Integration of seawater and grey water reuse to maximize alternative water resource for coastal areas: the case of the Hong Kong International Airport

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ABSTRACT

Development, population growth and climate change have pressurized water stress in the world. Being an urbanized coastal city, Hong Kong has adopted a dual water supply system since the 1950s for seawater toilet flushing for 80% of its 7 million inhabitants. Despite its success in saving 750,000 m^3/day of freshwater, the saline sewage (consisting of about 20–30% of seawater) appears to have sacrificed the urban water cycle in terms of wastewater reuse and recycling. Can seawater toilet flushing be applied without affecting the urban water cycle with respect to sustainable water resource management? To address this issue, we examined the entire urban water cycle and developed an innovative water resource management system by integrating freshwater, seawater and reclaimed grey water into a sustainable, low-freshwater demand, low-energy consumption, and low-cost triple water supply (TWS) system. The applicability of this novel system has been demonstrated at the Hong Kong International Airport which reduced 52% of its freshwater demand.

Key words | full-scale demonstration, grey water reuse, integrated water supply system, seawater supply

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INTRODUCTION

Water scarcity and lack of sanitation continues to be a worldwide issue. In 2008, about 900 million people lacked access to safe water and 2.6 billion people were without access to adequate sanitation (WHO 2010). The seriousness of this problem can be viewed from the fact that about 80% of all diseases occurring in developing countries are water-related (OECD 2006), resulting in the loss of 2.2 million lives of children every year (WHO 2010). To meet the United Nations' Millennium Development Goal, the sanitation for 1 billion people needs to be improved by 2015. However, one of the major constraints is lack of freshwater resources.

Population growth, urbanization and the associated global warming and climate change all affect the urban water cycle. Temperature increase will raise the evaporation rate resulting in higher water loss and water demand. Snow disappearing on the highlands will reduce our natural water storage capacity (Oki & Kanae 2006). Intensive but uneven precipitations resulting in flooding and drought, will increase the uncertainty and vulnerability of water resources. To face these growing global issues and to meet the demand of freshwater and sanitation requirements, we need to identify more economic and environmentally friendly alternative water resources.

ALTERNATIVE WATER RESOURCES

Wastewater reuse

Reclaiming treated wastewater is one of the most economically viable and sustainable alternative water resources. In light of the large amount of water being used for toilet flushing in urban areas, the Irvine Range Water District of California has started the application of reclaimed water toilet flushing for high-rise office buildings since 1991. The results indicated that up to 75% of the water demand of

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the commercial buildings can be reduced through this system (Young *et al.* 1998). Despite this great potential, the amount of reclaimed water used for toilet flushing in Irvine is below 10,000 m^3/day (California 2002). Similarly, the amount of reclaimed water used for toilet flushing in Florida remains quite minimal. Although Japan appears to have relatively high percentage of wastewater reuse for toilet flushing, the majority is contributed by on-site in-building recycling of grey water for large commercial and apartment buildings only. The use of reclaimed water from public sewage treatment works (PSTW) for toilet flushing is very minimal, as shown in Table 1.

The key concern in providing reclaimed water for toilet flushing in residential buildings is the fear of cross-connection between the freshwater and reclaimed water pipes. Although it has been considered that a comparatively lower quality of water can be provided for uses with 'no direct contact', such as toilet flushing, gardening or landscape irrigation, highly treated reclaimed water is usually required for toilet flushing to minimize the health risks associated with cross-connection (Ogoshi *et al.* 2001; Asano *et al.* 2007), as shown in Table 2. Moreover, in light of the difficulty in detecting cross-connections, which occurred in the past (Fernandes *et al.* 2007), some authorities, such as the Netherlands and California (California 2001; Oesterholt *et al.* 2007) have discouraged or even prohibited the supply of reclaimed water for any internal use to residential developments.

Seawater desalination

Seawater desalination appears to be a universally applicable option as it produces high quality water suitable for potable uses. It is extensively applied in many areas, such as the Middle East and North Africa (World Bank 2007). Although there have been recent developments in reverse osmosis and energy recovery devices, it is still an energy intensive process consuming 2.5–4.0 kWh per m^3 of water produced (World Bank 2004).

Table 1 | Statistics on the use of reclaimed water in Florida and Japan

Types of uses	Florida (Florida 2010) Flow (m^3/day)	Percentage[a]	Japan (Ogoshi *et al.* 2001) Flow (m^3/day)	Percentage[a]
Irrigation	1,685,000	66.8%	45,000	8.0%
Environmental/wetlands	139,000	5.5%	175,000	31.0%
Ground water recharge	336,000	13.3%	–	–
Industrial and cleansing	345,000	13.7%	65,000	11.5%
Others	16,000	0.6%	76,000	13.5%
Toilet flushing (from PSTW)	2,000	0.1%	8,000	1.5%
Toilet flushing (on-site reuse)	–	–	195,000	34.5%
Total	2,523,000	100%	564,000	100%

[a]Percentage of all reclaimed water used.

Table 2 | Effluent reuse criteria for toilet flushing

Criteria (Reference)	USEPA (USEPA 2004)	Japan (Ogoshi *et al.* 2001)	Australia (AATSE 2004)	California (California 2001)	Florida (USEPA 2004)
Fecal coliforms (counts/100 mL)	Not detectable	$\leq$1,000	<10	<2.2	75% samples not detectable
Turbidity/SS	$\leq$2 NTU	–	$\leq$2 NTU	$\leq$2 NTU	<5 mg SS/L
Residual chlorine	$\geq$1 mg/L	Trace amount	$\geq$1 mg/L	–	$\geq$1 mg/L
BOD	$\leq$10 mg/L	–	–	Oxidized	$\leq$20 mg/L
pH	6–9	5.8–8.6	6.5–8.5	–	6–8.5
Appearance	–	Not unpleasant	–	–	–
Odour	–	Not unpleasant	–	–	–

Seawater for toilet flushing

Hong Kong is one of the most severe water-scarce areas in the world. The average annual rainfall in Hong Kong is 2,383 mm, and about one-third of our land has been reserved as water gathering grounds for the collection of rainwater. Due to the extremely high population density of Hong Kong, the annual per capita renewable water supply is limited to only 125 m^3. This number is far below the 'scarcity' level of 1,000 m^3, and much lower than that of 1,100 m^3 in the Middle East and North Africa (World Bank 2007). To alleviate this problem, since the 1950s Hong Kong has applied a dual water supply system which provides freshwater for potable uses and seawater for toilet flushing. As seawater can be easily detected from its taste, the health risk associated with cross-connections is quite minimal. In 2008/09, Hong Kong supplied an average of 750,000 m^3/day of seawater for toilet flushing covering 80% of its 7 million inhabitants. It is one of the largest alternative water supply systems in the world (Table 3).

The seawater toilet flushing system starts with the abstraction of raw seawater from the seafront. The raw water is passed through a coarse screen with mesh 5–10 mm for protecting the pumps. 3–6 mg/L of chlorine is dosed by an electro-chlorinator to control microbial growth in the pipes. The treated seawater is distributed by mild steel and ductile iron piping mains coated with internal cement mortar lining in order to prevent pipe corrosion (Lee & Yu 1997). For in-building services, polyethylene pipes are usually used. These pipes have a service life of 40–50 years. The seawater supplied is high in DO, low in *E. coli*, BOD_5, NH_4-N, SS and turbidity, and with no detectable odour and colour (Table 4). The seawater toilet flushing system is generally accepted by Hong Kong's residents as well as tourists. Complaints about salt precipitation at urinals and toilets were seldom reported and noticed over the past 50 years of experience.

Nevertheless, despite its success in saving about 20% of the total water supply in Hong Kong (WSD 2009), the saline sewage (consisting of about 20–30% of seawater) appears to have sacrificed some major potential water reuse options such as irrigation which accounts for around 1% of total

Table 3 | Alternative (reclaimed/sea) water usage in the world

Region	Water used (m^3/day)	Population (million)	Key alternative water resource
Middle East & North Africa (World Bank 2007)	6,500,000	364	Desalination
USA (USEPA 2004)	6,400,000	312	Wastewater reuse
Florida (Florida 2010)	2,500,000		Wastewater reuse
California (California 2002)	1,800,000		Wastewater reuse
Israel (World Bank 2007)	1,100,000	7.1	Desalination
Hong Kong (WSD 2009)	750,000	7.0	Seawater for toilet flushing
Japan (Ogoshi *et al.* 2001)	560,000	127	Wastewater reuse
Australia (AATSE 2004)	460,000	21	Wastewater reuse
Singapore (Singapore 2005)	320,000	4.6	NEWater + desalination

Table 4 | Water quality objectives and actual quality of seawater supplied in Hong Kong

Controlling parameters	Water quality objectives of seawater for toilet flushing system at Intake point	Distribution system	Average water quality of seawater for toilet flushing in 2009/2010 at Intake point	Distribution system
E. coli (count/100 mL)	<20,000	<1,000	4600	3
Colour (HU)	<20	<20	<3	<3
Turbidity (NTU)	<10	<10	4.4	3.9
Threshold odour unit	<100	<100	No odour	No odour
Ammonia nitrogen (mg/L)	<1	<1	0.19	0.03
Suspended solids (mg/L)	<10	<10	<10	<10
Dissolved oxygen (mg/L)	>2	>2	5.9	6.8
BOD_5 (mg/L)	<10	<10	<2.0	<2.0
Synthetic detergents (mg/L)	<5	<5	<0.01	<0.01

water demand in Hong Kong to 70% worldwide (OECD 2006). Could seawater toilet flushing be applied without affecting the current urban water cycle with respect to sustainable water resource management?

Our analysis indicated that by constructing separate freshwater, seawater and reclaimed grey water supply pipelines; together with separate grey water and black water sewerage, it is possible to integrate the supply of freshwater, seawater and reclaimed grey water into a triple water supply (TWS) system without affecting the wastewater reuse options. This smart water system has been successfully implemented at the Hong Kong International Airport (HKIA).

THE TRIPLE WATER SUPPLY (TWS) SYSTEM IN THE HONG KONG INTERNATIONAL AIRPORT (HKIA)

Situated on an artificial island of 12 km^2, the HKIA handled 280,000 air traffic movements in 2009. Unlike other airports where the water conservation goal is mainly achieved by reclaimed water and rainwater harvesting (BAC 2009; CA 2009), the HKIA has employed a TWS system composing of: (a) a freshwater supply system; (b) a seawater supply system for the carriage of toilet wastes and the centralized air conditioning system; (c) a reclaimed grey water irrigation system; and (d) a separate grey water and black water collection system, as shown in Figure 1.

The freshwater and grey water supply systems

The detailed flows in the TWS system at HKIA are shown in Figure 2. About 9,000 m^3/day of freshwater is used for catering services, water sinks, aircraft washing and fire-fighting services in HKIA. To conserve the valuable freshwater resource, a separate grey water and black water collection system is provided for the terminal building, airport catering and washing area while the rest of the HKIA is served by a combined system (Figure 1(d)). About 4,000 m^3/day of grey water is collected from this separate system for partial treatment by a dissolved air flotation unit and an upflow anaerobic sludge blanket (UASB) bioreactor to meet the required discharge limits and to reduce the trade effluent surcharge. Part of the partially treated grey water is further treated by a water reclamation plant which has adopted a membrane bioreactor (MBR) running in parallel with a submerged biological aerated filter (SBAF) for reclaiming grey water. The reclaimed water is then disinfected by a UV system

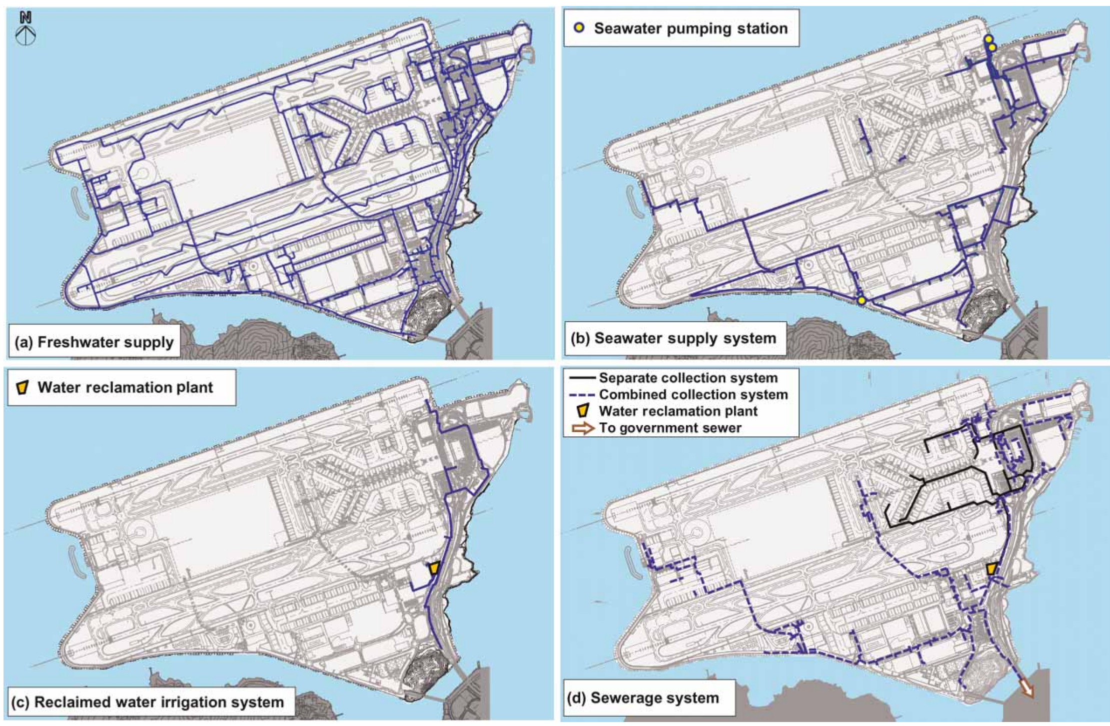

Figure 1 | The triple water supply system in the International Airport of Hong Kong.

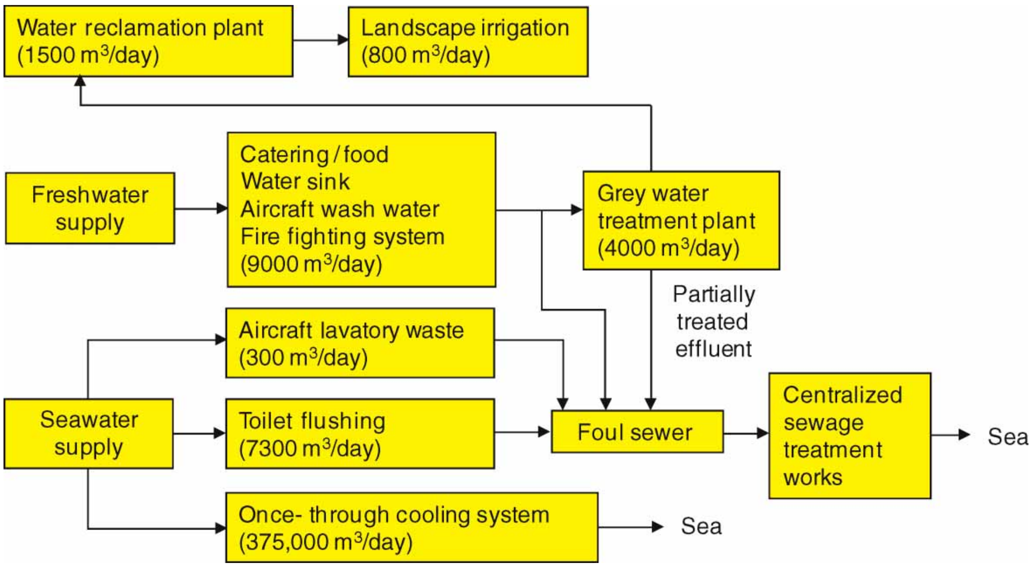

Figure 2 | Schematic of the triple water supply system in the Hong Kong International Airport.

prior to being supplied via a 8-km distribution network for reuse. This water reclamation plant has a total treatment capacity of 1,500 m^3/day, producing a reclaimed effluent quality of $BOD_5 < 15$ mg/L, SS < 15 mg/L and *E. coli* <100 counts per 100 mL. At present, about 800 m^3/day of grey water is reclaimed for landscape irrigation. The HKIA has a plan to increase the amount of landscaping features in the next few years, and then the requirement of grey water would increase substantially. On top of the grey water reclamation system, the HKIA has also selected three types of drought-resistant grasses, namely *Bermuda*, *Rhodes* and *Rye*, which do not need irrigation for its 2.8 km^2 of grassland at the airfield, saving 1,400 m^3/day of freshwater.

The seawater cooling and toilet flushing system

Seawater is abstracted through three pumping stations, followed by three layers of screens including a 20 mm bar screen, a 3 mm fine screen and a rotating drum screen of size 1.6 mm to remove large debris. The water is then disinfected by an electro-chlorination system with a chlorine dose at 0.6–0.8 mg Cl/L to meet the *E. coli* standard of 1,000 cfu per 100 mL (Table 4) and to suppress biofouling, prior to entering a distribution network of 36 km piping at the airport. Having a design capacity of 930,000 m^3/day, the seawater supply system supplied an average of 375,000 m^3/day of seawater for centralized air-conditioning in HKIA in 2009. As a side-stream of the seawater supply system, about 7,300 m^3/day (or 2%) of seawater is supplied for toilet flushing in each building, serving 127,000 passengers daily and 60,000 airport community staff. Moreover, about 300 m^3/day of seawater is used to dilute and flush the lavatory waste generated from aircrafts to sewers.

IMPLEMENTATION DIFFICULTIES AND ENVIRONMENTAL/COST BENEFITS OF THE TWS SYSTEM

The TWS system has enabled the HKIA to reduce its freshwater demand by 52%, of which 41% arises from seawater toilet flushing, 4% from grey water reuse, and 7% from minimizing irrigation water demand with the drought-resistant grasses. The implementation of this system is, however, not entirely problem-free. During the early stages, problems with the toilet flushing system were experienced. To deal with these problems effectively, the HKIA has, in collaboration with the equipment suppliers, undertaken the following measures: (a) replacing the uPVC pipes with polyethylene pipes within the terminal buildings; (b) enhancing the core parts of the automatic toilet flushing valve by using grade 316 stainless steel instead of grade 304 which is commonly adopted in the market for similar products; (c) revising the design of the body of the automatic toilet flushing valve to make it more maintenance-friendly; (d) changing the valve body material from brass to bronze; and (e) replacing the metallic moving parts of the automatic toilet flushing valve to plastic, etc. Through adopting these changes, the seawater toilet flushing system is more reliable and easier to maintain.

Despite these extra installation, operation and maintenance requirements, the overall economic and environmental benefits of the TWS system out-weigh those of conventional freshwater supply and water reclamation systems. This is mainly due to the minimal treatment processes required for producing seawater for toilet flushing as compared with that for producing freshwater or reclaimed water. As shown in Table 5, the supply of seawater for toilet flushing in HKIA has saved up to US$240,000, 2,800 MWh of energy, and 1,600 tonnes CO_2 emission annually as compared with the reclaimed water system.

Apart from the savings from water production, the seawater cooling system contributes to a significant amount of greenhouse gas reduction as water cooling systems are much more energy efficient than conventional air-cooling systems. In Hong Kong, there are around 90 once-through cooling systems abstracting 4 million m^3/day of seawater (Ma *et al.* 1998) for providing centralized air conditioning in commercial buildings, and HKIA is one of them. This does not include the seawater cooling system of power stations. As compared with conventional air-cooled systems, the seawater cooling system in HKIA saved US$2.6 million or 30,000 MWh of electricity and 17,000 tonnes of CO_2 emission in 2009.

As the cost of the seawater cooling system is 50 times higher than the seawater toilet flushing system, the incremental capital cost for attaching the toilet flushing system to the cooling system is very minimal. Established in 1998, the capital cost for the TWS system in HKIA was US$70 million. This included US$27 million for the reclaimed water system covering the separate grey water collection pipelines, grey water treatment plant, water reclamation plant and reclaimed water distribution system; as well as US$43 million for the seawater cooling and toilet flushing system covering the pump house, electro-chlorinator, and seawater distribution network. The annual cost savings by the TWS system in 2010 was US$3.8 million. This included US$2.5 million from electricity savings from seawater cooling system as compared with conventional air-cooling system, US$2.1 million from the cost of purchasing freshwater, US$0.4 million from sewage charge and trade effluent surcharge, less US$0.5 million for the maintenance cost of the seawater supply system, and $0.7 million for the operation of the grey water treatment plant and the water reclamation plant. To illustrate the cost benefits of the TWS system, we have prepared a cost comparison of three cases, namely a freshwater supply system as the basis, a conventional dual water supply system using freshwater and reclaimed water supply, and the TWS system. As shown in Table 6, the installation cost of the TWS system in HKIA can actually be recovered in about ten years.

Table 5 | Comparison of the energy, cost and CO_2 emission of alternative water sources

	Seawater for toilet flushing[a]	Freshwater supply[b]	Reclaimed water[c]
Energy consumption (kWh/m^3)	0.013–0.025	0.05	0.2–1
Comparison based on Airport Island's TWS system with flushing seawater flow of 7,600 m^3/day:			
Electricity cost[d] (US$ thousand/ year)	3.1–6.0	12	48–240
Energy consumption (MWh/year)	36–69	140	560–2,800
CO_2 emission[e] (tonne/year)	21–40	80	320–1,600

[a]Screening + electro-chlorination, estimated in this study.
[b]Conventional water supply system, cited from AATSE (2004).
[c]UV + microfiltration or reverse osmosis, cited from AATSE (2004).
[d]Based on electricity cost of US$0.087 per kWh.
[e]Greenhouse gas emission based on an actual emission factor of 0.58 kg CO_2/kWh for airport island.

POTENTIAL APPLICATIONS OF THE TWS SYSTEM

Water scarcity is expected to become more serious, with population living in water-stressed areas to be doubled from 1995 to 2025; and by 2030 around two-thirds of the world's inhabitants may experience moderate to high water stress (OECD 2006). The TWS system is one of the possible solutions. The HKIA has demonstrated that the TWS system has reduced 52% of its freshwater consumption. Apart from airports, the TWS system can be applied to other specialized areas such as new housing

Table 6 | Incremental costs of the dual and triple water supply systems

Water supply system	Additional capital cost	Annual cost saving
Fresh water only (see note) (as the basis for cost comparison)	US$0 million	US$0 million
Dual water system (i.e. fresh + reclaimed water)	US$62 million	US$1.6 million
Triple water system (i.e. fresh + seawater + reclaimed water)	US$20 million	US$2.1 million

Note: It is assumed that seawater cooling will be used in all the three cases.

developments, commercial complexes, universities, theme parks, as well as any coastal cities. There are 2.4 billion people living in the coastal areas worldwide, i.e. within 100 km from the sea. They include a large share of the 1.2 billion people in developing countries that lack access to clean and reliable freshwater. They also overlapped with the 2.7 billion poor in the world who lived on less than US $2 per day (World Bank 2004). Seawater desalination is too expensive to provide sanitation for them. Reclaimed water is not suitable for providing sanitation in residential buildings due to the high risk of cross-connection. The TWS system is an obvious and sustainable alternative.

Integrating seawater toilet flushing and a cooling system into the TWS system would not only reduce the freshwater consumption, but also contribute to a significant reduction of energy consumption and greenhouse gas emission. This includes energy savings from production of water as well as cooling. The seawater toilet flushing system in Hong Kong has saved a total cost of about US$27 million based on the difference between the average cost of treatment, operation and maintenance of freshwater and seawater system in 2008/09. Moreover, the development of a novel sulfate reduction, autotrophic denitrification and nitrification integrated (SANI®) process for treatment of saline sewage has given further incentives to this system as it waives primary treatment and sludge treatment (Lu *et al.* 2011; Lau *et al.* 2006; Wang *et al.* 2009).

In fact, more energy can be saved from the seawater cooling system. Air conditioning contributes to a large proportion of electricity consumption in major cities. In Hong Kong, the energy used for air conditioning amounted to 42,000 TJ in 2000 (EMSD 2010). This was equal to 32% of Hong Kong's total electricity consumption, of which 72% was consumed by non-domestic buildings which could be served by centralized air conditioning. By replacing the conventional air-cooled system with district seawater cooling systems, it is possible to save up to 35% electricity (EMSD 2003). While the financial viability of such a system is dependent on the design, local situation and cooling demand, due to the high initial cost for providing the pumping and piping network, it would probably require a payback period of 20–25 years (EMSD 2003, 2005). Nevertheless, the potential energy saving is high. Assuming that 50% of such systems can be replaced by seawater cooling systems, we can achieve a reduction of up to 4% of the city's electricity consumption ($32\% \times 72\% \times 35\% \times 50\% = 4\%$). According to OECD (2008), the total energy consumption of Brazil, Russia, India and China was expected to grow by 72% between 2005 and 2030. Unless ambitious policy action is taken, by 2030 greenhouse gas emission from these countries will grow by 46%. Integrating the TWS system with seawater cooling would contribute positively to the global warming issue.

As compared with the dual water system supplying freshwater and reclaimed water, a key obstacle to the implementation of the TWS system is possibly the additional requirement for constructing a separate grey water and black water sewerage system to facilitate reuse of treated grey water for irrigation. To enable such reuse of grey water and to minimize the capital cost of the TWS system, we may confine the separate sewer system to only part of the buildings instead of the entire service area. As demonstrated in the HKIA (Figure 1(d)), the separate grey water and black water sewerage system is only provided in the eastern part covering the terminal buildings and airport catering and washing area. The idea is to produce just sufficient reclaimed water as needed. Taking Hong Kong as an example for a fully urbanized city, as only 1% of the water demand is used for landscape irrigation, a 5% coverage of the separate water collection system should be sufficient to meet the city's demand of reclaimed water. This separate sewer system can be provided by gradual implementation through provisions in new development areas to avoid extensive retrofitting and construction works in the city.

CONCLUSION

Water stress and global warming are interrelated problems. To tackle water stress, there is a need to identify new alternative water resources. By constructing separate freshwater, seawater and reclaimed grey water supply pipelines; together with separate grey water and black water sewerage, we have integrated the supply of freshwater for potable uses, seawater for cooling and toilet flushing, and reclaimed grey water for irrigation into a TWS system at the HKIA. As the treatment processes required for seawater toilet flushing is much simpler than that of freshwater supply and wastewater reuse, the TWS system reduces freshwater demand with little energy consumption and greenhouse gas emission. Moreover, as the seawater cooling system uses much more seawater than toilet flushing, the incremental cost for integrating the toilet flushing system to the seawater cooling system is minimal. The HKIA has demonstrated that 52% of the freshwater demand can be reduced using this novel system. Furthermore, as water cooling systems are much more energy efficient than conventional air-cooling systems, based on the energy utilization and water consumption model of Hong Kong, we estimate that more than 20% of freshwater resources and up to 4% of the total electricity consumption of an urbanized coastal city can be saved if this TWS system is adopted.

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