

# Exergy-Based analysis of CO<sub>2</sub>e reduction by campus solar energy installation for sustainability improvement

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**Abstract.** Sustainability studies aiming to reduce CO<sub>2</sub>e emissions is increasing gradually. Generally energy-based approaches is being used in these studies. In this paper, the carbon footprint calculations of energy-consuming systems in the OSTİM Technical University building is examined, focusing on the use of solar energy for emission reduction. An Exergy-based approach, generally ignored in CO<sub>2</sub>e calculations, is adopted. The carbon emissions calculation is carried out according to the ISO14064 by monitoring the University's energy consumption. In order to reduce CO<sub>2</sub>e, use of solar energy PV panels for the University building is evaluated. Calculations showed that intended PV panels could meet 16% of the annual electricity demand, leading to an 18% reduction in CO<sub>2</sub>e emissions compared to grid reliance. For Exergy analysis, general electricity generation sources (fossil fuel, renewable, etc.) are considered in obtaining the CO<sub>2</sub>e caused by using grid electricity. It is concluded that using electricity generated from PV panels instead of grid electricity resulted in less exergy destruction and approximately 61% low in carbon emissions. The planned PV panel installation's payback period calculated as 5.1 years. The obtained results suggest that calculating CO<sub>2</sub>e emissions using the Exergy method provides a more realistic view, due to not only considering consumption but also taking into account energy generation, transmission, and distribution lines.

## 1 Introduction

Sustainable energy is so vital topic for humanity due to limited resources in the world. Therefore, the consuming of fossil fuels efficiently has great importance in the use of energy besides of the environmental effect. Today worlds more than 50% of power plants are depend on limited resources (fossil fuels), they pollute the environment, and they create greenhouse gas emissions (global warming). CO<sub>2</sub> is the most important greenhouse gas emitted by human activities that cause climate change. Thus using of renewable energy is inevitable.

The distribution of total energy consumption to primary sources ratio in 2022 is as follows: oil 29,95%, natural gas 26.25%, coal 24.96%, hydroelectric 8.99%, and other renewable sources 9.85% [1]. Due to the carbon emissions caused by fossil fuels and the limitations of

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resources, alternative energy applications are accelerating every day besides of renewable energy studies.

The academic community has a role and responsibility in researching, developing, and implementing more effective technological solutions in addition to educational activities in the field of sustainability. Therefore, study on the application and development of sustainable environment, reduction of carbon footprint, energy efficiency, and renewable energy technologies are a necessity for universities.

In this term, sustainability, reducing carbon footprint and increasing energy efficiency, the first step is the measurement and reporting of energy. Therefore, efficiency of the HVAC (Heating Ventilating Air Conditioning) system should also be considered in reducing carbon emissions. Standards and regulations worldwide have been established to define the efficiency of HVAC equipment and installations and to set limits such as ASHRAE/IESNA 90.1-2001 standard is developed to limit energy consumption in buildings [2]. In this scope, conducting necessary studies related energy management, HVAC and electrical systems efficiency, carbon footprint reduction, guidelines or standards are published like ISO50001, ISO 14064.

The studies related about carbon footprint reduction and efficiency in the literature generally applied by using energy (quantitative) methods and exergy (qualitative) perspective ignored. However, exergy based studies increasing gradually. Çomaklı [3] conducted a study on the energy and exergy analysis of the heating centre of Atatürk University TR. The energy and exergy losses occurring in the boiler used for the heating system were calculated in the study. From result of the analysis, he deduced the energy efficiency and exergy efficiency of the heating system were determined to be 0.8 and 0.6, respectively. Additionally, it was noted that fuel savings of around 10% could be achieved by using 10 cm insulation instead of the existing insulation in the building, implementing radiator back insulation, curtain applications, and using double glazing instead of single glazing. Zuhur et al. [4] stated in their study that the efficiency of a PV panel used for electricity generation increases when cooled during summer conditions. In their study, a Concentrated Photovoltaic Cooling System was designed and a prototype was produced. They conducted energy, exergy, and environmental cost analyses and expressed that the proposed system allows for savings of around 0.1 ¢ per hour due to reduced CO<sub>2</sub> emissions.

Kılış B.[5] has developed an exergy-based model that minimizes the carbon footprint and maximizes the optimum energy efficiency for minimum space heating systems. In the study, a model was presented for designing low-temperature regional heating systems that minimize the carbon footprint and maximize efficiency. Hakan [6] conducted a comprehensive study on solar collectors focusing on energy, exergy, environmental, enviroeconomic, exergoenvironmental (EXEN), and Exergoenvironmental (EXENEC) aspects. He highlighted the significant energy and exergy losses due to large temperature differences between the environment and the collector. He concluded that solar collector systems can be more effectively evaluated using exergy and economy-based EXEN and EXENEC methods. Yaghoubirad et al. [7] stated that photovoltaic (PV) systems are commonly used and feasible solar energy applications, providing clean and secure alternatives to fossil fuels. They conducted a multi-criteria analysis including energy, exergy, economic, and environmental analyses.

Lozano et al. [8] have identified some key elements necessary for integrating sustainability activities into universities. These elements include: Collaboration with other universities; Development of interdisciplinary studies; Making sustainability a fundamental part of the institutional framework; Creating campus life experiences; and establishing programs to train and encourage educators. In another study, Taqwa [9] drew attention to the role of universities in developing renewable energy strategies and creating management policies. Leal Filho et al. [10] examined the impact of universities' sustainability activities on

the economy, society, and the environment, focusing on building design and use for sustainability, waste reduction and management, sustainable procurement, and low-emission transportation. Devandran [11] emphasized the importance of on-campus awareness in reducing carbon footprint by calculating carbon emissions using the energy-based GHG method for Sunway University. Li [12] examined the carbon emissions of Tianjin University of Technology.

The common points of all these studies aim at facilities and infrastructure, energy and climate change, waste management and treatment, transportation, and related education and research. It is essential to conduct an energy study using international (LEEDS-GreenMetric-ZeroEnergy Building, etc.) or national (TSE, etc.) standards to show the importance of energy efficiency and environmental standards.

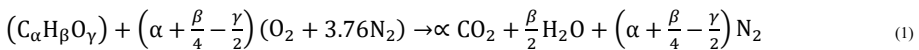
Therefore, in this study, the university's energy usage is addressed, and the impact of using PV panels on reducing carbon footprint is investigated from an energy-exergy perspective and within the scope of sustainability.

## 2 Materials and methods

Thermodynamics explains the energy interaction between a system and its surroundings and the transformations of energy between them. All energy transformations in the universe are governed by the first law of thermodynamics. In heating and cooling systems, energies obtained from electricity and natural gas are transferred to the fluid within the system to achieve the desired conditioning. In these systems, natural gas and electricity consumption can be measured on continuous manner, allowing for detailed analysis of heating and cooling systems and calculation of the system's efficiency by comparing energy changes in the environment with energy consumption.

The first law of thermodynamics is not sufficient for evaluating and analysing the thermal process because it does not provide information about the qualitative changes that occur during energy interactions. According to the second law of thermodynamics, the portion of a certain amount of energy or energy flow that can be converted into useful work until thermal equilibrium is reached with the surroundings within any process is called exergy. While the first law of thermodynamics is related to the quantity of energy, the second law of thermodynamics determines the quality of energy. Exergy efficiency is known as the efficiency of the second law that takes into account both the first and second laws of thermodynamics. Exergy analysis not only provides information about the quantity of energy but also demonstrates the efficiency and quality of energy utilization. Exergy efficiency is also used to measure the irreversibility degree of processes [13].

The carbon footprint caused by the combustion stoichiometry for a general hydrocarbon fuel can be expressed by using Eq.1 [14] based on the amount of energy usage and efficiency. The percentages of exhaust gases in the environment are provided in Table1.



**Table 1.** Exhaust gas percentage in the ambient [14].

	$O_2$	$CO$	$CO_2$	$H_2O$	$N_2$
y (%)	20,94	0,0007	0,035	3,03	75,98

In this study, a solution model incorporating exergy efficiency has been used [15]. For calculating exergy efficiency Electric Power percentage in Turkiye is used, and the power production rates related to the 2022 National Energy Plants are used, which are presented in Table-2. Hydroelectric power production decreases in winter months and increases in spring

months. In winter season, solar energy production also decreases, while in some regions, wind energy production increases. Therefore, in order to create an ideal solution environment in this report, the example scenarios provided should be analysed on an hourly basis using hourly power production data throughout the year. Although the performance of power plants has improved in recent years, it is still accepted that the average efficiency is around 45% for some of our natural gas power plants due to the decrease in recent years of their relatively low efficiencies.

The maximum value of the exergy can be calculated using Eq.2. In this equation,  $Ex_{max}$  represents maximum exergy,  $T_{ref}$  refers to the environmental equilibrium temperature,  $T_f$  denotes the energy source temperature, and  $Q$  represents heat power.

$$Ex_{max} = \left(1 - \frac{T_{ref}}{T_f}\right) Q \tag{2}$$

**Table 2.** Power Plants production in Turkiye for 2022 (assembled from online and EÜAŞ TR data).

Resource	Power Plant Type	Adiabatic Comb. Temp $T_f$ Kelvin	Specific CO <sub>2</sub> Emission, CO <sub>2</sub> kg/kWh	Exhaust/Waste-heat Temp $T_E$ Kelvin	Weight in the production % ( $a_i$ )	Total ratio in the energy production %	Average Efficiency
Fossil fuel	Coal	2440	0.35	750	31.4	64.2	0.27*
	Natural Gas	2340	0.2	317	32.7		
	Fueloil, nafta	2375	0.28	750	0.1		
Renewable energy source	Hydroelectric	5778	-	373	16.8	35.8	0.85**
	Solar Energy	559.44	-	323 (PV)	4		
	Wind Energy	478.3	-	350	9.39		
	Jeotermal	377	0.8	317	3.25		
	Biogas	1900	0.2	750	2.3		

\* Heat power of power plants, transmission efficiency-distribution efficiency of the grid (without leaks).

\*\*Transmission efficiency of the grid, including transformer losses (excluding leaks), PV distribution losses,etc.

In a series-connected system, the overall first law efficiency of the system  $\eta_T$  can be calculated using Eq.3, considering the product of the efficiencies of all system components  $\eta_i$ . In this case, the PEF (Primary Energy Factor) is calculated using Eq.4. The responsibility for the leakage in the natural gas boiler can be obtained using Eq.5 [16].

$$\eta_T = \prod \eta_i \tag{3}$$

$$PEF = \frac{1}{\eta_T} \tag{4}$$

$$CO_2 = \frac{0.196}{\eta_T} = 0.196 \times PEF \tag{5}$$

The exergy analysis for the system can be calculated using the method in Eq.6-7, indicating the amount of efficiency that can be obtained from the system [16]. In this case, transformation of energy from the fuel's adiabatic combustion temperature  $T_f$  (Flame temperature) to a reference ambient temperature ( $T_{ref}$ ) will be considered. In Table 2, various

fuel types are used for electricity production in Turkiye, and separate  $T_f$  values are available for each fuel type. The  $T_E$ , exhaust temperature values are also provided in Table 2. In this situation, the exergy efficiency can be calculated using Eq.7.

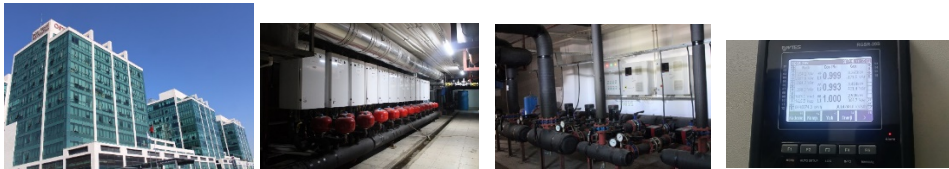
$$\left(1 - \frac{T_{ref}}{T_f}\right) = \sum_{i=1}^n \alpha_i \left(1 - \frac{T_{ref}}{T_{fi}}\right) \tag{6}$$

$$\psi_R = 1 - \left(\frac{\varepsilon_{des}}{\varepsilon_{sup}}\right) \tag{7}$$

Here,  $T_{ref}$  represents the ambient equilibrium temperature,  $T_f$  denotes the energy source temperature,  $Q$  represents thermal power, and  $\psi_R$ : indicates the exergy efficiency and  $\varepsilon$  specific exergy.

### 3 Result and discussion

In the study, a university building with a total area of 41,886 square meters was examined. There are 24 units of 128kW cascade-connected boilers in the building for heating. The heating and cooling systems have an efficiency class of EC3 for pumps. LED lamps are used for lighting. In the main electrical panel, there is also a compensation panel. Photos related to this in Fig.1 can be seen.



**Fig. 1.** OSTİM Technical University Building, Electrical (compensation) and Mechanical Components.

The primary energy sources used are electricity and natural gas in these systems in the campus building. As first step, the electricity and natural gas consumptions are observed. Table 3 provides the consumption amounts for electricity and natural gas in 2022. According to table-3, as it expected, summer season energy usage reduced.

**Table 3.** The consumption values obtained from the records of the bills.

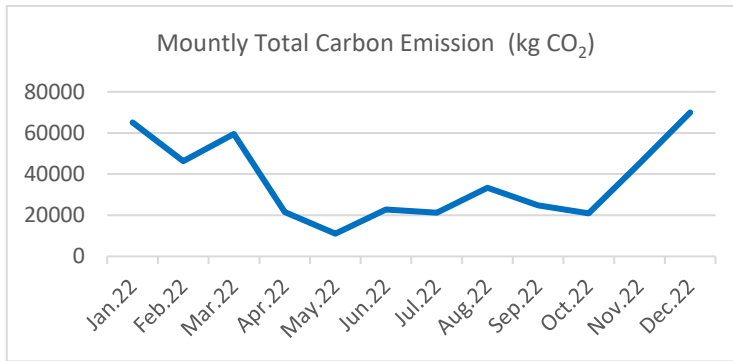
z	Electric Consumption (kWh)	Natural Gas Consumption (Sm <sup>3</sup> )
Jan.22	42,430.05	25,473.55
Feb.22	33,088.25	17,659.53
Mar.22	40,910.00	22,737.11
Apr.22	28,426.95	4,813.54
May.22	23,661.78	201,07
Jun.22	49,596.15	201,07
Jul.22	46,255.84	201,07
Aug.22	73,330.70	201,07
Sep.22	54,076.88	201,07
Oct.22	45,650.87	201,07
Nov.22	63,231.50	9,248.00

Dec.22	79,788.47	18,818.32
Toplam	580,447.43	99,956.51

The monthly carbon emissions are presented in Table-4 and Fig.2 based on the consumption data. The total carbon emissions for 2022 are approximately 442 tons. Considering the carbon emission scopes, it is seen that about 262 tons come from electricity consumption, and about 180 tons come from natural gas consumption. The scope diagram is shown in Fig.3. According to calculation, 59,27% of CO<sub>2</sub>e caused by electricity usage.

**Table 4.** Monthly Carbon Emissions wrt Energy Sources.

CO <sub>2</sub> e (kg)	Jan.22	Feb.22	Mar.22	Apr.22	May.22	Jun.22	Jul.22	Aug.22	Sep.22	Oct.22	Nov.22	Dec.22
cause by Electricity	19136	14923	18450	12820	10671	22368	20861	33072	24388	20588	28517	35984
cause by N.Gas	46000	31384	41060	8692	363	363	363	363	363	363	16701	33982
Total	65136	46307	59510	21512	11034	22731	21224	33435	24751	20951	45218	69966



**Fig. 2.** The calculated carbon emissions in 2022 based on energy consumption data.

When evaluating the 1<sup>st</sup> law efficiency by employing Eq. 3-5, the analysis of system components reveals a decrease in efficiency. The energy efficiency in generally can be assumed as 45% for the power plant, 85% for the transmission line 85% (including leakage) for the distribution efficiency, and 95% for the transformer efficiency. In this case, the total efficiency and the carbon emission calculated from Eq.3-5 are obtained as following.

$$\eta_T = 0.45 \times 0.85 \times 0.85 \times 0.95 = 0.30$$

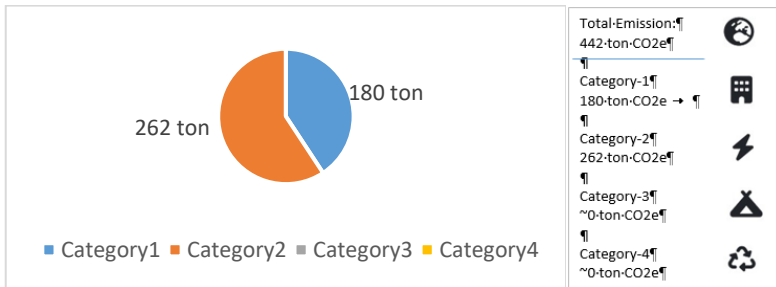
$$PEF = \frac{1}{\eta_T} = 3.33$$

$$CO_2 = 0.196 \times PEF = 0.652 \text{ kgCO}_2/\text{kWh}$$

In terms of electricity usage, using the 1<sup>st</sup> law of Thermodynamics, by employing of Eq.5, which is the unit carbon emission, the total carbon emission more than 442 tons. Because in this calculation the losses considered throughout the all conduction line from the powerplant to the university building (generation, transmission, and distribution etc.) as well. However, firstly investigation is confined related of the efficiency of the internal side of the university building. Hence, CO<sub>2</sub>e is calculated according to ISO 14064 standard by using Emission(CO<sub>2</sub>)=EF×AD. Here, EF: Emission Factor, AD: Activity Data.

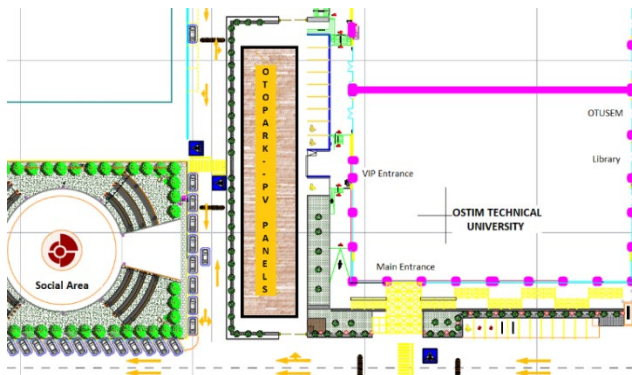
When carbon emission values are examined, ~59% of overall CO<sub>2</sub>e is seen to cause by indirect emissions such as electricity consumption. Even though wind energy usage is available at our university for some kind of lighting of environment low-level, major portion

of CO<sub>2</sub>e comes from. However, for reducing the carbon emissions, it is predicted to build a field of solar energy at the car park of the university and due to this reducing carbon emission is examined based on the exergy approach.



**Fig. 3.** Carbon emissions calculated by 2022 energy consumption values.

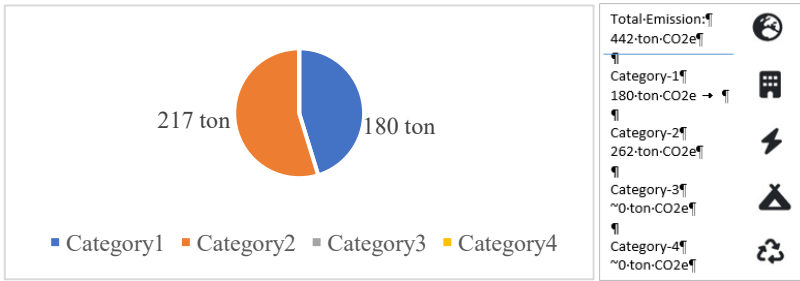
The roof of the car park area (12 m x 50 m), it is planned to build a 600 m<sup>2</sup> solar power field, given in Fig.4. Based on the feasibility study, using standard PV panels of dimensions: 1756 x 1039 x 30 mm, it is calculated to use approximately 218 panels of dimensions. Such a panel has the ability to generate 375 W of power which will produce 81,75 kWp in total.



**Fig. 4.** The proposed car park area on which a PV panel is to be built.

According to Türkiye’s Solar Energy Potential Atlas prepared by the Ministry of Energy and Natural Sources, the sunshine time for Türkiye’s capital city: Ankara is 2611 hours/year [17]. Annual average sunshine radiation value for Ankara is 1473 kWh / m<sup>2</sup>-year. Using this information, the total energy that can be supplied by all these 218 panels covering the car park roof will be approximately 102876,65 kWh. Taking the inverter losses and the transmission-distribution losses into account as 5%, this total energy value will approximately decrease to 97730 kWh. This energy amount corresponds to 16% of the electricity consumed at our university in 2022.

As can be seen in Fig.5, in case of establishing PV panel to the car park shed, the carbon emission for electricity consumption will decrease to approximately 397 tons of CO<sub>2</sub>e. There is no change in the carbon emission for natural gas, but electrical energy consumption-based carbon emission will be decreased by 18% to approximately 217 tons of CO<sub>2</sub>e.



**Fig. 5.** Carbon emissions when solar energy is used.

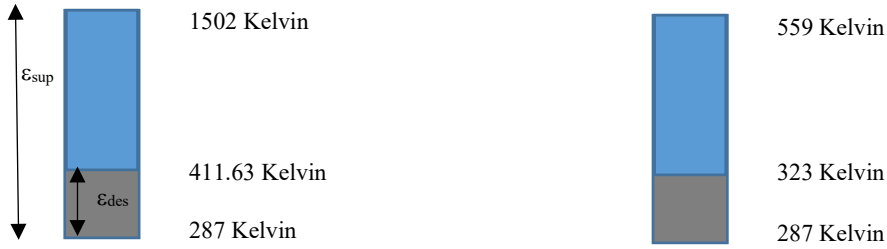
When the cost is examined the items listed in Table 5 are the values related, payback period of the system is predicted to be 5.1 years. The calculated payback period was considered reasonable. Standard quality products are assumed for installation. April 2024 prices are taken as basis for the values of these entity.

**Table 5.** Cost Analysis for PV Panel Solar Energy Installation.

	Unit Dimension	Quantity (count)	Specific cost (euro *)	Total Cost (euro)
<b>Expenditures</b>				
PV Panel (1756mm x1039 mm ~375W)	piece	218	99.83	21762.69
Support Construction (steel)	kg	6.500	2.57	16685.68
Invertor	piece	1	4278.38	4278.38
Distribution Panel (OnGrid)	piece	1	427.84	427.84
Shalt Panel	piece	1	427.84	427.84
Cables (TS EN 50115)	km	1	1426.13	1426.13
Control Unit	piece	1	42.78	42.78
Installation expenses	20%	1	9001.71	9001.71
			<b>Overall Cost</b>	54053.05
<b>Earning</b>				
Electric unit cost	Euro/kWh	97.730	0.09	9198.77
Tax saving	Euro/year	1	1404.51	1404.51
			<b>Saving</b>	10603.28
Payback time	Year			5.1

\* according to April 2024 Euro/TL parity.

However, taking into account the losses caused by the energy destroyed will provide a more rational approach to see the big picture when exergy-based efficiency approach used. For this calculation, firstly, the case of taking all the electricity from the city grid and after then using solar energy was calculated using Eq.6 according to the data given in Table 2. The calculated exergy destruction  $\epsilon_{des}$ , is shown in gray in Fig.6 for the case of taking electricity from the grid and producing all the required electricity with PV panels.



**Fig. 6.** Exergy flow bar for grid usage and electricity production with PV panels.

The exergy efficiency approach derived based on the Ideal Carnot Cycle was calculated as follows in case of using grid, Eq.7.

$$\psi_R = 1 - \left( \frac{\varepsilon_{des}}{\varepsilon_{in}} \right) = 1 - \left( \frac{1 - \frac{\varepsilon_{des}}{\varepsilon_{in}}}{1 - \frac{\varepsilon_{des}}{\varepsilon_{in}}} \right) = 1 - \left( \frac{1 - \frac{287}{411.63}}{1 - \frac{287}{1502}} \right) = 0.6257$$

$$\psi_R = 1 - \left( \frac{\varepsilon_{des}}{\varepsilon_{in}} \right) = 1 - \left( \frac{1 - \frac{\varepsilon_{des}}{\varepsilon_{in}}}{1 - \frac{\varepsilon_{des}}{\varepsilon_{in}}} \right) = 1 - \left( \frac{1 - \frac{287}{323}}{1 - \frac{287}{559}} \right) = 0.7709$$

If the same calculations are repeated for PV panel,  $\psi_R = 0.7709$  is obtained. Using the exergy efficiency, carbon emission can be obtained with  $dCO_2 \propto (1 - \psi_R)$  [15]. When these two cases are compared:  $(1 - 0.7709) / (1 - 0.6257) = 0.61$  is calculated. This result shows that if solar panels are used, exergy destruction will be less and carbon emissions will be 61% less than grid use.

The results shows that CO2e reduction by using exergy method is result in greater than energy method so as to exergy method not only considering consumption but also taking into account energy generation, transmission, and distribution lines. Therefore, calculating CO2e emissions using the Exergy method provides a more realistic and wide view.

## 4 Conclusion

In this study, it is aimed to provide basic data for energy management by examining the one-year (2022) energy consumption of the of OSTİM Technical University building. Carbon emissions is calculated by the total energy and exergy approach, take in account heating and electricity consumption. The obtained results for the purpose of monitoring energy consumption of the university building, determining its impact on carbon emissions and determining feasibility, in term of Sustainability, Energy and Efficiency are as follows:

- Results show that ~60% of carbon emissions came from electrical energy by 2022,
- The carbon emission obtained from the University energy density was calculated to be 442 tons CO2e, from the previous year's consumption data,
- Carbon emission responsibility is calculated as (0.652 kg/kWh) CO2e when components such as energy production power plant efficiency, transmission-distribution efficiency, transformer efficiency are taken into account and according to the EU PEF value,
- It has been determined that ISO14064 Category 2 carbon emissions are 18% less in the case of energy production bu using PV panels. It is noteworthy that the installation payback period is a reasonable period of 5.1 years,
- With the exergy-based approach, it has been concluded that the use of electricity produced by PV has less exergy destruction than the use of grid electricity, and carbon emissions will decrease by around 61% compared to grid use.

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