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Tridimensional Sustainability and Feasibility Assessment of Grid-Connected Solar Photovoltaic Systems Applied for the Technical University of Cluj-Napoca

Ciprian Cristea *, Maria Cristea, Dan Doru Micu, Andrei Ceclan, Radu-Adrian Tîrnovan and Florica Mioara Șerban

Faculty of Electrical Engineering, Technical University of Cluj-Napoca, 26-28 G., Barițiu Street, 400027 Cluj-Napoca, Romania
* Correspondence: ciprian.cristea@emd.utcluj.ro

Abstract: Nowadays, as the technology behind solar photovoltaic systems has been significantly improved, along with a significant decrease in costs, grid-connected photovoltaic systems are becoming an important option to reach a low-carbon energy transition. The high cost of electricity consumed at the Technical University of Cluj-Napoca represented a good reason for the university to increase its energy efficiency by adopting and increasing energy consumption from renewable energy sources. This paper assesses the technical, economic, and environmental feasibility of deploying four photovoltaic systems at the aforementioned university situated in the Northwestern part of Romania, according to the Romanian renewable energy legislation. PVSOL software has been used to estimate the performance of photovoltaic installations. The results indicated that the most viable distributed generation system is the one with a capacity of 100 kW, meeting approximately 23 percent of university electricity needs, and at the same time, reducing carbon dioxide emissions by approximately 460 tons. A sensitivity analysis has been performed to evaluate the effect of several critical parameters on the PV system's economic feasibility. The results provide valuable decision-making information regarding the buildings' solar potential for other universities, supporting the transition to solar energy.

Keywords: grid-connected photovoltaic system; renewable energy; solar energy; feasibility analysis; public building; energy efficiency; Romania

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1. Introduction

The energy sector has a significant influence on the economic growth of a country, and at the same time, on the social and environmental aspects of sustainability [1,2]. In the international sustainable agenda, energy is a major contributor, being an important provocation both for developed and developing states [3,4]. Global energy consumption registered an increase of over 63% between 1995 and 2019, from 8588.9 million tonnes oil equivalent (Mtoe) to 14,045.1 Mtoe [5,6]. This substantial increase has been mainly supported by large fossil fuel usage.

In the fall of 2015, all the leaders representing the 193 member countries of the United Nations General Assembly ratified the 2030 Agenda for Sustainable Development, including a set of seventeen Sustainable Development Goals (SDGs), to establish an indispensable international framework in order to promote Earth's sustainable future [7,8]. Nevertheless, it is very important that the countries' central and local public administration authorities establish rules and regulations for the accomplishment of these goals [9]. Sustainable energy plays a key role in the 2030 Agenda. Among the most important targets of SDG 7 (affordable and clean energy) is the significant growth of the renewable energy percentage in the international energy mix, a 100 percent increase boost as regards energy efficiency worldwide, and guarantying access to accessible, dependable, and modern energy services [7]. The achievement of SDG 7's targets interacts with the other SDGs' accomplishment, as reported by other investigations [10–12].

The integration of distributed generation units (DGUs) represents an essential solution to accelerate the SDGs' implementation. The DGUs represent an increasingly adopted solution for tackling the environmental, technical, and economical impediments of current electrical power systems. A DGU represents a small-scale generating unit that is deployed near the consumer. Due to the fact that notable advances are in progress, there is a tendency to generate electricity locally through DGUs, unlike classic large, centralized power plants [13], and those using solar power have especially become more and more efficient and accessible. As a result, in the past thirty years, the electricity generated by photovoltaic (PV) systems registered a growth rate of approximately thirty percent [14]. The grid-connected PV systems are DGUs that use solar power and are connected to the electric utility network. The PV installations' deployment speeds up the trajectory towards SDGs, providing affordable and reliable clean electrical energy, especially considering that 789 million people lack access to electricity.

During recent decades, a continuously growing urbanization process has been noticed. Since 2007, the world's population in urban areas has surpassed that of rural areas, and it is expected that the urban population will grow by another 10 percent by 2030 [15]. Metropolitan areas play a decisive role in the economic growth of the countries, providing more than 60 percent of the gross domestic product (GDP) worldwide, but at the same time, are responsible for over 70 percent of carbon emissions globally [15]. To cope with the world's rapid urbanization, SDG 11 (sustainable cities and communities) plans to ensure the safety, resiliency, and sustainability of cities and human settlements [7]. In the last decade, the concept of the smart and sustainable city has received increasing attention [16], due to the fact that between 60 and 80% of energy consumption occurs in metropolitan areas worldwide [17]. Renewable energy sources have gradually become more and more accepted for powering smart cities, especially solar power due to the high potential for deployment on buildings. Nevertheless, strong political involvement is essential for accelerating PV penetration at an urban scale to ensure the sustainability of urban environments.

Buildings are one of the largest consumers of energy, being responsible for more than 33 percent of energy consumption worldwide [18], and this is expected to reach approximately 57 percent by 2050 [19]. Besides important energy consumption, buildings are responsible for approximately 28 percent of energy-related greenhouse gas (GHG) emissions [20]. Improving energy efficiency and increasing the amount of energy generated from renewable sources represent successful measures for decreasing related GHG emissions of buildings [20]. Capozzoli et al. [21] highlighted the importance of identifying anomalies in buildings' energy management processes for enhancing energy efficiency. Grid-connected PV systems represent one of the most feasible ways for attaining a nearly zero-energy building, along with a significant decrease in costs of the principal solar-based electrical energy generation technology, significantly enhancing the energy efficiency of buildings.

Recently, the grid-connected PV system has become a topic of interest, with multiple investigations being developed to evaluate their feasibility in various locations around the world, such as China [22], Saudi Arabia [23], Malaysia [24], India [25], Iraq [26], Turkey [27], Kenya [28], Algeria [29], South Africa [30], Romania [31], and Hungary [32].

Universities around the world usually have considerable unused space on their buildings, which represents a significant opportunity for installing grid-connected rooftop solar PV systems. The performance of grid-connected solar PV systems that can exploit the vacant space on buildings belonging to higher educational institutes from various locations has been examined in the literature. The main findings of similar works are presented in Table 1.

Table 1. The findings of related investigations.

Location	Findings	Reference
University of Madrid	PV systems with a cumulated installed power of 3.3 MW are viable and cover approximately 40 percent of electricity consumption, diminishing carbon dioxide emissions by approximately 30 percent.	Olivieri et al. [33]
Colorado State University-Pueblo	The 1.2 MW on-grid PV plant is profitable with a 10% internal rate of return. The required period to break even is less than 8 years.	Paudel and Sarper [34]
University of New Haven	The deployment of a 67.27 kW PV system is profitable, with an 8.74% internal rate of return.	Lee et al. [35]
Mu'tah University	The investment in a 56.7 kW PV system is viable, with a 5.5-year payback period.	Al-Najideen and Alrwashdeh [36]
University of Jordan	The fixed-axis PV installation with an installed power of 15 MW PV is feasible with a 32% internal rate of return. The investment is expected to be recovered in 3 years.	Ayadi et al. [37]
University Malaysia Pahang	A 1MW solar PV system can produce, annually, approximately 1390 MWh of green electricity along with the diminishment of approximately 819 t of carbon dioxide emissions.	Kumar et al. [38]

The main objective of this paper is to investigate the technical, economic, and environmental feasibility of implementing four grid-connected solar PV systems at the Technical University of Cluj-Napoca. No study, to the best of our knowledge, has evaluated the viability of deploying grid-connected PV installations at a higher educational institute in Romania after the legislative ground on prosumers was established. This work intends to address the gap in the scientific literature, providing valuable information to decision-makers and promoting green and low-carbon universities.

2. Overview of the Prosumer Integration into Romanian Renewables Legislation

There has been registered a significant growth of prosumerism across European countries, particularly in the last decade. The European Parliamentary Research Service has grouped electricity prosumers into the following categories [39]:

- Residential prosumers—generate electric energy mainly through solar-power-based DGUs.
- Commercial prosumers—business organizations that generate energy especially for self-consumption, not as the main business activity.
- Community prosumers—including housing associations and charitable organizations.
- Public prosumers—colleges, universities, medical institutions, or other public institutions that produce electricity mainly for self-consumption.

In Romania, the legislative framework for promoting the generation of electric energy from renewable energy sources was enacted in 2003 [40,41]. Law no. 184/2018 and Orders no. 226/2018, 227/2018, and 228/2018 established the regulatory framework for prosumers in Romania [42–45].

A prosumer is legally defined as the final customer owning DGUs that are using renewable energy sources with an installed capacity of 27 kW or less [42]. They both consume and produce electricity and fall within one of the four categories defined above [39]. If electricity production exceeds the amount consumed, the difference can be injected into the utility grid. The surplus can be sold at a price corresponding to the weighted average price from the Day-Ahead Energy Market in the preceding year [42]. A settlement takes place at the end of each month. If the prosumer consumes up to 22.96 USD, a value lower than that of the energy injected into the network, then this value is deducted from the next month's bill; otherwise, the prosumer is paid this value [43]. The considered currency exchange rate was 4.3559 RON for 1 USD on 3 January 2022.

The main amendment of Law no. 184/2018 is represented by Order no. 15/2021, which modifies the maximum limit of the installed power for the renewable energy system up to 100 kW or less [46].

3. Materials and Methods

The general framework of the methodology employed in this investigation for assessing the technical, economic, and environmental advantages of deploying DGUs that use solar power at the largest technical university in Transylvania is presented in Figure 1. This investigation begins with obtaining the electricity consumption profile together with the suitable area identification for PV installation deployment at the examined university, considering the local solar energy potential. Further, the design and simulations of the solar-power-based DGUs are presented. After the technical assessment is performed, the economic and environmental assessment of PV systems is carried out. To complete the feasibility of the PV installations' assessment, a sensitivity analysis was performed, considering various critical parameters' values. A detailed presentation of the adopted methodology is provided in the following paragraphs.

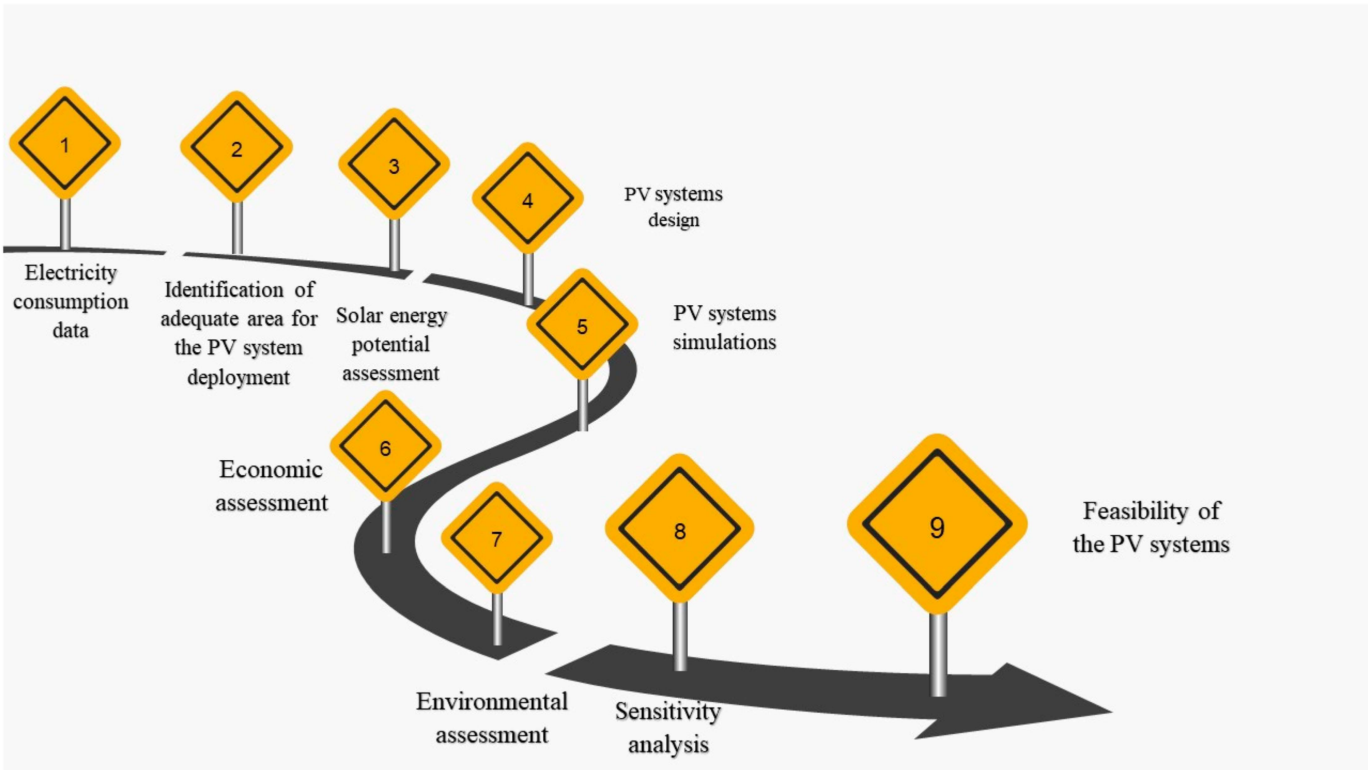


Figure 1. Schematic PV system application approach.

3.1. Location Assessment

The Technical University of Cluj-Napoca (TUCN) is the largest technical university in Transylvania and is one of the most important institutions of higher education in Romania. TUCN has developed a thorough and challenging strategic development plan, considering the importance of attaining energy-efficient buildings.

The main features of the TUCN building location where the grid-connected solar PV systems were set are:

- Location (Figure 2): Latitude—46°47′45.7″ N, Longitude—23°37′39.6″ E.
- Elevation above sea level—326 m.

- The building has a flat surface roof of approximately 2303 m^2 and is composed of laboratories, student course halls, and professors' offices.
- An exquisite advantage is that it faces South.

Figure 2. Geographical location of the TUCN (Image source: Google Earth 2022).

In the meteorological conditions concerned, it is important to mention that Cluj-Napoca stands in the temperate continental climatic zone. Typical Meteorological Year (TMY) datasets have been employed to generate the variables illustrated in Figure 3. TMY represents a set of meteorological data, containing 8760 weather parameters selected from at least ten years of data records, pointing out the typical weather scenario for a specific location [47]. TMY is one of the most accurate ways to present long-term climate particularities for a particular site [48].

Although Cluj-Napoca is not one of the best locations in terms of global irradiance on the horizontal plane in Romania, the annual average value is more than 1366 kWh/m^2. The daily average global irradiance on the horizontal plane ranged from 1.09 kWh/m^2 in December to 6.44 kWh/m^2 in July. August is the warmest month with an average ambient temperature value of 22.3 °C, while January is the coldest month with the average temperature dropping to −2.8 °C. According to the monthly average wind speed data, March is the month in which the wind recorded the highest intensity. At the other end of the spectrum, the lowest wind speed was recorded in November, while an upward monthly average wind speed trend is noticed from November to March. December was the month in which the highest relative humidity was recorded (90.43%), while in May, the lowest relative humidity was recorded (63.49%).

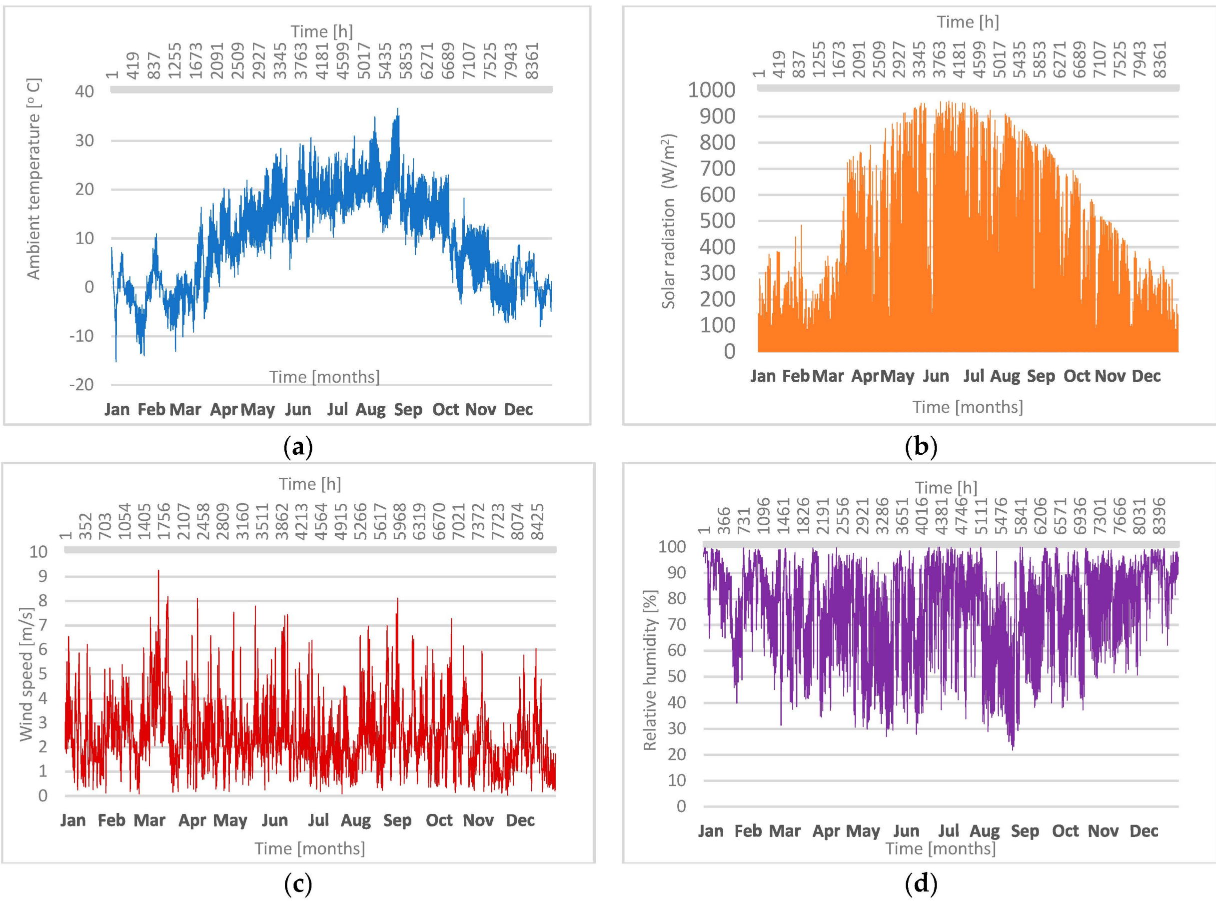


Figure 3. Weather data for a complete meteorological year in Cluj-Napoca. (**a**) Ambient temperature, (**b**) solar radiation, (**c**) wind speed, (**d**) relative humidity—based on data from [49].

The yearly electricity consumed at the TUCN in 2019 on an hourly basis is presented in Figure 4. The energy consumption of the university was provided by the electricity distribution system operator, using data from installed smart meters. The monthly electric power demand ranged between 23.3 MWh in August and 62.51 MWh in November. Being an institution of higher education, TUCN registered the highest electricity consumption during the academic year, based on two semesters, the first starting in autumn and the other in spring. These two semesters represent the two peak consumptions, with the highest electricity consumption values during the four months of the first semester (from October to January) during which specific teaching activities such as lectures, laboratory classes, seminars, and project classes were carried out. The daily average electric energy consumption values ranged from 1.92 MWh in December to 2.08 MWh in November.

The semestrial exam periods, following the teaching activities periods, registered lower energy consumption. The daily average electricity consumption values ranged between 1.91 MWh (end of the first semester–winter exam period) and 1.3 MWh (end of the second semester–summer exam period), respectively.

During Bank Holidays and weekends, when teaching activities stopped, TUCN registered the lowest power consumption, the longest period being for the summer holidays, between July and September, with a daily average electric energy consumption value between 0.75 MWh in August and 1.14 MWh in July.

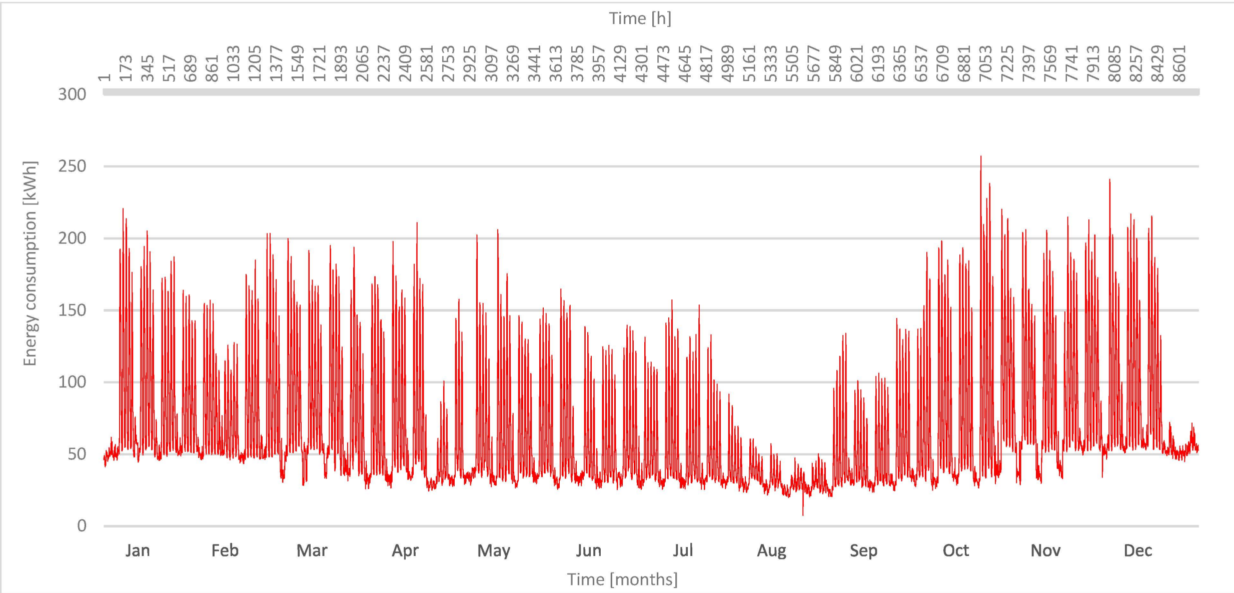


Figure 4. Yearly electricity consumption on an hourly basis.

3.2. PV Systems Description

This paper assesses the feasibility of deploying four grid-connected PV systems with an installed capacity of 25.2 kW, 50 kW, 75.6 kW, and 100 kW, selected because they cover the range of power requirements values outlined in Romanian prosumer law [46].

Numerical simulations and experimental studies represent the main methodologies employed for investigating the performance of PV installations. The principal strengths are the results obtained in a relatively short span of time and the reduced costs [50–52].

Several studies used PVSOL software to design PV systems and simulate their application. Ozcan et al. [53] investigated the electrical energy generated by PV installations, employing experimental investigations, simulation programs, and a theoretical approach, and pointed out that PVSOL provided the closest results to those obtained in experimental studies. The PVSOL premium 2022 software was chosen for designing the PV installations and simulating the electric energy production of the PV systems located on the buildings belonging to the higher educational institution, due to its proven reliability.

A grid-connected PV installation with similar characteristics to those investigated in this study was employed throughout the design phase and included the following major elements [54–56]:

- Solar PV modules convert the energy provided by the sun into direct current (DC) sustainable power.
- On-grid solar power inverters are employed to convert DC generated by the solar PV modules to alternating current (AC). To increase the amount of green energy generated by the solar PV modules, the inverters are equipped with maximum power point tracking (MPPT) capability.
- A PV mounting system is used to securely fix solar PV modules, inverters, and other elements of the PV installation.
- Solar PV cables are required to interconnect different electrical elements in a PV installation.
- Electrical safety equipment, such as fuses and breakers, is necessary for complying with the local regulations.
- A bi-directional energy meter is used to measure the electricity consumed from the utility grid, and, at the same time, the electric energy exported to the grid.

The examined PV installations produce green electric energy to cover the university's own consumption. When the electricity production of the PV system exceeds its own consumption, then the energy surplus is injected into the electricity system.

In this paper, monocrystalline panels were selected for the assessment because of their high efficiency, low maintenance cost, eco-friendliness, spatial efficiency, long life, and high reliability [57–61]. The main technical specifications of the PV modules that capture the solar energy and are part of the four PV systems are presented in Table 2, and the technical specifications of the inverters are presented in Table 3.

Table 2. Main PV modules' specifications [62].

Installed Power [kWp]	**25.2, 50, 75.6, 100**
Type of Modules	Monocrystalline
No. of Modules	63, 125, 189, 250
Azimuth/Inclination	180° (South)/30°
Maximum Power (P_{max}) [W]	400
Voltage at P_{max} [V]	37.6
Current at P_{max} [A]	10.64
Open Circuit Voltage (V_{OC}) [V]	44.8
Short Circuit Current (I_{SC}) [A]	11.42
Temperature Coefficient of I_{SC} [%/°C]	0.048
Temperature Coefficient of V_{OC} [%/°C]	−0.27
Temperature Coefficient of P_{max} [%/°C]	−0.35
Operating Temperature	−40 °C~+85 °C
Efficiency [%]	20
Panel Dimension (length × width × height) [mm]	1924 × 1038 × 35
Lifetime [years]	25

Table 3. Main inverters' specifications [63,64].

PV System	**25.2 kW**	**50 kW**	**75.6 kW**	**100 kW**
Input (DC)				5
Maximum DC power [kW]	30	16.4	15	30
Maximum input voltage [V]	1000	1000	1000	1000
MPPT voltage range [V]	420–800	267–800	80–800	370–800
Maximum input current [A]	33	16	25	33
Number of MPP trackers	2	2	2	2
Output (AC)				
Nominal AC rated power [kW]	20	8.2	10	20
Maximum output power [VA]	20,000	8200	10,000	20,000
AC output current [A]	28.9	11.8	16.4	28.9
Other parameters				
Maximum efficiency [%]	98.1	98	98.2	98.1
Ambient temperature range	−40 °C~+60 °C	−25 °C~+60 °C	−25 °C~+60 °C	−40 °C~+60 °C
Dimensions (height × width × depth) [mm]	725 × 510 × 225	645 × 431 × 204	594 × 527 × 180	725 × 510 × 225

The schematic circuit diagrams of the investigated solar power systems (SPSs) are presented in Figure 5. The PV installation, with a rated power of 25.2 kW, consists of 63 PV modules with a capacity of 400 W and one 20 kVA inverter. The PV panels were arranged in four parallel strings, with three of them containing 15 modules and one comprising 18 panels.

The second investigated PV system was equipped with 125 PV panels and five 8.2 kVA inverters. Two strings, made up of 12 and 13 PV modules, were connected to each inverter. The 75.6 kW and 100 kW PV systems contain 189 and 250 PV panels. The third examined PV installation was equipped with seven 16.4 kVA inverters, with two strings of 13 and 14 PV modules connected to each of the inverters. The investigated PV system with the highest rated power uses five inverters for converting DC to AC, each having a rating of 20 kW. Four parallel strings, with 12 to 13 PV panels in each string, were connected to each of the inverters.

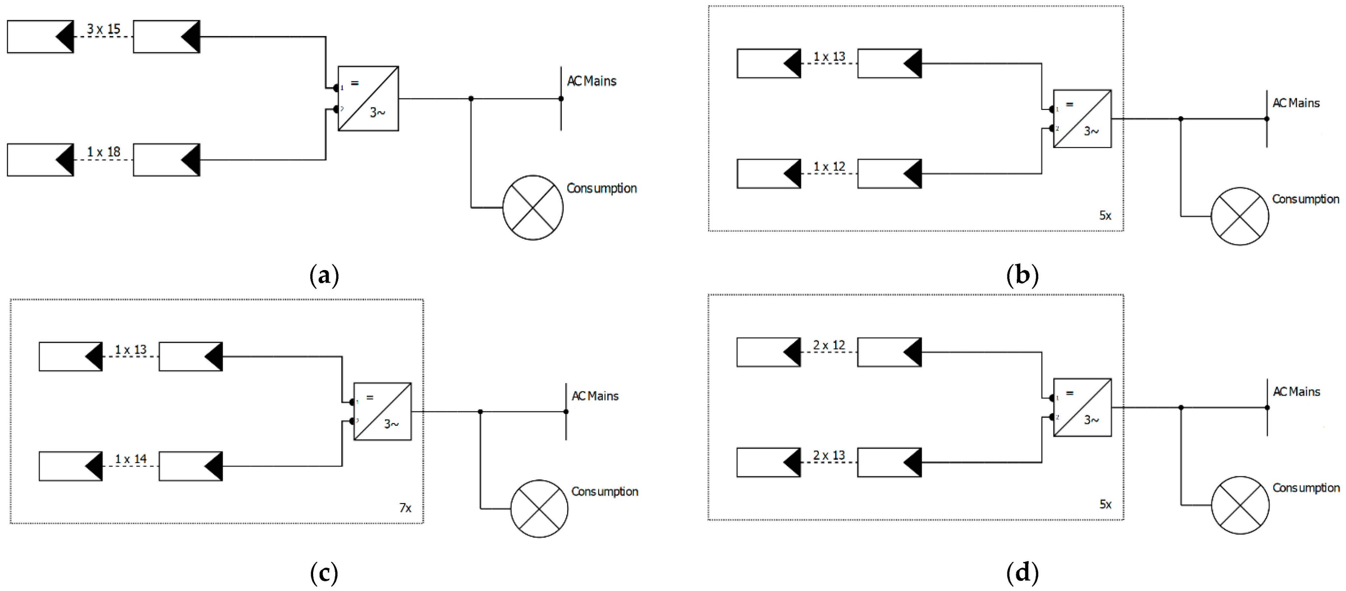


Figure 5. Schematic circuit diagrams for (**a**) 25.2 kW, (**b**) 50 kW, (**c**) 75.6, (**d**) 100 kW PV systems.

The design and simulation of the PV systems were carried out in PVSOL software. Because Romania is located in the northern hemisphere, the PV modules were oriented South, with a tilt angle of 30° at an azimuth angle of 0°. To avoid inter-row shading, 4.97 m between the rows of PV panels was considered. The PV module configurations were carried out to maximize the PV installations' electric energy production. The design of the PV installations was completed by selecting suitable inverters and electrical cable sizing. Shading analyses were carried out for determining the green electricity produced by the SPSs as precisely as possible.

3.3. Economic Analysis

In addition to the technical assessment, the economic feasibility evaluation plays a decisive role in the decision-making process, preceding the implementation of an investment [65]. The Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI), and Discounted Payback Period (DPP) were calculated to assess the economic feasibility of the investigated PV installations.

NPV is the most frequently employed method for the evaluation of investment projects [66]. NPV is calculated by subtracting the initial investment cost from the present value of the future expected net cash flows of the investment. The NPV was determined by using Equation (1) [67].

$$NPV = \sum_{i=1}^{n} \frac{NCF_i}{(1+r)^i} - C_{inv} \quad (1)$$

where n is the lifetime of the investment project, NCF_i represents the net cash flow registered in the year i, r is the discount rate, and C_{inv} represents the initial investment cost.

The net cash flow for a given year is determined as the difference between the cash inflows and cash outflows of that year. By summing up the electricity bill savings and the value of the energy injected into the network, the cash inflows are obtained. The cash outflows include operation and maintenance (O&M) costs. An investment project is viable if its NPV is positive. On the other hand, if the NPV of the investment project is negative, then it is not feasible.

The IRR highlights the investment project's forecasted profitability evidenced in percentage [68]. The IRR indicates that the discount rate leads to an NPV value of zero as indicated in Equation (2). The investment is not profitable when IRR is less than the discount rate.

$$\sum_{i=1}^{n} \frac{NCF_i}{(1+IRR)^i} - C_{inv} = 0 \quad (2)$$

PI, also known as benefit–cost ratio due to the fact that the numerator quantifies the benefits and the denominator the costs, calculates the present value of returns for each invested monetary unit. PI is calculated as a ratio between the present value of the investment project's forecasted cash inflows to the present value of expected cash outflows as indicated in Equation (3) [69].

$$PI = \frac{\sum_{i=1}^{n} \frac{CI_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{CO_i}{(1+r)^i} + C_{inv}} \quad (3)$$

where CI_i represents the cash inflow registered in year i and CO_i represents the cash outflow obtained in year i.

The costs are greater than the benefits, which implies the unfeasibility of the investment project when PI is less than 1.

The DPP is the required period of time in which the initial investment cost is recovered from the expected investment project's discounted net cash flows as indicated in Equation (4) [70].

$$\sum_{i=1}^{DPP} \frac{NCF_i}{(1+r)^i} = C_{inv} \quad (4)$$

The investment is not profitable when DPP is greater than the investment's lifespan, because the project is not going to break even.

The SPS total installation costs have registered a significant decline, particularly in the last decade. The total installation costs of the PV installations examined in this paper are shown in Table 4. The prices of fully equipped systems were determined based on the quoted prices received at the end of 2021 from ten Romanian solar PV installation companies. It can be noted that the SPS initial investment cost is influenced by the PV system's size, as a consequence of the economies of scale [69,71,72].

Table 4. PV systems' initial investment cost.

Rated Power [kW]	Total Cost (USD)
25.2	32,760
50	62,500
76.5	90,720
100	115,000

In 2022, TUCN paid approximately 0.3818 USD for each kWh of electric energy consumed from the electricity grid, while the green energy injected into the network could have been recompensed with approximately 0.1237 USD/kWh.

The economic assessment of the investigated SPSs considers the following assumptions: The discount rate is 5.6% [73], the considered lifetime of the PV installations is 25 years [74], the maintenance and operation costs are 1% of the total initial investment cost [69,75] with the replacements cost also included [76,77], and the annual derating factor is 0.7% [72].

3.4. Carbon Mitigation Analysis

The impact of energy produced using fossil fuels on the environment is highly adverse, especially due to GHG emissions. Energy generated from renewable sources is a viable solution to decrease GHG emissions and their effects on the climate [78]. Solar energy is one of the renewable energy sources that bring remarkable benefits to the environment [79].

The environmental assessment of the investigated SPSs is carried out by determining the amount of mitigated carbon dioxide emissions as a consequence of deploying them, as also noted by [80–82]. The cumulative environmental benefit (CEB) has been determined by using Equation (5) [81].

$$CEB = (NEF_1 - PVCIF) \cdot E_1 \cdot \left(\frac{1-(1-dr)^n}{dr}\right) - AD \cdot E_1 \cdot (1-dr) \cdot \left(\frac{1 - n \cdot (1-dr)^{n-1} + (n-1) \cdot (1-dr)^n}{d^2}\right) \quad (5)$$

where NEF_1 is the network emission factor for the first year of the investment project; $PVCIF$ represents the PV system's carbon intensity factor; E_1 is the electric energy generated in the first year of operation; dr represents the derating factor; and AD is the annual diminution of carbon intensity as a result of the increase in energy from renewable sources.

The considered AD is the average value (7.775 g CO_2/kWh) of the yearly diminution of carbon intensity from 2000 to 2020 in Romania [83]. The considered PVCIF is 40 g CO_2/kWh [84]. Based on the Romanian energy mix between 2000 and 2020, the NEF in 2022 was estimated to be 283.95 g CO_2/kWh [80].

4. Results

This paragraph presents the main results of the tridimensional (technical, economic, and environmental) sustainability and feasibility assessment. First, the renewable energy analysis for the PV installations is described. Then, the investment assessment is illustrated to determine the most feasible PV system. Finally, the environmental analysis is carried out for the examined SPSs.

Figure 6 presents the electric energy produced by each of the four PV installations in the first year of operation on an hourly basis. Estimating the electric energy generated by the investigated SPSs represents an important phase because it is further used as an input for the economic assessment.

Figure 7 shows how much of the electricity consumption at TUCN is covered by each of the four PV systems and by the grid.

As can be noted in Figure 7, the electricity generated by the PV systems is not enough to cover the year-round consumption. During winter, January has the highest amount of energy supplied from the network, and the electrical energy generated by PV panels covers between 2.41% for the 25.2 kW PV system and 9.13% for the 100 kW PV installation. Starting from January, the electrical energy generated by the SPSs increases month by month until July, which is the best month in terms of green electricity production during summer, with between 10.08% and 35.72% of the energy demand being met for the system with the lowest and the greatest rated power, respectively.

Figure 8 presents how the electric energy generated by the PV installations is being used. It can be observed that all the electricity produced by the 25.2 kW and 50 kW PV systems is directly consumed by the university during the winter months. As the installed power of PV systems increases, the energy purchased from the grid expands during summer, except for the PV installation with the lowest rated power where all the produced electricity is directly consumed all year round. August records the largest share of green energy surplus injected into the grid, ranging from 7.21% for the 25.2 kW PV installation to 33.85% for the 100 kW PV system, mainly because it is the summer holiday and the lowest monthly electrical energy consumption has been registered.

To provide valuable insight into the economic viability of the investigated SPSs, the parameters for the investment analysis described in the previous paragraph are determined below.

The economic assessment results are illustrated in Figure 9. Figure 9a presents the results of the NPV parameter. It can be seen that the PV system with the greatest rated power is the most profitable, generating an additional value of more than 465,000 USD over the investment's lifespan.

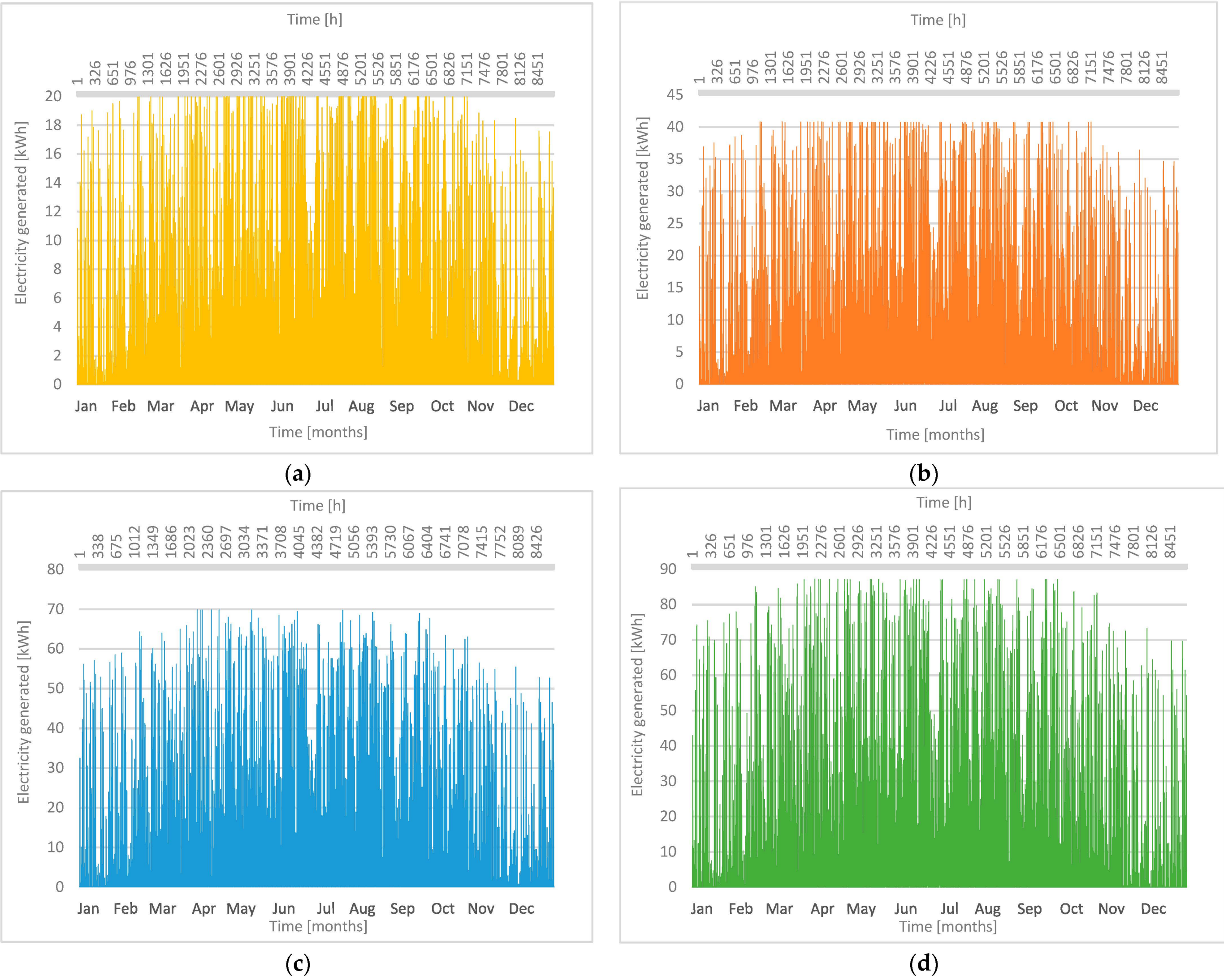


Figure 6. Hourly energy generated by (**a**) 25.2 kW, (**b**) 50 kW, (**c**) 75.6, and (**d**) 100 kW PV systems. The horizontal axis is time (h).

The NPV for the SPS with a rated power of 50 kW installed at TUCN Romania is more advantageous than the one deployed at the Institute of Chartered Financial Analysts of India University, Jaipur, where the NPV of the 50 kW PV installation was 72,935.38 USD [85]. Furthermore, the NPV for the investigated 75.6 kW PV system is more desirable than those installed at the University of New Haven and the Technical University of Madrid, where its values for 67 kW and 80 kW PV installations were 81,996 USD [35] and 78,800 Euro [33], respectively. The results indicate that investments in all SPSs are profitable and, as can be noted in Figure 9a, the higher the rated power of PV installations, the higher their NPV.

The IRR results are illustrated in Figure 9b. It can be observed that the highest rate of discount that leads to a zero-value NPV corresponds to the investment in the PV installation with an installed power of 100 kW. The IRRs of the 80 kW and 67 kW PV systems deployed at the Technical University of Madrid and the University of New Haven were 13.1% [33] and 8.74% [35], respectively, both being less favorable than the IRR of the 75.6 kW PV installation designed for the TUCN. Likewise, the IRR of the 50 kW PV system installed at the Institute of Chartered Financial Analysts of India University was 21% [85], being less advantageous than the one investigated in this paper.

Figure 7. Electricity consumption coverage for (**a**) 25.2 kW, (**b**) 50 kW, (**c**) 75.6, and (**d**) 100 kW PV systems. The horizontal axis is time (month).

The results point out that the IRRs of all the investigated PV systems are greater than the rate employed for discounting their cash flows, and as a result, it is recommended to make the investment.

The PI results are presented in Figure 9c. It can be noted that the best result was recorded for the PV installation with the greatest rated power, with the present value of the benefits being approximately 4.57 times larger than the present value of expenditures.

The present value of cash inflows is 2.62 times larger than the present value of cash outflows for the 50 kW PV system installed at the Institute of Chartered Financial Analysts of India University [85], being less favorable than the one examined in this study. The present value of expenditures is 1.28 times smaller than the present value of the benefits for the 67 kW PV system deployed at the University of New Haven [35], with this also being less advantageous than the 75.6 kW PV installation designed for TUCN.

The DPP results are illustrated in Figure 9d. As the installed power of SPSs decreases, the later the investment costs are covered by the cash flows generated by the investment project.

Figure 8. Use of PV energy for (**a**) 25.2 kW, (**b**) 50 kW, (**c**) 75.6, and (**d**) 100 kW PV systems. The horizontal axis is time (month).

The required period of time to break even for the investigated DGUs that use solar power is in the range of 2.86–3.01 years. The payback period for the studied 75.6 kW PV system is more favorable than those installed at the University of New Haven and Technical University of Madrid, where the initial investment cost of the 67 kW and 80 kW PV systems were recovered in 11 years [35] and 10.1 years [33], respectively. Furthermore, the payback period of the 50 kW and 56.7 kW PV installations installed at the Institute of Chartered Financial Analysts of India University and Mu'tah University in Jordan were 4.68 years [85] and 5.5 years [36], being less advantageous than the similar PV system investigated in this study. The Technical University of Madrid and TUCN were the only universities for which the payback periods factor in the time value of money, as only the simple payback periods were reported for the other universities, which are less accurate.

The favorable results of the economic feasibility assessment for the investigated grid-connected PV systems are influenced to a large extent by the surge of the electricity price paid by the university, and thus, due to the large amount of self-consumed clean electrical energy produced by the SPSs. Even though in the Northwestern part of Romania there is not a very high solar potential, there are considerable net cash flows for compensating the investment in PV installations at TUCN in a relatively short period.

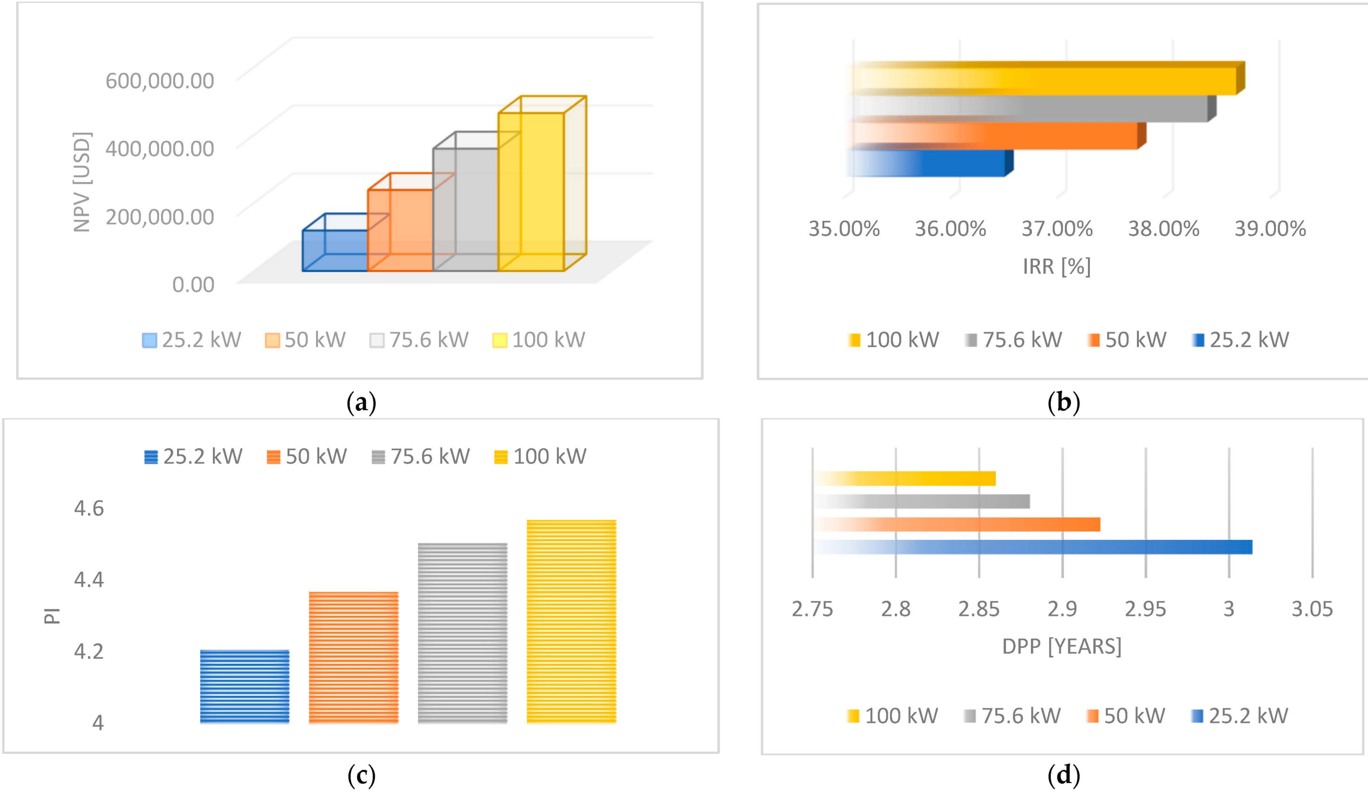


Figure 9. The economic assessment results: (**a**) NPV, (**b**) IRR, (**c**) PI, (**d**) DPP.

The findings of this investigation provide valuable practical solutions, assessing the viability of integrating four grid-connected PV systems at TUCN, by considering the range of power requirements values indicated in the Romanian regulatory framework for the prosumer. No study, to the best of our knowledge, has assessed the feasibility of rolling out several grid-connected rooftop solar PV installations, covering the range of installed capacity requirements values outlined in a national regulatory on prosumers, at a university. This study intends to help universities with comparable solar resources realize the potential feasibility of deploying SPSs, a long-term sustainable solution to tackle the energy crisis. The results are expected to accelerate the transition of universities from the status of a consumer to that of a prosumer, increasing the use of solar energy, avoiding the increase in GHG emissions, and improving their energy efficiency. Furthermore, the findings from this study should be used by the government and policymakers to promote the deployment of PV installations on public buildings, considering the significant untapped potential and a considerable increase in the electricity price. Figure 10 presents the results of the environmental assessment in terms of the amount of mitigated carbon dioxide emissions by deploying the PV systems. The electrical energy generated by SPSs has a significant beneficial effect on the environment because the use of solar energy, which is unlimited, considerably diminishes the negative effects of using other energy sources, such as fossil fuels, which represent one of the largest sources of carbon dioxide emissions.

The amount of carbon dioxide emissions avoided depends on the electricity produced by PV installations, and as can be observed in Figure 10, the PV system with the greatest rated power has the highest contributions to the TUCN decarbonization issue. The deployment of the examined SPSs has the possibility to reduce carbon dioxide emissions by values ranging from approximately 116 tons to 460 tons, contributing considerably to the diminution of GHG emissions.

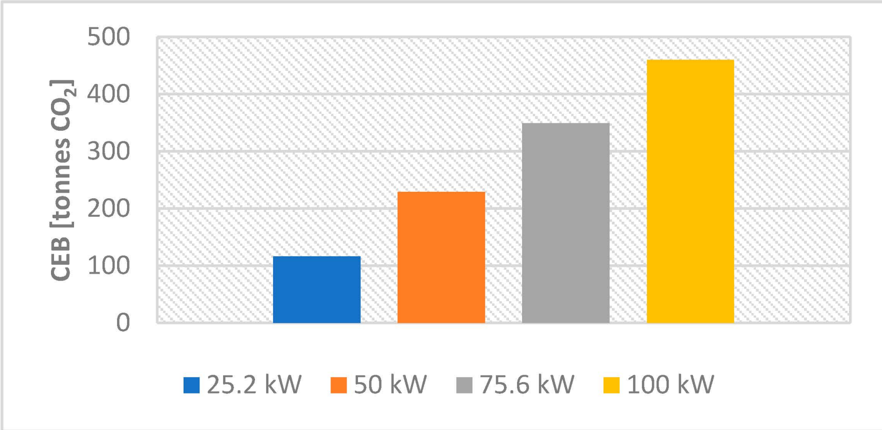


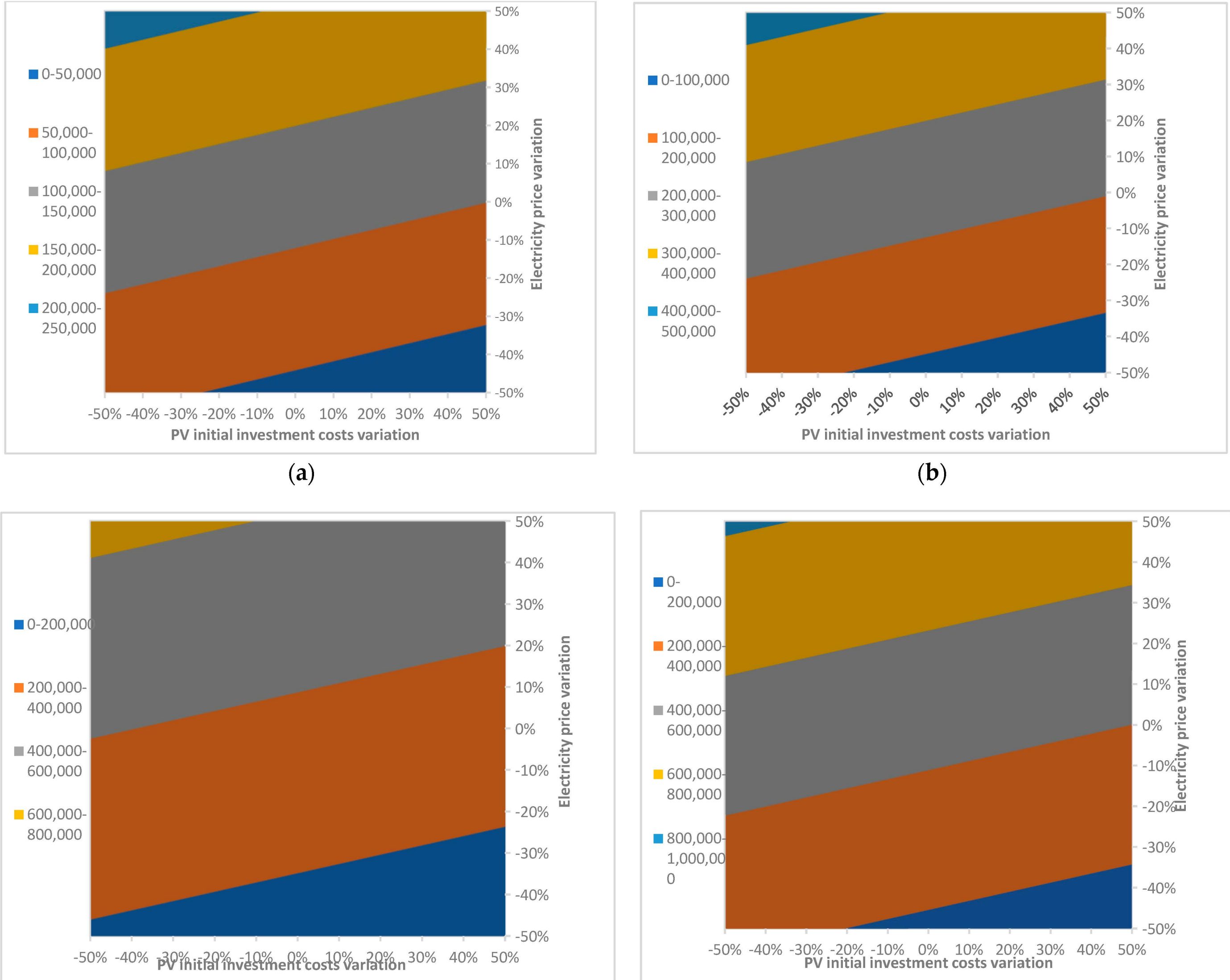
Figure 10. CEB of PV systems.

5. Sensitivity Analysis

The results of the economic feasibility assessment performed in the previous paragraph have been determined based on the assumption that the parameters were deterministic and certain. A sensitivity analysis has been employed to investigate the variation of critical parameters on the feasibility of deploying the PV systems at TUCN. The NPV method has been used to assess the economic feasibility of PV installations due to its reliability. The injected electricity price represents one of the most implemented policies used by governments to boost SPSs investment. However, this price-driven policy may be used to temper the investments in PV systems when the total installed rooftop solar panel capacity reaches the desired level. Besides the injected electricity price, the PV initial investment cost, electricity price, discount rate, and operation and maintenance costs are significant factors that have been chosen for the assessment due to their influence on the economic feasibility of the PV installations. The profitability of the investigated SPSs has been evaluated by varying the considered parameters by ±50% from their nominal values using 10% increments.

Figure 11 presents the sensitivity analysis of NPV with variations in the electricity price and PV initial investment cost for the examined PV systems. It can be noted that as PV initial investment cost decreases, the SPSs generate more additional value over the investment's lifetime. Moreover, it can be observed that the electricity price varies similarly to the returns yielded by the investment in PV installations. The decrease in electricity price and increase in PV initial investment cost lead to less likely profitable investment projects and vice versa. The results presented in Figure 11 point out that the present value of the future expected net cash flows of the investigated DGUs that use solar power is greater than the initial investment cost even if the electricity price decreases by 50% and, at the same time, the PV initial investment cost increases by 50%. It is worth mentioning that despite the significant increase in the PV initial investment cost and the considerable decrease in electricity price, the NPV remains positive, which means that all the examined PV power plants are economically feasible even if the values of the two parameters are less favorable.

Figure 12 illustrates the sensitivity of NPV based on the variation of the discount rate, injected electricity price, and O&M costs. The bars indicate the deviations from the results determined in the previous paragraph, and the shorter the bar, the lower the sensitivity. The discount rate has the greatest influence on the difference between the present value of the forecasted net cash flows of the investment project and the initial investment cost. It can be observed that as the discount rate increases, the investment becomes less and less worthwhile.



(**a**) (**b**) (**c**) (**d**)

Figure 11. Sensitivity analysis results of NPV with variation of electricity price and PV initial investment cost for (**a**) 25.2 kW, (**b**) 50 kW, (**c**) 75.6, and (**d**) 100 kW PV systems.

According to Figure 12, both the injected electricity price and O&M costs do not have considerable impacts on the NPV values. It is seen that the higher the installed power of SPSs, the higher the influence of the injected electricity price on the NPV, mainly because most of the green electricity produced by smaller systems is directly consumed by TUCN. The sensitivity analysis that has been performed in this paper provides extensive information to decision-makers. In this study, the effect of five critical parameters on the SPS' economic viability has been investigated, compared to [33,85], where the influence of one and two parameters on the feasibility was examined, respectively.

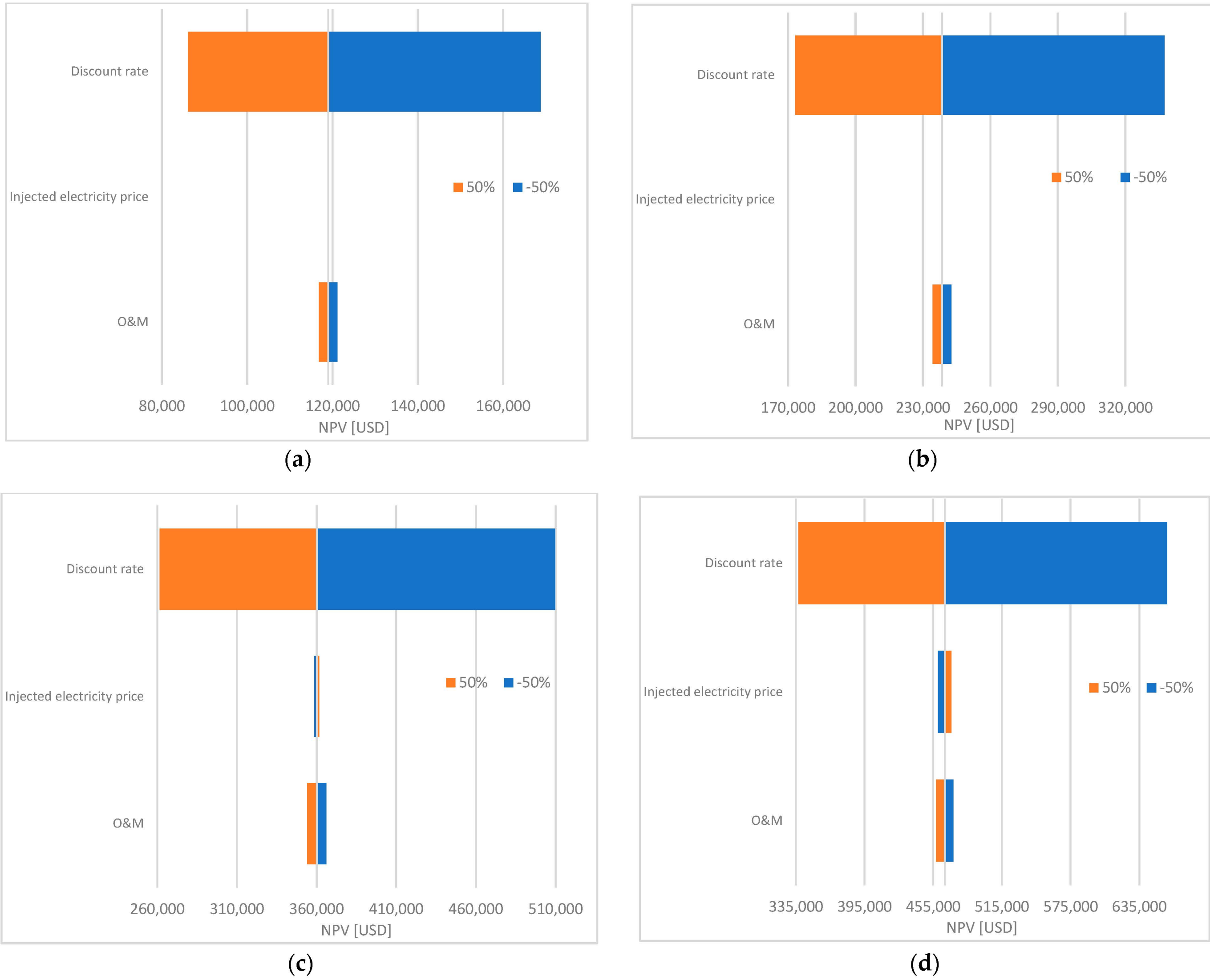


Figure 12. Sensitivity of NPV to variations of discount rates, injected electricity prices, and O&M for (**a**) 25.2 kW, (**b**) 50 kW, (**c**) 75.6, and (**d**) 100 kW PV systems.

6. Conclusions

Universities around the world have the responsibility to lead by example and promote sustainability practices. Solar power accounts for most of the renewable energy expansion in Romania, and this can be an opportunity for higher education institutions to use PV technologies to meet their growing electricity demand and contribute to reducing climate change's impact. This paper is assessing the technical, economic, and environmental sustainability and feasibility of deploying four grid-connected SPSs at TUCN. The rated powers of PV installations range between 25.2 kW and 100 kW, covering the range of power requirements values outlined in the Romanian prosumer law. The universities educate the next generation, making them responsible for promoting sustainable practices. The methodology presented in this study can be used or adapted by other universities with similar or different solar resources than TUCN. This investigation intends to inspire higher education institutions to integrate solar-power-based DGUs to reach net-zero carbon electricity.

The green electric energy produced by the investigated SPSs is inversely proportional to the university's electricity demand in both the fall and spring semesters. During the academic year, the highest electricity consumption in the fall semester was recorded in November, covered by between 2.39% for the 25.2 kW PV system and 9.13% for the 100 kW PV installation. On the other hand, during the spring semester, March was the month with the highest electric energy consumption, with the photovoltaic system with the lowest and highest power covering between 5% and 18.46%. The examined SPSs coupled with energy storage systems represent a solution for increasing the self-consumption at TUCN, especially for the systems with the highest installed capacity. As the cost of installing energy storage systems has dropped in recent years, their profitability in connection with PV installation is going to be studied further in future works.

The economic analysis results highlight that all the investigated PV installations are profitable. Even though the location of the investigated university does not benefit from a considerably high solar potential, the examined systems are feasible and highly attractive, mainly because of the high rate of electricity cost and the fact PV electrical energy is mostly consumed locally. As the installed power of the SPSs increases, their viability increases too. The proposed 100 kW PV system represents an exemplary match for TUCN because it uses part of the unused roof space, supplying approximately one-fifth of the university's electricity demand, considerably reducing GHG emissions and increasing environmental sustainability.

The results obtained in the economic feasibility assessment are also supported by the environmental impact analysis of deploying the proposed PV systems. The most economically feasible PV installation is the one recording the greatest decarbonization of the TUCN. Apart from generating additional value of more than 465,000 USD, developing 100 kW SPS would reduce the carbon dioxide emissions by 460 tons over the project's investment lifetime.

A sensitivity analysis has been performed to assess uncertainty by identifying the parameters that significantly influence the economic feasibility of deploying the examined SPS. The conducted analysis pointed out that the electricity price, PV initial investment cost, and discount rate are the most sensitive, playing significant roles in supporting future decision-making. The findings revealed that the development of PV systems at TUCN is economically feasible even if the PV's initial cost increases by 50% and the electricity price simultaneously decreases by 50%.

The findings of this study indicate that the deployment of the investigated DGUs that use solar power at TUCN is economically and technically feasible. To support sustainable development, the deployment of PV systems with the highest rated power at TUCN should be encouraged when considering the expected expansion of this university, which will lead to an increase in electrical energy costs. The outcomes of this investigation advise Romanian stakeholders and policymakers to support the transformation of universities from passive electricity consumers to prosumers. Furthermore, the findings of this paper are intended to inspire other higher education institutions to assess the feasibility of deploying grid-connected rooftop PV systems and become important players in the energy transition to achieve carbon neutrality.

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