Carbon footprint of clean water in Indonesia

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Abstract. The local state-owned water company (PDAM) in Indonesia is facing a challenge of an increased demand for sustainable water supply. This study aimed to evaluate the carbon footprint of water from PDAM, and to analyse the correlation between water supply efficiency and the Product's Carbon Footprint (PCF) of the water distributed. Fuel and electrical consumption of PDAM were accounted for in the PCF. Pearson's correlation test was used to analyse the association between the PCF and the idle capacity. Over the last ten years (2014 – 2023), the trend for GHG emissions increased, while for PCF, it was the opposite. The national average for greenhouse gas (GHG) emission in 2023 was 45,935.58 tCO_2-e, and 0.344 $kgCO_2.m^{-3}$ for the PCF. West Kalimantan and Yogyakarta were consistently among the provinces with a high PCF. Meanwhile, West Nusa Tenggara, Papua, and West Sumatra had a low PCF consistently in 2014 and 2023. Apparently, that was because of the emission factor for electricity consumption and the type of transmission and distribution (T&D) system. Despite no significant correlation being confirmed between PCF and idle capacity, further investigation into the correlation between PCF and spatial characteristics is recommended to test the finding from the spatial analysis.

1 Introduction

Urban water supply in Indonesia is facing simultaneous challenges from climate change. From the demand side, the water supply system is pressured by the increased rate of urbanization. A low percentage of pipeline services results in clean water provision by groundwater wells, which causes land subsidence. In coastal urban areas, the impact of land subsidence combined with sea level rise has worsened the damage caused by tidal floods [1]. An alternative to that is the pipeline water service. In Indonesia, the local state-owned water enterprise (PDAM) is responsible for delivering clean water to citizens in urban areas, mainly through pipeline services. Therefore, PDAM should increase its pipeline services, because the majority of cities in Indonesia are in coastal areas [2].

Amidst the urgency for sustainable production and the target for net-zero emissions in 2060. PDAM is therefore urged to account for the PCF of the water. Water plays a crucial role in all human activity. Moreover, a study showed that water supplied from PDAM has lower PCF than the groundwater [3]. It proves that water supplied from PDAM is superior to groundwater in terms of the sustainability aspect. Maintaining PCF evaluation annually for

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PDAM will subsequently contribute to the nationwide achievement of both SDG (Sustainable Development Goal) 6 and 13.

A study provided an example of accounting for water supply scenarios by integrating the system's carbon footprint as the determining factor. It comprehensively assesses the carbon footprint within its defined boundary, but lacks an explanation for the general purpose of the carbon footprint of the water supply in Indonesia [3].

To address the gap, this study aims to assess the current status of the water supply by accounting for the PCF (Product Carbon Footprint) of the water distributed by PDAM all over Indonesia. Hence, it serves for the general purpose of evaluating the sustainability of water service from PDAM. A correlation test between PCF and water supply efficiency was conducted to determine the factor for PCF reduction.

2 Method

In general, the methodology was divided into secondary data collection and quantitative analysis. The data collection aimed to retrieve activity data and emission factors, in which GHG emissions and PCF of water were then calculated. GHG emissions were calculated using the emission factor method. Moreover, idle capacity was also calculated by using the water supply performance data. Temporal and spatial analyses were done for total GHG emissions and PCF of water data. That was to analyse the national annual trend and compare the PCF of water between each province. To analyse the correlation between idle capacity and PCF of water, Pearson's method was used. Results were then discussed to formulate policy strategies for ghg emissions mitigation from the development of urban water supply. The details are presented in Figure 1.

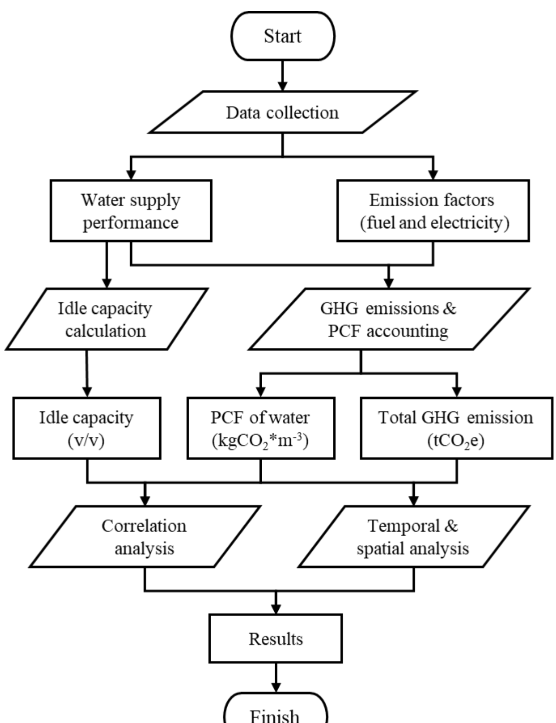

Fig. 1. Research methodology flowchart.

2.1 Data collection

For GHG emission accounting, activity data and emission factors were collected. The activity data were retrieved from the water supply performance as published by the Ministry of Public Works and Housing (PUPR) of Indonesia. Meanwhile, the emission factors used were in accordance with the national standard published by the Ministry of Environment and Forestry (KLHK) of Indonesia.

Table 1. Data source.

No	Data type	Variable	Value (Unit)	Source	Annotation
1	Activity data (AD)	Cost of fuel and lubricant by province	*(IDR)	• Water statistics 2014 – 2019 [4] • Water statistics 2019 – 2023 [5]	
2		Cost of electricity by province	*(IDR)		
3		Volume of clean water distributed by province	*(m^3)		
4		Clean water production by province	*(m^3)		
5		National average subsidized gasoline price	**(IDR/L)	• [6]	
6		National average electricity price for industrial use	** (IDR/kWh)	• *Statistik PLN 2023* [7]	
7		Energy produced from gasoline combustion	33 x 10^{-6} (TJ/L)	• *Pedoman Penyelenggaraan Inventarisasi Gas Rumah Kaca Nasional Buku II* [8]	Assumed to be the same for all years
8	Emission factor (EF)	CO_2 emission from gasoline combustion	69,300 (tCO_2/TJ)		
9		CH_4 emission from gasoline combustion	33 (tCH_4/TJ)		
10		N_2O emission from gasoline combustion	3.2 (tN_2O/TJ)		
11		CO_2 emission from electricity generation	* (tCO_2/MWh)	• *Faktor Emisi GRK Ketenagalistrikan tahun 2019* [9]	EF for all years was assumed to be the 2019 EF
12	Global Warming Potential (GWP) relative to CO_2	CH_4	27	• IPCC (Intergovernmental Panel on Climate Change)	Estimated from the range of 25 – 28
13		N_2O	265		

Note: *As published for each province
**As published for each year

The system boundary included Scope 1 and Scope 2 of the water supply activity of PDAM. Scope 1 consists of fuel consumption, while Scope 2 consists of electricity consumption. The fuel and electricity consumption data for water supply by PDAM were published in a cost unit. Therefore, it was first transformed into a data format that matches the emission factor. So that when the data activity was multiplied by the emission factor, it would result in GHG emissions in a mass unit of CO_2. The accounting period was from 2014 to 2023. The data to calculate GHG emissions and PCF of clean water supplied by PDAM are shown in Table 1.

The clean water production data (Table 1, No. 4) published in each report were only for the last year of the data reported. For example, in the Water Statistics 2019 – 2023, the clean water production data was published only for 2023. The same case for the other two reports. Therefore, the data for other years were assumed to be the same as the available data. Clean water production data in 2014 was assumed to be similar to the 2015 data; the data in 2016 – 2018 were the same as the 2019 data; and the 2020 – 2022 data were the same as the 2023 data.

Another assumption was for the CO_2 emission factor from electricity generation (Table 1, No. 11), which was used to estimate CO_2 emissions from electricity consumption by PDAM. The data was published for up to level 2 of state administration (city level). Thus, for the province-level emission factor, the average data for all cities within the same province were used. However, no data were published for Bali and *Kalimantan Selatan* (South Kalimantan). To estimate the missing value for both provinces, we used the EF from the closest province to them. The EF for Bali was assumed to be the same as *Jawa Timur* (East Java), and the EF for South Kalimantan was the same as that for Central Kalimantan (*Kalimantan Tengah*).

2.2 Data analysis

2.2.1 GHG emissions and PCF accounting

GHG emissions were accounted for annually in Scope 1 from fuel combustion using the cost of fuel and lubricant data, and in Scope 2 from electricity consumption using the cost of electricity data. The accounting for each year is described by Equation 1 – 6.

$$\text{Total GHG emission} = \sum_n GHG\ emission_{(n)} \quad (1)$$

$$GHG\ emission_{(fuel)} = \sum_{ghg} GWP_{(ghg)} \times E.fuel_{(ghg)} \quad (2)$$

$$E.fuel_{(CO2)} = Activity\ data_{(fuel)} \times EF\ CO2_{(fuel)} \quad (3)$$

$$E.fuel_{(CH4)} = Activity\ data_{(fuel)} \times EF\ CH4_{(fuel)} \quad (4)$$

$$E.fuel_{(N2O)} = Activity\ data_{(fuel)} \times EF\ N2O_{(fuel)} \quad (5)$$

$$Activity\ data_{(fuel)} = Cost\ of\ fuel_{(prov)} \times Gasoline\ price \times Energy\ from\ combustion \quad (4)$$

$$GHG\ emission_{(electricity)} = Activity\ data_{(electricity)} \times EF\ CO2_{(electricity)} \quad (5)$$

$$\text{Activity data}_{(electricity)} = \sum_{prov} Cost\ of\ electricity_{(prov)} \times Electricity\ price_{(prov)} \quad (6)$$

Note:
GWP = Global warming potential relative to CO_2
E.fuel = Emission from fuel
EF = Emission factor

The annual total GHG emission for each province was then divided by the volume distributed, resulting in the PCF (Product's Carbon Footprint) of clean water (Equation 7).

$$PCF = \frac{Total\ GHG\ emission}{Volume\ of\ water\ distributed} \quad (7)$$

2.2.2 Idle capacity

To determine the water supply efficiency, idle capacity was estimated by calculating the gap between the volume of water being produced and the volume being distributed (Equation 8). Hence, the idle capacity was described as the ratio of the clean water volume produced that was undelivered to the customers.

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$$Idle\ capacity = \frac{Volume\ production - Volume\ distribution}{Volume\ production} \tag{8}$$

The definition of idle capacity in this regard differs from that of the Ministry of Public Works (PU). It defines idle capacity as the production capacity (in volumetric rate, $L.s^{-1}$) that can be utilized but is not optimized for clean water provision [5]. Meanwhile, this research defined idle capacity as the ratio of clean water produced (in a volume unit, m^3) that was lost before distribution.

2.2.3 Correlation analysis

The PCF of water was determined by the fuel and electricity consumption, as well as the volume of clean water distributed. Correlation analysis between the PCF of water and the idle capacity aimed to identify the contribution of idle capacity to PCF. The initial hypothesis was that PCF would increase with an increase in idle capacity, implying a positive correlation between both parameters. Pearson's correlation test was conducted for this analysis.

3 Results and discussion

In general, the water supply performance of PDAM was evaluated by the health index. It evaluates several aspects, including financial, service, operational, and human resources. Although the evaluation for the sustainability aspect was already included in the financial aspect, such as the Operation Ratio (OR), it was still implicit. To address PDAM's action towards the Net Zero target, therefore, accounting for PCF of clan water distributed by PDAM is necessary. This research complements the PDAM's annual performance report published by PU, which comprehensively analyzed the health index status and the strategy for improvement. Therefore, to simplify the water supply performance analysis in this research, only the volume of water produced and distributed would be used, as the raw data for these two parameters were available. Both parameters also directly indicate the operational condition that determines the GHG emissions and the PCF of clean water distributed. The national average for the volume of clean water produced and distributed is shown in Figure 2.

The volume of clean water produced increased from 2014 to 2023, with a relatively constant volume produced during 2016 – 2018, and 2020 – 2023. The constant volume was because it took years to add the water production capacity until it was ready to be utilized. Although the overall trend for the volume of clean water distributed was increasing, there was a decreasing trend from 2015 to 2017. The gap between the volume of water produced and distributed was the idle capacity, which would later be analyzed to determine its effect on the PCF of clean water.

The increment reached 27.02% for the production, and 62.25% for the distribution, both in 2023, relative to 2014. The average of 2.75% and 5.75% increased each year, subsequently for production and distribution. The distribution increase was higher than that of the production, indicating a linearity with the recommendation for distribution expansion, one of which is accelerating the installation of new pipelines [10].

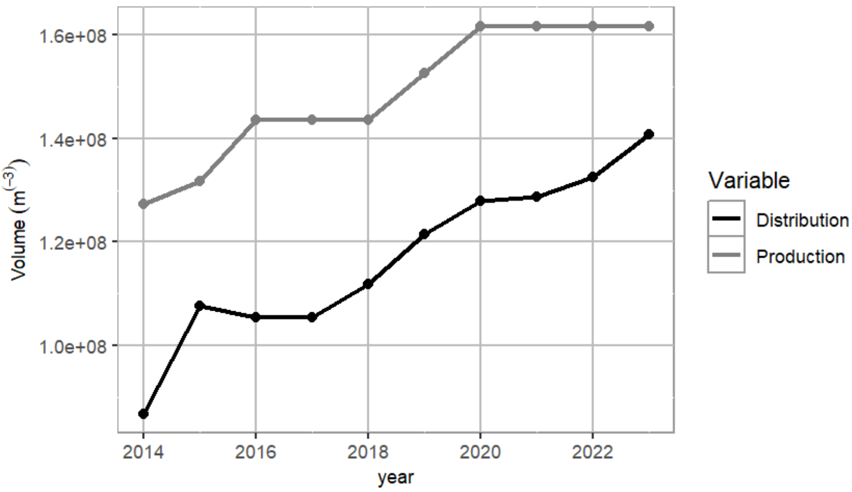


Fig. 2. National average of clean water produced and distributed by PDAM.

3.1 Carbon footprint of water

The total CO_2 in tonnes of CO_2 equivalent (tCO_2e) comprises GHG emissions from fuel and electricity consumption. Meanwhile, PCF ($kgCO_2.m^{-3}$) shows the carbon footprint from the water supplied by PDAM. The national annual trend for both parameters is shown in Figure 3.

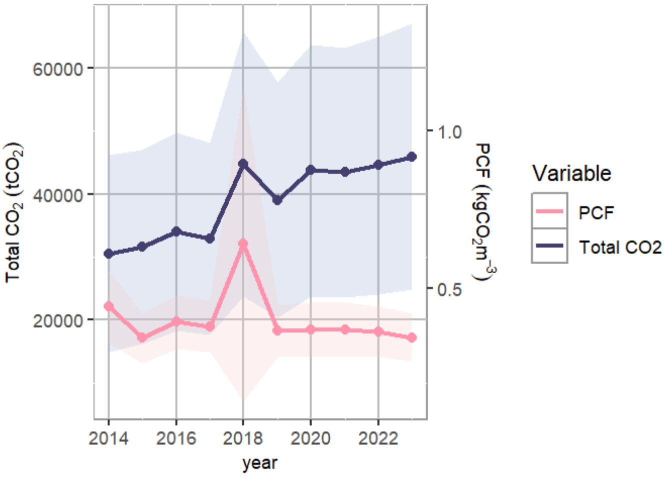


Fig. 3. Product's carbon footprint (PCF) of water supplied by PDAM in Indonesia.

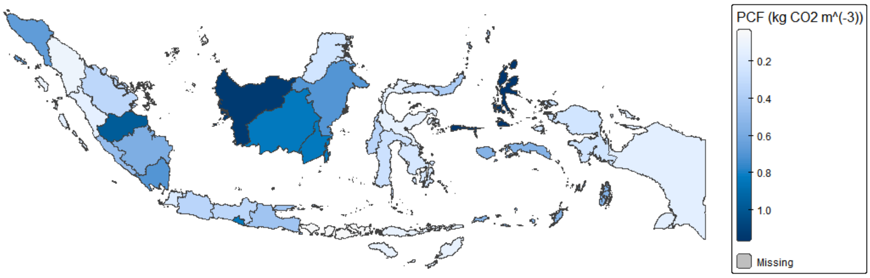
Both trends for total CO_2 and PCF showed the same fluctuation in 2017 – 2019. This can be attributed to the inconsistency of the data collection method by PUPR, resulting in inaccurate data. Since the water supply performance data was published once every five years, the transition between the 2014 – 2019 and 2019 – 2023 publications may cause the inconsistency. Besides the fluctuation, the trend for total CO_2 was increasing, while the trend for PCF was decreasing.

PCF was calculated by dividing the total CO_2 by the volume of water distributed. Therefore, the larger the amount of water distributed, the smaller the PCF of water.

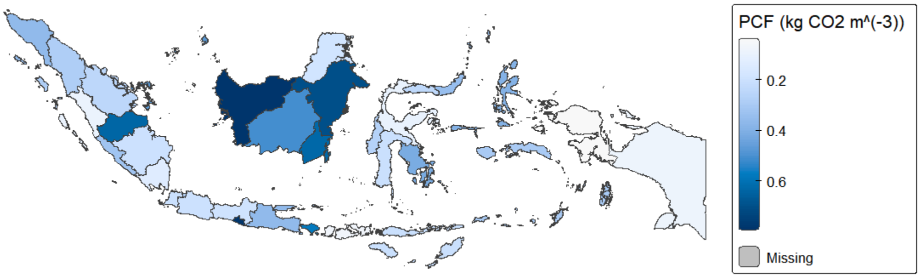
Meanwhile, the amount of water distributed indicates an increase in water production. Thus, the larger the volume of production, the more fuel and electricity consumed. That explains the difference in trend between the total CO_2 and PCF.

In 2014, the national average GHG emission was 30,474.98 (CI 95%: 148,27.91 – 46,122.05) tCO_2-e and 0.442 (CI 95%: 0.328 – 0.555) $kgCO_2.m^{-3}$ for the PCF of water. It was increased to 45,935.58 (CI 95%: 24,856.18 – 67,014.97) tCO_2-e or 50.73% for the GHG emission and decreased to 0.344 (CI 95%: 0.268 – 0.42) $kgCO_2.m^{-3}$ or 22.18% for the PCF of water in 2023. The average PCF of water in Indonesia was more competitive than that in Bangladesh, with a value of 0.18 and 0.27 $kgCO_2$-e from treatment and distribution, respectively [11]. The temporal trend shows that measurement has been taken to optimize the water supply by PDAM.

Nonetheless, spatial variability was also important to consider the province of priority for assistance. Figure 4 shows the PCF of water for all 34 provinces. The difference between the maximum range value of PCF in 2014 and 2023 once again shows that, in general, the PCF of water across Indonesia was decreasing.



(a)



(b)

Fig. 4. Product's carbon footprint for each province in the year of (a) 2014, and (b) 2023.

North Maluku had the highest (1.168 $kgCO_2.m^{-3}$), and Riau Island had the lowest (0.017 $kgCO_2.m^{-3}$) PCF in 2014. Another province with PCF higher than 1.0 $kgCO_2.m^{-3}$ was West Kalimantan (1.134 $kgCO_2.m^{-3}$), and there were eight other provinces that had PCF lower than 0.2 $kgCO_2.m^{-3}$, which were West Nusa Tenggara, Bali, North Sumatra, East Nusa Tenggara, Central Sulawesi, West Sumatra, Papua, and Banten. However, it was shifted in 2023, with the highest PCF in Bangka Belitung Island (0.829 $kgCO_2.m^{-3}$) and the lowest in West Papua (0.043 $kgCO_2.m^{-3}$). While there was no province with PCF higher than 1.0 $kgCO_2.m^{-3}$ in 2023, there were several provinces that had PCF at a high level (> 0.6 $kgCO_2.m^{-3}$), which were South Kalimantan, East Kalimantan, West Kalimantan, and Yogyakarta. Eight other provinces had PCF lower than 0.2 $kgCO_2.m^{-3}$, with some of these provinces also at a low level in 2014, namely West Nusa Tenggara, Papua, West Sumatra, and Central Sulawesi.

West Kalimantan appears to be constantly at a high level of PCF, which was the result of a high emission factor (EF) for electricity consumption of 1.65 tCO_2/MWh. That was the highest among other provinces. It was different in Yogyakarta, with the majority of its water source coming from spring, deep, and shallow wells, which accounted for 60% of the total input. It had to utilize pumping systems for both transmission and distribution [12]. PCF for Yogyakarta had been consistently at about 0.8 $kgCO_2.m^{-3}$, the highest among other provinces in Java Island, which shared the same EF for electricity consumption of 0.84 tCO_2/MWh. An intense fuel and electricity consumption for the clean water production and distribution resulted in a high PCF for Yogyakarta, although being the province with the lowest clean water distribution volume.

West Nusa Tenggara, Papua, and West Sumatra notably had PCF at a low level both in 2014 and 2023. That was the result of most of the water being distributed through gravity, where the available static head plays a key role. In 2019, the percentage of water distributed through gravity in West Nusa Tenggara, Papua, and West Sumatra was 75.57%, 85.69%, and 61.67%, respectively [13].

The result from the spatial analysis indicates the notable effect of the pumping system on the level of PCF of clean water. Dominant use of the pumping system for both transmission and distribution contributes to high fuel and electricity consumption. Further investigation needs to be done for the correlation between spatial characteristics, such as latitude variation, and fuel and electricity consumption for pipeline water service. It was also confirmed that diversification in water sources can optimize the water supply efficiency. Moreover, groundwater as a source is not only overlooked for PDAM’s operational cost, but it can also harm the environment if used excessively [14].

3.2 The correlation between idle capacity and PCF of water

Pearson’s correlation test for PCF and idle capacity resulted in a correlation factor of 0.332 (p-value = 6.252e-10). Therefore, only 33.2% of PCF can be explained by idle capacity, indicating no significant correlation between the two parameters. It means the value of PCF cannot be explained by idle capacity and vice versa. This result shows the need to conduct a correlation analysis with other factors, such as spatial characteristics, as previously mentioned. Several other parameters, such as flexibility for flow rates and system configuration, because it had been reported to affect the efficiency of water supply [15].

4 Conclusion

From the latest report of water statistics published in 2024, the sustainability aspect of water supply service from PDAM was left unaccounted. This research serves as a complementary for that through the evaluation of GHG emissions and PCF of the water distributed. The trend for both the volume of water produced and distributed increased during the last ten years (2014 – 2023). That trend was implied in the national average GHG emissions trend. However, the trend for the national average for PCF of water distributed was the opposite, which was a good sign of a more efficient water supply system. West Kalimantan and Yogyakarta consistently had a high PCF in 2014 and 2023, which was caused by a high emission factor for electricity consumption and intense utilization of pumping systems, respectively. On the other hand, provinces with a constantly low PCF of water showed a dominance of the gravitational distribution system, consequently had lower fuel and electricity consumption compared to the pumping system. Therefore, it was clear that the emission factor and the presence of pumping systems affect the PCF of water. However, the result of the correlation test did not indicate a significant correlation between PCF and idle capacity. It further confirmed the need for further investigation into the effect of spatial characteristics that determine the type of transmission and distribution systems, and the PCF of water.

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