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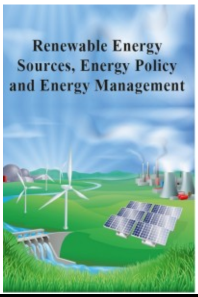

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Original Research Article

Capacity Calculation and Subsidization Proposals for Rooftop PV Energy for a Residential Building in İstanbul

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ABSTRACT

Urban transformation works ongoing in metropolitan cities pose an opportunity for application of PV energy for multi-story residential buildings. In this study, PV energy production capacity of a 6-floor (14 flats) residential building located in İstanbul is modeled using PVsyst software, with its cost payback period to household owners calculated as 23 years without any energy feed-back scheme. When excess energy is sold back to the grid at 0.133 USD/kWh, the payback period reduces to 6.6 years. An alternative incentive scheme providing 60% of the initial cost by the state reduces owner's payback to 9.4 years while the state's share is paid back in 18.3 years with a price of 0.04 USD/kWh, which is lower than 0.06 USD/kWh production cost of conventional power plants, suggesting a policy to replace investment on new power plants with PV incentives to building owners. For 121 MWh production, saved carbon emissions is calculated as 44.692 t CO_2/year.

Keywords: Rooftop PV system design, renewable energy, solar energy feasibility, energy production for self consumption, urban transformation, energy subsidization policy

1.Introduction

Residential buildings constitute an average of 20% -in developed countries- to 35% -in developing countries- with expected increase in demand in the future [1]. In Turkey, residential buildings consume 24% of the total electricity production [2]. Focusing on the supply of electricity for residential buildings from renewable sources can contribute considerably to sustainable development, since it will have positive impacts from the environmental, economic and social points of view, in reference to the sustainability triangle [3]. That is, environmental benefits of reducing the use of non-renewable natural sources for energy can be achieved along with the social benefit of providing robustness for occupants in terms of independence from the energy grid along with the long-term economic benefits for occupants and national economy, especially for energy-dependent countries.

As of February 2021, the distribution of Turkey's installed power according to resources is; 32.2 percent hydraulic energy, 26.6 percent natural gas, 21.0 percent coal, 9.5 percent wind, 7.1 percent solar, 1.7 percent geothermal and 1.9 percent based on other sources [4]. Although Turkey has great solar energy potential, solar energy installations are lagging behind most of the European countries, such as that of Germany, which is capturing 60 percent less solar rays, [5].

1.1. Analysis Objectives

The analysis presented in this study aims to investigate feasibility of roof-top photovoltaic (PV) power for multi-storey residential buildings to supply electricity load of the whole building. Although there are studies on feasibility of PV power for various types of buildings, the study presented here aims to include the efficiency losses of shading in a dense community, to reflect efficiency losses, as well as sufficiency of roof area to supply energy load of the whole residential building having a typical size that may be found in İstanbul. The analysis further tries to assess financial feasibility of roof-top PV for owners and tries to relate alternative subsidization policies for building owners to savings that may be achieved from de-investments on power plants at the country scale.

The paper is organized in three sections. Section 1 introduces the motivation for this study as well as literature review relevant to the objectives of this study. Section 2 describes the methodology and analysis. Section 3 provides discussions and policy proposals base d on the findings. Finally, Section 4 presents conclusion and recommendations of the analysis.

1.2. Literature Review

There have been some applications and studies on feasibility of photovoltaic (PV) power plants in Turkey for rural areas, showing a payback period of 6.7 years, [6]. Comparison of feasibility of an 8,865 kWp installed capacity PV-powerplant for three major cities of Turkey; namely Istanbul, Ankara and Izmir shows a payback period of 13.6, 6.7 and 7.0 years to support 6,518, 7,257 and 7,802 households annually, for an ideal four-season inclination of PV modules at 32.60º, 32.70º and 32.80º, respectively, [7].

There are also studies on feasibility of PV-energy for own-use. It is shown that initial investment on the PV systems for residential buildings dominate their feasibility and on-grid systems may produce a saving of 0.27 USD/kWh/year [8]. Another study for the application of PV systems for university campus buildings in Isparta, Turkey has shown a payback period of 14 years for grid-connected 25 kW PV-capacity on building roofs, providing 15% of the energy requirement, [9]. A study for residential use in Adıyaman, Turkey, where solar radiation potential is given as 1,600-1,750 kWh/m2-year shows that for a house with annual consumption of 3,647 kWh and daily demand of 10 kWh, designing the system for extra 50% increase in demand, the initial cost was calculated as approximately 5800 USD based on the rates of the study date, payback period was calculated as 10 years and the required area for the PV system was 24 m2 for this demand, [10]. An application for a smart home, which is consuming as low as 149.925 kWh/year energy is also studied and it was calculated that a 2.5 kW off-grid system cost would be approximately 4,300 USD and on-grid system cost would be approximately 3,100 USD based on the rates of the study date, the difference being due to the cost of battery system needed and the payback period was calculated as 8 years for both systems, [11].

Provision of off-grid PV energy for rural areas where on-grid supply is not available or feasible or for providing self-sustainability of these modes of living has also been an area of interest because the renewable energy becomes a necessity rather than a preference. A study by Ahsan et al. includes design and cost analysis and field testing of a 1.0 kW off-grid roof-top PV energy system for a small house in New Delhi rural area, consisting of 5 PV modules and 2 batteries, supporting a small home designed by using the PVsyst software and found that the solar energy generated was 3,102.2 kWh/year supplying 2,933.4 kWh/year, due to insufficient demand at times or insufficient storage capacity; and stated that with 50% incentive for the initial cost the system needed no additional payment by the user, [12]. A study of similar context was carried out for off-grid energy supply of plateau houses having a weekly demand of 25,207.5 kWh (daily demand of 3.6 kWh) and a system with 5.54 kWh supply is designed with 8 PV modules having an installed power of 3 kW and costs were calculated as approximately 5,300 USD and 6,900 USD based on the rates of the study date for a stationary system and a moving system, respectively. It is also shown that the costs would be factored with 3.2 and 3.5, respectively if the installed power was increased to 10 kW [13].

Regarding feasibility of grid connected PV-energy; Mounouni et al. studied usage of a 5 kW residential grid-connected photovoltaic system and calculated that the electricity bills were reduced to 8.03% to 12.20% of the utility bill from May to July in Nevada, [14]. Bukar et al. studied 4.4 kWp peak power capacity photovoltaic grid-connected system in Nigeria, having lithium-ion battery storage to study the economic contribution of the battery as compared with the case without the battery and found that the energy consumption from the grid is reduced by 45.7%, [15]. Ellabban and Alassi analyzed the economic parameters of an existing PV-connected residential region with an average of 2.45 kWp PV system size on a case study in Australia, and based on 54 customers' data, various tariff schemes were proposed which yielded a payback period of 7.61 to 10.75 years with an internal rate of return (IRR) of 18% to 14%, [16]. In another study by Davi et al., for on grid-connected residential buildings in Brazil with capacities of 3.68 and 4.14 kWp, a payback period of 13 to 31 years were calculated, [17]. A study for Honduras shows that the payback period is 10 years, for 5.12 kWp system for an annual production of 6.3 MWh/year [18]. Another study involves a house with PV system in France to have 25 years of the payback period for a certain range of price and it was concluded that incentive-based policies were necessary, [19]. A study for Romania involving 5.5 kW rooftop solar system with battery capacities of 3.3, 6.5 and 9.8 kW concludes that due to high investment costs, the system could only be profitable with subsidies, which already exist as 90% of investment costs and supported by a feed-back price of 0.0587 USD compared to the tariff rate of 0.1567 USD per kWh, as calculated for an investment cost of 1,500 USD/kW and operational cost of 1% of total investment [20].

2. Methodology

In this study, an on-grid roof-mounted PV system was designed for a multi-story residential building by using PVsyst software. It is aimed to determine the energy that can be supplied given the roof space constraint, taking into account the shading from neighboring buildings. Later, economic analysis of the system was studied based on the payback period for the building owners. Finally, alternative subsidization policy schemes are analyzed to reduce the economic burden to the building owners. Economic burden of the subsidization to the state is also compared with the payback from the savings on the operational costs of the conventional power plants. It is investigated whether the subsidization costs to the state can be paid back with de-investment from conventional power plants. Thus, it is aimed to understand the applicability of PV energy for mass housing projects in cities to create a large impact in state economy by diverting high investment costs on conventional power plants as subsidies to building owners.

2.1. Design Parameters for Photovoltaic (PV) Systems

Determining meteorological data is the first step of the PV system design. The coordinates of the building are taken from Google Earth and it is fed on the PVsyst software. PVsyst provides access to several meteorological databases. In this project, monthly meteorological data were imported from Meteonorm 7.2. in PVsyst software, and generated hourly data is used for improvement of the models, [21].

The location of the building was selected as Istanbul, Turkey since there has been major residential building constructions under the urban transformation law. In this study, simulation of a typical single building with 6 floors having 18 meters building height and a basement floor plan area of 803.25 m^2 was conducted. Coordinates of the location, time zone, altitude, dimensions, number of floors, and height of the building are given in Table 1.

Table 2 shows the horizontal global irradiation, horizontal diffuse irradiation, temperature, wind velocity, linke turbidity, and relative humidity values for the selected location, as calculated from PVsyst database. PV system is designed and simulated according to the worst-case scenario, when the lowest irradiation is obtained. Although this approach produces more expensive PV system, it was aimed that the apartment would provide the 100 percent of energy demand in the month having lowest irradiation and sell excess electricity to finance this cost, while making the building independent of the grid, except for failure of the system. In Istanbul, the lowest irradiation is in December. On annual basis, 1,350.7 kWh/m^2 of horizontal global irradiation and 680.3 kWh/m^2 of horizontal diffuse irradiation is gained. A more elaborate study can be carried out to take into account the winter and summer seasons. For instance, from April to September, the average horizontal global irradiation and horizontal diffuse irradiation are 162.8 kWh/m^2.month and 77.9 kWh/m^2.month, respectively. In the worst-case scenario, from October to March, the average horizontal global irradiation and horizontal diffuse irradiation values are calculated as 62.3 kWh/m^2.month, and 35.5 kWh/m^2.month, respectively. In the case of yearly irradiation yield, PVsyst software showed the loss with respect to optimum as -5.1% and computed the global irradiation on collector plane as 1,457 kWh/m^2. In contrast, for the summer season including April to September, the loss with respect to optimum, and global irradiation on the collector plane are found as -0.9% and 1,008 kWh/m^2, respectively. In winter season that corresponds to the period from October to March, these values are found as -20.1% and 449 kWh/m^2.

Table 1 - Information on the building and location

Coordinates of the building	40.97 ˚ N 29.05 ˚ E
Time Zone	UT +3
Altitude	10 m
Dimensions of the building in the basement floor plan	25.5x31.5 m^2
Number of floors	6
Number of flats	14
Height of the building	18m (6 floors)

Table 2 - Geographic site parameters obtained from PVsyst Database

Months	Horizontal Global Irradiation kWh/m^2.month	Horizontal Diffuse Irradiation kWh/m^2.month	Temperature ˚C	Average Wind Velocity m/s	Linke Turbidity [-]	Relative Humidity %
January	43.5	26.3	6.2	4.79	2.700	75.6
February	55.6	31.6	6.3	4.89	2.933	75.7
March	95.0	59.3	9.1	4.50	3.152	71.4
April	132.1	69.9	12.4	4.10	3.422	67.3
May	173.7	76.9	17.9	4.00	3.222	65.2
June	186.2	91.6	22.5	4.19	3.290	59.9
July	191.2	88.2	25.7	4.70	3.290	58.5
August	167.0	81.0	25.5	4.80	3.422	63.4
September	126.8	59.8	20.9	4.30	3.222	68.1
October	85.3	44.0	17.1	4.20	2.933	72.7
November	54.1	28.7	11.9	4.29	2.857	75.6
December	40.2	23.0	8.3	4.89	2.700	73.5
Year	1350.7	680.3	15.3	4.5	3.095	68.9

2.2. Photovoltaic (PV) System Components

Photovoltaic (PV) Systems use solar energy and consists of solar cells that are composed of semiconductor materials basically characterized by two behaviors; while exhibiting insulator effects at lower temperatures, if energy is available, they can act as conductors [22]. According to the study of Almosni et al., there are three generations of PV cells, namely mono and poly crystalline silicon cells, thin film cells, and the third-generation cells, among which selection of the base material is dominated by various factors such as production cost, lifetime, and efficiency [23]. There are major energy losses in producing electricity from solar energy, related to transmission and thermalization losses and several approaches are proposed, including hot-carrier solar cells, intermediate band solar cells and multi-junctions to decrease the loss levels [23]. However, from the practical point of view, still mono crystalline and poly crystalline PV cells are common in the industry.

Basically, PV systems an be implemented as on-grid systems or off-grid systems. In on-grid systems, excess production of electricity can be fed into the utility grid and in case of inadequate solar electricity production which occurs generally at nights, electricity can be received from the utility grid. Unlike on-grid systems, off-grid systems contain battery or hydrogen technologies in order to store excess electricity production for later use, when there is insufficient PV energy production. In this study, an on-grid system design is proposed for reliability.

Main components of an on-grid system are PV arrays, solar inverters, fuse box, utility meter, solar cables and grid lines. The basic layout of the system is shown in Figure 1. PV modules produce DC from solar energy, and a solar inverter converts DC to AC that is the commonly used current. PVsyst database allows selection of the PV system components from a vast number of manufacturers.

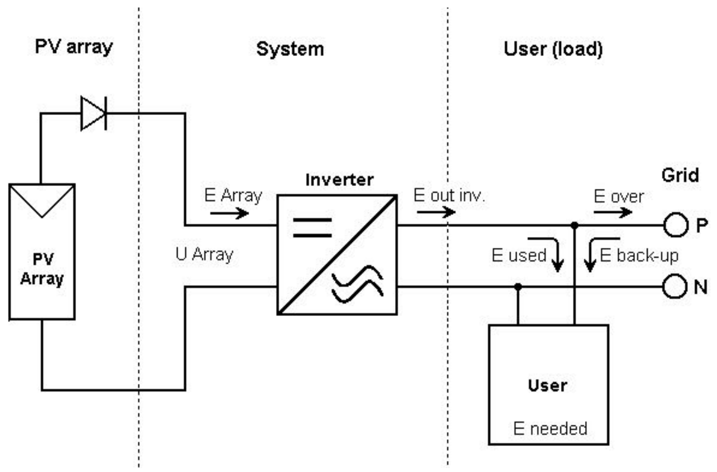

Figure 1 - Basic layout of the system modeled by the software

Mechanical and electrical data of the modules selected are given in Table 3 and Table 4. In this system, 305 Wp of Si-mono PV modules were used and each module has 1.919 m^2 area and 23 kg weight. The efficiency of the cells is given as 17.7 % by the manufacturer.

Table 3 - Mechanical Data of the PV modules

Module		Cells	
Length	1,954 mm	In series	72
Width	982 mm	In parallel	1
Thickness	40 mm	Cell area	238.9 cm^2
Weight	23 kg	Total no of cells	72
Module Area	1.919 m^2	Cells area	1.72 m^2

Table 4: Electrical Data of the PV modules

Technology	Si-mono
Nominal Power at STC	305 Wp
G_{ref}	1,000 W/m^2
I_{sc}	8.840 A
I_{mpp}	8.330 A
Temperature coefficient	5.3 mA/˚C
T_{ref}	25 ˚C
Open circuit, V_{oc}	45.20 V
V_{mpp}	36.60 V

2.3. Orientations of the PV Modules

In this study, a gable roof was used for simulation. Since the gable roof has a slope, the optimum angle was not considered in simulation because the erection of the modules may be a problem and may lead to high labor costs. If a flat roof is used to design, the optimum tilt angle should be investigated with respect to location and azimuth angle of the installation. Hence, two sub-arrays were placed on both sides of the gable roof of the building, based on their azimuth angles; the first sub-array was planned to be placed on the roof with -44˚ and the other one was planned to be placed with 136˚, with tilt angle as 20˚ as shown in Figure 2. To be able to obtain accurate results from the simulation, azimuth angles should be correctly defined. Azimuth angles were taken from the location of the building by using Google Earth tool. Once the azimuth angles and tilt angles were determined according to dimensions of the roof of the building, these parameters were defined to the orientation section of the PVsyst software.

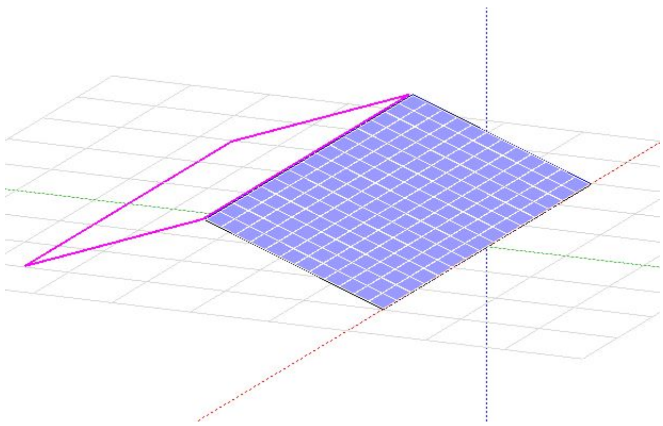

Figure 2: Landscape positioning of the PV modules on the roof

2.4. Calculation of the Nominal Power of the Array

Each sub-array consists of 180 PV modules laid out in 10 strings and 18 modules in series, and with two inverters, with total PV array covering the roof area of 690 m^2.

Nominal (STC) Array Global Power was determined by multiplying the total number of modules with the nominal power of the PV module (305 Wp) given in Table 4. As a result, Nominal Array Global Power was determined as

54.9 kWp. (*Table 5*). 25 kW inverters were used in sub-arrays. The total power of the arrays and total power of the inverters were determined as 110 kWp and 100 kWac, respectively.

Table 5: Sub-array #1 and sub-array#2 data

Number of PV modules in series	18 modules
Number of PV modules in parallel	10 strings
Total number of PV modules	180
Nominal (STC) Array Global Power	54.9 kWp
Array Global Power at operating condition (50˚)	48.7 kWp
Array Operating Characteristics (50˚) for U_{mpp}	582 V
Array Operating Characteristics (50˚) for I_{mpp}	84 A
Unit Nominal Power of the Inverter	25.0 kWac
Operating Voltage of the Inverter	280-950 V
Number of Inverters	2
Total Arrays Global Power (Nominal STC)	110 kWp
Total Module Area	691 m^2
Total Cell Area	619 m^2
Total Power of Inverter	100 kWac

$P_{nom}\ ratio$ can be defined as the ratio of the array power to the inverter power. In Turkey, array power is recommended to be approximately 10 percent greater than the inverter power, [24]. The ratio was calculated as 1.10 by Equation (1). Hence, it is possible to say that the designed system is acceptable.

$$P_{nom}\ ratio = \frac{54.9\ kWp}{2 \times 25\ kWac} = 1.10 \quad (1)$$

2.5. Performance of On-grid PV Systems

The study of Sharma, Chandel, and the study of Marion et al., shows the parameters for the performance of on-grid PV systems based on International Energy Agency (IEA) [25, 26]. According to the study of Marion et al., among the IEC standard 6174 performance parameters, final PV system yield, performance ratio, and reference yield parameters can predict the overall response of the PV system, where final PV system yield is defined as the ratio of the net energy output to the power of the installed PV array, reference yield as the ratio of the total in-plane irradiance to the reference irradiance of the PV [26]. Performance ratio (PR), one of the key parameters in order to evaluate the performance of the designed PV system, can be determined using Equation (2), [27].

$$PR = Y_f / Y_r \quad (2)$$

where, Y_f and Y_r are mean final PV system yield and reference yield, respectively. In PVsyst, the performance ratio is defined by Equation (3). Based on performance evaluation of the PV system, design can be rectified or modified, considering the aforementioned parameters.

$$PR = \frac{E_{grid}}{Glob_{inc} \times P_{nom}} \quad (3)$$

Based on performance evaluation of the PV system, design can be rectified or modified, considering the aforementioned parameters.

2.6. 3-D Model of the System Considering Shading Effects

In order to carry out a realistic analysis, shading must be taken into account for PV systems because it reduces electricity production, due to the decreasing receival of irradiation from the sun. Generally, it is impossible to get rid of shading in the PV system completely because of many reasons such as dust, obstacles, wrong mounting process. Several studies claim that even small amount of shadows may lead to power reduction of the entire PV systems. For the problem of hot-spots leading to high temperatures that result in reduced currents [28], it is proposed to use bypass diode in order to avoid hot-spot [29, 30, 31, 32]. Tripathi, Aruna and Murthy carried out an experimental study for the impact of shading on the monocrystalline and poly crystalline PV systems' response in terms of open circuit voltage (V_{OC}) and short circuit current (I_{SC}). They state that 25% of shading as measured by the ratio of the shaded area to the total area of the PV system leads to 47.72% of short circuit reduction in mono crystalline PV module and 60.86% of reduction in poly crystalline one. Besides, they found that the decrement of the maximum power output of mono crystalline PV module is less than that of poly crystalline PV module [28]. As a consequence, it is possible to say that under the same shading level, mono crystalline modules are less affected than poly crystalline ones. In this study, this result from Tripathi, Aruna and Murthy was also taken into account and mono crystalline PV modules were selected for the simulation in order to obtain more electricity production.

Since this study was performed as a rooftop PV system for residential buildings in Istanbul, Turkey, where majority of the buildings are constructed very close to each other, two higher buildings were placed as obstacles on two sides of the building under consideration. Once the system components such as PV modules, and inverters are defined, 3-D model of the buildings are prepared as shown in Figure 3. Two buildings of 24 m height are located on both sides of the designed building at approximately 10 m distance from the building on which the PV system is installed. PV modules are defined on the roof, and shading analysis is performed according to the module layout. The software also allows animations for the desired day.

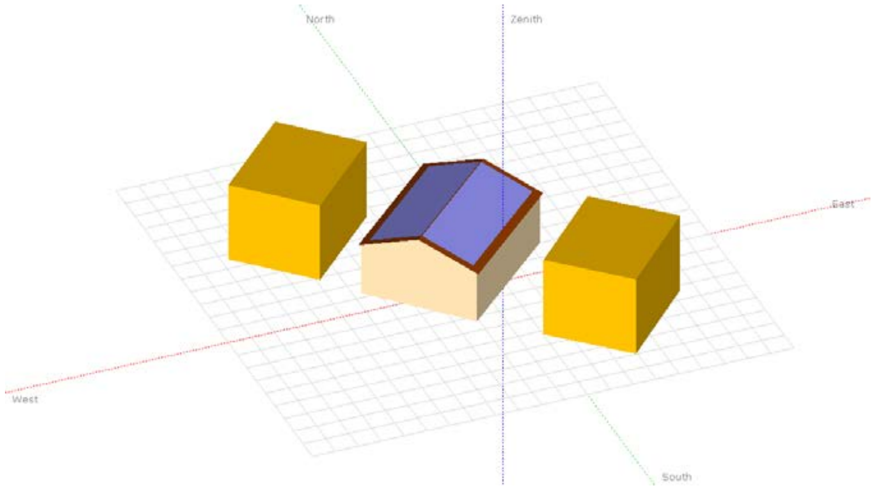

Figure 3: 3-D view of the system

2.7. Economic Analysis Based on Payback Period

A comprehensive feasibility analysis on a real case would require calculation of the net present value and internal rate of return (IRR) besides the payback period, to substantiate the benefits of investing on solar energy. However, for the sake of understanding the order of magnitude of the investment in response to the benefits, payback period is calculated from equation (4), for the household owners, given various subsidization models from the state, as well as the payback period on the state's side based on the production costs of the conventional energy alternatives.

$$Payback\ Period = \frac{Initial\ Investment}{\sum(Earning\ From\ Selling\ to\ Grid +\ Annual\ Savings\ from\ Electricity\ Bills)} \quad (4)$$

3. Results

3.1. Results of the PVsyst Analysis of the System

Simulation results reported by PVsyst show that system production is 121 MWh/year, specific production is 1,102 kWh/kWp/year, and normalized production is 3.02 kWh/kWp/day. Figure 4 shows the normalized production distribution within a year and the useful energy after losses.

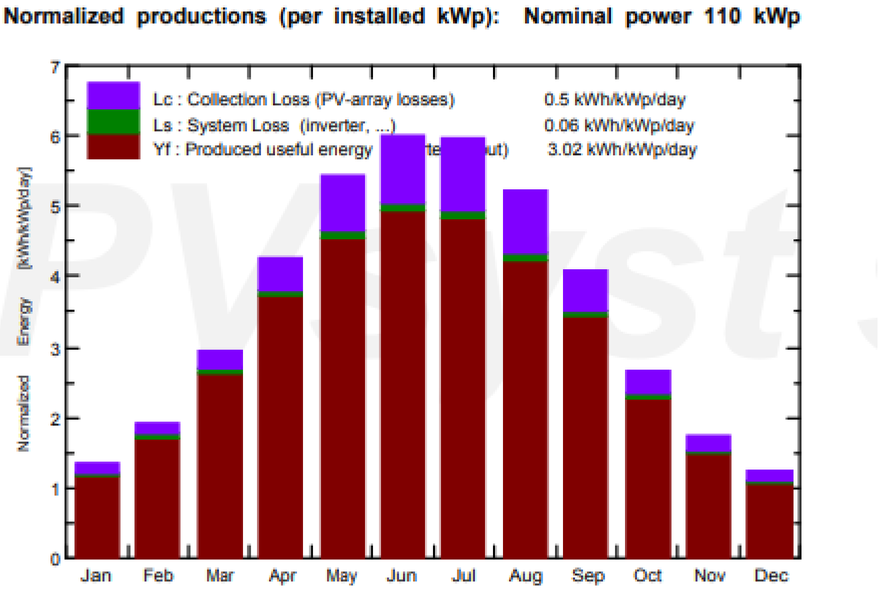

Figure 4: Normalized Production Distribution Within a Year

Performance ratio (PR) was determined by PVsyst as 0.843.

Figure 5 shows the performance value variation in months. It is possible to say that the largest values of the PR were obtained in February and March, due to the fact that there is less shading and lower ambient temperature, resulting in lower loss hence higher PR.

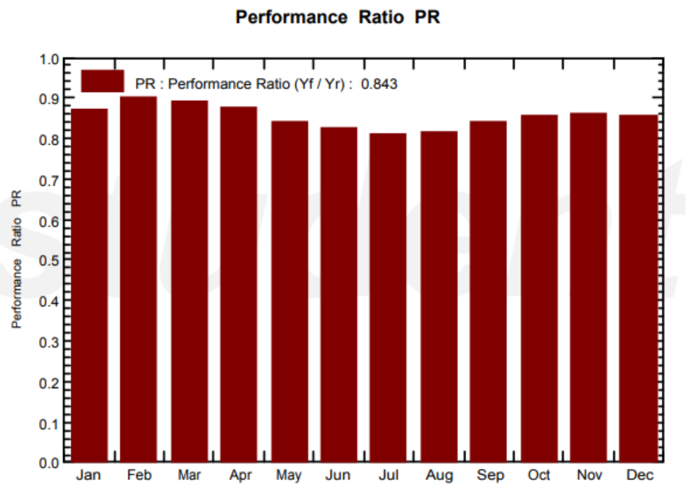

Figure 5: Performance Ratio

Table 6 shows the results of the analysis in terms of several parameters with respect to the months. According to the results, the average ambient temperature was 15.37 ˚C. The system generates 123.57 MWh with 121.03 MWh of energy fed back to the grid in a year. According to the loss diagram of the system, where although horizontal global irradiation amount is 1,351 kWh/m^2, the collector can receive 96.8 % of this amount which corresponds to 1,307.8 kWh/m^2. Effective irradiation on the collector was determined by Equation (5), after other losses. Due to 15.89 % of efficiency at the standard test condition, 136.3 MWh was calculated as the array's nominal energy. Additionally, the system was exposed to several losses such as shading, temperature, ohmic wiring, etc. According to the diagram, the major loss of the system is related to the temperature which is 6.79 %.

Table 6: Results of the simulation

	GlobHor (kWh/m^2)	DiffHor (kWh/m^2)	T_Amb (°C)	GlobInc (kWh/m^2)	GlobEff (kWh/m^2)	Earray (MWh)	E_Grid (MWh)	PR
January	43.5	26.30	6.22	42.6	39.4	4.19	4.08	0.873
February	55.6	31.58	6.27	53.8	50.6	5.44	5.31	0.899
March	95.0	59.26	9.05	91.8	86.9	8.97	8.97	0.891
April	132.1	69.87	12.42	127.4	121.6	12.23	12.23	0.874
May	173.7	76.94	17.88	167.8	160.5	15.48	15.48	0.840
June	186.2	91.57	22.47	179.9	171.7	16.29	16.29	0.825
July	191.2	88.20	25.68	184.9	176.7	16.42	16.42	0.809
August	167.0	80.95	25.54	161.4	154.2	14.44	14.44	0.814
September	126.8	59.75	20.93	123.0	117.1	11.33	11.33	0.839
October	85.3	43.98	17.05	82.8	78.1	7.79	7.79	0.857
November	54.1	28.70	11.93	52.8	49.1	4.98	4.98	0.859
December	40.2	22.96	8.26	39.4	36.2	3.71	3.71	0.858
Year	1,350.7	680.05	15.37	1,307.5	1,242.1	123.57	121.03	0.843

$$Effective\ irradiation\ on\ collectors = 1242\ \frac{kWh}{m^2} \times 691\ m^2 = 858.2\ MWh \quad (5)$$

3.2. Energy Demand of the Building

According to Energy Market Regulatory Authority (EPDK) of Turkey, the minimum monthly electricity consumption of a family of four-people is 230 kWh. However, the system is designed for 253 kWh consumption excluding heating demand for each flat. Given the constant building roof area, the percentage of the demand that can be supplied with PV energy at each month are given in Table 7, with respect to the grid energy capacities (E_Grid) given in Table 6. It can be observed that the PV system can provide all of the demand throughout the year, providing the ability for survival in case of power cut in addition to eliminating the energy cost of the users. In December where the energy supply is minimum, the system provides 104.7% of the energy demand.

Table 7: Energy Demand of the 14-flats building and energy supply of the system

Months	Energy Demand (kWh)	Surplus Energy (kWh)	Percent of the Supplied Energy for Demand
January	3,542	538	115.2%
February	3,542	1,768	149.9%
March	3,542	5,428	253.2%
April	3,542	8,688	345.3%
May	3,542	11,938	437.0%
June	3,542	12,748	459.9%
July	3,542	12,878	463.6%
August	3,542	10,898	407.7%
September	3,542	7,788	319.9%
October	3,542	4,248	219.9%
November	3,542	1,438	140.6%
December	3,542	168	104.7%

3.3. Economic Analysis of the System

Considering the initial cost of the PV system, shown in Table 8 which is quite high since PV-units are imported, it is calculated that for a 6-floor residential building, the payback of the system is calculated as 23.4 years, based on the parameters listed in Table 9 and based on the rates of the study date, [33]. However, if the surplus energy is fed back to the grid at 0.133 USD/kWh price that was implemented previously by the state, then the payback period becomes 6.6 years, as shown in

Table 11. When the generated electricity is sold at 0.08 USD/kWh, which is approximately the unit price of electricity for residential consumers, then the payback is calculated as 9 years. Calculations for other variations of feed-back price are shown in Table 11. According to a study [34], energy production cost of the powerplant investors per kWh is in the range of 0.066-0.151 USD/kWh for coal-based power plants and 0.061-0.087 USD/kWh for natural gas-based power plants as of 2014, in Turkey. So, even a feed-back price of 0.04 USD/kWh, which is lower than the cost of production of energy to the energy producer, the payback period for the consumer is reduced to 13.3 years, while this price becomes a saving that is transferred from the production cost to the consumer, creating also a future saving from new plant investment. Alternatively, a more encouraging scheme for the consumers would be a feed-back scheme with 0.133 USD/kWh price for the first 5 years, 0.08 USD/kWh for the second 5 years, and 0.04 USD/kWh for the remaining years, which imply an incentive by the state for the first five years, the payback period is calculated as 8.2 years.

Table 8: Initial Investment Cost

Investments	Quantity	Unit Price	Total Price
PV modules	360	200 USD	72,000 USD
Inverter	4	2,500 USD	10,000 USD
Supports for modules	110 kWp	0.08 USD/Watt	8,800 USD
Installation and other expenses (bi-directional meters, cables, etc.)	Lump-sum	Lump-sum	5,000 USD
Total			95,800 USD

Table 9: Payback Period of the System without Feeding Back to Grid

Unit price of the electricity per kWh (USD/kWh)	0.1171
Energy consumption of each flat per month (kWh)	253
Monthly electricity bill cost of each flat (USD/month)	24,33
Total electricity cost of each flat per year (USD/year)	291.93
Initial investment cost of the system (USD) - for 14 flats	95,800
Payback period of the system (year)	23.4

Table 10: Payback Period of the System with Feeding Back to Grid

Unit selling price to the grid (USD/kWh)	0.133
Earning from the surplus energy per year (USD/year)	10,443.96
Total saving from electricity cost of the building per year (USD/year)	4,086.98
Total earning from the system (USD/year)	14,530.94
Payback period (year)	6.59

Table 11: Payback Period of the System with Feeding Back to Grid in Different Prices

Description	%60 of 0.133 USD	%50 of 0.133 USD	%40 of 0.133 USD	%30 of 0.133 USD
Unit selling price to the grid (USD/kWh)	0.08	0.07	0.05	0.04
Earning from the surplus energy per year (USD/year)	6,266.37	5,221.98	4,177.58	3,133.19
Total earning from electricity cost of the building per year (USD/year)	10,353.35	9,308.96	8,264.56	7,220.17
Payback period (year)	9.25	10.29	11.59	13.27

3.4. Alternative Subsidization Schemes for Initial Cost of the System

Alternative subsidization schemes are also possible to decrease the initial investment burden on the households, which may increase the willingness to adopt the rooftop PV electricity generation.

It is proposed that 60% of state incentives on the initial investment cost, which corresponds to 57,480 USD can be exchanged for the excess energy that is produced throughout the year until this incentive is paid back, where this pay-back duration for the state is calculated as 18.3 years based on the 0.04 USD/kWh saving that can be achieved from the conventional energy production cost. By doing so, the payback period for households can reduce to 9.38 years, as shown in Table 12, among other alternative subsidization shares. One should also consider the additional saving on the state's side by refraining from new power plant investments in this proposed scheme while the auto-producers are provided with part of the capital that is hardly available for an average income family.

Table 12: Payback Period of the System in case of Incentive

Percent that compensates the initial investment cost of the system (%)	0%	10%	20%	30%	40%	50%	60%
Initial Investment cost (USD)	95,800	86,220	76,640	67,060	57,480	47,900	38,320
Payback period (years)	23.44	21.10	18.75	16.41	14.06	11.72	9.38

This subsidization scheme can be further developed. For example, the state can subsidize the system 100% and receive free energy from the system (producers) until this investment is paid back to the state. This system completely discharges the financial burden on the auto producers while gradually shifting the residential buildings to be part of an inter-active power plant system serving the self- and also the higher energy demanding buildings, replacing the polluting power plants alternatives.

3.5. Carbon Balance Calculations of the System

According to a study by Shahsavari and Akbari, 80% of carbon dioxide emissions and more than half of the greenhouse gas emissions is due to energy production [35]. They state that 4,600 GW of installed PV capacity can save more than 4 gigatons of carbon dioxide emissions annually, because PV systems do not lead to greenhouse gases in its operation and do not cause other pollutants [36]. PV systems generate electricity with low carbon emissions compared to non-renewable ones. The amount of saved CO_2 emissions were evaluated in this study, by using Carbon Balance Tool in PVsyst software for the on-grid PV system design with a capacity of 110 kWp. The calculation based on Life Cycle Emissions (LCE) takes into account the total life cycle of components used in design or the energy amount. The Carbon Balance Tool executes this calculation by comparing the electricity produced by the designed PV system and the electricity supplied by the existing grid by calculating the difference between the produced and saved amount of CO_2 emissions [37]. In PVsyst, carbon balance is calculated from four key factors which are the designed PV system production obtained by simulation for one year, system lifetime, life cycle emissions (LCE) of the grid, and life cycle emissions of the designed PV system [37]. LCE of the grid is given in $\frac{gCO_2}{kWh}$, and means the average CO_2 emissions for the electricity supplied by the grid. In contrast, LCE of the designed PV system is given in tCO_2 and includes the total CO_2 emissions due to the process of the installation and the construction [37]. In this study, annual degradation was taken as 1% for the simulation. Saved CO_2 emissions were determined as 1,340.761 tons for 30 years of system lifetime, by using Equation (6) that is taken from PVsyst and yearly carbon savings are calculated as shown in Table 13.

$$E_{grid} \times System\ Lifetime \times LCE\ Grid - LCE\ System = Carbon\ Balance \quad (6)$$

Table 13: Carbon Balance Values with respect to kWp and years

E_{grid}	121 MWh
System Lifetime	30 years
LCE Grid	489 g CO_2/ kWh
LCE System	199.8 t CO_2
Carbon Balance	1,340.761 t CO_2
Carbon Balance	44.692 t CO_2 / year
Carbon Balance	12.211 t CO_2 / kWp
Carbon Balance	0.407 t CO_2 / kWp / year

Variation of CO_2 balance with time is plotted by PVsyst software as shown in Figure 6.

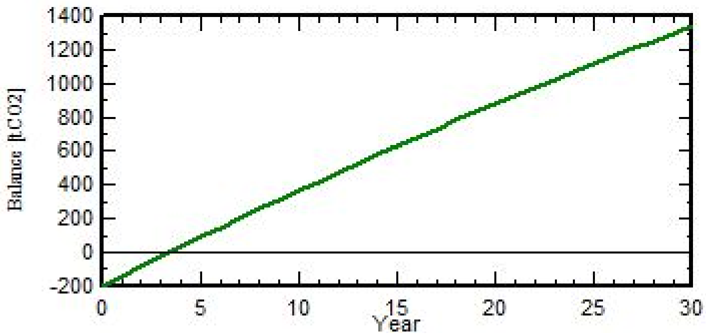

Figure 6: CO_2 Balance with respect to Years

4. Conclusions and Policy Implications

An on-grid PV rooftop system is designed to supply 100 percent of the electricity need in each month for a 6-floor, 14 flats residential building in Istanbul. A PV array with a capacity of 110 kWp, providing a monthly demand of 3,542 kWh/month was housed on the roof area of 691 m^2. System produces an annual 175 kWh/m^2 of installed array, which is less than 228 kWh/m^2 for a much smaller house demand of 3,647 kWh/year with 50% extra capacity in Adıyaman [10]. Cost of the 110 kW capacity system designed can be calculated as 871 USD/kW, which is very small compared to a 5.5 kW capacity system with battery in Romania [20], having a cost of 1,500 USD/kW and to the 2.5 kW on-grid system studied in Turkey [11], having a cost of 1,240 USD/kW, suggesting a smaller cost for multi-storey systems. For an off-grid system with a small capacity of 3 kW in Turkey, cost was calculated as 1,767 USD/kW [13].

Economic analysis of the system showed that, when all of the initial cost of the system was compensated by households, the payback period was determined as 23.4 years. Payback periods for various on-grid systems having much smaller capacities ranging from 2.5 kW to 5.5 kW reported to range between 8 to 11 years, [10, 11, 16, 18], whereas for a 25 kW residential system is Turkey payback is calculated as 14 years [9], suggesting a less feasible system with increased capacity for roof-top PV systems. Although PV powerplants with larger capacities show a payback of 7 to 14 years [6, 7], this cannot be compared to roof-top PV, because of different efficiencies in production and distribution.

Alternative subsidization schemes are investigated under two headings. The first subsidization scheme involved feeding-back the excess energy to the city grid. It is proposed that, if energy is sold back to the grid at 0.133 USD/kWh, the pay-back time is 6.6 years which may be tolerable by the household owners. However, this scheme may not be preferred on the state's side, since after 6.6 years household owners start to profit from this scheme. Hence, an alternative incentive scheme of 0.133 USD/kWh for first 5 years and later, a price set approximately at the cost of production of energy of conventional power plants is proposed as 0.08 USD/kWh for the second 5 years, and reduced by half to 0.04 USD/kWh for the remaining years with a 8.2 years payback period.

The second group of subsidization scheme considers partial subsidization of the initial investment by the state. A subsidy of 60% of the initial investment yields 9.4 years of payback period for the households. The state then may receive the excess energy free of charge from these households until the subsidized amount is paid back in 18.3 years to the state, with the saving from the production cost of 0.06 to 0.15 USD/kWh that the state would pay otherwise. It is proposed in other countries that subsidization of the initial investment is necessary, given the very long payback time [19] and the rate of subsidization proposed were as much as 50% to 90% [12, 20].

It is shown that an optimum subsidization scheme that would encourage investment of the household owners while saving the state from capital intensive and polluting power plant investments is possible, and may help faster adoption of the PV energy while leading to a substantial saving on carbon emissions of the buildings.

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