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Article

CO_2 Emission Factor for Rainwater and Reclaimed Water Used in Buildings in Japan

Yasutoshi Shimizu *, Satoshi Dejima and Kanako Toyosada

ESG Promotion Department, TOTO LTD, 2-1-1, Nakashima, Kokurakita-ku, Kitakyushu 802-8601, Japan; E-Mails: satoshi.dejima@jp.toto.com (S.D.); kanako.toyosada@jp.toto.com (K.T.)

* Author to whom correspondence should be addressed; E-Mail: yasutoshi.shimizu@jp.toto.com; Tel.: +81-93-952-3315; Fax: +81-93-952-3468.

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Abstract: From the standpoint of the preservation of water resources, rainwater and reclaimed water have been widely used in buildings in many countries. However, the CO_2 emission factors of these two waters—factors that determine their environmental impacts—have not been calculated. In a previous study, the CO_2 emission factor of water for waterworks and sewer systems was determined. In this paper, we evaluate the emission factors of rainwater and reclaimed water in the same manner. First, the emission factor for pumping water in buildings is determined using published values for operating performances. About half of the residential dwellings in Japan are multistory apartments, and these apartments use pumps for the delivery of water. The emission factor of pumping is calculated as 0.69 kg CO_2/m^3, which adds 16% to the emission factor of waterworks and sewer systems. Next, the CO_2 emission factors of rainwater and reclaimed water are calculated for different water delivery cases in buildings. As a result, it is found that the use of reclaimed water increases CO_2 emissions by 62%, compared to the use of ordinary water.

Keywords: CO_2 emission factor; energy consumption rate; environmental impact; rainwater; reclaimed water

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1. Introduction

In recent years, studies associating water use with CO_2 emissions have been performed around the world [1–3]. In Japan, research linking the water-saving performance of bathroom fixtures, such as toilets and showers, with a reduction in CO_2 emissions has progressed, and the fact that the widespread use of water-saving fixtures can be effective in cutting CO_2 emissions has been recognized [4,5]. As a result, a carbon credit project based on the adoption of water-saving apparatuses has been launched in Japan. In addition, feasibility studies in China and Vietnam have been carried out as Bilateral Offset Credit Mechanism projects, which the Japanese government is promoting [6,7].

Carbon credits are calculated by measuring the amount of water saved by replacing conventional equipment with energy-saving or water-saving products and multiplying this value by the CO_2 emission factor to convert the values into the amount of CO_2. The CO_2 emission factor of water has been calculated by using the energy consumption values for waterworks and sewer systems.

A report on Hong Kong, where buildings consists of skyscrapers, states that energy consumption related to pumping water in a building accounts for 45% of the total energy consumption of water usage [8]. In a previous paper, the latest value for the CO_2 emission factor of water in Japanese waterworks and sewer systems was determined [9]. In this research, the emission factor from pumping water in Japanese buildings was calculated.

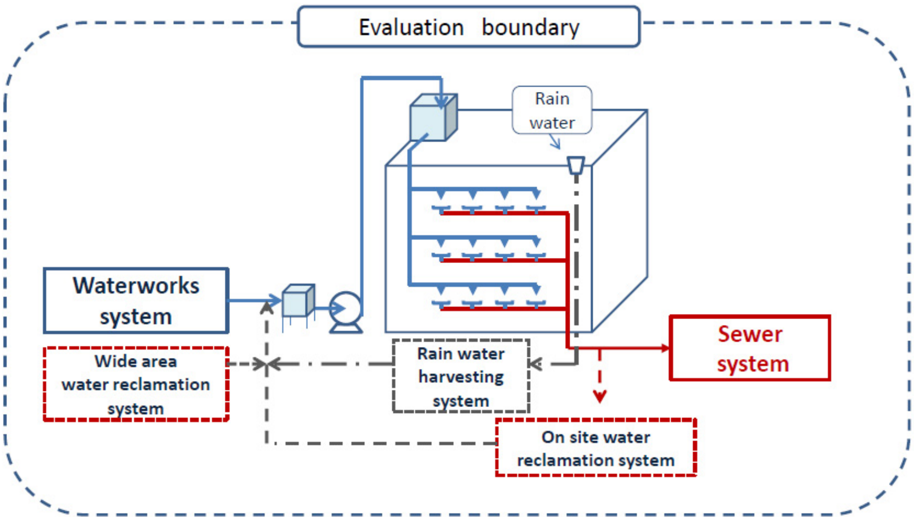
From the standpoint of preserving water resources, rainwater and reclaimed water have been widely used in buildings in Japan. According to "Water Resources of Japan", published by the Ministry of Land, Infrastructure, Transport and Tourism, rainwater and reclaimed water systems had been introduced by about 3400 institutions by 2008 [10]. Comparisons of the different environmental impacts resulting from the use of ordinary water *versus* the use of rainwater or reclaimed water in buildings have been studied by many researchers [11–14]. However, as neither the calculation boundaries nor the calculation conditions—such as an energy coefficient—used are unified, the evaluation results cannot be compared. The most ambiguous point of existing research is the CO_2 emission factor of the water for waterworks and sewer systems used as a standard value in evaluations. The emission factors in Japan are 0.59 kg CO_2/m^3, as presented by the Ministry of the Environment in 1996, and 2.011 kg CO_2/m^3, as given in "LCA Guideline Buildings, 1999", published by the Society of Architecture of Japan. Considering that electricity accounts for more than 90% of the energy required for the operation of waterworks and sewer systems and that the CO_2 emission factor for electricity changes annually depending on the composition ratio of the type of power-generation processes—such as nuclear and thermal power generation—the CO_2 emission factor derived from energy consumption should be reexamined every year [15]. When comparing the environmental impacts of rainwater and reclaimed water use with the value of ordinary water use, the adoption of the same energy coefficient is vital. Thus, by using the reported values for the energy consumptions and treated water volumes for each process, the environmental impacts were calculated as CO_2 emission factors using the same evaluation boundary and energy coefficient.

2. Analysis

2.1. Establishing the Evaluation Boundary and Model

The energy consumption rates and CO_2 emission factors of rainwater and reclaimed water used for toilet flushing and watering in buildings were calculated and compared with ordinary water use. The evaluation boundary was established as the series of processes from water generation to wastewater treatment. Only energy consumption in the operation phase was targeted in the evaluation. Rainwater and reclaimed water are used in large buildings of a multistory structure, such as public facilities. In such buildings, water has to be pumped. Therefore, the water-pumping process in buildings is taken into consideration in this research. The evaluation boundary and model are shown in Figure 1.

Figure 1. Evaluation boundary and model.



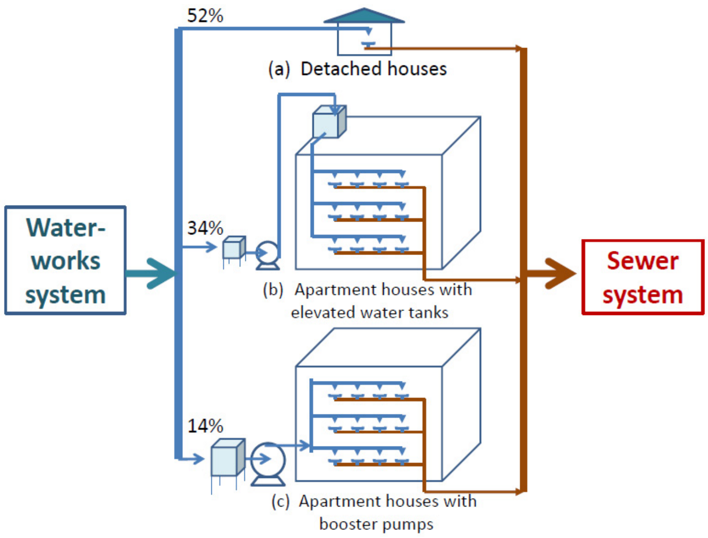
2.1.1. Water-Generation Process

In the water-generation process, waterworks, rainwater harvesting and the water-reclamation process were evaluated. The energy consumption rate and CO_2 emission factor for waterworks were taken from previous research. The reported values were the weighted averages of data for all Japanese facilities composited from raw water intake, purification and the delivery process. For the evaluation of large areas and on-site water-reclamation systems, the reported values of treated water amounts and consumed energy values were used for analysis [16–20]. According to a Ministry of Land, Infrastructure, Transport and Tourism report, "Rainwater and Reclaimed Water Use Institution Survey", a common rainwater-harvesting system is processed by using potential energy [21]. Rain is collected on the roof of a building and flows down through sedimentation, filtration and disinfection by chlorine processes toward a basement tank. Therefore, it was thought that the energy consumption used in the operation process for rainwater harvesting was very small. Therefore, the energy for water supply in a building was taken into consideration in rainwater use.

2.1.2. Water-Pumping Process in Buildings

For water delivery in buildings, elevated tank systems were commonly used until 1994. However, it became widely known as a result of TV reports and other sources that there were buildings where the management of water in the elevated tanks had not been undertaken to a satisfactory sanitary level and that improvement was required. Therefore, the booster pump system, which is a more sanitary water supply system, is used in buildings in Japan built since that time. An outline of the system is shown in Figure 2. Based on the reported values [22] for the energy consumption of pumps, the energy consumption rates and CO_2 emission factors were calculated. The average values of the energy consumption rate and emission factor for a Japanese residence were calculated by considering the adoption rate for each water distribution system.

Figure 2. Water delivery systems in buildings.



2.1.3. Wastewater-Treatment Process

Drainage from each water system is handled by sewers, and the energy consumption rate and CO_2 emission factor were quoted from the previous research. The water-reclamation system removes the pollution in wastewater discharged from buildings. Therefore, the pollution load of sewer systems decreases with the spread of the water-reclamation system. However, reclaimed water usage was only 259 million m^3/year [10]—about 1.8% of the 14,440 million m^3/year of the annual sewer treatment amount [23]—and since it is small, this effect can be ignored.

2.2. Calculation

The energy consumption and CO_2 emission per cubic meter of water were calculated by using Equations (1) and (2) for each of the above-mentioned processes. In the calculation, the energy consumption for operation was positioned as the object of evaluation, and the emission factor of electricity was adopted as the average value for all power sources in Japan at both the receiving and generating ends after credit compensation by assuming its application in Clean Development Mechanism and the Bilateral Offset Credit Mechanism [6,7].

$$CEw = \sum Ew(i) / Qw \quad (1)$$

$$CFw = \sum\{Ew(i) \cdot CFe(i)\} / Qw \quad (2)$$

where C*Ew* is the energy consumption rate of water (MJ/m^3), *Ew*(*i*) is the energy consumption of each energy source (MJ/year), *Qw* is the volume of water treated by the system (m^3/year), *CFw* is the CO_2 emission factor for water (kg CO_2/m^3) and *CFe*(*i*) is the CO_2 emission factor for each energy source (kg CO_2/MJ).

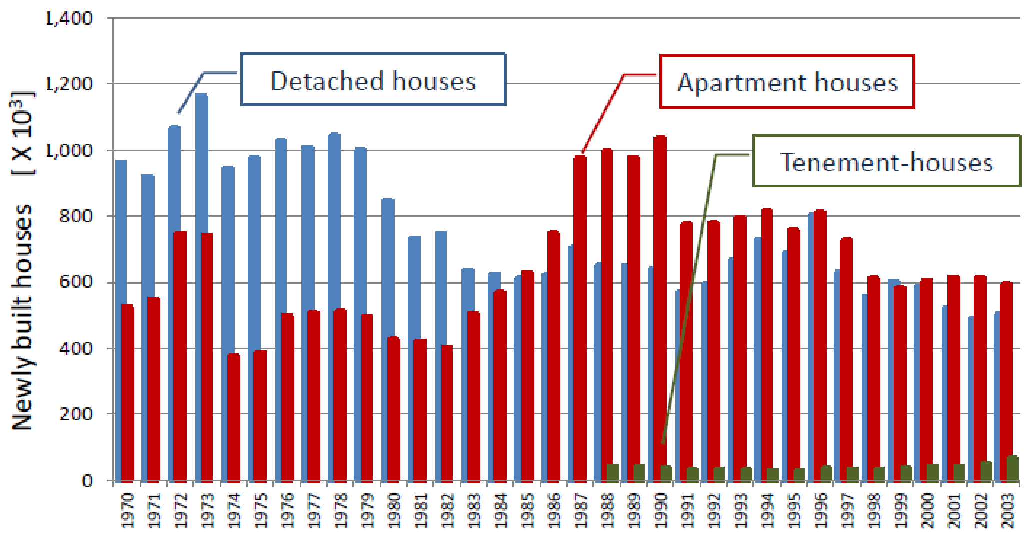
3. Results and Discussion

3.1. Energy Consumption Rate and CO_2 Emission Factor for Pumping in Buildings

Statistical data on non-residential buildings, such as the number of buildings, their purpose and the year of construction, is not compiled in Japan. Thus, the energy consumption rate and CO_2 emission factor for pumping was calculated for residential buildings, for which ample data for analysis is available. In detached houses in Japan, water is supplied by tap water pressure, and the use of individual water tanks and pumps is not common. Apartment buildings, however, have water-delivery systems that use elevated tanks or booster pumps.

The number of detached houses and apartment buildings constructed every fiscal year is recorded in the annual report on construction statistics published by the Ministry of Land, Infrastructure, Transport and Tourism. An example is shown in Figure 3. The water-delivery systems of apartment buildings have changed since 1994, as mentioned earlier. However, there are no statistics values, such as numbers classified by the water-supply system of buildings. Thus, based on the hearing from building designers and owners, buildings constructed before 1994 were assumed to have elevated tanks, and for buildings constructed after 1994, 80% of them use booster pumps, 20% use elevated tanks and the building ratio of each system was calculated. The result is shown in Figure 2. The ratio of detached houses without pumping, apartment buildings with elevated tanks and apartment buildings with booster pumps was estimated as 52%, 23% and 14%, respectively.

Figure 3. Changes in the numbers of newly built houses in Japan.



Next, data on the power consumption of water pumps for houses were extracted from pump manufacturers' report [22], as shown in Table 1. The energy consumption rate of pump to elevated tank was 0.8 MJ/m^3, according to a major pump manufacturer. The calculated value, 1.00 MJ/m^3, was about the same as the manufacturer's value, and it was decided that the calculated value was appropriate. For an elevated tank system, pressurized water of around 0.2 MJ is delivered to each apartment using potential energy (gravity). In a booster pump system, the piping pressure is maintained at around 0.2 MJ by pump operation. Therefore, a booster pump system consumes more energy than an elevated tank system. For the operation of booster pumps, there are control systems with pump inverters and systems that combine the operation of two or more pumps. The energy efficiency of such systems was calculated as 1.2–4.4 MJ/m^3, and an average value of 2.52 MJ/m^3 was adopted in this research.

Table 1. Energy consumption for housing pump system in Japan.

Type	Pump system	Delivered water (m^3/year)	Consumed energy (kWh/year)	Energy consumption rate (MJ/m^3)
Apartment house with elevated water tank	T-405X5S-M3.7	12,410 *	3,444	0.999
Apartment houses with booster pumps	KDP2-40A2.2A	12,410 *	8,616	2.499
	50KNV325P2.2	12,410 *	15,000	4.351
	KF2-32P1.9	12,410 *	8,376	2.430
	KF2-50R3-3.7	36,500 **	12,396	1.223
	100KNV505R3-3	36,500 **	21,384	2.109

* 17-story apartment (34 houses; pumping height: 50 m); ** 13-story apartment (100 houses; pumping height: 39 m).

Although this calculation regarded the water supply for apartment buildings, the authors studied the water supply for office buildings using these findings. Office buildings of a size suitable for the application of data on water-delivery systems for apartment buildings were selected for this study. According to "Plumbing sanitary planning/designing know-how", published by the Society of Heating, Air-Conditioning and Sanitary Engineering of Japan, water consumptions by men and women in an office are 50 L and 100 L/(person·day), respectively [24]. When the man-to-woman ratio of an office is set at 75:25, the average consumption is 62.5 L/(person·day). From this, it was presumed that the water-delivery system for apartment buildings mentioned above was equivalent to an office for 540–1600 people. Therefore, it was considered that the environmental impact of the water-delivery system for houses, as shown in Tables 2 and 3, is applicable for a general office building.

Table 2. Energy consumption rates of Japanese water system for housing (MJ/m^3).

Classification of buildings	Waterworks system	Water supply in buildings	Sewer system	Total
(a) Detached houses	1.98	0	2.22	4.20
(b) Apartment houses with elevated water tanks		1.00		5.20
(c) Apartment houses with booster pumps		2.52		6.72
Average values	1.98	0.69	2.22	4.89

Table 3. CO_2 emission factor of Japanese water system for housing (kg-CO_2/m^3).

Classification of buildings	Calculated with generating end electricity (0.335 kg CO_2/kWh)	Calculated with receiving end electricity (0.373 kg CO_2/kWh)
(a) Detached houses	0.376	0.415
(b) Apartment houses with elevated water tanks	0.469	0.519
(c) Apartment houses with booster pumps	0.611	0.676
Average values	0.441	0.487

3.2. Energy Consumption Rates and CO_2 Emission Factors of Rainwater and Reclaimed Water

Although the use of reclaimed water has progressed in public facilities and evaluation research into the energy consumption rate has been conducted in Japan, the boundary of evaluation is not uniform, and as mentioned above, the results cannot be compared. Therefore, the energy consumption and CO_2 emissions for ordinary water, as well as rainwater and reclaimed water use, in buildings were evaluated under the same conditions. The operation data for the energy consumption for a water-reclamation system was extracted from reports, as shown in Table 4. The correlation between energy consumption and the processing scale, processing system, *etc*., was not observed.

From these results, rainwater and reclaimed water use were compared with ordinary water use, water for waterworks and sewer systems. The results are shown in Figure 4. In the evaluation of ordinary water use, the energy consumption for the water-delivery process in buildings was added. As for the water-purification process, the rainwater-harvesting system exploited potential energy after collection from roofs, and since it was filtered and stored, the energy consumption presupposed that it can be ignored; we counted only the energy consumption for the water-delivery process in buildings from storage tanks. In a water reclamation system, water treatment and pumping energies were contained in the extracted operation data. In addition, for all systems, wastewater treatment after use was needed, and the energy required was added. As a result, energy consumption is in the order: rainwater use < waterworks and sewerage use < reclaimed water use in a building; and reclaimed water use was found to consume 1.4-times more energy than ordinary water use. The emission factor for water was determined for each water resource, as shown in Table 5.

Figure 4. Energy consumption rates of water systems for non-residential buildings with booster pumps (MJ/m^3).

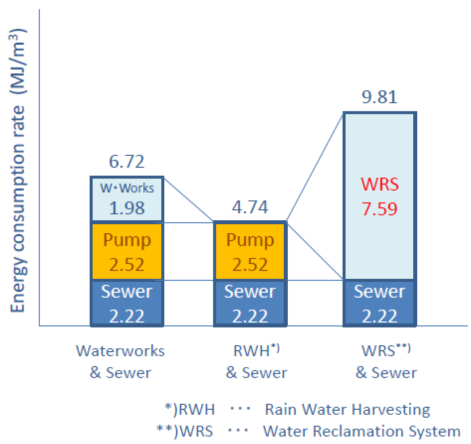


Table 4. Energy consumption for grey water treatment system in Japan.

Treatment method	Facility	Treatment method						Treated water volume (m^3/year)	Energy consumption (kWh/year)	Energy consumption rate (MJ/m^3)	Source
		B/T	M/F	S/F	SE	O_3	AC				
Wide area water reclamation system	Facility A	○			○	○		52,484	276,930	19.00	[15]
	Facility B			○	○	○		1,917,964	2,509,400	4.71	
	Facility C	○	○	○		○		1,267,332	2,215,000	6.29	
	Facility D			○		○		823,116	553,662	2.42	
	Shibayama Housing Complex	○				○		55,896	110,507	7.12	[17]
	Heijou New-town	○		○		○		20,955	76,500	13.14	
On-site water reclamation system	Facility F			○				92,407	59,260	2.31	[15]
	Facility G	○		○			○	28,244	43,281	5.52	
	TV Center (Tokyo)	○					○	58,400	111,325	6.86	[16,19]
	Office Building (Tokyo)	○		○				146,000	251,685	6.21	[18]
	Apartment House (Fukuoka)	○				○		9,855	16,584	6.06	
	Factory (Mie)	○		○			○	25,550	80,899	11.40	

B/T: bio-treatment; M/F: membrane filtration; S/F: sand filtration; SE: sedimentation; O_3: ozone treatment; AC: activated carbon treatment.

Table 5. CO_2 emission factors of Japanese water system (kg CO_2/m^3).

Classification of buildings		Calculated with Generating end electricity (0.335 kg CO_2/kWh)	Calculated with receiving end electricity (0.373 kg CO_2/kWh)
Detached houses	Waterworks and sewer system	0.376	0.415
Apartment houses/buildings with elevated water tanks	Waterworks and sewer system	0.469	0.519
	RWH and sewer system	0.288	0.318
	WRS and sewer system	0.901	1.003
Apartment houses/buildings with booster pumps	Waterworks and sewer system	0.611	0.676
	RWH and sewer system	0.429	0.476
	WRS and sewer system	0.901	1.003

RWH: rain water harvesting; WRS: water reclamation system.

The above mentioned evaluation is the case for Japan, a country with comparatively abundant water resources.

It is known that the water-transfer process accounts for 80 percent of the energy consumption of a waterworks system [9]. One report states that in California, where the water source area and the consuming area are separated, waterworks require a larger amount of water-transfer energy than reclaimed water generation [25]. It is necessary to carry out evaluation of the environmental impact of water in consideration of the water situation for each country.

Moreover, this research was an evaluation that paid attention only to energy consumed in the operation of the water system. To carry out an entire lifecycle assessment, which would include every step, from facility construction to abandonment, for rainwater harvesting through to water reclamation, the installation of exclusive water-piping systems and water-purification facilities must be taken into consideration. In that case, the environmental impact of rainwater and reclaimed water use increases. Moreover, as it is thought that various substances are dissolved and become mixed in with rainwater and reclaimed water, the risk to maintenance, such as piping and the degradation of pump speeds, must be considered. Further study along these lines will be necessary in the future.

4. Conclusions

Through this research, the energy consumption rate and the CO_2 emission factor of water, required for the environment assessment of a multistory building, have been established. As a result of the establishment of this value, the carbon credit program established for detached houses, achieved by the spread of the water-saving apparatus, will expand to multistory buildings, such as apartment buildings, hotels and public facilities.

In addition, the energy consumption rate and the CO_2 emission factor of rainwater and reclaimed water used in buildings were also determined. Water reclamation systems introduced mostly for public facilities in many countries were found to have an environmental impact that was larger than ordinary water use. Therefore, it was judged that the meaning of the environmental impact reduction by water saving in a water reclamation system was large. From now on, a carbon credit program resulting from the adoption of water-saving apparatus spread can be developed, ranging from houses using ordinary water, to buildings using rainwater and reclaimed water. This is expected to contribute to measures against global warming.

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