Effects of the Implementation of Photovoltaic Power Plants on Electricity Consumption and CO_2 Emissions in Small and Medium-Sized Enterprises

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It is widely recognized that global energy consumption continues to increase year after year. Industry is one of the world's major energy consumers and is expected to remain among the leading sectors in total final energy consumption in the future. The efficient and rational use of energy constitutes a fundamental prerequisite for addressing long-term energy challenges. Although access to energy is essential for social and economic development, the use of fossil fuels has a negative impact on the environment and climate, creating a need for a transition toward renewable energy sources (RES). The increase in electricity prices, together with their expected volatility and the simultaneous rise in the costs of other energy sources, has led to growing interest in energy efficiency (EE) among small and medium-sized enterprises (SMEs). The declining costs of RES technologies, particularly small-scale photovoltaic power plants (PVPPs), have further stimulated SMEs' interest in adopting RES. Their implementation enables a reduction in grid electricity consumption, financial savings, and a decrease in carbon dioxide (CO_2) emissions. The objective of this study is to evaluate the effects of PVPPs on grid electricity consumption, electricity costs, and CO_2 emissions in two SMEs from different industrial sectors in Tuzla Canton, Bosnia and Herzegovina (BiH). The contribution of this study is to provide a comparative, data-driven assessment based on actual operational data from industrial photovoltaic (PV) systems and to demonstrate how the effects of PV implementation vary according to the electricity-consumption characteristics of different industrial sectors.

Key Words: *photovoltaic power plants, CO_2 emissions, electricity consumption in SMEs*

1. INTRODUCTION

According to [1], global final energy consumption increased approximately 2.3 times between 1971 and 2018, reaching 9 238 Mtoe in 2018, with industry remaining the largest energy-consuming sector, accounting for 38% of total final energy consumption. According to [2], final energy consumption exceeded 450 EJ in 2024, with industry accounting for nearly 40% and contributing approximately two-thirds of the total increase in global energy demand since 2019. By 2035, final energy consumption is projected to reach 374 EJ, with industry remaining the largest consumer at 130 EJ, including 30 EJ from RES [3]. According to [4], the share of RES in global electricity generation is expected to increase from 28% in 2021 to approximately 60% by 2030 and nearly 90% by 2050. Fossil-fuel-based electricity generation contributes significantly to

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greenhouse gas emissions, while rising electricity prices emphasize the importance of improved EE to reduce costs and environmental impacts [5]. Reference [6] highlights the growing investment in RES in Europe and worldwide in response to climate change and energy security concerns. According to [7], solar PV systems, particularly grid-connected systems, play an important role in reducing CO_2 emissions and supporting environmental sustainability.

According to [8], PV systems in industrial facilities can provide significant energy, environmental, and economic benefits by reducing dependence on conventional energy systems (NES) and fossil fuels. PV-based systems can achieve high levels of energy autonomy and reduce greenhouse gas (GHG) emissions by more than 90% compared with conventional fossil-fuel-based systems. According to [9], a 15% increase in solar power generation could reduce annual CO_2 emissions in the U.S. electricity sector by an estimated 8.54 MMT, corresponding to approximately 12.38% of the annual reduction target of 69 MMT required to achieve a total 20-year reduction of 1 380 MMT under U.S. Environmental Protection Agency (EPA) requirements. According to [10], integrating PV systems with energy storage, surplus electricity export to the grid, and distributed power trading can substantially reduce CO_2 emissions in industrial buildings, with solar energy covering up to 84% of total electricity consumption and supporting a transition toward near-zero-carbon electricity use. According to [11], distributed rooftop PV systems in rural households reduced grid electricity purchases by 32.06 kWh per month and CO_2 emissions by approximately 20.97 kg per month. However, a rebound effect increased total electricity consumption by 78.46 kWh per month, while solar energy accounted for approximately 38.4% of total consumption. Empirical evidence on the effects of PVPPs on grid electricity consumption and CO_2 emissions in SMEs in BiH remains limited, particularly regarding differences between industrial sectors.

Therefore, this study provides an empirical assessment based on actual operational data from two SMEs in different industrial sectors in Tuzla Canton, BiH. Its scientific contribution lies in comparing the effects of PVPPs on grid electricity consumption, electricity costs, and CO_2 emissions in the meat-processing and plastic-production sectors.

Unlike simulation-based studies, the research uses actual PV generation and electricity-consumption data from operational industrial facilities and compares electricity consumption before and after PV installation over several years, providing an empirical basis for assessing the role of PV systems in the local industrial energy transition.

2. GLOBAL RES SHARE, PV SYSTEMS, AND CO_2 EMISSIONS

According to [12], total final energy consumption was 294 EJ in 2008, with industry as the largest consumer at 98 EJ (11 EJ from RES), followed by transport at 96 EJ (2 EJ from RES), residential at 92 EJ (including 4 EJ of traditional biomass and 8 EJ from other RES), and agriculture at 8 EJ (1 EJ from RES). By 2035, total final energy consumption is projected to reach 374 EJ, with industry remaining the largest consumer at 130 EJ (30 EJ from RES), followed by transport at 119 EJ (18 EJ from RES), residential at 116 EJ (including 4 EJ of traditional biomass and 34 EJ from other RES), and agriculture at 9 EJ (2 EJ from RES), as shown in Figure 1.

These data confirm that industry remains a major energy consumer with increasing demand, while the share of RES is expected to grow across all sectors.

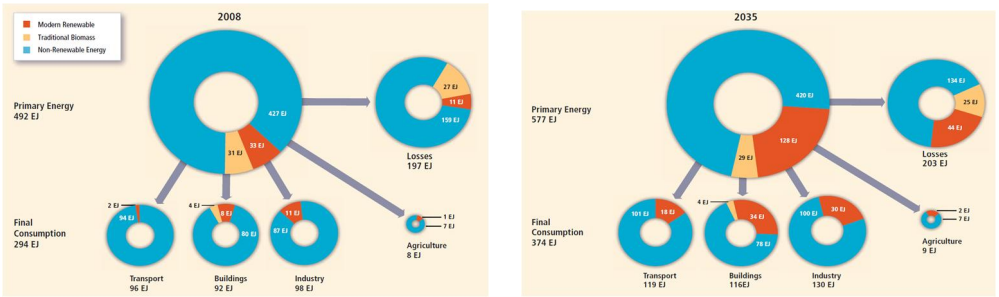


Figure 1 – Share of RES in global final energy consumption for the period 2008–2035. [*12*]

According to [12], most scenarios limiting atmospheric GHG concentrations to around 450 parts per million (ppm) CO_2 project that RES will provide more than 50% of low-carbon primary energy by 2050. Figure 2 presents the global technical potential of RES for 2050, expressed in EJ/year, with solar energy identified as the dominant resource. According to [4], in the Net Zero Emissions by 2050 Scenario (NZES), the share of RES in global electricity generation is projected to increase from approximately 28% in 2021 to over 60% in 2030 and nearly 90% by 2050. By 2030, additional PV and wind capacities are expected to reach approximately 650 GW and over 400 GW, respectively.

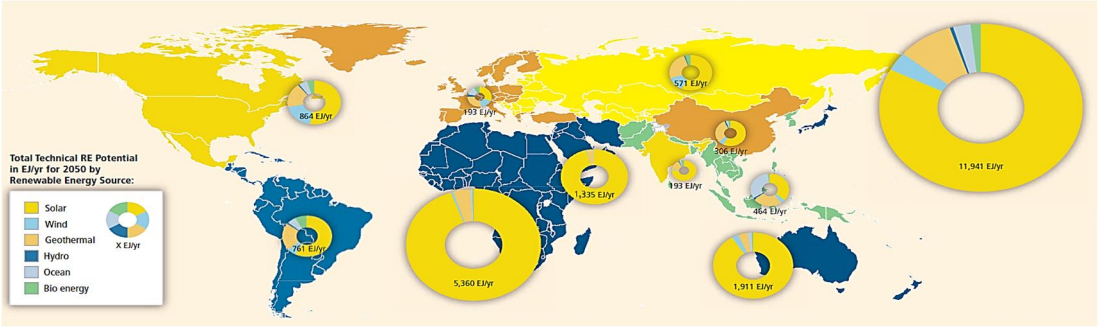


Figure 2 – Analysis of renewable energy potential worldwide. [12]

The industrial sector is the second-largest CO_2 emitter, accounting for approximately one-third of global emissions. For calculating CO_2 and other anthropogenic GHG emissions, the IPCC (Intergovernmental Panel on Climate Change) methodology was developed under the United Nations Framework Convention on Climate Change (UNFCCC). Based on the location of occurrence, emissions are classified as direct and indirect. Direct emissions occur at the site of final energy consumption. Direct CO_2 emissions from fossil fuel combustion are calculated using Equation (1).

$$EM = EF_c \cdot H_d \cdot O_c \cdot \frac{44}{12} \cdot B \ [kg] \qquad (1)$$

where:

$EF_c \left[\frac{\text{kgC}}{\text{GJ}}\right]$ – carbon emission factor;

$H_d \left[\frac{\text{MJ}}{\text{kg}} \text{ili} \frac{\text{MJ}}{\text{m}^3}\right]$ – lower heating value of the fuel;

O_c [–] – fraction of oxidized carbon;

$\frac{44}{12}$ – stoichiometric ratio of CO_2 to C;

B [t ili m^3] – amount of fuel combusted.

If carbon emission factors are not available, it is recommended to use the factors given in Table 1, where the presented lower heating values represent average values for the Federation of BiH.

Table 1. CO_2 emission factors for different fossil fuels according to the IPCC methodology. [13]

Energy source	$EF_c \left[\frac{\text{kgC}}{\text{GJ}}\right]$	$H_d \left[\frac{\text{MJ}}{\text{kg (m}^3\text{)}}\right]$	O_c [-]	$EF_c \cdot H_d \cdot O_c \cdot \frac{44}{12} \left[\text{kgCO}_2/\text{kg(m}^3\text{)}\right]$
Extra light fuel oil*	20,2	43	0,99	3,153018
Fuel oil *	21,2	40	0,99	3,06372
Liquefied petroleum gas	17,2	41	0,99	2,559876
Hard coal (bituminous coal)	25,8	27,5	0,98	2,54947
Brown coal (sub-bituminous coal)	26,2	19	0,98	1,788761
Lignite	27,6	11,3	0,98	1,120689
Natural gas	15,3	33,3	0,995	2,065322

* Extra light and light fuel oil are grouped and presented as extra light fuel oil, while medium and heavy fuel oil are grouped and presented as fuel oil.

For calculating CO_2 emissions from electricity and/or thermal energy consumption, indirect emissions are considered, as they occur at the energy generation site. Indirect CO_2 emissions are calculated using Equation (2).

$$EM = AD \cdot EF \qquad (2)$$

where:

EM [kg] – CO_2 emissions;

AD [kWh] – consumed amount of electrical/thermal energy;

EF [kgCO$_2$/kWh] – specific CO_2 emission factor for electricity or thermal energy.

Table 2. Specific CO_2 emission factors. [13]

CO_2 emission factor		
Energy source	Per unit of electrical energy [kgCO$_2$/kWh]	Per unit of useful heat [kgCO$_2$ /kWh]
Electricity	0.7446	0.7597

The specific CO_2 emission factor represents the average CO_2 emissions from power plants in the Federation of BiH, considering their shares and primary energy sources. The corresponding values are presented in Table 2.

The reduction in CO_2 emissions is calculated as the difference between emissions before and after implementing emission reduction measures, such as EE measures, according to the following formula:

$$EM_S = EM_P - EM_N \quad (3)$$

where:

EM_S [kg] – CO_2 emission reduction;

EM_P [kg] – CO_2 emissions before implementation of measures;

EM_N [kg] – CO_2 emissions after implementation of measures.

3. IMPACT OF PVPPS ON GRID ELECTRICITY CONSUMPTION AND CO_2 EMISSIONS

For the purpose of this study, two companies from different industrial sectors were selected: a meat processing company (X-MI) and a company engaged in the production and processing of plastics (Y-IPP). Data were collected directly from company representatives through field visits and meetings, during which relevant available data were identified and subsequently provided in accordance with internal data-disclosure policies. The collected data included electricity consumption, PVPP electricity generation, installed PV capacity, and other parameters relevant to the analysis.

At X-MI, the PVPP was commissioned in April 2022, with an installed capacity of 440 kW and a projected annual electricity generation of 570.000 kWh. Since the system was commissioned in April 2022, the analysis covered April–October 2022, with data collected during October and November 2022.

Actual PVPP generation was monitored and recorded using the company's PVPP monitoring software rather than estimated from the projected annual generation. The monitoring data enabled comparison of PVPP generation, company electricity consumption, and electricity supplied from the distribution grid.

Thus, actual PVPP generation and electricity-consumption data were used in the analysis, while the projected annual generation of 570.000 kWh was used only as a technical parameter describing the designed characteristics of the PVPP.

Based on these data, the contribution of the PVPP to reducing the company's electricity demand from the distribution grid was assessed.

A monthly comparison of grid electricity consumption and PV electricity generation in X-MI for 2022 is presented in Figure 3.

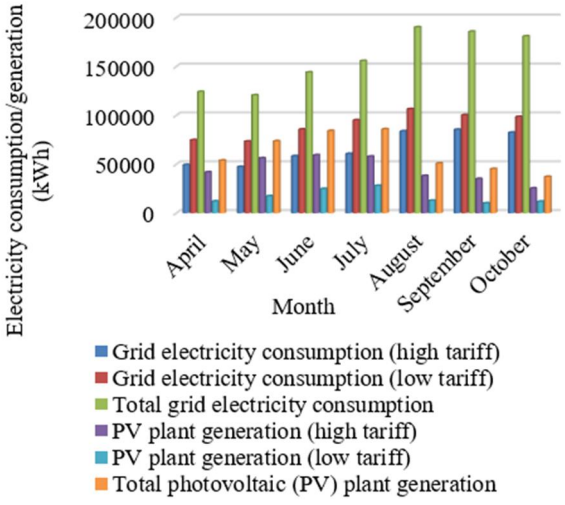


Figure 3 - Monthly comparison of grid electricity consumption and PV electricity generation in 2022.

During April–October 2022, total grid electricity consumption amounted to 1 101 404 kWh, with associated costs of 116 813.7 Bosnia and Herzegovina Convertible Marks (BAM), while PV generation amounted to 430 912.1 kWh. Total electricity demand, defined as the sum of grid electricity purchases and PV generation, was 1 532 316.1 kWh. PV generation therefore covered 28.1% of total electricity demand, substantially reducing the company's dependence on grid electricity. Although grid electricity remained dominant, PV generation represented a significant share of demand. Grid electricity was mainly purchased during low tariff periods (LT), whereas PV generation occurred during high tariff periods (HT). The highest PV generation was recorded in July (85 954.9 kWh), while the lowest was recorded in October (37 172.8 kWh), depending on solar irradiation availability.

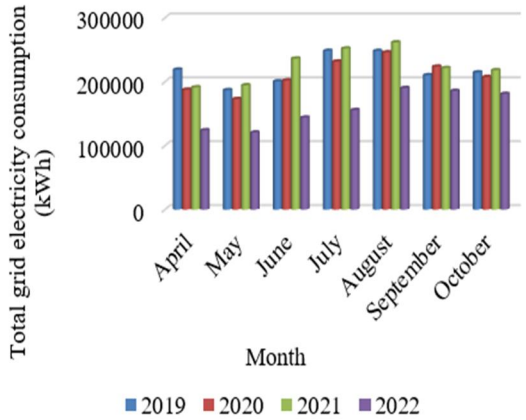


Figure 4 - Monthly total grid electricity consumption during the period 2019–2022 in X-MI.

Figure 4 presents a comparison of monthly total grid electricity consumption in X-MI during 2019–2022. The results show a significant reduction in grid electricity consumption in 2022 following PV system installation. Compared with 2019, 2020, and 2021, total grid electricity consumption in 2022 decreased by 27.92%, 25.14%, and 30.09%, respectively, indicating a substantial improvement in the company's energy performance.

In Y-IPP, the PV system was commissioned in April 2022; therefore, the analysis covers April–October 2022. The installed PV system capacity is 440 kW, with a planned annual electricity generation of approximately 506 000 kWh.

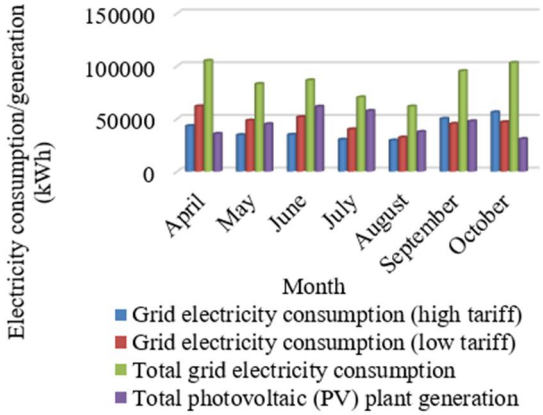


Figure 5 - Monthly comparison of grid electricity consumption and PV electricity generation in 2022 in Y-IPP.

Figure 5 presents the monthly grid electricity consumption and PV electricity generation in Y-IPP for 2022. During the observed period, total electricity demand, defined as the sum of grid electricity purchases and PV generation, amounted to 921 172 kWh. PV generation covered 34.3% of total electricity demand, indicating a higher contribution than in X-MI. This difference may be attributed to variations in electricity demand patterns, production schedules, and the temporal coincidence between PV generation and electricity consumption.

The effectiveness of a PV system in reducing grid electricity consumption depends not only on installed capacity and solar irradiation but also on the coincidence between PV generation and the facility's demand profile. Although grid electricity remained dominant, PV generation accounted for a significant share of total electricity demand. The highest PV generation was recorded in June and the lowest in October, mainly due to weather conditions and solar irradiation levels.

Figure 6 compares monthly total grid electricity consumption in Y-IPP during 2019–2022. The results show a significant reduction in grid electricity consumption in 2022 following PV system commissioning. Grid electricity consumption decreased from 1 273 671.9 kWh in 2020, the highest value during the observed period, to 605 158 kWh in 2022, while associated electricity costs decreased from 143 359.8 BAM to 87 694.58 BAM. Compared with 2019, 2020, and 2021, grid electricity consumption in 2022 was reduced by 36.5%, 52.4%, and 49.9%, respectively.

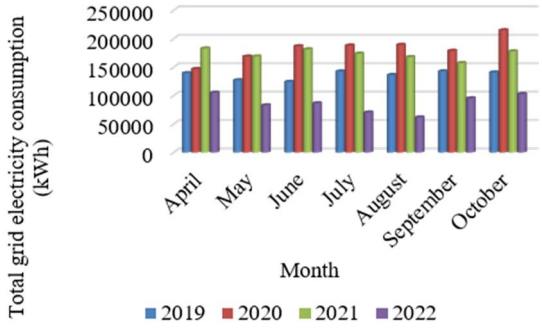


Figure 6 - Monthly comparison of total grid electricity consumption in Y-IPP for the period 2019–2022.

Following PV system commissioning, consumption was 49.9% lower than in 2021. However, this reduction cannot be attributed solely to PV implementation, as changes in production volume, operating schedules, equipment, and electricity demand patterns also occurred. Therefore, the observed reduction reflects the combined effects of PV generation and other operational changes within the company. The payback period for the PV system investment is 8.5 years for X-MI and 8.7 years for Y-IPP. Although the investment cost was slightly higher for X-MI, its estimated PV electricity generation was also higher.

Combined with slight differences in electricity prices between the companies, these factors resulted in nearly identical payback periods. Incentives, low-interest loans, and government support or subsidies could further reduce the investment payback period. Based on Equation (1), direct CO_2 emissions at X-IPP were calculated, with Table 3 comparing emissions before and after PV system installation. According to Equation (3), CO_2 emissions decreased by 66 kg/m²a, corresponding to 489 t/year or a 25.9% reduction during the observed period.

Table 3. Comparison of CO_2 emissions before and after the construction of the PV plant in X-MI.

CO_2 emissions	[kg/m^{2}yr]	[t/yr]
Before the PV plant installation	253.8	1 886.3
After the PV plant installation	188	1 396.9
CO_2 emissions reduction	66	489

Table 4. Comparison of CO_2 emissions before and after the construction of the PV plant in Y-IPP.

CO_2 emissions	[kg/m^{2}yr]	[t/yr]
Before the PV plant installation	320.3	1 601.6
After the PV plant installation	244.2	1 221.1
CO_2 emissions reduction	76.1	380.5

4. LIMITATIONS OF THE STUDY

Several limitations should be considered. The study included only two SMEs from different industrial sectors, limiting the generalizability of the findings to SMEs in BiH. The post-installation period covered only April–October 2022 and did not include a complete annual cycle or several consecutive years of post-installation data. In addition, reductions in grid electricity consumption cannot be attributed solely to PV implementation, particularly in Y-IPP, where production volume, operating schedules, equipment, and electricity demand patterns also changed. The analysis relied on company-provided data and PV monitoring systems without independent verification. CO_2 reductions were estimated using the specific electricity emission factor for the Federation of BiH, without accounting for possible changes in the electricity generation mix or emission factor. Therefore, the results should be interpreted as an empirical assessment of observed changes rather than a strict causal estimate of the isolated PV effect. Future research should include more SMEs and industrial sectors, longer observation periods, higher-resolution data, and control groups or methods such as difference-in-differences to better assess the causal impact of PV systems on grid electricity consumption and CO_2 emissions.

5. CONCLUSION

The results show that PV systems can significantly contribute to electricity demand in industrial SMEs,

covering 28.1% of total demand in X-MI and 34.3% in Y-IPP. CO_2 emissions were reduced by 25.9% in X-MI and 23.75% in Y-IPP, although changes in grid electricity consumption cannot be attributed exclusively to PV generation. The comparison confirms that PV effectiveness depends not only on installed capacity and solar availability but also on industrial demand profiles and the coincidence between PV generation and electricity consumption. The study provides empirical evidence based on actual operational data from two SMEs in different industrial sectors in BiH, covering PV generation, grid electricity consumption, electricity costs, and CO_2 emissions. Payback periods of 8.5 years for X-MI and 8.7 years for Y-IPP indicate potential environmental and economic benefits, which could be further improved through financial incentives and support mechanisms. Despite the limitations related to the number of companies and observation period, the findings support the role of PV systems in reducing grid electricity dependence and CO_2 emissions in industrial SMEs. Future research should include more companies and sectors, longer observation periods, and higher-resolution data.

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REZIME

EFEKTI PRIMJENE FOTONAPONSKIH ELEKTRANA NA POTROŠNJU ELEKTRIČNE ENERGIJE I EMISIJE CO_2 U MALIM I SREDNJIM PREDUZEĆIMA

Opštepoznato je da potrošnja energije u svijetu iz godine u godinu raste. Industrija je jedan od glavnih svjetskih potrošača energije, te se očekuje da će i u budućnosti ostati jedna od vodećih grana u ukupnoj finalnoj potrošnji energije. Efikasna i racionalna upotreba energije predstavlja osnovu za dugoročno rješavanje energetskih izazova. Iako je pristup energiji presudan za društveni i ekonomski razvoj, a korištenje fosilnih goriva ima negativan uticaj na okoliš i klimu, nameće se potreba za tranzicijom ka obnovljivim izvorima energije (OIE). Zabilježen porast cijene električne energije, kao i njena očekivana nestabilnost uz istovremeni porast troškova za druge energente, dovodi do povećanog interesa za efikasnom potrošnjom energije u oblasti malih i srednjih preduzeća (MSP). Pad cijena tehnologija OIE, naročito malih fotonaponskih elektrana (FNE) dodatno je potakao interes MSP za korištenjem OIE. Njihova implementacija omogućava smanjenje potrošnje električne energije iz mreže, ostvarenje finansijskih ušteda i smanjenje emisija ugljen dioksida (CO_2). Cilj ovog istraživanja je procijeniti uticaj FNE na potrošnju električne energije iz mreže, troškove električne energije i emisije CO_2 u dva MSP iz različitih industrijskih sektora u Tuzlanskom kantonu, Bosna i Hercegovina (BiH). Doprinos ovog istraživanja ogleda se u pružanju komparativne, na podacima zasnovane procjene, koja se temelji na stvarnim operativnim podacima industrijskih fotonaponskih sistema, kao i u prikazu načina na koji se efekti implementacije fotonaponskih sistema razlikuju u zavisnosti od karakteristika potrošnje električne energije u različitim industrijskim sektorima.

Kjučne riječi: *fotonaponska elektrana, emisije CO_2, potrošnja električne energije u MS*