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Changes in energy and carbon intensity in Seoul's water sector

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ABSTRACT

The water sector accounts for a significant proportion of the total energy consumption in urban areas; therefore, that sector can contribute to energy transition in urban areas. Seoul, South Korea has promoted the use of renewable energy and sewer heat as part of city-wide energy transition efforts. This study built energy consumption inventories for the urban water cycle in Seoul for 2012 and 2015 and investigated changes in net energy intensity and corresponding net carbon intensity during that period. It found that Seoul's energy transition efforts reduced net energy intensity in the water sector from 5.83 MJ/m^3 in 2012 to 5.42 MJ/m^3 in 2015, even with the increased use of energy-intensive advanced water treatment technology. In addition, this study estimated that about 8.52% of the water sector's current energy consumption could be saved in 2020 if 18.4 million m^3/year of water were reused and 2.40 million m^3/year of rainwater were harvested. This study showed a way to extend energy transition efforts into the urban water sector by reducing energy demand through reducing water demand.

1. Introduction

Climate change, population growth, and aspiration for a better life have increased pressure on water availability (Hubacek, Guan, Barrett, & Wiedmann, 2009; IEA, 2012, 2016; Sahin, Siems, Richards, Helfer, & Stewart, 2017; Smith, Liu, Liu, Liu, & Wu, 2017). Furthermore, water shortages could be exacerbated in the absence of coordination between water and energy policies (Sovacool & Sovacool, 2009). Therefore, perspective on the water-energy nexus is needed.

Half of the world's population already lives in urban areas, and about 60 percent of it is expected to reside in urban areas by 2030 (UN, 2016). Significant demands for resources will be concentrated in these areas; therefore, urban areas will be influenced by the availability of resources (Artioli, Acuto, & McArthur, 2017). Activities in urban areas, in turn, greatly affect resource supply.

Seoul is a megacity, home to some 10 million people and a large consumer of resources. In 2015, Seoul consumed 636 million GJ (Gigajoules) of energy (on the basis of Total Final Energy Consumption (TFEC)) (KEEI, 2016) and used 1,130 billion liters of water (excluding leakage), which equates to 335.2 liters of water per capita per day (MOE, 2016b).

To reduce its effects on climate change and increase energy self-sufficiency, the Seoul Metropolitan Government (SMG) initiated the One Less Nuclear Power Plant (OLNPP) initiative on April 26, 2012. The OLNPP aimed to reduce energy consumption by 83.7 million GJ, equivalent to the annual amount of energy generated by a nuclear power plant, by the end of 2014 (SMG, 2014). By mobilizing stakeholders and citizens while shaping and implementing this policy (Kim, 2016, 2017a; T. Lee, Lee, & Lee, 2014), the SMG achieved its target six months earlier than planned. Since then, the SMG has increased its target to 167 million GJ (SMG, 2014). As a part of the OLNPP, the SMG is trying to increase the use of renewable energy and recover sewer heat from the water sector. In 2017, 15.5 MW of solar PVs have been installed at water utilities (SMG, 2018). In addition, 340,000 Gcal of sewer heat was recovered from two wastewater treatment facilities (SMG, 2017d). In 2015, the energy generated in water facilities comprised 0.523% of Seoul's TFEC (authors' calculation).

These efforts to increase energy self-sufficiency affect net energy consumption and energy intensity in the water sector. However, these changes have not been investigated using empirical observations. Furthermore, Seoul's energy-water nexus has rarely or never been studied.[1] Studies of the water-energy nexus in urban areas and

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[1] To the best of the authors' knowledge, no single study has been conducted on this topic for Seoul. There are a few studies that look into water use for energy provision (Kim, 2017b). The interlinkage between these sources has not attracted much interest because South Korea imports almost all of its energy, and energy conversion used a very small amount of fresh water. However, the interlinkage needs to be explored from different points of view.

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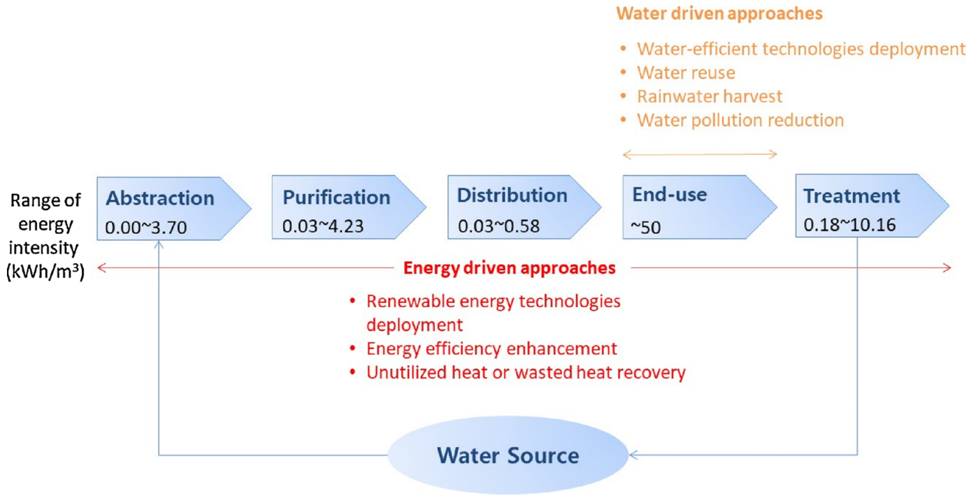

Fig. 1. Opportunities for Energy Transition in the Urban Water Cycle.
Source: This figure was constructed by modifying the flowcharts for the urban water cycle presented in M. Lee et al. (2017); Wakeel and Chen (2016). The ranges of energy intensities were attained from M. Lee et al. (2017).

of energy transition in the water sector have generally concentrated on the wastewater treatment stage (Gikas, 2017; Kollmann et al., 2017; Nowak, Enderle, & Varbanov, 2015; Stokes & Horvath, 2010).

To fill these gaps in knowledge, this study examines the effects of energy transition efforts on net energy consumption and on energy and carbon intensities in the water sector. It draws implications for more comprehensive approaches to energy transition in the water sector from the perspective of the water-energy nexus.

To achieve this goal, this study poses the following questions: 1) In Seoul's water sector, which stages account for the most total energy consumption? 2) How much has the energy transition initiative contributed to reductions in the energy and carbon intensities of Seoul's water sector? 3) If water consumption in Seoul decreases thanks to various countermeasures, how much energy and carbon could be saved or reduced?

To answer these questions, this study constructed inventories of energy consumption at each stage of the urban water cycle for 2012 and 2015, and then calculated and compared the energy and carbon intensities for 2012 and 2015. In addition, this study estimated the energy saving and CO_2 reduction potential from water reuse and rainwater harvest. This study thus contributes to building a more coordinated approach for energy transition in the water sector.

The findings of this study will provide meaningful implications for energy transition in urban areas by emphasizing the role of the water-energy nexus and coordination between energy and water policies. Furthermore, the study's findings will fill a gap in the distribution of urban water-energy nexus literature in the Asia region, as literature has concentrated on cities in China (Duan & Chen, 2017; Li, Li, & Qiu, 2017; Wang & Chen, 2016).

2. Background

Fig. 1 illustrates the urban water cycle and possible opportunities for energy transition in the urban water sector. Water is supplied to people through a series of steps: raw water abstraction, treatment, distribution, end-use, collection, and treatment. Raw/untreated water is withdrawn from various sources, including groundwater, surface water, and seawater. The withdrawn water is distributed after being treated as needed. Energy is used for end-use purposes, such as heating or pumping water. Then, used water is collected and treated, and finally discharged into a lake or river (M. Lee et al., 2017; Wakeel & Chen, 2016).

Previous attempts to estimate energy intensities for each stage of the urban water cycle revealed that the values are site-specific because they are influenced by factors such as climate, topography, operational efficiencies, and treatment levels (Chini & Stillwell, 2018; Chini, Konar, & Stillwell, 2017; Lam, Kenway, & Lant, 2017; Lee et al., 2017; Sowby & Burian, 2017). Even with a great deal of effort to estimate energy consumption or production at the purification and wastewater treatment stages, the identified interlinkage has been rarely used to identify ways to promote the transition of this sector to low-carbon sources and thereby curb CO_2 emissions.

Note: The end-use stage was not included in this study due to unavailability of data on hot water consumption and energy consumption for heating water.[2]

Transforming the energy system is one of the most important challenges in urban areas. Options for energy transition in the water sector can be divided into energy-driven approaches and water-driven approaches. Energy-driven approaches are activities that reduce energy consumption through energy efficiency enhancement or produce energy using alternative resources in water facilities. These activities are applicable at every stage of the urban water cycle, and directly reduce energy consumption. Water-driven approaches are activities that indirectly reduce energy consumption in the urban water cycle by decreasing water demand through interventions such as rainwater harvest and reducing water pollution.

Various ways to increase energy self-sufficiency or reduce carbon emissions at wastewater treatment plants have been investigated. These include obtaining and using biosolids as fuel for electricity generation (Gikas, 2017), reducing the energy demand at wastewater treatment facilities by using discharged industrial cooling water or wastewater, and producing more energy by adding organic matter such as food waste to the digester (Nowak et al., 2015).

In addition to directly reducing net energy consumption in the water sector by enhancing energy efficiency, producing renewable energy, and recovering waste heat, it is possible to reduce energy consumption by reducing water consumption. Many studies have estimated the potential of specific water-saving interventions

[2] In South Korea, water sometimes is heated by boilers in individual houses, but often hot water is collectively supplied to households through a district heating service. The energy demand for heating water is difficult to separate from the energy demand for heating spaces.

Fig. 2. Map of Water Facilities in Seoul.
Note: Some purification facilities (Amsa and Gangbuk) abstract raw water as well.

(Engström et al., 2017; Malinowski, Stillwell, Wu, & Schwarz, 2015; Smith et al., 2017). For example, deploying low-flow toilets in New York City could cut 5,000–8,000 tCO_2 (Engström et al., 2017) each year; changing the way water is pumped in high-rise buildings could cut 8600 tCO_2 in a city in China (Smith et al., 2017). Energy transition in the water sector should incorporate both energy-driven and water-driven approaches across all stages of the urban water cycle, from water abstraction to wastewater treatment.

3. Seoul's Water cycle and energy transition efforts in Seoul's Water Sector

3.1. Water supply and wastewater treatment in Seoul

In South Korea, 161 local waterworks enterprises and one multi-regional waterworks enterprise (Korea Water Resources Corporation, K-Water[3]) supply water to about 98.8% of its 2015 national population of 52.7 million people (MOE, 2016b). All of Seoul's citizens are supplied with water by the SMG Office of Waterworks (MOE, 2016b).

Fig. 2 describes the location of water facilities in Seoul; Fig. 3 presents how water is supplied to households in Seoul, along with statistics for 2015. Raw/untreated water is taken from the upper reaches of the Han River at four water abstraction stations operated by the SMG. In 2015, 1.09 billion m^3 of raw water was withdrawn by these facilities. The 81.7 million m^3 of raw water withdrawn by K-Water was sent to Gwangam station (MOE, 2016b).

In 2015, 1.17 billion m^3 of withdrawn and imported raw water was delivered to six purification facilities where raw water goes through a treatment and purification process to remove floating material, other elements, and odor. Advanced treatment technologies were used to purify 74.6% of the water[4]; 15.2 million m^3 of water was used to dilute wastewater during these processes. Of the 1.16 billion m^3 of treated water, 26.6 million m^3 is exported to other water service providers. The treated or purified water is delivered to 102 water reservoirs,[5] where the water is stored for emergencies or distributed to households. In 2015, 1.13 billion m^3 of treated water was supplied to Seoul citizens, which was equivalent to about 301 L per capita per day. Excluding the water lost through leakage (56.2 million m^3), Seoul citizens consumed about 286 L per person per day in 2015 (MOE, 2016b).

About 1.10 billion m^3 of sewage was generated in Seoul in 2015 (MOE, 2016a). In addition, about 4.16 million m^3 of human wastes were created in Seoul in 2015. A small proportion of the human waste generated (0.374%) was collected by trucks; the rest of the waste, along with leachate and other sewage (0.912 million m^3) was collected and transported by a network of pipes to three wastewater treatment facilities. Human and foul waste is first physically or biologically treated in the plants, then it is mixed with sewage and treated again.[6] In 2015, 1.45 billion m^3 of sewage was purified at four municipal treatment plants[7]. In 2015, about 90.3 percent of sewage was treated using advanced technology.

The treated water is discharged into the Han River. In 2015, 121

[3] K-Water is a state-owned corporation and its main business contribution is construction, operation, and management of water resource facilities, multi-regional waterworks, local waterworks, and sewage. In addition, it is involved in the development of urban waterfront and industrial complexes and the installation and operation of renewable energy facilities.

[4] While physical treatment and biological treatment is defined according to its approach, advanced water treatment is defined as "a process designed to remove nitrogen and phosphorus," followed by a secondary treatment to produce effluent clean enough to discharge (MOE, 2016a). In other words, regardless of the kind of treatment technology, any treatment that aims to remove residual N and P and achieve clean effluent falls into the advanced category.

[5] Water reservoirs are generally located on hills in order to deliver water to households at a stable water pressure. However, pumps are required to send water to the hilltops. Some treated water is sent to pumping stations. There are 205 pumping stations in Seoul (MOE, 2016b).

[6] According to Article 2 of Sewerage Act (Act No. 14839), sewage is differentiated from foul waste, and the statistics are collected separately. Sewage refers to "water contaminated by a mixture of liquids or solids created from human living and economic activities and rainwater and ground water that flow from the premises of buildings, roads, and other facilities into sewerage systems." Foul waste means "liquid or solid contaminants collected from collecting type toilets (including sludge created in the course of cleaning private sewage treatment facilities)."

[7] The difference between the amount of sewage generated and the amount of sewage treated can be attributed to inflow of groundwater, runoff, and other factors.

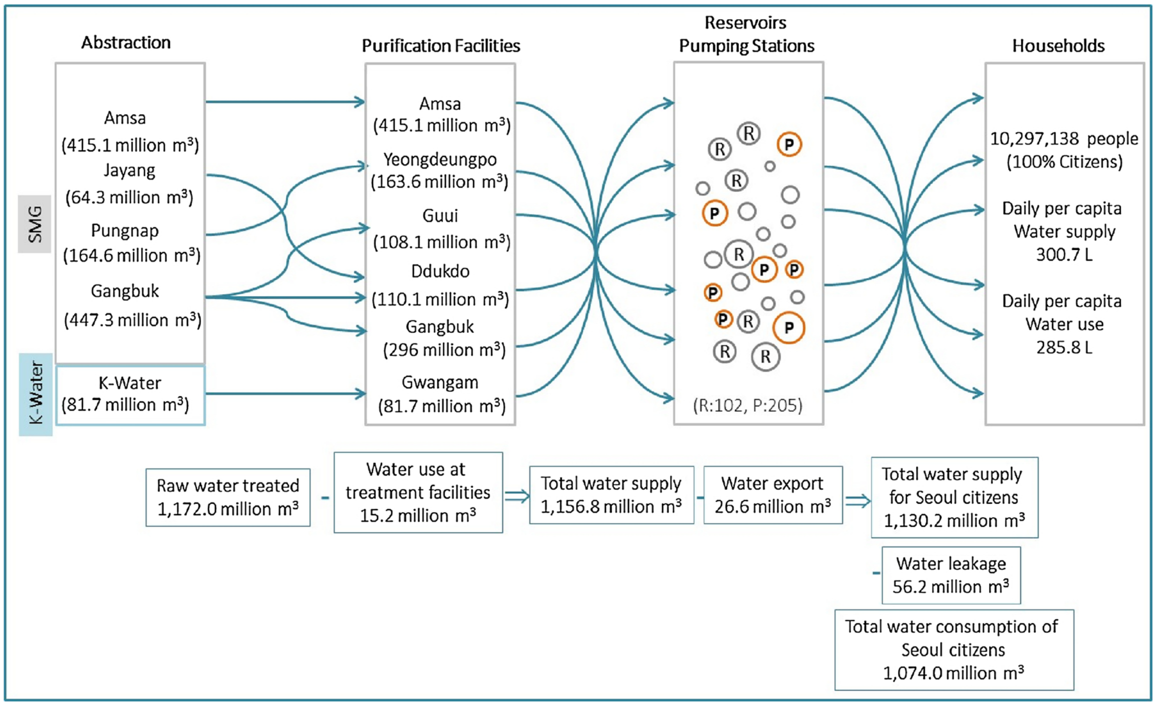

Fig. 3. Water Service Supply in Seoul.
Note: SMG stands for Seoul Metropolitan Government. R and P stand for reservoirs and pumping stations, respectively.
Source: The author built this flowchart based on MOE (2016b).

Table 1
The Amount of Sewage Treated and Reused in 2015.
Source: The author built this table based on MOE (2016a).

	Feces and Urine (million m^3)	Sewage (million m^3)			Sewage Reuse (million m^3)
		Biological Process	Advanced Process	Total	
Jungnang	1.58E+00	8.39E+01	3.66E+02	4.50E+02	8.65E+01
Nanji	2.19E+00		1.91E+02	1.91E+02	8.39E+00
Tancheon			2.68E+02	2.68E+02	1.84E+01
Seonam	1.30E+00	5.75E+01	4.86E+02	5.43E+02	7.95E+00
Total	5.08E+00	1.41E+02	1.31E+03	1.45E+03	1.21E+02

Note: All the sewage goes through a biological process after the physical process.

million m^3 of water (8.34% of the total wastewater treated) was reused to clean, wash, and cool municipal treatment facilities and to dilute wastewater for more effective treatment. Some treated water was also reused outside these facilities for agricultural or industrial purposes (Table 1) (MOE, 2016a).

3.2. Energy transition efforts in Seoul's Water Sector

3.2.1. Energy-driven approaches

The SMG has tried to increase energy production at water facilities. These activities did not begin with the recognition of the water-energy nexus. Rather, the SMG saw available vacant lots at water facilities and the potential of using renewable and unutilized energy to achieve the OLNPP target. However, the pursuit of increasing energy self-sufficiency at water facilities is closely related to the water-energy nexus.

In 2010, the MOE (2010) established its "Basic Plan for Energy Self-sufficiency in Wastewater Treatment Facilities," which aimed to increase energy self-sufficiency at wastewater treatment facilities by 50% by 2030. Although electricity consumption at those facilities accounted for only 0.5% of the national total, the energy self-sufficiency of the wastewater treatment facilities was as low as 0.8% (MOE, 2010).

In addition to this statewide plan, the SMG has installed various renewable technologies at water abstraction and purification centers and wastewater treatment facilities in Seoul as part of the OLNPP.[8] In 2015, the SMG aimed to increase renewable energy use, recover unutilized energy, and enhance the energy efficiency of the processes in order to achieve energy self-sufficiency in the water sector by 2030 (SMG, 2017c). As of 2017, 842 kW of geothermal facilities have been installed at two purification centers, and 15.5 MW of solar PVs have been installed at purification centers and wastewater treatment facilities. A sewer heat recovery system was installed at the Tancheon Wastewater Treatment Center at the end of 2014: 190,000 Gcal of energy is annually recovered and delivered to about 20,000 nearby households. In addition, biogas produced in the wastewater treatment process, which previously had been incinerated, is now used as fuel for 3.1 MW of combined heat and power (CHP) at the Nanji Wastewater Treatment Center. Biogas (26,000 m^3 per day) is also provided to Korea District Heating Corporation, which uses it to produce 20,000 MW h of electricity and 24,000 Gcal of heat yearly (SMG, 2014).

[8] Prior to the OLNPP, the SMG also tried to deploy new and renewable energy facilities to realize the new and renewable energy target of 10% in Seoul, 20% for the public sector, by 2020 (Lee, 2017).

Fig. 4. Installed Small-scale Rainwater Tanks in Seoul.
Source: (SMG, 2016)

3.2.2. Water-driven approaches

The SMG aims to increase the water reuse rate to 14.4% of total water use, which is an aggressive target given the 2010 water reuse rate of 3.86%. The SMG aims to increase rainwater use from 393 thousand m^3/year in 2010 to 2400 thousand m^3/year in 2020. To achieve this target, the SMG financially supports 90% of the installation costs of rainwater tanks, such as those shown in Fig. 4 (Seoul Solution (Producer) (2017)). Rainwater use is actively being adopted as part of urban regeneration projects (SMG, 2017b). The water collected is used for gardening, cleaning, and other household purposes. The SMG also aims to increase water reclamation and reuse from 2.84 million m^3/year in 2010 to 18.4 million m^3/year in 2020, and plans to increase water reuse at wastewater treatment facilities from 47.3 million m^3/year in 2010 to 188 million m^3/year in 2020 (SMG, 2013).

4. Energy transition in Seoul's Water Sector

4.1. Energy consumption and production in Seoul's Water Sector

Table 2 presents the amount of energy used at each stage of the urban water cycle in 2012 and 2015.[9] The electricity consumption data is obtained from MOE (2013a, 2013b, 2016a, 2016b), and the information on consumption and production from other energy sources is obtained from the SMG. Energy units are converted from physical units (e.g. kWh for electricity, liters for diesel) to GJ to calculate total energy consumption, total energy production, and the ratio of energy self-sufficiency. The Energy Conversion Factor that is regularly updated according to Article 5.1 of Enforcement Rules of the Energy Law in South Korea was used. The factors are provided in Table A1.

The total energy consumption of the water sector accounted for about 23.7% of the TFEC of public and other sectors in 2015 (41.9 million GJ).[10] The total energy consumption of water sector increased about 27.5% from 2012 levels even though per capita water consumption decreased slightly from 302 (MOE, 2013b) to 301 liters per capita per day from 2012 to 2015 (MOE, 2016b). In 2015, the wastewater treatment process accounted for the most significant proportion (53.5%) of total energy consumption in Seoul's water sector, followed by raw water purification (24.1%) and raw water abstraction (12.5%). The distribution step consumed the smallest share of energy.

[9] Although the author constructed a more specific inventory, the specific data cannot be presented because these facilities are controlled by the Korea Emission Trading Scheme.

[10] Calculated using the sectoral TFEC in Seoul in 2015, as found in the Yearbook of Regional Energy Statistics (KEEI, 2016).

Electricity's proportion of the total energy consumed is relatively low at wastewater treatment facilities, ranging from 70.8% to 84.5% in 2015, while other stages depended almost entirely on electricity. In addition to using a lower proportion of electricity, the energy consumption patterns of wastewater treatment facilities are completely different from those of other stages. About 62.5% of the energy consumed at these facilities was offset by the energy produced. 1.28 million GJ of energy was internally produced and consumed at the facilities, while 2.04 million GJ of energy was produced at the facilities and externally distributed. Biogas contributed the most to the amount of energy produced (42.6%); followed by dried sludge (16.2%), which is sold as fuel; and waste heat recovered from incineration facilities, CHPs, biogas power plants, sludge dryer, and biogas boilers (14.7%).

4.2. Changes in energy and carbon intensities in Water Sector in Seoul

The energy intensity of individual stages of the water cycle is derived by dividing energy consumption by the amount of water processed at each stage. By multiplying energy consumption by the emission factor (see Table A1), CO_2 emissions are estimated; this does not incorporate other greenhouse gas (GHG) emissions and is confined to direct emissions. CO_2 intensities are estimated by dividing emissions by the amount of water processed.

Fig. 5 presents the net and actual energy and CO_2 intensities at each stage of Seoul's water cycle for 2012 and 2015. The total energy intensity (the sum of energy intensities across individual stages) increased from 5.83 MJ/m^3 in 2012 to 7.71 MJ/m^3 in 2015. The energy intensity of the wastewater treatment stage greatly increased, which can be attributed to the increased use of advanced treatment technologies. In 2012, 23.7% of wastewater was treated using advanced treatment technologies (MOE, 2013a); this increased to 90.3% in 2015 (MOE, 2016a). The energy intensity of raw water purification also increased, from 1.60 to 2.04 MJ/m^3. As of 2012, advanced purification technology accounted for only 10.3% of the total capacity of purification facilities; rapid filtration technology was generally used to purify abstracted raw water (MOE, 2013b). In 2015, the capacity of advanced purification technology increased to 74.6%; advanced purification was generally used along with rapid filtration (MOE, 2016b).

Even with increased energy consumption at waste treatment facilities, the total net energy intensity of the water sector, which subtracts the amount of energy produced from the amount of energy consumed, was lower in 2015 (5.42 MJ/m^3) than in 2012. This can be mostly attributed to the significant amount of energy produced and recovered at the four wastewater treatment facilities.

Over the same period, the carbon intensity of the water sector

Table 2
Energy Consumption and Production by Energy Source and Stage of Water Cycle in Seoul in 2012 and 2015.
Source: This table has been built by the author(s) based on MOE (2013a, 2013b, 2016a, 2016b) and internal raw data provided by the SMG.

Urban water cycle	Facilities	2012		2015				
		External energy		External energy		Energy produced and internally consumed		
		Electricity (GWh)	Petroleum products & LNG (GJ)	Electricity (GWh)	Petroleum products & LNG (GJ)	Geothermal (GJ)	Solar Energy (GWh)	Waste Heat Recovery (GJ)
Raw water abstraction	Subtotal	1.64E+02	–	1.40E+02	–	–	–	–
	Amsa	6.20E+01	–	6.01E+01	–	–	–	–
	Jayang	7.51E+00	–	4.97E+00	–	–	–	–
	Pungnab	2.09E+01	–	2.06E+01	–	–	–	–
	Gangbuk	4.48E+01	–	5.45E+01	–	–	–	–
	Guui [d]	2.91E+01	–	–	–	–	–	–
Raw water purification	Subtotal	2.17E+02	4.60E+03	2.48E+02	1.87E+03	2.79E+02	3.14E-01	–
	Youngdengpo	4.49E+01	9.37E+02	4.35E+01	6.81E+02	2.77E+02	3.14E-01	–
	Amsa	6.01E+01	1.91E+03	7.55E+01	6.93E+02	2.34E+00	–	–
	Guui	1.45E+01	3.73E+02	2.41E+01	8.62E+01	–	–	–
	Ddukdo	3.94E+01	2.16E+02	3.10E+01	2.09E+02	–	–	–
	Gwangam	2.80E+00	3.96E+02	6.24E+00	8.39E+01	–	–	–
	Gangbuk	5.57E+01	7.74E+02	6.76E+01	1.18E+02	–	–	–
Distribution		9.38E+01	–	9.04E+01		–	–	–
Wastewater Treatment	Subtotal	4.00E+02	4.65E+04	4.18E+02	7.75E+03	–	7.11E-01	4.88E+05
	Jungnang	1.29E+02	6.87E+03	1.55E+02	3.86E+03	–	5.79E-01	1.63E+05
	Nanji	5.88E+01	1.87E+03	6.82E+01	1.53E+03	–	1.18E-01	1.49E+05
	Tancheon	7.31E+01	3.56E+04	6.53E+01	1.08E+03	–	3.65E-03	7.36E+04
	Seonam	1.39E+02	2.15E+03	1.30E+02	1.28E+03	–	9.96E-03	1.03E+05
Total		8.76E+02	5.11E+04	8.97E+02	9.62E+03	2.79E+02	1.03E+00	4.88E+05

Urban water cycle									
	Energy produced and internally consumed	Energy produced and externally supplied					Total Energy Consumption[a] (GJ)	Total Energy Production[b] (GJ)	Self-sufficiency[c]
	Biogas(GJ)	Solar Energy (GWh)	Small-scale Hydro (GWh)	Sewer Heat Recovery (GJ)	Dried Sludge (GJ)				
Raw water abstraction	–	–	–	–	–	–	1.35E+06	–	–
	–	–	–	–	–	–	5.79E+05	–	–
	–	–	–	–	–	–	4.78E+04	–	–
	–	–	–	–	–	–	1.98E+05	–	–
	–	–	–	–	–	–	5.25E+05	–	–
	–	–	–	–	–	–	–	–	–
Raw water purification	–	–	–	–	–	–	2.39E+06	3.30E+03	1.38E-03
	–	–	–	–	–	–	4.23E+05	3.30E+03	7.80E-03
	–	–	–	–	–	–	7.28E+05	2.34E+00	3.22E-06
	–	–	–	–	–	–	2.32E+05	–	–
	–	–	–	–	–	–	2.99E+05	–	–
	–	–	–	–	–	–	6.02E+04	–	–
	–	–	–	–	–	–	6.51E+05	–	–
Distribution	–	–	–	–	–	–	8.71E+05	–	–

(continued on next page)

Table 2 (*continued*)

Urban water cycle	Energy produced and internally consumed	Energy produced and externally supplied					Total Energy Consumption[a] (GJ)	Total Energy Production[b] (GJ)	Self-sufficiency[c]
	Biogas(GJ)	Solar Energy (GWh)	Small-scale Hydro (GWh)	Sewer Heat Recovery (GJ)	Dried Sludge (GJ)				
Wastewater Treatment	7.82E+05	6.34E+05	6.96E+00	2.87E-01	8.00E+05	5.38E+05	5.32E+06	3.32E+06	6.25E-01
	4.04E+05	1.29E+05	9.88E-01	–	–	2.39E+05	2.07E+06	9.50E+05	4.59E-01
	1.20E+05	2.00E+05	–	–	6.88E+02	1.11E+05	9.27E+05	5.81E+05	6.27E-01
	1.33E+05	0.00E+00	7.99E-03	–	7.99E+05	1.88E+05	8.36E+05	6.36E+05	7.60E-01
	1.25E+05	3.06E+05	5.97E+00	2.87E-01	–	–	1.48E+06	5.94E+05	4.01E-01
Total	7.82E+05	6.34E+05	6.96E+00	2.87E-01	8.00E+05	5.38E+05	9.93E+06	3.32E+06	3.35E-01

Note: a Total energy consumption is the summation of "external energy" and "energy produced and internally consumed." b Total energy production is the summation of "energy produced and internally consumed" and "energy produced and externally supplied." c Self-sufficiency is calculated by dividing total energy production by total energy consumption. The unit of electricity consumption was converted to GJ to estimate the total energy consumption and the total energy production. The Energy Conversion Factor announced according to the Enforcement Rule Article 5 of the Energy Law in South Korea was used to convert the values from physical units (See details in Table A1). d Guui abstraction station is currently closed; the space is currently used as art center.

increased from 0.293 to 0.325 kg CO_2/m^3. This increase can be primarily attributed to increased electricity consumption. Specifically, 20.9 thousand tons of CO_2 emissions from increased electricity consumption offset the 2.42 thousand tons of CO_2 emissions from decreased use of petroleum products and LNG (see details of CO_2 emissions by fuel in Table A2).

The net CO_2 intensity for 2015 could be estimated after taking into consideration the energy produced using renewables or waste heat that substituted for energy that would otherwise have been supplied externally. This study estimates net CO_2 emissions and net CO_2 intensities. Renewable electricity is assumed to replace the electricity produced externally, and heat energy, e.g., biogas, is assumed to replace LNG and diesel consumption. In 2015, the net CO_2 intensity (0.198 kg CO_2/m^3) was lower than that in 2012 due to CO_2 emissions reduction in the waste treatment process.

4.3. Energy saving and CO_2 reduction potentials of Water consumption reduction

In addition to these energy production efforts, attempts to reduce water demand through water reclamation, recycling, and rainwater harvest indirectly influence energy consumption in the water sector. Based on the assumption of constant energy intensities at each individual stage of the water cycle,[11] energy savings and CO_2 reductions once the SMG achieves its targets for water reuse and rainwater harvest (SMG, 2013) are estimated and compared to business-as-usual energy consumption.

Table 3 presents the potential savings: In 2020, 846 thousand GJ of energy could be saved and CO_2 emissions could be reduced by 40.2 thousand tons. This would be a relatively small proportion (8.52%) of the energy consumption by the water sector in 2015. However, greater achievement could be attained through various water saving interventions.

5. Discussion

Other studies estimating the energy intensity of the water sector have focused on electricity consumption. This study collected actual energy consumption data including non-electric energy in an urban water infrastructure and estimated changes in the energy intensity of individual stages of the urban water cycle.

The energy intensities of individual stages of Seoul's water cycle were consistent with the findings of M. Lee et al. (2017) and Loubet, Roux, Loiseau, and Bellon-Maurel (2014). In Seoul, the wastewater treatment stage was the most energy intensive. While the most energy intensive stage of water use is generally the end-use stage, such as hot water use in buildings, (Kenway, Lant, Priestley, & Daniels, 2011; Lee et al., 2017), this was not included in the analysis due to the unavailability of data.

As M. Lee et al. (2017) pointed out, the level of treatment and technology is the major factor influencing energy intensity in the water sector. The increased use of advanced treatment technology resulted in increased energy consumption and energy intensity in Seoul's water sector over the period from 2012 to 2015. However, as the SMG utilized or recovered waste heat and sewer heat and deployed new and renewable energy in the water sector, the net energy intensity of the water sector actually decreased from 2012 to 2015. In a metropolis surrounded by a built environment, renewable energy potential is relatively low and difficult to realize. However, Seoul's case showed the feasibility of using wastewater treatment facilities as an "unexpected

[11] If water is reused, it is not necessary to withdraw, purify, and distribute the amount of water reused or reclaimed and rainwater that harvested. Therefore, to estimate the potentials, this study multiplies the water reuse targets with the sum of energy and carbon intensities, excluding the intensities of the wastewater treatment stage.

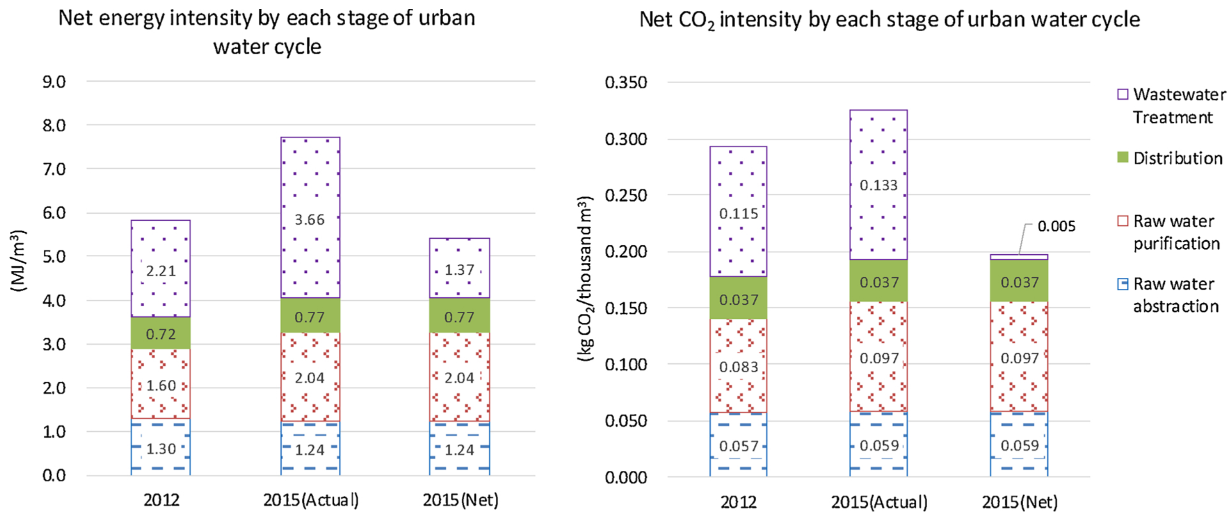

Fig. 5. Net Energy and CO_2 Intensities by Each Stage of Seoul's Water Cycle.
Note: The left figure shows the net and actual energy intensities by stage of the urban water cycle in 2012 and 2015. The right figure presents the corresponding changes in net and actual CO_2 intensities over the period. The net intensity is equivalent to the actual intensity in 2012, since there was no energy produced.

Table 3
Energy Saving and CO_2 Reduction Potential of Water Reuse and Rainwater Harvest by 2020.
Source: the author calculated the energy saving and CO_2 reduction potential using the 2020 targets for water reuse (SMG, 2013).

	Category	2016	2017	2018	2019	2020
Energy Saving (GJ)	Total Energy Saving	5.75E+05	6.53E+05	7.32E+05	7.89E+05	8.46E+05
	Energy Saving from Wastewater Reuse	5.11E+05	5.85E+05	6.58E+05	7.10E+05	7.62E+05
	Energy Saving from Water Reclamation	5.58E+04	6.01E+04	6.44E+04	6.94E+04	7.43E+04
	Energy Saving from Rainwater Use	8.12E+03	8.56E+03	9.00E+03	9.36E+03	9.72E+03
CO_2 Reduction (ton)	Total CO_2 Reduction	2.74E+04	3.11E+04	3.48E+04	3.75E+04	4.02E+04
	CO_2 Reduction from Wastewater Reuse	2.43E+04	2.78E+04	3.13E+04	3.38E+04	3.62E+04
	CO_2 Reduction from Water Reclamation	2.65E+03	2.86E+03	3.06E+03	3.30E+03	3.54E+03
	CO_2 Reduction from Rainwater Use	3.87E+02	4.08E+02	4.28E+02	4.45E+02	4.63E+02

and locally available renewable energy source" (Kollmann et al., 2017, p. 119), based on the observation that energy recovered or produced at wastewater treatment facilities is provided to residents of nearby areas. In addition to wastewater treatment plants, a "hybrid energy system" using fossil fuels and renewables could be pursued in the water supply system (Vakilifard, Anda, A. Bahri, & Ho, 2018).

According to Seoul's ambitious target of energy self-sufficient wastewater treatment plants by 2030, these facilities are expected to be energy producers, like German wastewater treatment facilities (e.g., the Köhlbrandhöft/Dradenau plant (Garleff, 2018)), not energy consumers. Furthermore, the deployment of renewables along with the use of an energy storage system could reduce dependence on external energy supplies (Vakilifard et al., 2018). Although Seoul is at the very initial stage (energy production using renewables was 0.131% at raw water purification facilities and 51.6% in wastewater treatment facilities in 2015), its case shows a path for a city to pursue energy transition in the water sector.

Curbing energy demand should be pursued along with producing energy from renewable resources (Kim, 2018). Otherwise, energy transition from fossil fuels to renewables is impossible. When it comes to the water sector in urban areas, reducing water consumption reduces energy consumption. The estimated potential energy savings from water reuse and rainwater harvest was about 8.5% of the current energy consumption of Seoul's water sector. The energy saving potential of water reuse or recycling depends on the system. Generally, decentralized water reuse is perceived as energy saving measures while the energy saving effects of centralized water reuse is controversial (Chang, Lee, & Yoon, 2017). This study assumes that water is reused in a decentralized manner, which is generally less energy intensive.

In addition to these measures, there are other ways to reduce water demand and indirectly reduce energy consumption. The water-energy nexus perspective should be embedded in urban planning because the built environment affects resource consumption patterns for a long time (Cotgrave & Riley, 2012). In addition to technological approaches, behavioral modification could reduce water consumption and related energy consumption (Jiang et al., 2016). The various interventions studied imply that there is a great potential for reducing energy consumption and GHG emissions through implementing water demand reductions.

Energy transition is a critical agenda item pursued by both the South Korean government and the SMG. Their efforts are biased towards increasing energy production (Kim, 2018); indirect energy savings through reducing water demand is not recognized as part of energy transition. Recently, the SMG announced the "City of the Sun: Seoul," a very aggressive plan to deploy 1 GW of solar PVs, equivalent to the capacity of a nuclear power plant, by 2022 (SMG, 2017a). Along with transition to a low carbon-based energy system, reducing energy demand through reducing water demand could greatly contribute to energy transition in the water sector and in Seoul.

6. Conclusion

Although the water-energy nexus in urban areas is an important issue, it has rarely been studied for Korean cities due to lack of data. Beyond building an energy consumption inventory for each individual stage of Seoul's water cycle, this study estimated changes in net energy intensity and corresponding net carbon intensity between 2012 and 2015 to investigate the effect of Seoul's energy transition initiative on the water sector. This study found that Seoul's energy transition efforts decreased net energy intensity from 2012 to 2015, despite the increased use of advanced water treatment technology.

In addition to efforts to increase energy self-sufficiency directly at water facilities, this study explored the potential for indirect energy saving and carbon emissions reduction through increased water reuse and rainwater harvest. Currently, these interventions are just seen as countermeasures for water issues. Given the energy saving and CO_2 reduction potential of various water saving interventions, water-driven approaches need to be incorporated into energy-transition initiatives.

This study constructed a detailed inventory of energy consumption at each stage of Seoul's water cycle and found that Seoul's energy initiative reduced net energy and net carbon intensities. This study also expanded the perspective of the water-energy nexus to include energy transition in the water sector in urban areas. Finally, this study filled a gap in the areas where the water-energy nexus has been studied.

In future research, Seoul's energy consumption at the end-use stage of the urban water cycle should be investigated. In addition, the energy intensity of each stage of Seoul's water cycle needs to be compared with other cities like Sowby and Burian (2017) and Chini and Stillwell (2018)' studies, taking into account the various factors that can influence it.

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Appendix A

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Table A1
Energy Conversion Factors and CO_2 Emission Factors.
Source: The total heating values of diesel, kerosene, propane, LNG, and electricity are obtained from Energy Conversion Factors that are announced and regularly updated according to the Article 5.1 of the Enforcement Rules of the Energy Law in South Korea. CO_2 emission factors of fuels (except electricity) are gathered from the National GHG Emission Factors that are issued according to the same rule. The CO_2 emission factors do not include other GHG emissions. In addition, the CO_2 emission factor for electricity is obtained from Korean Power Exchange. The total heating values of biogas and dried sludge are provided by the wastewater treatment facilities in Seoul.

	Total heating value (kcal)	CO_2 emission factors (kg CO_2/TJ or kg CO_2/MWh)
Diesel (liter)	9.010E+03	7.410E+04
Kerosene (liter)	8.790E+03	7.190E+04
Propane (kg)	1.205E+04	6.450E+04
LNG (Nm^3)	1.043E+04	5.610E+04
Electricity (kWh)	2.300E+03	4.585E+02
Biogas (Nm^3)	5.200E+03	
Dried Sludge (kg)	3.328E+03	

Note: 1 kcal of energy is equivalent to 4.1868 J of energy.

Table A2
CO_2 emissions in 2012 and 2015.

Unit of measurement: ton of CO_2

Year	Stage of urban water cycle	CO_2 emissions by fuel										CO_2 emissions	Net CO_2 emissions
		Electricity	Petroleum products	LNG	Geothermal	Solar Power	Waste Heat Recovery	Biogas	Small-scale Hydro	Sewer Heat Recovery	Dried Sludge		
2012	Raw water abstraction	6.43E+04	–	–	–	–	–	–	–	–	–	6.43E+04	6.43E+04
	Raw water purification	9.97E+04	1.38E+02	1.53E+02	–	–	–	–	–	–	–	1.00E+05	1.00E+05
	Distribution	4.30E+04	–	–	–	–	–	–	–	–	–	4.30E+04	4.30E+04
	Wastewater Treatment	1.83E+05	7.31E+02	2.05E+03	–	–	–	–	–	–	–	1.86E+05	1.86E+05
	Total	3.90E+05	8.69E+02	2.20E+03	–	–	–	–	–	–	–	3.93E+05	3.93E+05
2015	Raw water abstraction	6.43E+04	–	–	–	–	–	–	–	–	–	6.43E+04	6.43E+04
	Raw water purification	1.14E+05	1.96E+01	8.90E+01	−1.57E+01	−1.44E+02	–	–	–	–	–	1.14E+05	1.14E+05
	Distribution	4.15E+04	–	–	–	–	–	–	–	–	–	4.15E+04	4.15E+04
	Wastewater Treatment	1.92E+05	4.57E+02	8.81E+01	–	−3.52E+03	−2.65E+04	−7.55E+04	−1.31E+02	−4.49E+04	−3.02E+04	1.92E+05	1.17E+04
	Total	4.11E+05	4.76E+02	1.77E+02	−1.57E+01	−3.66E+03	−2.65E+04	−7.55E+04	−1.31E+02	−4.49E+04	−3.02E+04	4.12E+05	2.31E+05

Note: Carbon emissions are estimated by multiplying energy consumption with South Korea's national greenhouse gas emission factors by fuel. The emission factor for electricity is obtained from the Korea Power Exchange (KPX, 2018). Carbon intensity is calculated by dividing carbon emissions by the amount of water abstracted or purified or delivered or treated. Energy produced using renewable energy or waste heat is assumed to replace external energy such as electricity, LNG or diesel.

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