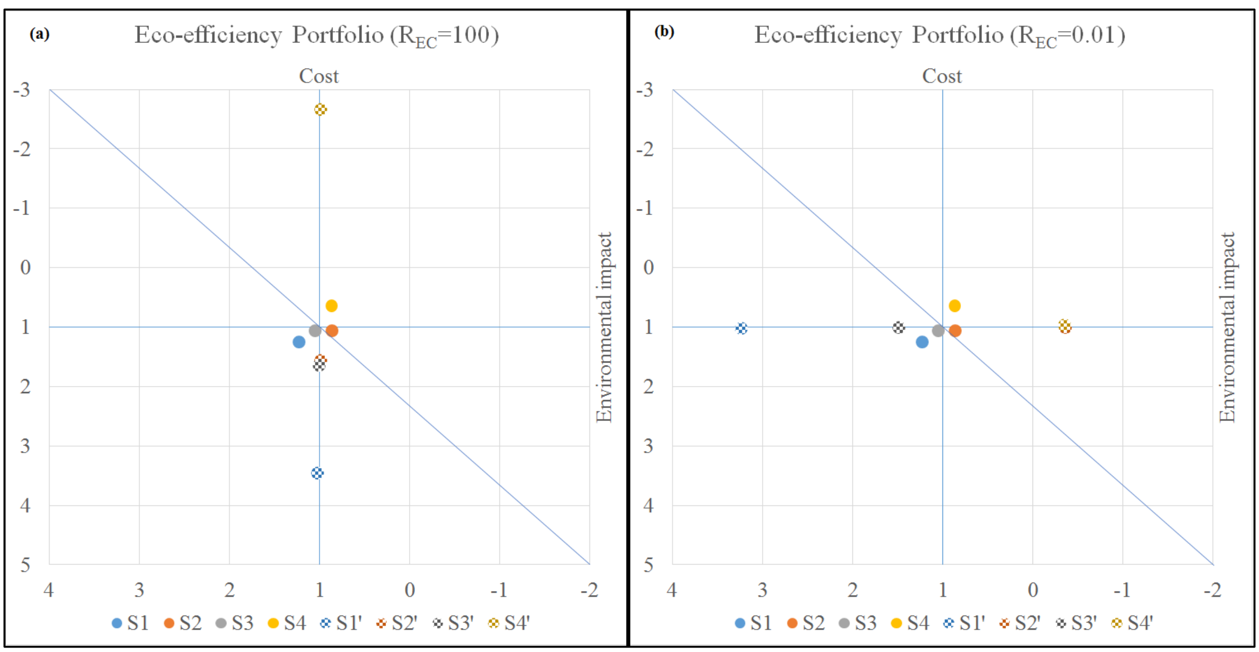

Figure 10 Eco-efficiency portfolio ((a) R_{EC}=100; (b) R_{EC}=0.01)

Conclusions

Sustainability in water management and harvesting energy from wastewater have been gaining more attention in the past decade. The anaerobic greywater reuse system employing AFMBR technology for non-potable uses have been proposed to promote sustainability, and the technical feasibility of the system has been tested. For the purposes of assisting decision-making and informing the public effectively, this study developed an EEA framework to comprehensively evaluate the eco-efficiency of decentralized water management options by linking their economic and environmental performances. The inclusive and clear results of this EEA study are presented with an EE portfolio to facilitate convenient communication to decision-makers, the public, and the other users. Unlike previous research that focused on the technical performance of the reactors, this study compared advanced greywater recycling with other options on a single-building scale with the detailed engineering designs of the systems. The EEA framework was demonstrated using a case study in Hong Kong.

The results of the EEA indicate that the anaerobic greywater reuse system (S4) would be the most eco-efficient option to adopt (Figure 5). The features of the system enable energy recovery, recycling of water resources, and alleviation of sewage treatment loading, thus giving the option both economic and environmental advantages over the other strategies. Considering freshwater and greywater as substitute goods for non-potable uses, this study also investigated the effects of changes in freshwater price on the economic favorability of the scenarios against time period. The anaerobic greywater reuse option was concluded to be the most economically advantageous scenario for operation over 21 years or longer (Figure 6). The study offers an improved decision-supporting tool for water management and demonstrates that the EEA framework fits the purpose of evaluating the sustainability of greywater reuse systems.

This study only evaluated water systems within a building, including the plumbing, piping, pumping, and greywater treatment components, the system for water conveyance outside the building being excluded. The economic and environmental consequences of constructing and operating the water conveyance and distribution systems also depend on the distance between facilities and the density of the community. To further refine the EEA framework developed in this study, the application of greywater recycling in a community or on a city-wide scale should be evaluated in the future. Geographic information and temporal patterns of water consumption should also be considered to further increase the comprehensiveness of the evaluation tool.

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