Assessment of the Role of Photovoltaic Systems in Reducing the Carbon Footprint of Wastewater Treatment Plants

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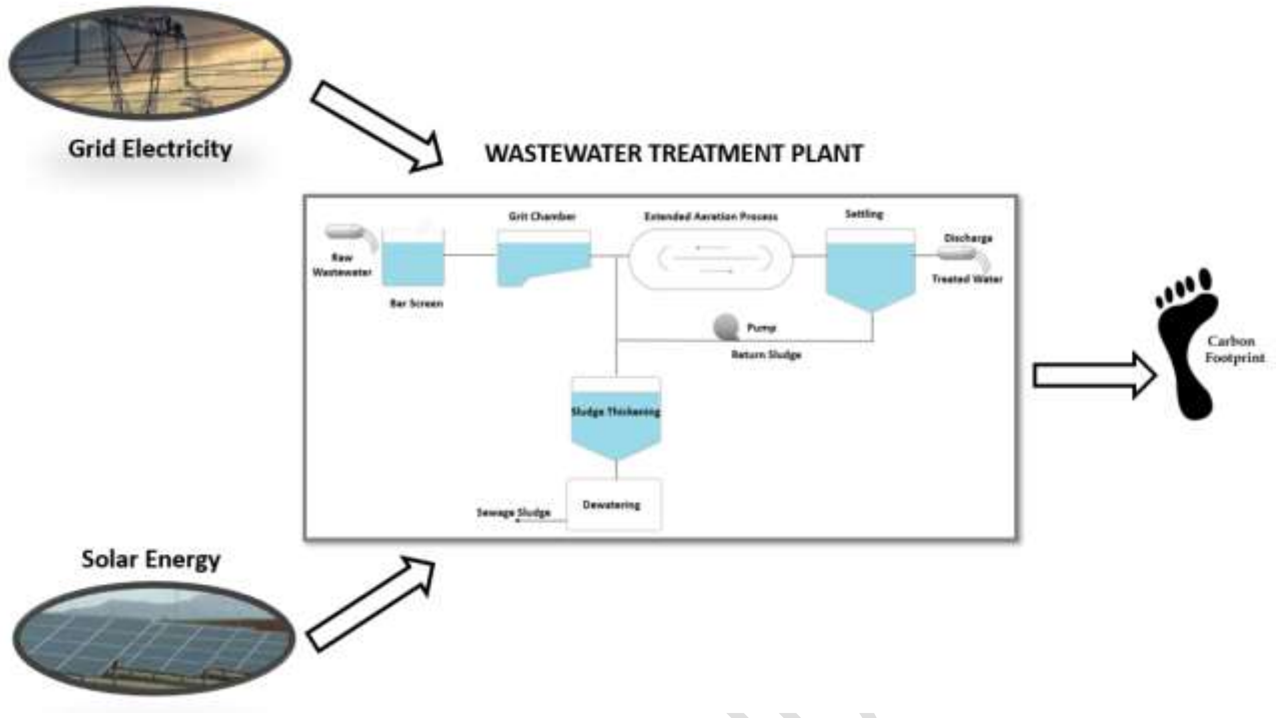
Graphical Abstract



ABSTRACT

Wastewater treatment plants (WWTPs) consume large amounts of energy and thus cause an increase in carbon footprint. For this reason, it has become important not only to meet the discharge criteria in treatment plants, but also to reduce the carbon footprint resulting from treatment processes and energy use. In this study, the effect of supplying the energy required by a real domestic biological wastewater treatment plant from a photovoltaic (PV) system on the reduction of its carbon footprint was investigated. For this purpose, the annual energy consumption profile of the plant was prepared, and direct emissions from treatment processes and indirect emissions from electricity consumption were calculated for 2020 and 2021. Indirect emissions contribute 54% and 69% to the total carbon footprint of the plant for 2020 and 2021, respectively, while direct emissions contribute 46% and 31%. With the partial transition of the plant to a PV system in 2021, annual electricity consumption decreased by 401,000 kWh/year and the carbon footprint decreased by 21% to 819 tCO_{2e}. In this way, the plant also achieved 40% economic savings. If the plant meets all the energy it needs from the PV system, it will reduce its carbon footprint by 45%.

Keywords: Municipal wastewater treatment, carbon footprint, renewable energy, solar energy

1. Introduction

Wastewater treatment plants (WWTPs) aim to reduce harmful wastewater discharge by removing pollutants to ensure the protection of natural water resources and public health (Borzooei et al., 2020). However, WWTPs are also the main source of greenhouse gas emissions that contribute to climate change (Delre et al., 2019). The production of greenhouse gases (GHG) such as CO_2, CH_4 and N_2O during the treatment of wastewater, which are harmful to nature and human health, and the high energy demand of the processes in the plant increase the carbon footprint of the plant and make it difficult to implement its operation in a sustainable manner (Mamais et al., 2015; Demirbas and Ates, 2021). It is known that greenhouse gas emissions during wastewater treatment are responsible for 2.8% of global GHG emissions (IPCC, 2007). In wastewater treatment plants, GHG are produced either directly through biological treatment (CO_2, CH_4 and N_2O) or indirectly through energy and chemical consumption (Xi et al., 2021). Carbon emissions from energy consumption account for a large share of 38 to 50 per cent of the plant's total GHG emissions (Xu et al., 2017). On top of that, since the energy consumption of the plant constitutes a large part of the total cost, it brings a great financial burden to the plant. For this reason, studies to investigate energy saving potentials and to reduce the carbon footprint of WWTPs have increased recently, making WWTPs energy neutral or positive and carbon neutrality have become important issues. Delre et al. 2019, evaluated the carbon footprint of seven WWTPs with different wastewater and sludge technologies within the framework of life cycle assessment (LCA) and stated that due to the differences between energy systems, the electricity supplied from the power grid at the plant has a large impact on the carbon footprint. Wang et al., 2023; investigated the potential of wastewater treatment plants to become energy and carbon neutrality through the upgrading and reconstruction. They found that the three upgrading and reconstruction models contributed to improving the energy neutrality and carbon neutrality of the plant.

In addition, there are various sources for energy recovery in WWTPs and the most frequently used energy production method is biogas production from anaerobic digestion of sludge. However, some studies have shown that the energy produced from sludge in various ways in WWTPs can only meet a part of the electricity demand of the plant (David et al., 2014; Maktabifard et al., 2018). In addition, the Environmental Protection Agency (EPA) has also stated that biogas produced by anaerobic digestion in WWTPs with an influent flow rate of less than 19,000 m^3/day (5 million gallons/day) is not sufficient for electricity and thermal energy production (EPA, 2011). For this reason, efforts to ensure both energy saving and reduction of carbon footprint in WWTPs by providing the energy needed in the plant from renewable energy sources such as solar, wind, hydroelectricity have gained momentum (Mo and Zhang, 2012; Biswas and Yek, 2016).

Renewable energy sources have significant advantages such as being cost-effective, sustainable and having low carbon emissions (Helal et al., 2013). Photovoltaic (PV) systems, based on the direct conversion of sunlight into electricity in PV cells, are one of the most widely used technologies for energy saving in wastewater treatment plants due to their high energy efficiency potential (Ho et al., 2014; Boncescu and Robescu, 2021). Since the energy of PV panels depends on the geographical location of the area where they are located, Turkey is in an extremely advantageous position in this respect. Located between 26^o-45^o eastern meridians and 36^o-42^o north parallels, Turkey's annual total sunshine duration is 2,741 hours and the annual average solar radiation value is 1,527.46 kWh/m^2. Türkiye's installed capacity of electricity based on solar energy has increased from only 249 MW in 2015 to 8479 MW in 2022 (8% of the total installed capacity) with the incentives provided by the government and is expected to increase rapidly in the coming years (MENR, 2022).

So far, studies on the use of PV energy in WWTPs are generally based on the creation of PV systems according to scenario analysis, modelling and simulation results and accordingly environmental and energy analysis or economic feasibility (Strazzabosco et al., 2019; Xu et al., 2017; Boncescu and Robescu, 2021). Therefore, more studies are needed to evaluate the results of the adoption of renewable energy sources in wastewater treatment plants, to see their shortcomings and benefits. This paper will assess how much carbon footprint can be reduced by reducing electricity demand with PV systems. For this purpose, a real treatment plant that meets its electricity needs from a PV system has been selected and the paper provides the following simple steps A) In the first part of the paper, three different situations in WWTP are analysed. Firstly, the amount of electricity consumed by the WWTP when using only grid electricity (without PV system) is presented and the carbon emission generated is calculated (Current actual situation of the plant-for the year 2020). B) In the second case; the amount of electricity when the grid electricity is used together with the PV system of the plant is analysed and the carbon emission is calculated (Current actual situation of the plant-for the 2021 year). C) Finally, carbon emission is calculated assuming that the plant uses PV system completely. In these three cases, in addition to the indirect emissions of the plant due to electricity consumption, direct emissions are also included in the calculation. In the second part of the article, the economic benefits of using PV system in the plant are presented.

2. Material and Methods

2.1. Characteristics of the WWTP

In this study, a biological treatment plant in Türkiye, designed for the treatment of domestic wastewater, was selected for carbon footprint analysis. An important reason for choosing this plant is that it meets the electricity needs of the plant during daytime operation from solar panels with 1000 Kw power installed by the municipality. The required electricity at night is also purchased from the grid. The plant is a medium-sized facility with an average wastewater flow of 4,500 m^3/day [50,000 Population equivalent (PE)]. Figure 1 shows the process flow for the wastewater treatment plant. The wastewater is discharged into the Eğirdir Lake after passing bar screens, grit chamber and the extended aeration activated sludge process respectively. The sludge from the extended aeration process is transferred to the sludge thickening and dewatering unit. The dewatered sludge is sent to the relevant units after being stored in a designated place within the plant for a while.

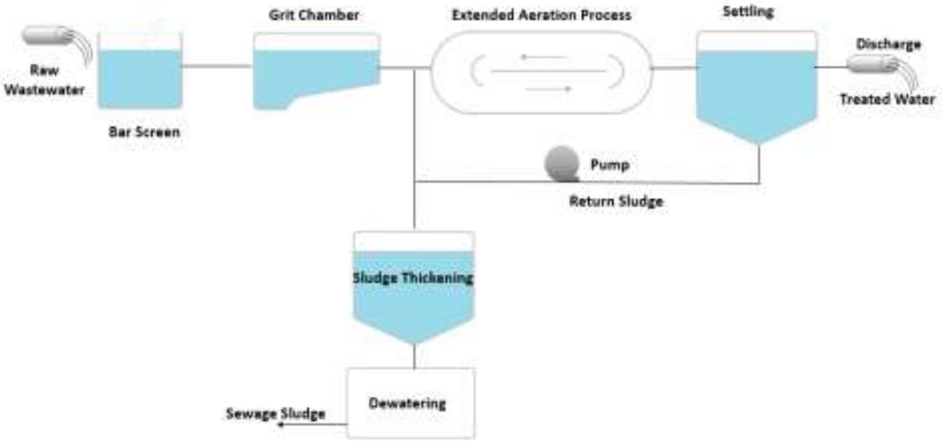


Figure 1. Flow diagram (flow chart) of wastewater treatment plant

2.2.Data Collection and Analysis of GHG Emissions

The carbon footprint calculation is based on data such as wastewater quality and flow rate, electricity and diesel fuel consumption collected directly from the plant's operational records. These data provided are for the years 2020 and 2021. Since the treated water is discharged to Lake Eğirdir, the effluent of the plant must meet the criteria specified in the "Lake Eğirdir Special Provisions" within the scope of Water Pollution Control Regulation (MAF, 2012). The characteristics of influent and effluent of the plant and the standards that the plant must meet for discharge into the lake are given in Table 1. The removal efficiencies of the plant in the parameters of Chemical Oxygen Demand (COD), Biological oxygen demand (BOD), Total Suspended Solids (TSS), Total nitrogen (TN) and Total phosphorus (TP) are on average 91 %, 90 %, 91 %, 66 % and 56 %, respectively and the plant meets the discharge criteria.

Table 1. Characteristics of influent and effluent (annual average) and discharge requirements of the investigated treatment plant

Parameter	Unit	2020		2021		Standard (Lake Eğirdir Special Provisions)
		Influent	Effluent	Influent	Effluent	
TSS	mg/L	130	12.07	135	12.22	60
COD	mg/L	448	47.53	420	33.81	100
BOD	mg/L	140	15.25	130	13.07	45
TN	mg/L	33	10.6	30	10.54	20
TP	mg/L	4.5	2.1	4.2	1.72	3
pH	-	7.4	7.13	7.7	7.26	6—9
Temperature	°C	-	16.6	-	16.4	-

Abbreviations; TSS: Total Suspended Solids; COD: Chemical Oxygen Demand; BOD: Biological oxygen demand; TN: Total nitrogen; TP: Total phosphorus, pH: Hydrogen ion concentration,

This study includes direct emissions from wastewater treatment and indirect emissions from electricity and diesel consumption for unit processes in the treatment plant. Direct emissions from the sewer network, emissions from sludge treatment were not included due to unreliable data. The Intergovernmental Panel on Climate Change (IPCC) guidelines (2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories) is used to calculate direct emissions (CH_4 and N_2O emissions) (IPCC 2019) while the mass balance approach is used to calculate indirect emissions from electricity and diesel fuel consumption. According to the IPCC, CO_2 emissions from treatment should not be included in the total emissions due to its biogenic origin (IPCC, 2019). Therefore, this study only considered CH_4 and N_2O emissions in the calculation of direct emissions from WWTPs.

2.2.1. Calculation of Direct Emissions

The following equations specified by the IPCC 2019 were used to calculate the methane (CH_4) emissions:

$$CH_{4_{Emissions_j}} = \left[(TOW_j - S_j) \cdot EF_j - R_j \right] \quad (1)$$

$$EF_j = B_0 \cdot MCF_j \quad (2)$$

The following equations were used in the calculation of nitrous oxide (N_2O) emissions:

$$N_2O\ Plants_{DOM} = \left[\sum U_i \cdot T_{ij} \cdot EF_j \right] \cdot TN_{DOM} \cdot \frac{44}{28} \quad (3)$$

$$TN_{DOM\_j} = \left(P_{treatment\_j} \right) \cdot Protein \cdot F_{NPR} \cdot N_{HH} \cdot F_{NON-CON} \cdot F_{IND-COM} \quad (4)$$

$$Protein = Protein_{Supply} \cdot FPC \quad (5)$$

Average protein supply in food for Türkiye population was obtained from the Food and Agriculture Organization (2017) (FAO, 2017).

CH_4 and N_2O emissions were converted to carbon dioxide equivalent (CO_{2e}) with 28 and 265 global warming potentials (GWP), respectively (IPCC 2013). Total direct greenhouse gas emissions were calculated by summing methane and nitrous oxide emissions.

2.2.2. Calculation of Indirect Emissions

The amount of indirect CO_2 emissions caused by electricity consumption is calculated with the equation given below.

$$GHG_{electricity} = E \cdot EF_e \quad (6)$$

where, $GHG_{electricity}$: Indirect carbon emissions from electricity consumption (t CO_{2e}/year); E: Electricity consumption of WWTP (kWh/year); EF_e: Country emission factor for electricity generation was 0.4153×10^{-3} t CO_2/kWh for Türkiye (MENR, 2020).

In addition, a diesel generator is used in case of electrical power cuts at the plant. For this reason, the carbon footprint resulting from the use of diesel fuel is also included in the calculation of indirect emissions. The following equation is used to calculate the carbon equivalent of diesel consumption.

$$GHG_{diesel} = D \cdot EF_d \qquad (7)$$

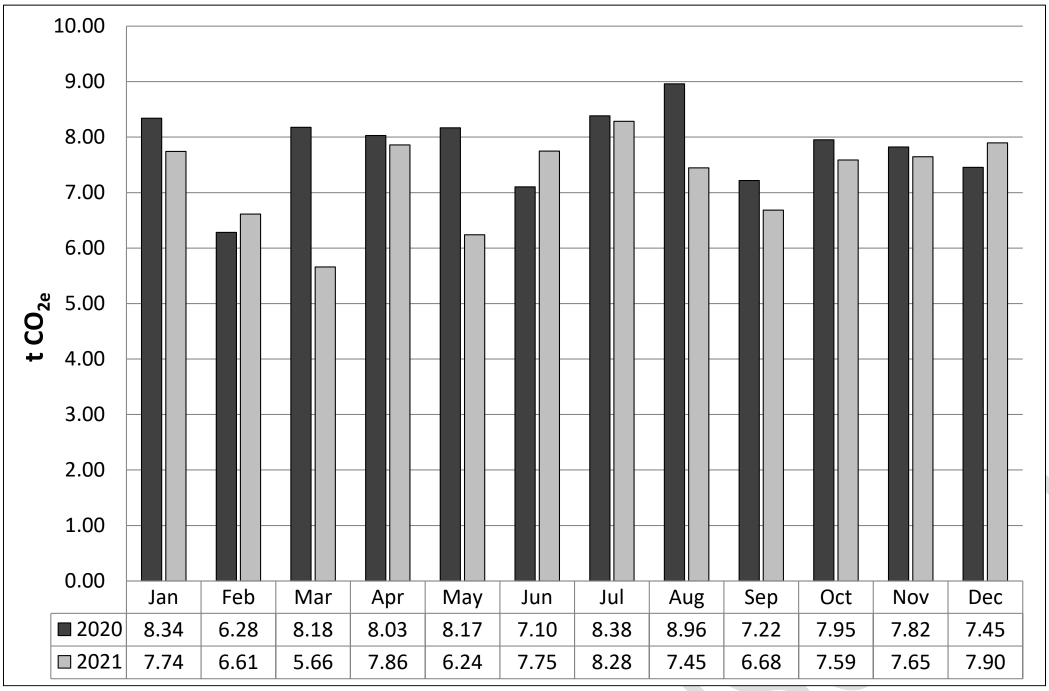
where, GHG_{diesel}: Indirect carbon emissions from diesel consumption (t CO_{2e}/year), D: Diesel consumption of WWTP (L/year); EF_d: diesel emission factor = 10.21 kgCO_2/Gallon = 0.00269 t CO_2/L (EPA, 2023).

Indirect emissions are the sum of emissions from diesel consumption and emissions from electricity consumption.

3. Results and Discussion

3.1.Direct Emissions

The amount of biodegradable organic matter has a major contribution to the calculation of methane emissions (Buadit et al., 2013). The higher the organic matter removal efficiency of the plant, the more methane is expected to be released to the atmosphere (Bahi et al 2020). While a total of 3.35 tons/year of methane is released into the atmosphere from the treatment plant in 2020, the methane released in 2021 is 3.12 tons/year. CH_4 emissions released from the plant were calculated according to the IPCC-2019 methodology (Equation (1)) and the assumptions made are as follows; $B_{0:}$ the maximum CH_4 producing capacity=0.6 kgCH_4/kgBOD; MCF:methane correction factor= 0.03; Sj: organic component removed from the treatment system in the form of sludge=0; Rj:= amount of methane recovered from the treatment system=0 (no CH_4 recovery). Figure 1 shows the monthly calculated CH_4 emissions for 2020 and 2021.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
■ 2020	8.34	6.28	8.18	8.03	8.17	7.10	8.38	8.96	7.22	7.95	7.82	7.45
▨ 2021	7.74	6.61	5.66	7.86	6.24	7.75	8.28	7.45	6.68	7.59	7.65	7.90

Figure 2. CH_4 emissions for 2020 and 2021

In 2020 and 2021, since there were no major changes in the amount, quality and organic matter removal efficiency of the wastewater entering the plant throughout the year, no major differences were observed in the amount of methane emissions generated. CH_4 emissions range between 6.28 -8.34 tCO_{2e} for 2020 and 5.66-8.28 tCO_{2e} for 2021. CH_4 emissions are highest in June and August and lowest in February and March. The carbon dioxide equivalent of the total methane emitted from the plant to the atmosphere is calculated as 94 tCO_{2e}/year and 87 tCO_{2e}/year for 2020 and 2021, respectively.

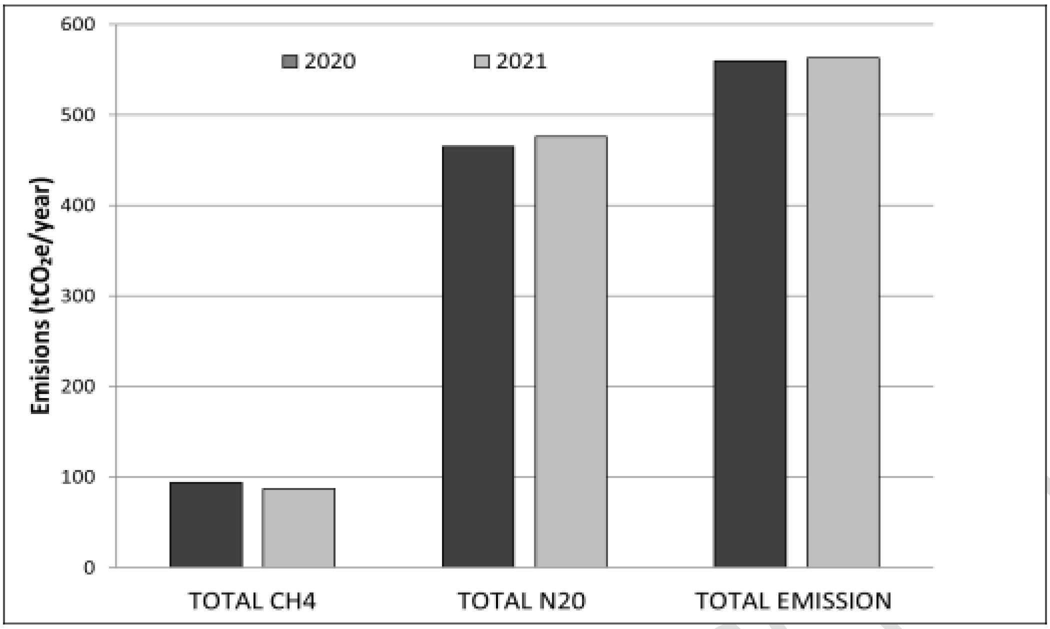


Figure 3. Direct greenhouse gas emissions calculated for 2020 and 2021

Nitrous oxide emissions were calculated annually using Equation 3 based on the IPCC 2019 method. Parameters such as total nitrogen in wastewater, degree of utilization of the treatment plant and emission factor were considered. The assumptions made for the calculations are as follows; Protein supply (annual per capita protein supply): 36.94 and 37.12 kg protein/person for Türkiye in 2020 and 2021, respectively.; FPC: fraction of protein consumed=0.9; F_{NPR}:0.16 kg N/kg protein; N_{HH}:1.1; $F_{NON\text{-}CON}$:1.06 kg N/kgN; $F_{IND\text{-}COM}$:1.25 kg N/kg N; Ui: the fraction of population=0.94; Tij: degree of utilization of treatment=0.44; $EF_{Effluent}$: emission factor for N2O emissions=0.016 kg N_2O-N/kg N; P: human population= 21807 for 2020 year and 22124 for 2021 year.

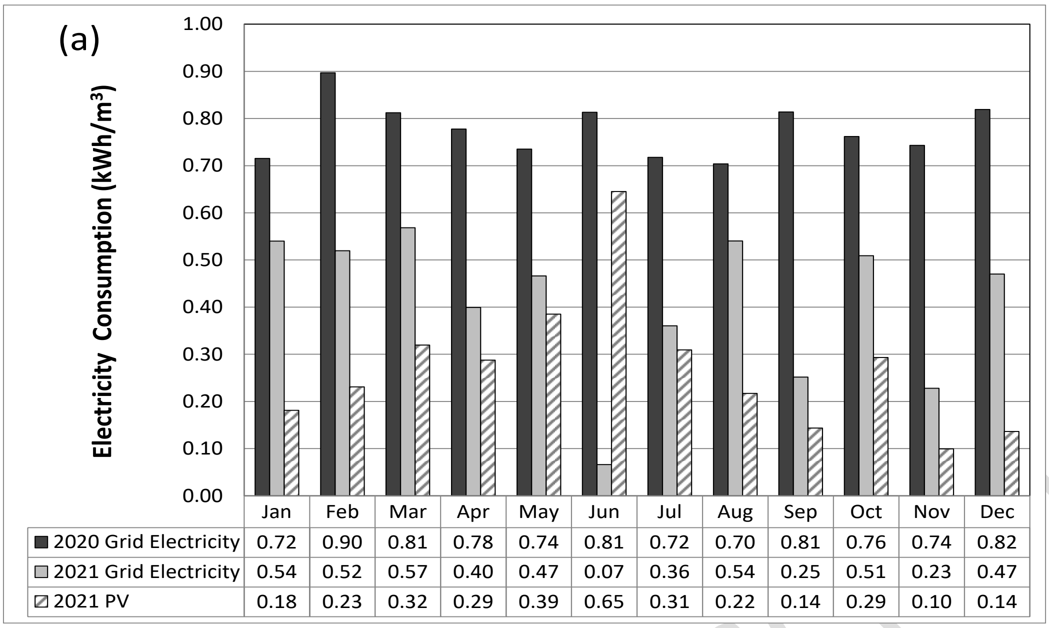
As can be seen from Figure 3, while total N_2O emissions were 465 tCO2e/year in 2020, it increased by 2.15% to 476 tCO2e/year in 2021. Parameters that have a major impact on N_2O emission are population and protein consumption. Therefore, the 2.15% increase in N_2O emissions from 2020 to 2021 can be attributed to the increase in population and protein consumption. Similar reasons were also highlighted in the study by Ramírez-Melgarejo et al., 2020. For 2020 and 2021, total direct greenhouse gas emissions are 559 tCO_{2e}/ year and 563

tCO_{2e}/ year, respectively. As can be seen from Figure 3, N_2O emissions from the plant are much higher than CH_4 emissions. The contribution of N_2O emissions to direct emissions is 83% and 85% for 2020 and 2021 while the contribution of CH_4 emissions is 17% and 15.2%, respectively. These findings are consistent with the studies in the literature (Gustavsson and Tumlin, 2013; Xi et al., 2021; Sharawat et al., 2021).

3.2. Indirect Emissions

In addition to the direct greenhouse gas emissions of the plant, indirect emissions based on electrical energy were also calculated. The electrical energy consumed in wastewater treatment plants has a large share of 84% in total energy consumption (Sharawat et al., 2021) accordingly, the carbon footprint resulting from electrical energy has a large share in the total carbon footprint of the plant. According to the literature, the energy consumed in wastewater treatment plants varies between 0.243-0.89 Kwh/m3 depending on population, location and size of the plant, treatment processes, age of the plant and wastewater standards (Ritter and Chitikela, 2014; Gu et al., 2017; Maktabifard et al 2018; Kadam et al 2023).

Figure 4(a) illustrates the electricity consumption per treated wastewater volume of the wastewater treatment plant in 2020 and 2021. It partially switched to the use of electricity generated by PV systems in 2021 while the plant provided electricity it consumed only from the grid in 2020. As can be seen from the figure, the electricity consumption of the plant, which uses only grid electricity in 2020, varies between 0.72-0.90 kWh/m^3 according to months. The total electricity consumption of the plant in this year is 1153x103 kWh/year. Río-Gamero et al., 2020, reported the annual energy consumption as $2956x10^3$ kWh for a 10,000 m^3/day wastewater treatment plant consisting of primary and secondary treatment.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
■ 2020 Grid Electricity	0.72	0.90	0.81	0.78	0.74	0.81	0.72	0.70	0.81	0.76	0.74	0.82
□ 2021 Grid Electricity	0.54	0.52	0.57	0.40	0.47	0.07	0.36	0.54	0.25	0.51	0.23	0.47
▨ 2021 PV	0.18	0.23	0.32	0.29	0.39	0.65	0.31	0.22	0.14	0.29	0.10	0.14

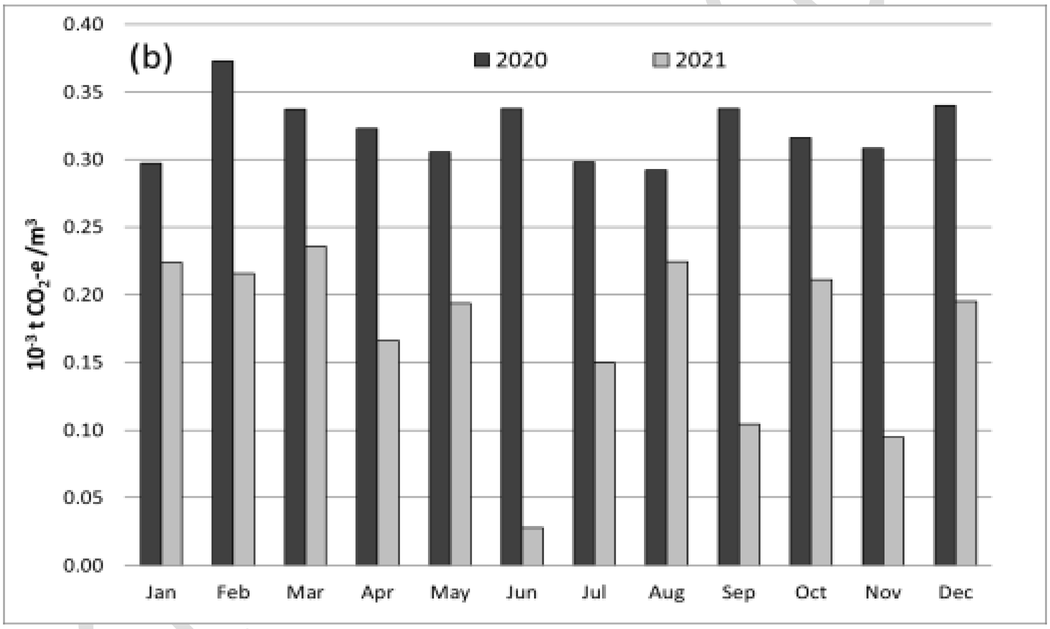


Figure 4. (a) Annual specific electricity consumption of wastewater treatment plant (b)Greenhouse gas emissions from electricity consumption for 2020 and 2021.

In 2021, the plant used electricity generated by solar panels in addition to grid electricity and the amount of electricity used from the grid varies between 0.07-0.54 kWh/m^3 and the amount of electricity used from solar panels varies between 0.1-0.65 kWh/m^3 depending on the month. The total electricity consumed from the grid by the plant is 602 x 10^3 kWh/year in 2021. The solar panels utilised by the plant have a power of 1 MW and were installed by the municipality on a land outside the plant. The energy produced here meets the electricity of the city's parks, gardens, and green areas in addition to the treatment plant. For this reason, it is difficult to fully link the solar energy used in the plant to the seasons. However, it is possible to say that the plant maximum benefits from solar panels in June and minimum in November. This is consistent with the monthly average radiation distribution of Türkiye, which is high in June-July-August and low in November-December-January (MENR, 2022). The plant can be said to achieve 40% electricity savings by procuring 401,000 kWh/year of the electricity required from solar panels in 2021 (by minimizing the use of grid electricity). In other words, when the consumption in 2020 and 2021 are compared, the electricity requirement from the grid in 2021 decreased by 52% compared to 2020. Strazzabosco et al. (2019) state that solar energy will meet 30-100% of the plant energy demand in wastewater treatment plants with a flow rate below 19,000 m^3/day (5MGD).

Figure 4b depicts the specific carbon footprint of the plant's electricity consumption for 2020 and 2021. The specific carbon footprint ranges between 0.29-0.37x 10^{-3} tCO_{2e} /m^3 for 2020 and 0.03-0.24 x10^{-3} tCO_{2e}/m^3 for 2021. Furthermore, the total emissions from electricity consumption of the plant were calculated according to Equation 6 and found to be 479 tCO_{2e}/year and 250 tCO_{2e}/year for 2020 and 2021, respectively.

In addition, the treatment plant consumed 1,657 and 2,064 L of diesel fuel in 2020 and 2021, respectively, due to the generator used during power outages. Details can be seen in Table 2. Emissions from the diesel generator were calculated assuming an emission factor of 0.00269 tCO_{2e} /L and found to be 4.46 and 5.55 tCO_{2e} /year for 2020 and 2021, respectively. Considering emissions from both grid electricity and diesel consumption at the plant, total indirect emissions are 483 and 256 tCO_{2e}/year for 2020 and 2021, respectively.

Table 2. Indirect emissions from generator and grid electricity

	Consumption	**EF**	**Total Emission** (tCO$_{2e}$/year)
Grid Electricity	1153819 kWh/year	0.4153x10^{-3} t CO2/kWh	479
Generator	1657 L/year	0.00269 t CO2e/L	4.46
2020			**483**
Grid Electricity	602106 kWh/year	0.4153x10^{-3} t CO2/kWh	250
Generator	2064 L/year	0.00269 t CO2e/L	5.55
2021			**256**

Figure 5 illustrates the total emissions from the plant for three different conditions of the plant. Indirect emissions account for 46% of the total emissions in the WITHOUT PV case (when the plant is fully using grid electricity-2020), while they decrease to 31% in the PARTIAL PV case (when the plant partially switches to a PV system in 2021). Delre et al 2019 reported that the contribution of direct emissions in the total emissions of seven wastewater treatment plants with different wastewater and sludge treatment technologies was 44-71%. As can be seen in Figure 5, the total GHG emissions of the plant are 1042 and 819 tCO$_{2e}$/year for WITHOUT PV (2020) and PARTIAL PV (2021) respectively. In other words, the plant partially switched to solar energy use in 2021 and reduced its carbon emissions by 21%. If the plant is assumed to switch to a full PV system (FULL PV), the total emissions of the plant will be 569 tCO$_{2e}$/year and a 45% reduction in total emissions will be achieved. Boncescu and Robescu, 2021, calculated that the amount of carbon emissions can be reduced by up to 12% by saving 40% energy in the treatment plant with the PV system according to the simulation results of the PVsyst program.

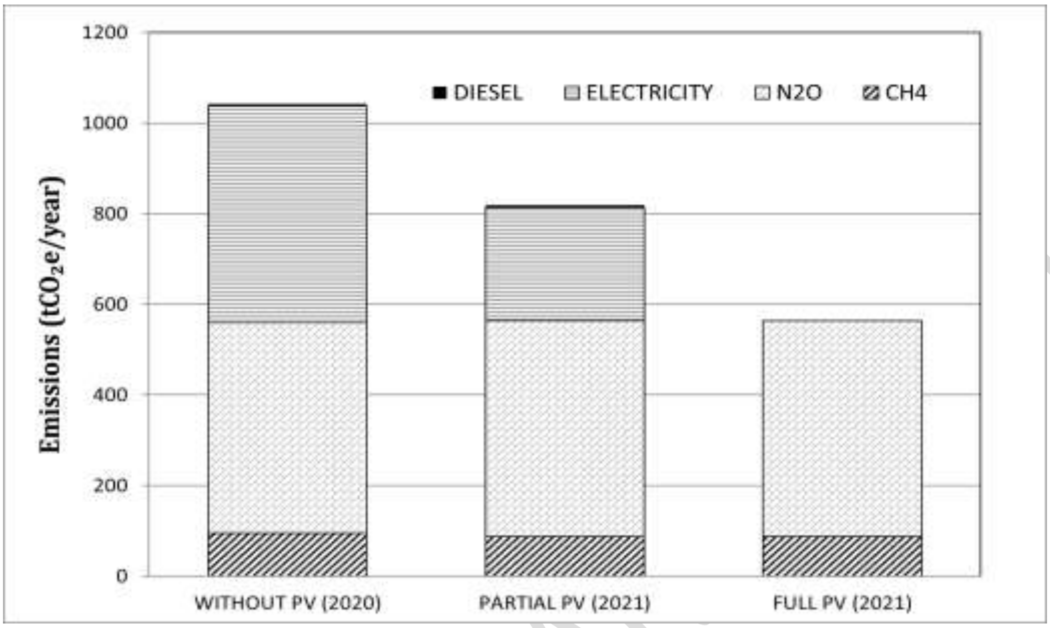


Figure 5. Comparison of three different situations of the treatment plant

3.3.Potential Economic Benefits of the PV System

By counting the cost arising from the electricity consumption of the treatment plant, the economic benefits of the PV system can be clearly demonstrated. Figure 6 shows the electricity costs per volume of wastewater treated for the WITHOUT PV (2020) and PARTIAL PV cases (2021). The plant consumed 9.31 kWh/m^3 of electricity from the grid in the WITHOUT PV case, while in the PARTIAL PV case, it consumed 4.92 kWh/m^3 electricity as it met its electricity needs from the grid only during night hours. The electricity consumption cost of the plant was calculated by considering the current market price for wastewater treatment as 0.029US$/kWh for 2020 (WITHOUT PV) and 0.033US$/kWh for 2021 (PARTIAL PV) (1TL=0.051 US$ for the second quarter (April-June) of 2023 in Türkiye) (TURKSTAT, 2021). Accordingly, it can be seen that the plant has reduced the electricity cost from 0.27 US$/m^3 to 0.16 US$/m^3 by adopting a PV system, even partially, and achieved a 40% saving (Figure 6).

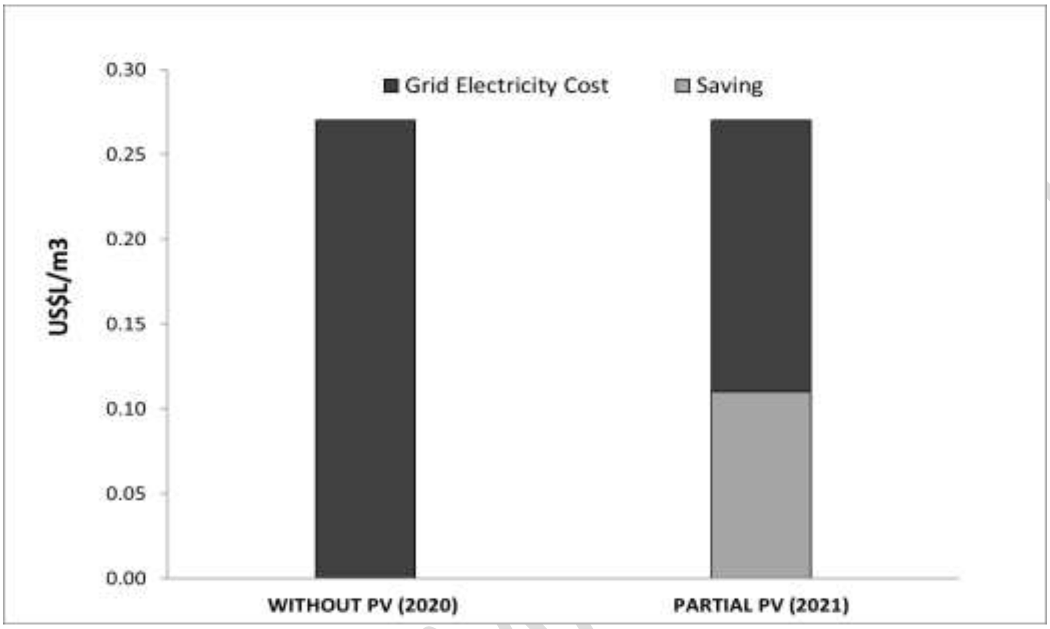


Figure 6. A Comparison of electricity costs for the WITHOUT PV (2020) and PARTIAL PV (2021) cases

4. Conclusions

This study evaluated the impact of the use of energy generated by solar panels in wastewater treatment plants on the carbon footprint of the plant. For this purpose, a real domestic biological treatment plant, which provides its energy from PV systems installed outside the plant by the municipality, is examined. The plant provides all the energy it needs from the grid in 2020. In 2021, it partially switched to a PV system by using the energy obtained from the solar power plant during daytime hours and using grid electricity at night. With the partial transition of the plant to a PV system, the carbon footprint decreased by 21%, from 1042 tCO_{2e}/year to 819 tCO_{2e}/year. In addition, the cost of electricity consumption decreased by 40%. If the plant can utilize the energy produced by PV systems during night hours through storage, it can fully switch to a PV system and get closer to becoming an energy neutral treatment plant. In this case, the carbon footprint of the plant will be reduced to 569 tCO2e/year, a 45% reduction compared to the case without PV system. By increasing the share of PV systems for electricity generation, the carbon footprint of the plant can be reduced and contribute to the sustainable operation of the plant.

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