water

MDPI

Article

Estimation of Energy Consumption and CO_2 Emissions of the Water Supply Sector: A Seoul Metropolitan City (SMC) Case Study

Li Li [1], Gyumin Lee [2] and Doosun Kang [2,*]

[1] Global Engineering Institute for Ultimate Society (GENIUS), Sungkyunkwan University, 2066, Seobu-ro, Jangan-gu, Suwon-si 16419, Gyeonggi-do, Republic of Korea; lili0809@skku.edu
[2] Department of Civil Engineering, College of Engineering, Kyung Hee University, 1732, Deogyeong-daero, Giheung-gu, Yongin-si 17104, Gyeonggi-do, Republic of Korea; greenbeing@khu.ac.kr
* Correspondence: doosunkang@khu.ac.kr

Abstract: A model that computes the per-unit process energy consumption, energy intensity, CO_2 emission, and CO_2 intensity of water treatment plants is developed. This model is used to estimate the total energy consumption of six water treatment plants in Seoul Metropolitan City (SMC), which is comprised 80–85% for finished water pumping, 6–10% for ozone disinfection, 2–4% for rapid mixing, and 1–3% for non-process loads. The model results are validated against actual data for 2020 and 2021. The net energy consumption considering renewable energy production and use is then calculated, and the corresponding level of CO_2 emissions is predicted. Four scenarios based on the projected water requirements for the year 2045 were evaluated as follows: increased energy efficiency in finished water pumping (Scenario 1), increased renewable energy production in water treatment plants (Scenario 2), increased energy efficiency in raw water pumping (Scenario 3), and reduced water supply per capita (Scenario 4). Compared to a baseline do-nothing scenario (Scenario 0), the net energy consumption is reduced by 3.57%, 2.61%, 3.42%, and 4.67% for Scenarios 1–4, respectively. Scenario 4, which is a water-driven approach, is best for reducing CO_2 emissions, while Scenario 1 and 3, which are energy-driven approaches, are more effective at reducing CO_2 intensity.

Keywords: water supply sector; water extraction; treatment; distribution; energy consumption; CO_2 emissions

check for updates

Citation: Li, L.; Lee, G.; Kang, D. Estimation of Energy Consumption and CO_2 Emissions of the Water Supply Sector: A Seoul Metropolitan City (SMC) Case Study. *Water* **2024**, *16*, 479. https://doi.org/10.3390/w16030479

Academic Editors: Yurui Fan and Wendy Huang

Received: 17 January 2024
Revised: 29 January 2024
Accepted: 30 January 2024
Published: 31 January 2024

1. Introduction

Climate change adversely affects human life, infrastructure, and the ecosystem. Specifically, the increase in the Earth's surface temperature is predicted to raise sea levels and the incidences of intense floods and droughts [1]. In 2021, South Korea emitted 616 million metric tons of CO_2 and was ranked 10th among the countries in the world with the highest greenhouse gas (GHG) emissions [2]. South Korea has committed to net-zero CO_2 emissions by 2050, with an interim goal of a 40% reduction in CO_2 emissions by 2030 compared to the 2018 levels [3]. "Carbon neutrality", the state of net-zero carbon dioxide emissions, has become an important goal in the sustainable development of essential distributed utilities like energy and water [4]. Consequently, numerous government organizations and utility companies are transitioning to low-carbon solutions [5,6].

Energy is critical for urban water supply. The United Nations Organization (UNO) reported that global energy consumption in relation to water pumping, treatment, and distribution accounts for approximately 8% of the total energy consumption [7]. Rothausen and Conwasy [8] reported that increasingly large amounts of energy would be required by water systems to meet the tightening regulatory requirements and counter the environmental effects of the significant rise in GHG emissions due to energy use. Water, energy, and carbon emissions are interconnected and critical for urban water sustainability and carbon emissions reduction [9]. Therefore, opportunities to improve energy and water use efficiency and recover and produce more energy should be identified to achieve the management of sustainable urban water supply [1].

Different aspects of energy consumption and CO_2 emissions have been investigated in the previous literature on urban water systems. Horvath and Strokes [10] estimated and compared the energy consumption and CO_2 emissions of California's water supply alternatives, and Venkatesh and Brattebo [11] studied the energy consumption, cost, and environmental impacts of Oslo's urban water cycle services. Research on South Korea's domestic water supply includes studies by Chang et al. [12], who investigated the energy consumption and GHG emissions of water supply and reuse systems involving 42 extraction plants, 37 water treatment plants, and 23 distribution pumping stations. Kim and Chen [13] also studied the changes in energy and carbon intensities for the Seoul Metropolitan City (SMC) water supply sector. These studies quantified the total energy consumption and CO_2 emissions for sub-systems of the water supply sector, such as raw water pumping and drinking water treatment. However, studies on the energy consumption of individual unit processes in the water supply system are lacking.

Raw water pumping and finished water distribution to end users require a large amount of energy and dominate the energy use of the water supply sector [14]. In a water treatment facility, large amounts of energy are required to remove sediments, contaminants, and chemicals so that the treated water meets drinking water standards. The accurate measurement of unit process-based energy consumption can identify which unit process accounts for the highest energy consumption and can help formulate comprehensive and targeted approaches for reducing energy consumption. This study quantified the amount of energy consumed by major water treatment processes and ranked the unit processes according to their energy consumption and CO_2 emissions. Net energy consumption and CO_2 emissions were also estimated after considering renewable energy production and use.

To estimate the energy consumption and CO_2 emissions for the major unit processes in potable water treatment, we developed a model and calibrated it against empirical data. However, there remain data challenging for model calibration owing to the need for the precise and individualized empirical measurement of consumed energy by many unit processes involved in the water treatment. Nevertheless, the results of the model provide the first comprehensive estimates of energy consumption for individual unit processes of water treatment plants in the SMC. More importantly, the predictive performance of this model can be improved in the future as more data become available.

In addition, the effects of various efforts to reduce the net energy consumption and CO_2 emissions in the water supply sector are then examined. This study assesses how energy needs might change after 20 years with the implementation of the following four improved scenarios: an improvement in energy efficiency for raw and finished water pumping, an increase in renewable energy production, and a reduction in water supply consumption per capita. The effects of these four scenarios were analyzed by calculating a reduction in energy consumption and carbon emissions in water supply facilities in the SMC and comparing the results to a do-nothing baseline scenario that maintained the characteristics of the 2020 water supply service. The key findings of this study can aid water utilities, city planners, engineers, and researchers in the field in estimating the energy consumption of typical unit processes associated with water treatment facilities where measured data are scarce or unavailable. Furthermore, the findings of this study can enable policymakers to make better-informed decisions regarding resources and energy management and climate change mitigation in the water supply sector.

The remainder of this paper is organized as follows. Section 2 describes the study area and target water supply facilities, the methodology used for energy consumption and CO_2 production in the water treatment process, and applied future scenarios. Section 3 discusses the results of this study, and Section 4 presents conclusions and future research directions.

2. Materials and Methods

2.1. Study Area

The SMC is the capital of South Korea, and approximately 20 percent of the entire population of South Korea, which was reported to be 9,655,918 in 2023 [15], are SMC residents. The water supply services of SMC are operated by the Seoul Metropolitan Government (SMG) Office of Waterworks, and 100% of the population in the SMC is connected to the water supply system. This study investigated four water extraction and six water treatment facilities located in the SMC, as presented in Figure 1. The primary source of the city's water supply is the Han River. In 2020, 1,063,300,876 m^3 of raw water extracted from four extraction stations (Amsa, Jayang, Pungnab, and Gangbuk) was sent to five water treatment plants (Gangbuk, Ddukdo, Guui, Amsa, and Youngdengpo), and 83,181,840 m^3 of raw water taken by the Korea Water Resources Corporation (K-water), which is a separate entity from SMG, was conveyed to the Gwangam treatment plant [16]. The raw water delivered to the six treatment plants undergoes an advanced treatment process, and purified water is distributed to the end users. Figure 2 shows these processes of the water supply system in the SMC.

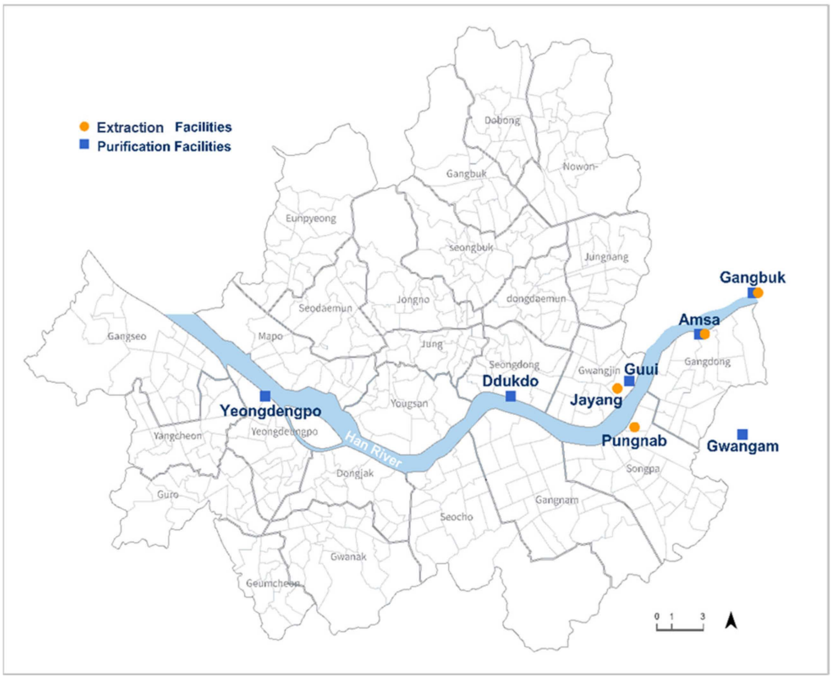


Figure 1. Location of SMC water supply facilities modelled in this study.

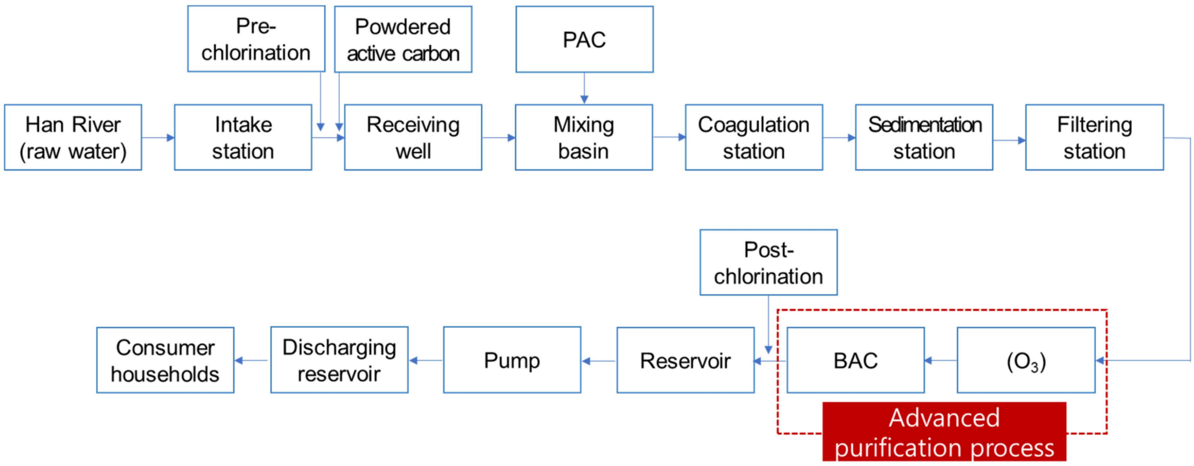


Figure 2. Schematic of advanced water purification system implemented in SMC water treatment plants. (Modified from [17]).

2.2. Methodology and Data Sources

Owing to the scarcity of measured energy consumption data for unit operations of water systems in the SMC, the energy used by each unit process was estimated based on a report estimating the daily energy usage for common water treatment unit processes in the USA [18]. This report estimated the energy intensity for all unit processes in drinking water treatment as a function of the average flow rate, as shown in Table 1. To develop the energy intensity values, information from government entities, private research groups, the literature, and other sources were analyzed to characterize the water industries in terms of the number and type of facilities, processes, and electricity use. Each industry was then segmented based on parameters such as size, key process elements, and functions. A bottom-up approach based on available data was used to develop energy intensity values for various unit processes [18].

Table 1. Estimates of energy intensity of public water supply unit processes (in kWh/day) based on Reekie et al. [18].

Unit Process		Efficiency	Plant Production (MGD)						
			1	**5**	**10**	**20**	**50**	**100**	**250**
Source Water Pumping	Raw surface water pumping	High	118	589	1177	2355	5887	11,774	29,435
		Medium	145	725	1449	2898	7246	14,491	36,228
		Low	188	942	1884	3768	9419	18,838	47,096
Clarification	Rapid mixing		40	175	310	620	1540	3080	7700
	Flocculation		10	50	90	180	450	900	2260
	Sedimentation		15	45	90	175	440	875	2190
	Chemical feed systems		65	65	65	65	65	65	65
	Microfiltration (in lieu of sedimentation)		100	500	1000	2000	5000	10,000	25,000
	Ultrafiltration (contaminant removal)		800	4000	8000	16,000	40,000	80,000	200,000
	Reverse osmosis (brackish water)		6000	29,800	59,500	119,000	226,600	453,200	738,400
	Reverse osmosis (ocean water)		12,000	60,000	120,000	240,000	600,000	1,200,000	3,000,000
	Dissolved air flotation		110	895	1790	3600	8950	17,900	44,700
	Air stripping		375	1850	3740	7475	N/A	N/A	N/A
	Repumping within treatment plant		-	-	-	-	1950	3900	9750

Table 1. *Cont.*

Filtration and Solid Handling	Backwash water pumps		15	60	125	250	660	1290	3220
	Residuals pumping		4	20	40	80	200	400	1000
	Thickened solid pumping		-	-	-	125	310	620	1540
Disinfection, Pumping and Non-process Loads	Onsite chlorine generation for disinfection		85	420	830	1670	4160	8325	20,820
	Ozone disinfection		140	560	1125	1500	3840	7670	19,175
	UV disinfection		62	310	625	1250	3120	6240	15,600
	Finished water pumping	High	845	4328	8969	17,520	39,629	79,257	198,143
		Medium	1040	5327	11,038	1563	48,774	97,547	243,868
		Low	1352	6925	14,350	8032	63,406	126,811	317,029
	Non-process loads (buildings, HVAC, lighting, computers, etc.)		300	1200	2100	3600	9000	18,000	45,000

Based on tables containing small to large flow rates (i.e., 1–250 million gallons per day (MGD)), the composite energy usage for each of the six drinking water treatment plants made up of a series of combinations of unit processes was estimated using the model developed in this study. The six plants used advanced treatment technology involving the same unit processes. Compared to standard drinking water treatment, advanced treatment technologies additionally involve ozone treatment and biological-activated carbon (BAC) treatment [17], as shown in Figure 2. Unit processes, including rapid mixing, flocculation, sedimentation, chemical feed system, backwater pumping, residual pumping, thickened solid pumping, ozone disinfection, finished water pumping, and non-process load, were included in this model to compute the energy used by water treatment plants in the SMC. The process of applying this model is illustrated in Figure 3. The energy consumption of the finished water distribution is related to the energy efficiency of the finished water pumping process. The specific estimation of energy efficiency for the current finished water pumping process is beyond the scope of this study. Therefore, the energy consumption for the finished water pumping process was not estimated in this study. Instead, the approximate energy efficiency range for the finished water pumping process was obtained by comparing the measured energy consumption to the estimates in relation to the three energy efficiencies (i.e., low, medium, and high) from Table 1.

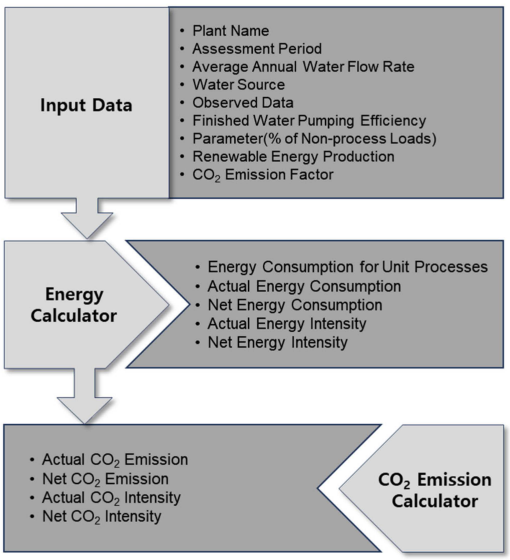


Figure 3. Process for computing energy consumption and CO_2 emissions of water treatment plants.

The energy used for buildings, such as office equipment, lighting, and air conditioning, is typically less than the process energy. However, this can account for a large portion of the total energy use (more than 30%) of smaller plants [18]. The energy consumed for the non-process load was reported to account for 2.88% of the total energy consumption for the "G" water treatment plant located in SMC, which is operated by K-water [19]. In this study, the percentage of energy used for the non-process load was calibrated as a parameter.

The developed model was calibrated by adjusting the percentage of the energy used for the non-process load to obtain the best fit between the calculated and observed daily energy consumption. Observed data were obtained from the South Korean Ministry of Environment (MOE) [16,20]. In this model, net energy consumption was calculated after including renewable energy production. Corresponding actual and net CO_2 emissions were estimated using the appropriate CO_2 emission factor. A screenshot of the graphical user interface (GUI) of the developed model is shown in Figure 4. The annual electricity consumption data for water extraction and treatment plants were obtained from the MOE [16,20], and the in situ renewable energy production data were obtained from the MOE [16] and SMG.

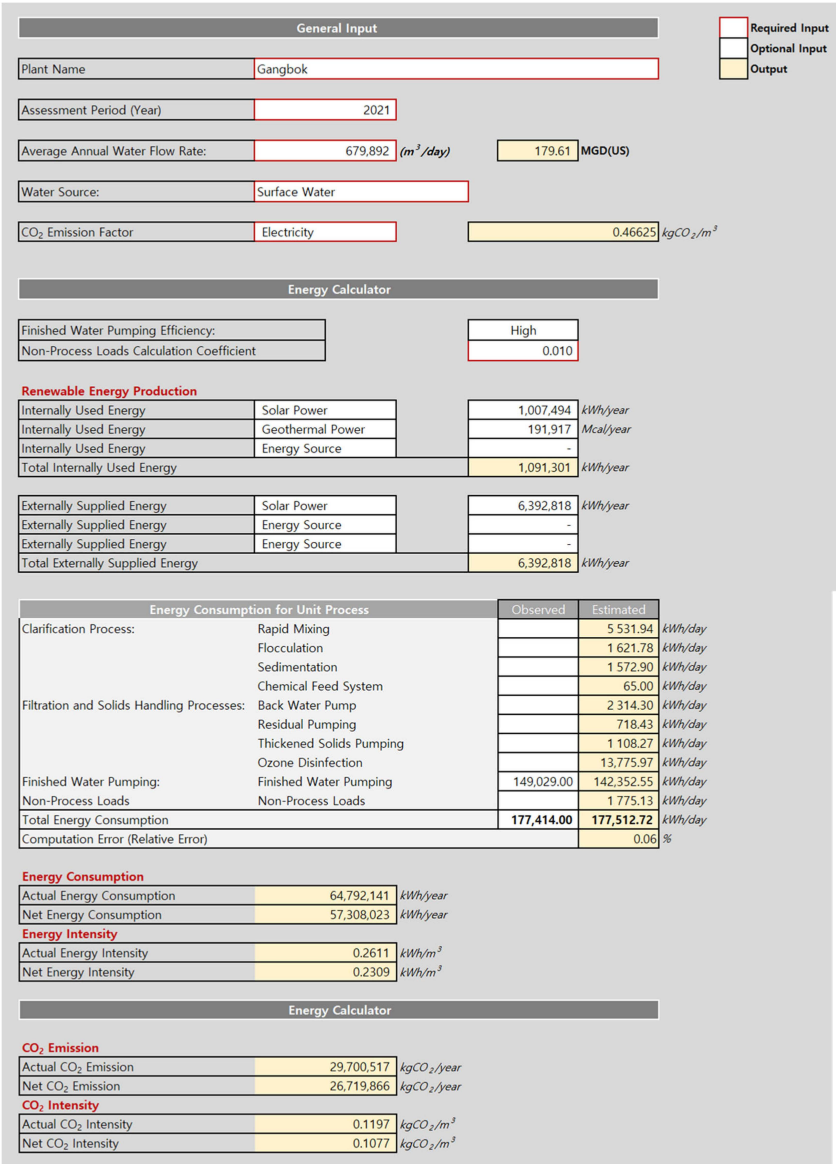


Figure 4. Screenshot of user interface of developed model.

2.3. Scenario Development

The population of SMCs is projected to decrease from 9,911,000 in 2020 to 8,810,000 in 2045 [21]. The population across the water distribution districts of the six water treatment plants is assumed to decrease equally in this study. However, the daily water consumption per capita has increased over the last 10 years due to climate change and an increased number of households with one or two people [22], as shown in Figure 5. The Waterworks Office of SMG reported that, in the case of SMC, the daily water consumption per capita increases by 10 L when the temperature rises by an average of 10 °C [22]. Based on the trendline in Figure 5, the daily water supply per capita is expected to increase to 311 L by 2045. Overall, the required water supply is expected to increase from 1,134,613,170 m^3/year in 2020 to 1,135,271,344 m^3/year in 2045 despite the decreasing population. To achieve a reduction in net CO_2 emissions in the SMC water supply sector, four plausible future scenarios were analyzed and compared with a baseline scenario. Scenarios 1–3 were energy-driven approaches, and Scenario 4 was a water-driven approach. Energy-driven approaches involve a direct reduction in consumed energy by improving energy efficiency or energy production in water supply facilities. In contrast, the water-driven approach indirectly reduces energy consumption by reducing water demand [13].

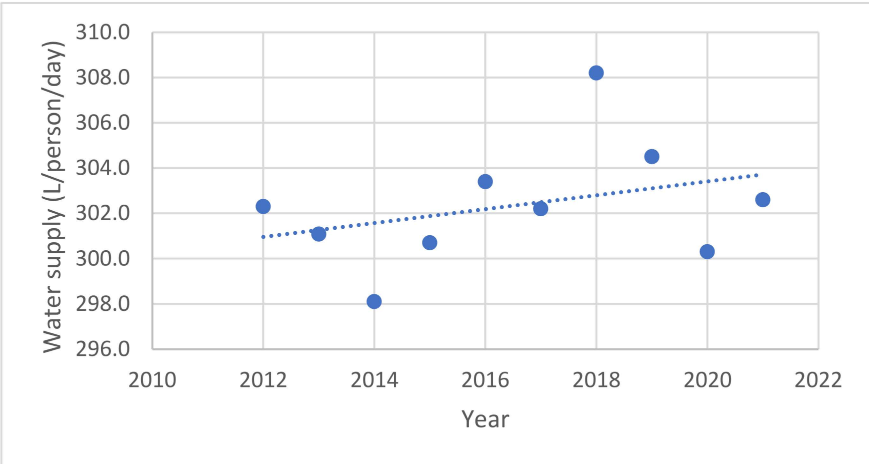


Figure 5. Annual SMC water supply requirement per capita for the last 10 years.

2.3.1. Scenario 0: Baseline Scenario

The baseline scenario assumes that the energy profile for water supply services in 2020 continues until 2045 (i.e., Scenario 0, the do-nothing scenario). The energy consumption and renewable energy production by type of the SMC water supply sector in 2020 are presented in Table 2. The energy intensities of raw water pumping and treatment for 2020 are 0.12 kWh/m^3 and 0.24 kWh/m^3, respectively (Table 3). Energy intensity was derived by dividing the energy consumed by the amount of processed water. The energy intensities of raw water extraction and water treatment observed in 2020 were applied to the baseline scenario up to 2045. The CO_2 emissions were estimated by multiplying the emission factor, which was reported as 0.46625 kg CO_2/kWh in 2020, by the energy consumption. Finally, CO_2 intensities were estimated by dividing CO_2 emissions by the amount of processed water. The energy intensity for the Gwangam plant was relatively low compared to that for other plants because finished water from this plant was distributed through the gravity flow.

Table 2. Energy consumption and renewable energy production of SMC water supply facilities in 2020.

Water Supply	Facilities	Electricity Usage [a] (kWh)	Energy Produced and Internally Consumed [b]		Energy Produced and Externally Supplied	Total Energy Consumption [c] (kWh)	Total Energy Production [d] (kWh)	Self-Sufficiency [a] (%)
			Solar Energy (kWh)	Geothermal Energy (kWh)	Solar Energy (kWh)			
Raw water extraction	Amsa	55,854,852	-	-	-	55,854,852	-	-
	Jayang	24,024,444	38,960	-	-	24,063,404	38,960	0.16
	Pungnab	19,963,265	61,012	-	-	20,024,277	61,012	0.30
	Gangbuk	33,711,791	-	-	-	33,711,791	-	-
	Subtotal	133,554,352	99,972	-	-	133,654,324	99,972	0.07
Drinking water treatment	Gangbuk	63,639,536	217,874	60,246	6,369,316	63,917,656	6,647,436	10.40
	Gwangam	6,559,274	-	-	1,843,156	6,559,274	1,843,156	28.10
	Guui	29,160,838	-	-	758,182	29,160,838	758,182	2.60
	Ddukdo	46,535,928	-	-	651,503	46,535,928	651,503	1.40
	Amsa	65,292,441	334,217	69,909	7,150,979	65,696,567	7,555,105	11.50
	Youngdenpo	45,001,532	-	-	990,034	45,001,532	990,034	2.20
	Subtotal	256,189,549	552,091	130,155	17,763,170	256,871,795	18,445,416	7.18

Note: [a] Data obtained from the 2021 MOE Report [16]. [b] Raw data provided by SMG. [c] Sum of "Electricity usage" and "Energy produced and internally consumed". [d] Sum of "Energy produced and internally consumed" and "Energy produced and externally supplied".

Table 3. Energy intensities for water extraction and treatment.

	Facility	Energy Intensity (kWh/m^3)
Raw water extraction	Amsa	0.15
	Jayang	0.11
	Pungnab	0.12
	Gangbuk	0.10
	SMC average	0.12
Drinking water treatment	Gangbuk	0.26
	Gwangam	0.09
	Guui	0.23
	Ddukdo	0.33
	Amsa	0.21
	Youngdenpo	0.28
	SMC average	0.24

2.3.2. Scenario 1: Increased Finished Water Pumping Efficiency

An et al. [19] reported that the "G" water treatment plant operated by K-water consumes 77.33% of the total energy for finished water pumping. Due to the significant impact of finished water pumping on the overall system's energy use, the energy efficiency of the pumping system should be enhanced [18]. An approximate estimated range of current wire-to-water efficiencies for finished water pumping was obtained by comparing the measured energy consumption with reference estimates by Reekie et al. [18]. The energy use estimates for finished water pumping with wire-to-water efficiencies of 50% (low), 65% (medium), and 75% (high) are presented in Table 1. Scenario 1 assumes that the wire-to-water efficiencies of six water treatment plants are improved to be equal to or greater than 75% by the year 2045. Based on the energy use estimates for finished water pumping [18], the current ranges of energy efficiencies for the six water treatment plants were determined, as shown in Table 4. The wire-to-water efficiencies for Scenario 0 describe the current state of the finished water pumping process, and Scenario 1 assumes improved efficiencies (Table 4). As mentioned above, the efficiency of the Gwangam plant was not included in the analysis because its product water was distributed to customers via gravity flow. The improved efficiencies of finished water pumping were applied to the Gangbuk, Ddukdo, and Youngdengpo plants, and the consumed energy was computed using the developed model.

Table 4. Wire-to-water efficiencies of finished water pumping at six water treatment plants.

	Efficiency of Finished Water Pumping (%)					
Scenario	**Gangbuk**	**Gwangam**	**Guui**	**Ddukdo**	**Amsa**	**Youngdengpo**
Scenario 0	65–75	N/A	75	50–65	75	65–75
Scenario 1	75	N/A	75	75	75	75

2.3.3. Scenario 2: Increased Renewable Energy Production

The One Less Nuclear Power Plant (OLNPP) was initiated by the SMG on 26 April 2012 to mitigate climate change and increase energy self-sufficiency [13]. The goal of OLNPP was to reduce energy usage by GJ 83.7 million by the end of 2014, which is equal to the amount of energy generated annually by a nuclear power plant [23]. As part of the OLNPP initiative, the SMG has introduced various technologies to recover energy, increase renewable energy use, and improve the energy efficiency of processes at water extraction and treatment facilities to achieve energy self-sufficiency in the water sector by 2030 [24]. The energy production efforts include 15.5 MW solar PVs installed at water treatment plants and wastewater treatment plants and 842 kW geothermal power stations installed at two water treatment plants [13]. These efforts to increase renewable energy production to help meet the energy requirements of these plants affect the net energy consumption and energy intensity in the water supply sector. Scenario 2 involves increasing renewable energy production by 50% compared to the energy produced in 2020 (as shown in Table 2).

2.3.4. Scenario 3: Increased Raw Water Pumping Efficiency

Water was pumped from four extraction plants (Amsa, Jayang, Pungnap, and Gangbuk) and sent to five water treatment plants (Amsa, Yeongdeungpo, Guui, Ddukdo, and Gangbuk). The related energy consumption for water supplied by the Gwangam treatment plant was not considered in this study. Table 5 presents the amount of water pumped annually, energy consumption, energy intensity, CO_2 emissions, and CO_2 intensity in 2020. Scenario 3 assumes that the energy intensity for water pumping is reduced by 10% due to improved water pumping efficiencies in the four water intake facilities.

Table 5. Energy consumption and CO_2 emissions for raw water pumping.

Year	Volume of Water Withdrawals (m^3/year)	Energy Consumption (kWh/year)	Energy Intensity (kWh/m^3)	CO_2 Emission (t/year)	CO_2 Intensity (kg/m^3)
2020	1,079,674,327	133,654,324	0.1238	62,270	0.0577

2.3.5. Scenario 4: Saving Energy by Saving Water

According to the data provided by the Food and Agriculture Organization of the United Nations (FAO) in 2020 [25], Korea is a country with a high level of water stress at 85.22%. However, daily water use per capita in the SMC is approximately twice as high as that in major European cities. Although there are numerous technologies for improving the operational efficiency of water pumping and treatment, proactive actions to reduce water consumption by end users and throughout the water supply could have a significant effect on energy savings. In addition, water can be saved by water reuse, rainwater harvesting, and reducing water leaks [13]. The SMG has adopted rainwater collection as part of an urban regeneration project [26]. Several studies have assessed the effects of water-driven approaches [27,28]. In this study, a reduction in the per capita water usage by 5% compared with 2020 was analyzed in Scenario 4. For decreased water usage, we assumed that the energy intensity of the water treatment process remained constant. This assumption is based on the fact that the reduced daily water treatment volumes at the six water treatment plants continue to fall within the same interpolation ranges as the data presented in Table 1.

3. Results and Discussion

3.1. Energy Consumption in Water Treatment Process

The estimates of daily energy use for common water unit processes in the U.S. were applied to the main unit processes of SMC water treatment plants, except for finished water pumping and the non-process load. The percentages of the total energy used for the non-process load were calibrated for individual water treatment plants, and the estimated values are presented in Table 6. The percentage of total energy for the non-process load was estimated as 6.3% for smaller plants (up to 50 MGD), 2.9% for middle-size plants (up to 100 MGD), and 1.0% for large plants (greater than 180 MGD). The estimated percentage of the total energy used for the non-process load for medium-sized plants was found to be consistent with that estimated by An et al. [19], which was reported as 2.88%. Figure 6 shows the observed and computed daily energy consumption, and Table 7 presents the relative errors between the observed and computed values for the six water treatment plants. The annual average relative errors of these plants were less than 6%, except that for the Amsa plant, which was 12.34%.

Table 6. Calibrated percentage of total energy used for non-process load.

	Gangbuk	Gwangam	Ddukdo	Guui	Amsa	Youngdengpo
Plant capacity (MGD)	182	57	107	97	256	117
Percentage of total energy used for the non-process load	1.0%	6.3%	2.9%	2.9%	1.0%	2.9%

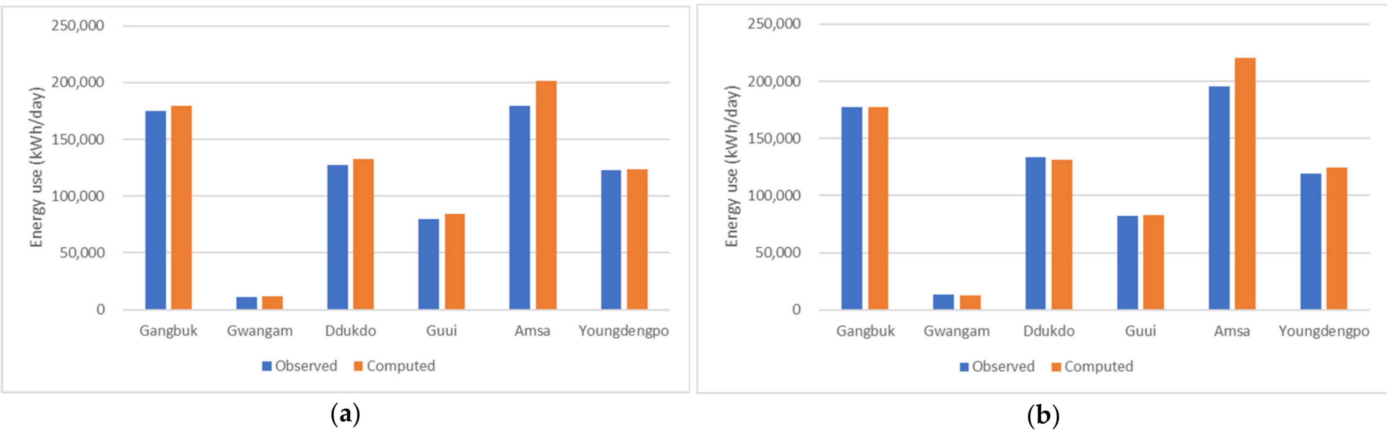


Figure 6. Computed and observed energy consumptions for (**a**) 2020 and (**b**) 2021.

Table 7. Relative absolute errors (%) between observed and computed daily energy consumption.

	Gangbuk	Gwangam	Ddukdo	Guui	Amsa	Youngdengpo
2020	2.94	6.71	5.38	4.57	12.09	0.61
2021	0.06	5.18	0.97	2.18	12.59	4.32
Average	1.50	5.95	3.18	3.38	12.34	2.47

Figure 7 presents the energy usage per-unit process in water treatment plants in 2020. The results show that the percentages of energy used for a range of different treatment processes were 80–85% for finished water pumping, 6–10% for ozone disinfection, 2–4% for rapid mixing, and 1–3% for non-process loads. The Gwangam plant is an exception because finished water pumping is not required.

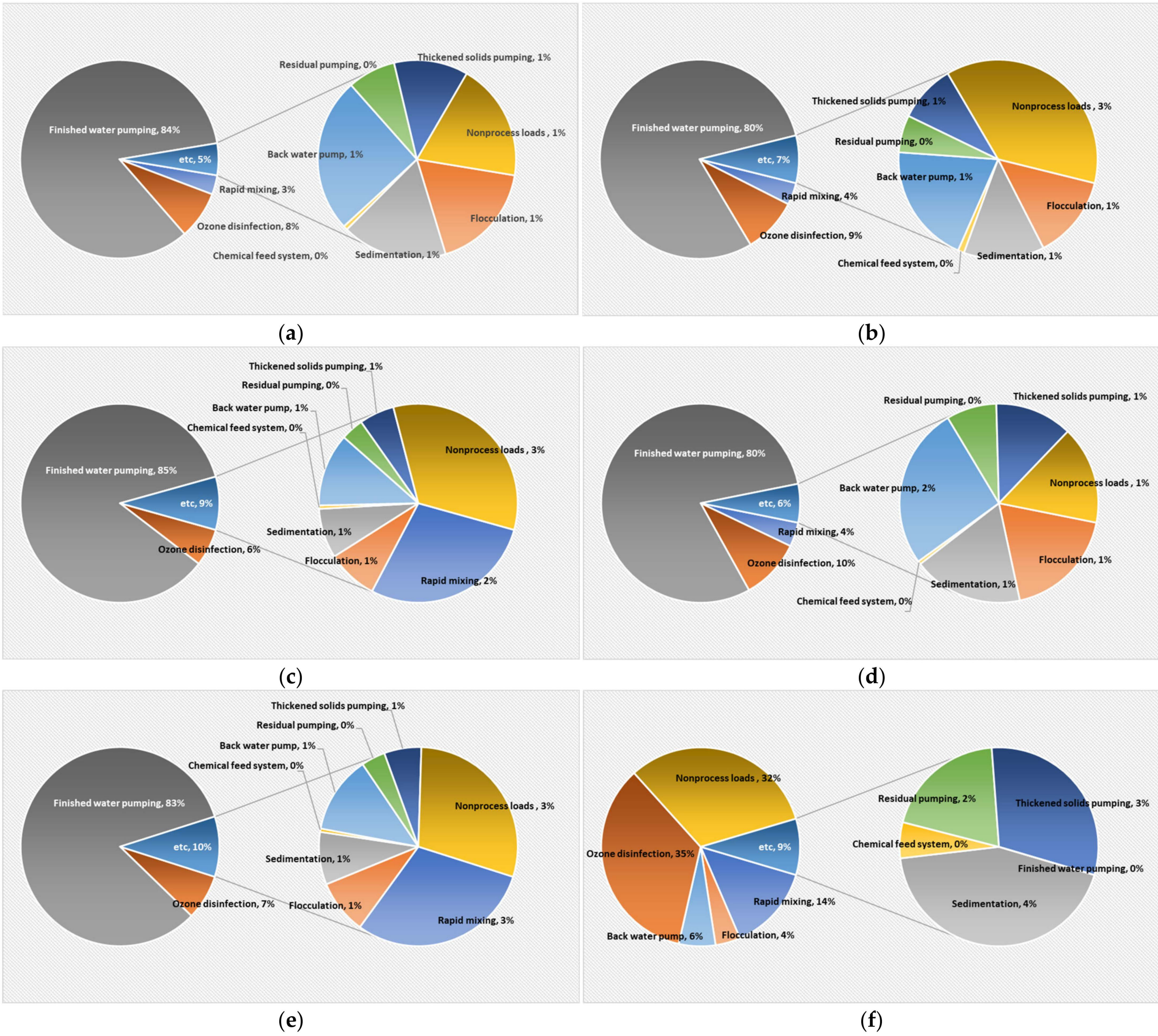


Figure 7. Energy use proportion per-unit process for (**a**) Gangbuk, (**b**) Guui, (**c**) Ddukdo, (**d**) Amsa, (**e**) Youngdengpo, and (**f**) Gwangam water treatment plants.

Using the same CO_2 emission factor (0.46625 kg CO_2/kWh) as the MOE [16,20], the CO_2 intensities of individual water treatment plants in 2020 and 2021 were computed and compared to the values provided by the MOE [16,20] (Figure 8).

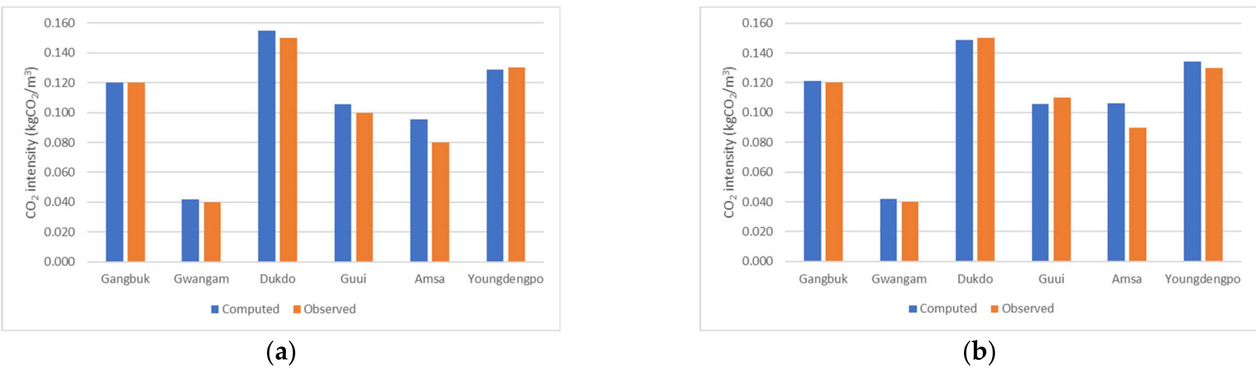


Figure 8. Computed and observed CO_2 intensity in (**a**) 2020 and (**b**) 2021.

3.2. Scenario Comparison

Most of the energy in the water supply sector is consumed in the form of electricity. Therefore, this study mainly considered CO_2 emissions from electricity use. Figure 9 shows the annually averaged ratios of water production via the six water treatment plants over the last 10 years [16,29–37]. Based on these ratios, the amount of water required in 2045 is allocated in proportion to the six water treatment plants. Amsa and Gangbuk plants constituted 32.6% and 22.1% of the total amount of treated water, respectively.

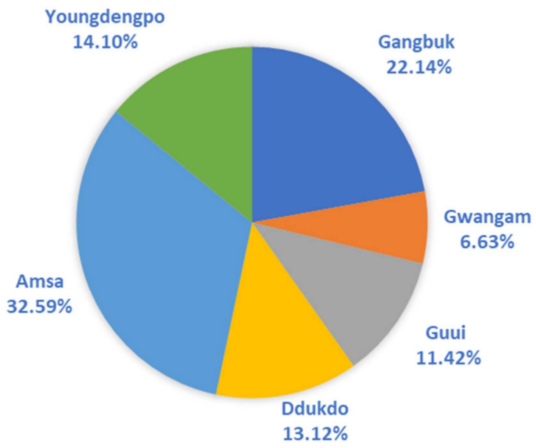
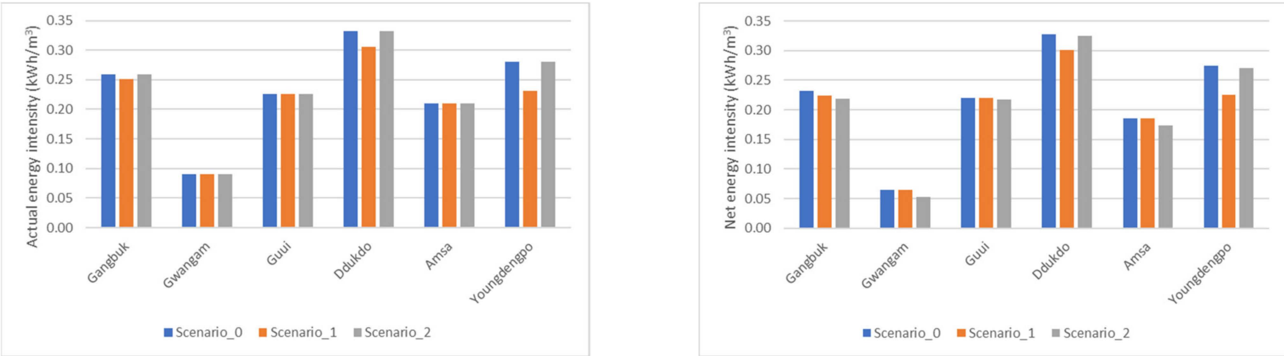


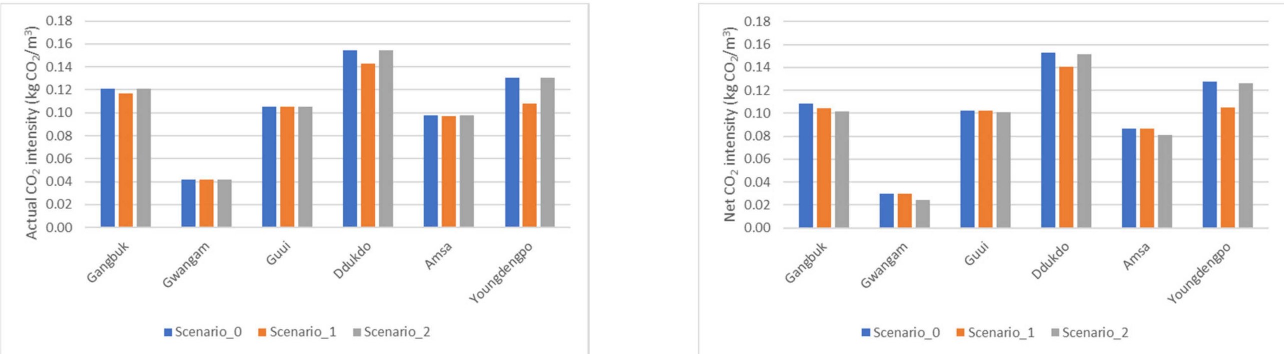
Figure 9. Annually averaged water production ratios of individual water treatment plants.

CO_2 emissions can be reported in terms of actual and net emissions. Net CO_2 emissions represent the total emissions reduced by CO_2 sequestration through carbon offsets, such as replacing electricity or fossil fuels with renewable energy [38]. Solar, wind, geothermal, and hydropower do not directly emit CO_2 and are, therefore, considered carbon-free energies. It follows that the CO_2 emissions factor for carbon-free energy is zero [39]. Figures 10 and 11 graphs the energy intensity, net energy intensity, CO_2 intensity, and net CO_2 intensity of six water treatment plants for the three scenarios. This study assumes that renewable energy replaces electricity from non-carbon-free sources when calculating net energy and CO_2 emissions. The net energy was obtained by subtracting the amount of energy produced from the amount of energy consumed. The actual energy intensities presented in Figure 10a show reduced energy consumption at the Gangbuk, Ddukdo, and Youngdengpo plants because of the improved efficiency of the finished water pumping process. Figure 10b shows that the net energy intensity of the Gangbuk plant decreased by 3.4% in Scenario 1, while it decreased by 5.8% in Scenario 2 compared to the baseline scenario. The Ddukdo and Youngdengpo plants revealed that Scenario 1 was more effective at reducing the net energy intensity and net CO_2 intensity than Scenario 2 (Figures 10b and 11b). There was no energy efficiency improvement for finished water pumping at the Gwangam, Guui, and Amsa plants, and no differences among the three scenarios were observed in terms of the actual energy intensity, as presented in Figure 10a. The actual energy intensity for the Gwangam plant is considerably smaller than that for the other plants because the energy consumption for finished water pumping, which accounts for the largest proportion of the total energy consumption, is zero for this plant because it distributes water using gravity. The greater actual energy intensity for the Ddukdo plant was due to the lower efficiency of the finished water pumping process, as shown in Table 4.



(**a**) (**b**)

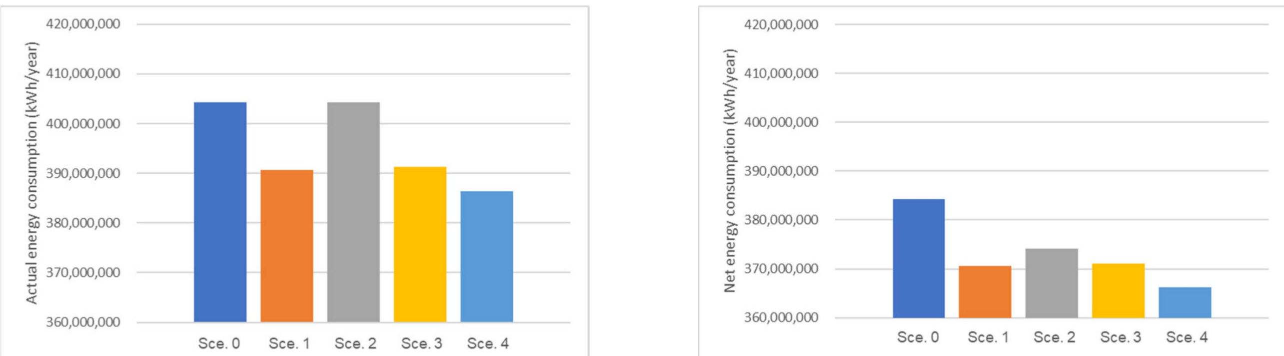
Figure 10. Energy intensities for the six water treatment plants for Scenarios 0–2. (**a**) Actual energy intensity and (**b**) net energy intensity.



(**a**) (**b**)

Figure 11. CO_2 intensities for six water treatment plants for Scenarios 0–2. (**a**) Actual CO_2 intensity and (**b**) net CO_2 intensity.

Figure 12 shows the potential energy savings after applying the four improved scenarios to the SMC water supply system. The total energy consumption in the baseline scenario (Scenario 0) was estimated to be 404,358,746 kWh/year. With the implementation of Scenario 4, the consumed energy and net energy were reduced by 4.44% and 4.67%, respectively, indicating that reducing per capita water consumption could be an important approach to saving energy. Improving the efficiency of finished water pumping to 75% (Scenario 1) and reducing the energy intensity of raw water pumping by 10% (Scenario 3) produced similar actual and net energy consumptions.



(**a**) (**b**)

Figure 12. Energy consumption of the applied scenarios. (**a**) Actual energy consumption and (**b**) net energy consumption.

Figure 13 shows the actual and net CO_2 emissions and CO_2 intensities. The net CO_2 emissions and net CO_2 intensity were estimated considering the onsite-produced energy. Figures 12 and 13a,b prove that Scenario 4 is the most effective approach for achieving considerable reductions in energy consumption and CO_2 emissions. However, this water-driven approach does not effectively reduce CO_2's intensity, as shown in Figure 13c,d, because it does not involve energy efficiency improvements for raw water pumping and drinking water treatment processes or an increase in renewable energy production. Scenarios 1 and 3, which are energy-driven approaches, reduce 3.39% and 3.25% of actual CO_2 intensities, respectively.

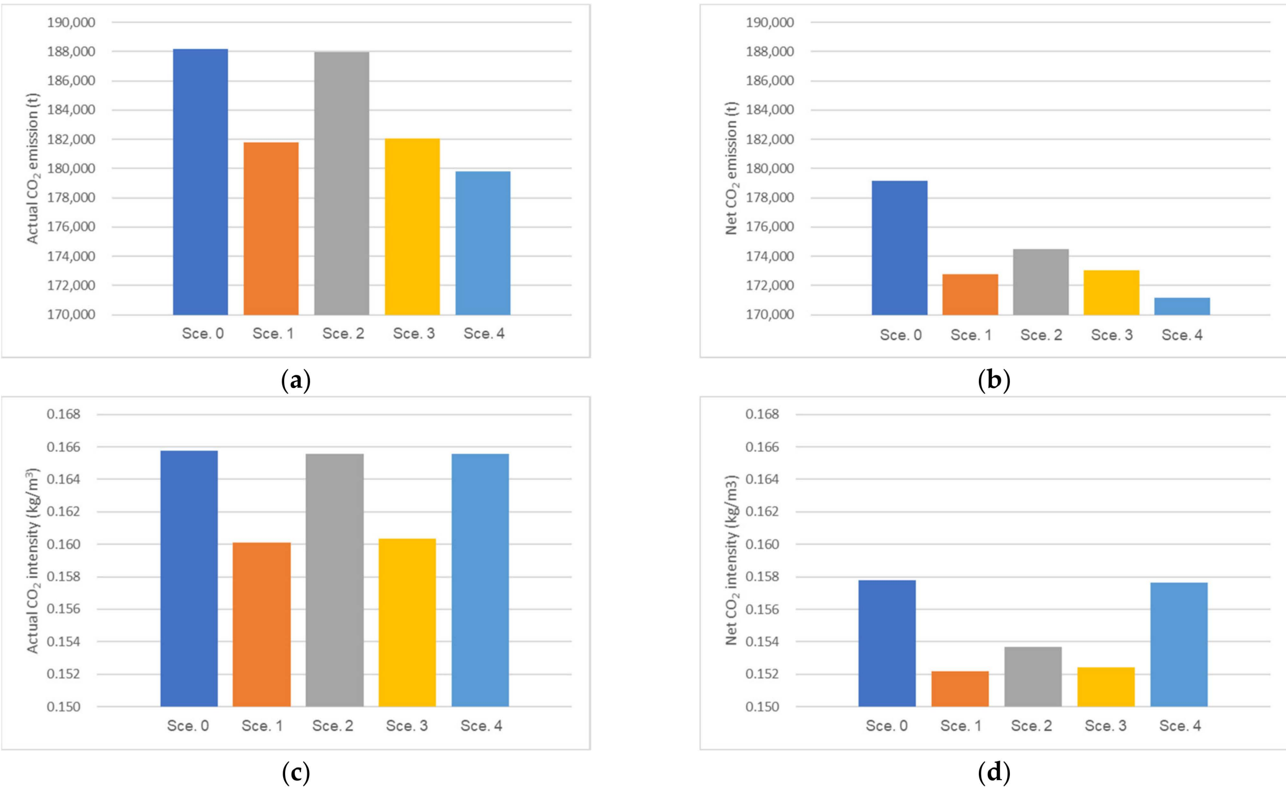


Figure 13. CO_2 emissions and CO_2 intensities of the applied scenarios. (**a**) Actual CO_2 emissions, (**b**) net CO_2 emissions, (**c**) actual CO_2 intensity, and (**d**) net CO_2 intensity.

To investigate the impact of varying raw water pumping efficiencies in Scenario 3 and per capita water demand reductions in Scenario 4 on the CO_2 emissions of the SMC, a comparative analysis was conducted. Specifically, we compared reductions in energy intensity of 5%, 10%, and 15%, and per capita water demand reductions of 1%, 3%, and 5%, with Scenarios 0–2, as depicted in Figure 14. The analysis revealed that a 15% reduction in the energy intensity of raw water pumping and a 5% decrease in per capita water usage result in a greater net reduction in CO_2 emissions compared to Scenarios 1 and 2. However, if the reductions in Scenarios 3 and 4 are limited to 5% and 1%, respectively, these scenarios prove less effective than Scenarios 1 and 2 at reducing the SMC's net CO_2 emissions.

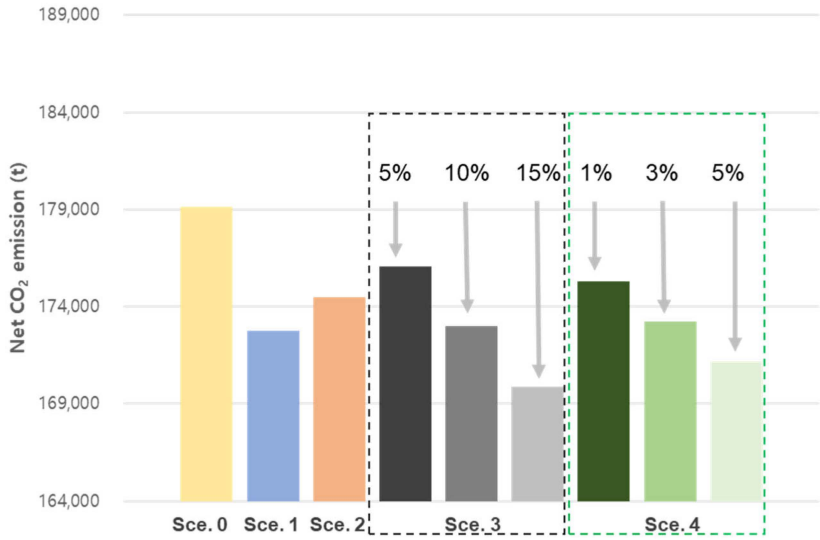


Figure 14. Comparison of net CO_2 emissions for different scenarios.

4. Conclusions

This study identified the major unit processes of the advanced water treatment process implemented in six water treatment plants in Seoul, South Korea, and developed a model to accurately compute the corresponding energy consumption. This model was calibrated using the reported energy consumption data from the MOE. For water treatment plants, the majority of energy use is associated with finished water pumping, accounting for 80–85% of the total energy consumption. To the best of our knowledge, no study has been conducted on this topic for SMC's water supply sector. The results of this study can help water treatment facilities and electric utilities to better understand the link between water and energy.

The potential factors influencing the energy requirements for each water treatment process include topography, climate, operational efficiency, variability in treatment system design, and water use patterns [40]. Reekie et al. [18] presented energy intensity values for various unit processes commonly observed in water treatment facilities. In our study, we assumed that the six water treatment plants within the SMC employ standard advanced water treatment unit processes, except for finished water pumping. Consequently, applying the energy consumption estimates from U.S. water facilities to those in the SMC could introduce some estimation errors for water treatment energy use. However, our model, developed based on these initial assumptions, successfully predicted the per-unit process energy consumption for different SMC water treatment facilities, as validated with actual MOE data. The effective transferability of U.S. energy consumption data to the SMC was facilitated by combining Reekie et al.'s energy intensity data [18] with local empirical data, including the energy intensity of finished water pumping. Therefore, the model can enable water utilities, regulators, and policymakers to assess the energy use of specific processes and facilities and find opportunities to improve energy and CO_2 management practices in the water supply sector in the SMC.

This study analyzed four plausible scenarios involving three energy-driven approaches and a water-driven approach and compared them to a do-nothing baseline scenario. The scenarios analyzed in this study quantified energy savings ranging from technically feasible to realistically achievable. The results of scenario analysis showed that the application of Scenarios 1–3, which are energy-driven approaches, reduces 3.57%, 2.61%, and 3.41% of net CO_2 emissions, respectively, and the application of Scenario 4, which is a water-driven approach, reduced 4.44% of net CO_2 emissions compared to the baseline scenario. Based on these results, reducing the per capita water consumption in combination with water reuse and conservation could be the most effective way to reduce the actual and net CO_2 emissions of the SMC water supply sector. However, water operators need to continue to use more energy-efficient technologies to satisfy more stringent treatment requirements. Lee et al. [41] noted that energy intensity in the water sector is highly affected by the level of treatment and technology. The scenario of analysis in this study showed that improving the finished water pumping efficiency (Scenario 1) and raw water pumping efficiency (Scenario 3) was more efficient at decreasing actual and net CO_2 intensities than the other two scenarios. Overall, we conclude that improving energy efficiency, increasing renewable energy production and use, and enhancing water conservation and reuse can help the potable water supply sector achieve carbon neutrality. The results of this study can be applied to sustainable water management and climate change mitigation for the water supply sector in urban areas.

Future studies should optimize and adapt this model to estimate the energy consumption and CO_2 emissions of the potable water supply sector in other metropolitan areas. In addition, a similar analysis of wastewater treatment plants and sewer networks should be conducted to expand this study and include the entire urban water sector.

Author Contributions: Conceptualization, D.K.; methodology, L.L. and D.K.; software, G.L.; validation, L.L., G.L. and D.K.; formal analysis, L.L.; investigation, L.L., G.L. and D.K.; resources, L.L. and G.L.; data curation, L.L. and G.L.; writing—original draft preparation, L.L.; writing—review and editing, D.K.; visualization, L.L. and G.L.; supervision, D.K.; project administration, D.K.; funding acquisition, D.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the (1) Korea Environment Industry & Technology Institute (KEITI) through the Water Management Program for Drought, funded by the Korean Ministry of Environment (MOE) (RS-2023-0023194) and (2) the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT—Ministry of Science and ICT) (grant number NRF-2020R1A2C1005554).

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Muhammetoglu, A.; Al-Omari, A.; Al-Houri, Z.; Topkaya, B.; Tumbul, T. Assessment of energy performance and GHG emissions for the urban water cycle toward sustainability. *J. Water Clim. Chang.* **2023**, *14*, 223–238. [CrossRef]
2. Global Carbon Project. Carbon Dioxide Emissions of the Most Polluting Countries Worldwide in 2010 and 2022 (In Million Metric Tons). Available online: https://www.statista.com/statistics/270499/co2-emissions-in-selected-countries/ (accessed on 3 January 2024).
3. International Trade Administration. South Korea—Energy—Carbon Neutrality Initiatives. In *South Korea Country Commercial Guide*; International Trade Administration: Washington, DC, USA, 2022.
4. Bae, S.; Kim, Y.M. Carbon-neutrality in wastewater treatment plants: Advanced technologies for efficient operation and energy/resource recovery. *Energies* **2021**, *14*, 8514. [CrossRef]
5. Ballard, S.; Porro, J.; Trommsdorff, C. *The Roadmap to a Low-Carbon Urban Water Utility: An International Guide to the WaCCliM Approach*; IWA Publishing: London, UK, 2018.
6. Water UK. *Net Zero 2030 Routemap*; Water UK: London, UK, 2020.
7. United Nations Organization (UNO). Partnerships for improving water and energy access, efficiency and sustainability. Prepared by UN-Water Decade Program on Advocacy and Communication (UNW-DPAC) with United Nations University (UNU) and United Nations Industrial Development Organization (UNIDO). In Proceedings of the 2014 UN-Water Annual International Zaragoza Conference, Zaragoza, Spain, 13–16 January 2014.
8. Rothausen, S.G.S.A.; Conway, D. Greenhouse-gas emissions from energy use in the water sector. *Nat. Clim. Chang.* **2011**, *1*, 210–219. [CrossRef]
9. Chhipi-Shrestha, G.; Hewage, K.; Sadiq, R. Water-energy-carbon nexus modeling for urban water systems: System dynamics approach. *J. Water Resour. Plann. Manag.* **2017**, *143*, 04017016. [CrossRef]
10. Stokes, J.; Horvath, A. *Life-Cycle Energy Assessment of Alternative Water Supply Systems in California*; University of California: Berkeley, CA, USA, 2011.
11. Venkatesh, G.; Brattebo, H. Energy consumption, costs and environmental impacts for urban water cycle services: Case study of Oslo (Norway). *Energy* **2011**, *36*, 792–800. [CrossRef]
12. Chang, J.; Lee, W.; Yoon, S. Energy consumptions and associated greenhouse gas emissions in operation phases of urban water reuse systems in Korea. *J. Clean. Prod.* **2017**, *141*, 728–736. [CrossRef]
13. Kim, H.; Chen, W. Changes in energy and carbon intensity in Seoul's water sector. *Sustain. Cities Soc.* **2018**, *41*, 749–759. [CrossRef]
14. Lam, K.L.; Kenway, S.J.; Lant, P.A. Energy use for water provision in cities. *J. Clean. Prod.* **2017**, *143*, 699–709. [CrossRef]

15. Seoul Metropolitan Government. Population. Available online: https://english.seoul.go.kr/seoul-views/meaning-of-seoul/4-population/ (accessed on 23 January 2024).
16. MOE. *2020 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2021.
17. Seoul Metropolitan Government (SMG). *Water Production: Advanced Water Purification System*; SMG: Seoul, Republic of Korea, 2016. Available online: https://seoulsolution.kr/en/content/water-production-advanced-water-purification-system (accessed on 10 January 2024).
18. Reekie, L.; Pabi, S.; Amarnath, A.; Goldstein, P. *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries*; Electric Power Research Institute: Palo Alto, CA, USA, 2013.
19. An, S.B.; Hong, S.T.; Kim, K.I.; Sung, M.S. A study on the reduction of energy consumption in WTP by using AI-driven composite sensors. In Proceedings of the KICS Winter Conference, Yong Pyong Resort, Pyeongchang, Republic of Korea, 8–10 February 2023.
20. MOE. *2021 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2022.
21. Statistics Korea. *Population Projections for Provinces (2015~2045)*; Statistics Korea: Daejeon, Republic of Korea, 2017.
22. The Office of Waterworks. Water Supply News. Available online: https://news.seoul.go.kr/env/archives/514374 (accessed on 26 January 2024).
23. Seoul Metropolitan Government (SMG). *One Less Nuclear Power Plant, Phase 2*; SMG: Seoul, Republic of Korea, 2014.
24. Seoul Metropolitan Government (SMG). *Seoul Metropolitan Government-Initiated Energy Self-Sufficient Management of Wastewater Treatment Plants*; SMG: Seoul, Republic of Korea, 2017.
25. FAO. Progress on Level of Water Stress. Available online: https://www.sdg6data.org/en/indicator/6.4.2 (accessed on 3 January 2024).
26. Seoul Metropolitan Government (SMG). *Seoul Creates Rainwater Village Linking Urban Regeneration and Village Community*; SMG: Seoul, Republic of Korea, 2017.
27. Engström, R.E.; Howells, M.; Destouni, G.; Bhatt, V.; Bazilian, M.; Rogner, H.-H. Connecting the resource nexus to basic urban service provision—With a focus on water-energy interactions in New York City. *Sustain. Cities Soc.* **2017**, *31*, 83–94. [CrossRef]
28. Malinowski, P.A.; Stillwell, A.S.; Wu, J.S.; Schwarz, P.M. Energy-water nexus: Potential energy savings and implications for sustainable integrated water management in urban areas from rainwater harvesting and gray-water reuse. *J. Water Resour. Plan. Manag.* **2015**, *141*, A4015003. [CrossRef]
29. MOE. *2011 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2012.
30. MOE. *2012 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2013.
31. MOE. *2013 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2014.
32. MOE. *2014 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2015.
33. MOE. *2015 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2016.
34. MOE. *2016 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2017.
35. MOE. *2017 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2018.
36. MOE. *2018 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2019.
37. MOE. *2019 Statistics of Waterworks*; MOE: Sejong, Republic of Korea, 2020.
38. Chen, L.; Msigwa, G.; Yang, M.; Osman, A.I.; Fawzy, S.; Rooney, D.W.; Yap, P.-S. Strategies to achieve a carbon neutral society: A review. *Environ. Chem. Lett.* **2022**, *20*, 2277–2310. [CrossRef] [PubMed]
39. Ministry of Trade, Industry and Energy. Act on the Promotion of the Development, Use and Diffusion of New and Renewable Energy. MOTEI Act, No. 18095. 2021. Available online: https://www.law.go.kr/LSW/eng/engLsSc.do?menuId=2&section=lawNm&query=Act+on+the+Promotion+of+the+Development,+Use+and+Diffusion+of+New+and+Renewable+Energy&x=0&y=0#liBgcolor0 (accessed on 3 January 2024).
40. Sowby, R.B.; Burian, S.J. Survey of energy requirements for public water supply in the United States. *J. Am. Water Work. Assoc.* **2017**, *109*, E320–E330. [CrossRef]
41. Lee, M.; Keller, A.A.; Chiang, P.C.; Den, W.; Wang, H.; Hou, C.H.; Wu, J.; Wang, X.; Yan, J. Water-energy nexus for urban water system: A comparative review on energy intensity and environmental impacts in relation to global water risks. *Appl. Energy* **2017**, *205*, 589–601. [CrossRef]