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3-Years Energetic and Economic Analysis of a 30kWp Rooftop PV Power Plant

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ABSTRACT

A 30 kWp rooftop solar photovoltaic (PV) power plant was modelled using energy balance equations, 3-year energy production and its economic return is calculated according to the feed-in tariff agreement. Hourly measured electricity generation and Excel spreadsheet simulation results were closely compatible. The system generated 45.35 MWh, 47.05 MWh and 46.34 MWh of energy in year 1, 2 and 3, respectively. It has been observed that the performance ratio of the PV system varies between 84.50 % and 90.27 %, while the capacity factor varies between 17.26 % and 17.63%. While 93.90 MWh of electrical energy has been injected into the grid over a 3-year period, 46.40 MWh of energy has been taken from the grid. The price of electricity injected and consumed was calculated according to the FIT conditions at the time the system was installed, and the payback period was calculated as approximately 6 years.

Keywords: Photovoltaic, rooftop PV, performance assessment, building-ıntegrated PV, economic analysis

30kWp Çatı Tipi PV Santralinin 3 Yıllık Enerjik ve Ekonomik Analizi

ÖZ

30 kWp'lik bir çatı üstü fotovoltaik (FV) güneş enerji santrali, enerji dengesi denklemleri kullanılarak modellenmiş ve 3 yıllık enerji üretimi ile ekonomik getirisi kurulduğu gündeki tarife anlaşmasına göre hesaplanmıştır. Excel'de yapılan modelleme ve benzetim sonuçları ile sistemden saatlik bazda ölçülen elektrik üretimi verilerinin oldukça uyumlu olduğu görülmüştür. Sistem 1., 2. ve 3. yılda sırasıyla 45,35 MWh, 47,05 MWh ve 46,34 MWh enerji üretmiştir. FV sistemin performans oranının %84,50 ile %90,27 arasında değişirken, kapasite faktörünün de %17,26 ile %17,63 arasında değiştiği gözlemlenmiştir. 3 yılda üretim fazlası olarak 93,90 MWh elektrik enerjisi şebekeye verilirken, şebekeden 46,40 MWh enerji çekilmiştir. Enjekte edilen ve tüketilen elektriğin bedeli, sistemin kurulduğu andaki bağlantı anlaşması koşullarına göre hesaplanmış ve geri ödeme süresi yaklaşık 6 yıl olarak bulunmuştur.

Anahtar Kelimeler: Fotovoltaik, çatı üstü FV, performans değerlendirmesi, binaya entegre FV, ekonomik analiz

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1. INTRODUCTION

Energy is as vital as air, water and food, but the way it is generated often contributes to global warming because of the greenhouse gasses (GHG) released during both production and consumption. It is estimated that 79.7% of the energy consumed in the world comes from fossil fuels (REN21, 2019). In 2018, the amount of electrical energy produced from fossil fuels worldwide was 26,614.8 TWh, of which 38% was from coal and 23% from natural gas (BP, 2019). The share of renewable resources in this production in that same year was 26.2% of which 15.8% was hydro-electric, 5.5% wind and 2.4% solar (REN21, 2019). Most countries have begun to move towards renewable technologies and low carbon emissions from energy production to control this climate-changing trend in the world. Solar technology is expected to play an important role in the coming years because of technological advances and falling prices among low carbon emission technologies (Adaramola, 2015). The CO2 emissions from electricity generation by wind, solar, hydroelectric, natural gas, diesel and lignite were 10, 23, 26, 499, 888 and 1054 tons per GWh respectively (WNA, 2011). According to these emission values, the most suitable source for electricity generation is the sun. Generally, photovoltaic (PV) systems are installed on (1) marginal agricultural lands, (2) building surfaces and roofs, and (3) water surfaces (Ates, Yilmaz, & Gulgen, 2020). However, there is little or no marginal agricultural land or water surface in urban areas. Therefore, rooftop PV power plants are particularly advantageous there, as the cost of operation and maintenance is very low, the systems are quiet, and they do not create visual or environmental pollution.

There are abundant studies of the technical or economic performance of rooftop PV systems. A study of 170 rooftop PV systems in Germany in 1997 found that the performance ratio (PR) ranged from 47.5% to 81% with an average of 66.5% (Decker & Jahn, 1997). In 2004, the evaluations of PV systems on 235 buildings in Germany and 133 buildings in other EU countries found PR values between 63.9% and 69.4% (Jahn & Nasse, 2004). The average performance ratio of the 6868 rooftop PV systems in France was 76% in 2010 (Leloux, Narvarte, & Trebosc, 2012). An evaluation of the building stocks of the 27 EU member states found that there was a building integrated PV technical potential of 951GWp, and that 840TWh of electricity could be generated annually (Defaix, van Sark, Worrell, & de Visser, 2012). The evaluation of four rooftop PV systems in Abu Dhabi, UAE, found PR values between 70% and 81% (Emziane & Al Ali, 2015). In addition, the PR of rooftop PV systems were between 60% and 93.3%, and specific yields ranged between 812.76 kWh/kWp/year and 1802kWh/kWp/year, in Poland (Pietruszko & Gradzki, 2003), Northern Ireland (Mondol, Yohanis, Smyth, & Norton, 2006), the island of Crete (Kymakis, Kalykakis, & Papazoglou, 2009), Dublin (Ayompe, Duffy, McCormack, & Conlon, 2011), Muğla, Turkey (Eke & Demircan, 2013), Durban, South Africa (Ebhota & Tabakov, 2021), Malaysia (Farhoodnea et al., 2015; Humada et al., 2016), Sohar, Oman (Kazem et al., 2014), Norway (Adaramola, 2015; Adaramola & Vågnes, 2015), Algeria (Cherfa et al., 2015; Dabou et al., 2016), Serbia (Milosavljević et al., 2015), Morocco (Attari et al., 2016), Portland, India (Dondariya et al., 2018; Yadav & Bajpai, 2018), Kuwait (Al-Otaibi, Al-Qattan, Fairouz, & Al-Mulla, 2015) and Singapore (Wittkopf, Valliappan, Liu, Ang, & Cheng, 2012). In addition, there are many studies evaluating the economic and environmental performance of PV systems (Datta, Kalam, & Shi, 2020; Njoku & Omeke, 2020; Rughoo & Ramasesha, 2020; Tırmıkçı & Yavuz, 2020).

The first aim of householders who install rooftop PV systems is to reduce their electricity bills and, if possible, earn income by selling electricity to the grid. This requires making legal arrangements with the government. Two different mechanisms are generally used for injecting energy from renewable sources to the grid: feed-in tariffs (FIT) and net metering. According to FIT, households can sell the PV-generated surplus electricity to distribution or electricity companies at a certain price, while they can buy the electricity, they consume at the standard electricity price. There is a bidirectional electric meter in this system, and the amounts of electricity injected to the grid and consumed from the grid are recorded and accounted for separately. In a net metering system, there is only one electricity meter. It rotates forwards when electricity is consumed from the grid and backwards when electricity is injected to the grid. At the end of each billing period, the amount owed or gained by the householder is assessed (Yamamoto, 2012).

FIT is the one of the most widely used policies in the world to promote renewable energy (T. D. Couture, Cory, Kreycik, & Williams, 2010; T. Couture & Gagnon, 2010). It has had success in the German and Spanish renewable energy markets. In addition, it is used in more than 40 countries around the world and in many states and municipalities in the USA (Cory, Couture, & Kreycik, 2009). In Turkey, legal arrangements were made in 2013 when the FIT model was introduced. According to that model, 13.3 cent/kWh is the tariff for injecting PV-generated electricity to the grid (EPDK, 2013).

This study analyses the technical performance and economic income of a 30kWp rooftop PV system under the feed-in tariff conditions that applied in Turkey at the time the system was installed.

2. PHOTOVOLTAIC (PV) SOLAR POWER PLANT (SPP)

The PV system was installed on the roof of the MCBU Koprubasi Vocational School, 38.751 Latitude, 28.395 Longitude, and 251m above sea level in Manisa, Turkey. The system had 116 modules which were mounted 15 cm above the roof surface to allow for natural ventilation. Because of the shape of the roof and the building's orientation, the tilt angle was 12 degrees, and the azimuth angle was -20 degrees (Fig 1).

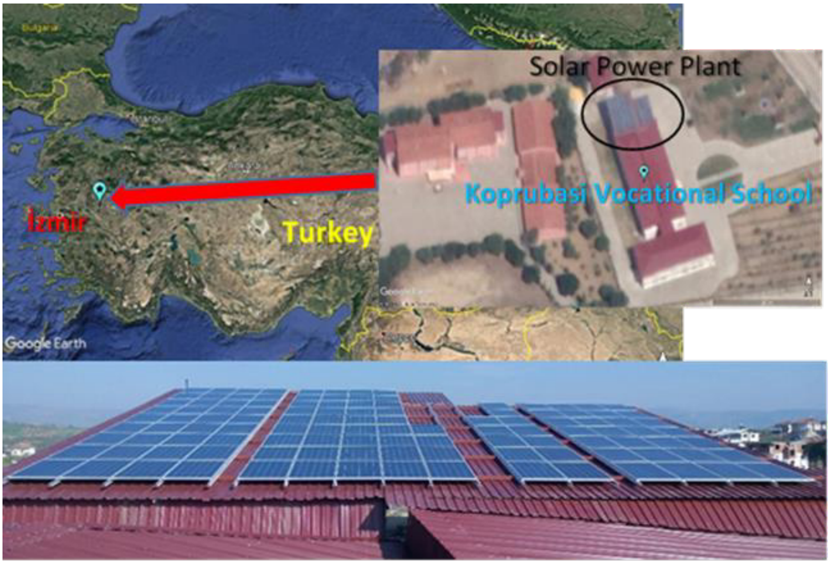

Fig 1. Location of the Koprubasi Vocational School and its Solar Power Modules

Each Odul solar OSP260 module had 260Wp output power and contained 60 polycrystalline silicon cells. The modules efficiency was %16 and Temperature Coefficient of Pmax was -0,45 %/ °C. The PV modules were not manually cleaned in any way during the monitoring period, except for rain.

PV modules consisting of 6 strings were connected to the input of a 30 kWp Huawei SUN2000-33KTL inverter with 3 MPPT inputs. The 3-phase inverter with an efficiency of 98.6% was directly connected to the 220V grid via a bidirectional energy meter and the data was recorded for 3 years as of July 2018.

3. METHODOLOGY

3.1 Modelling the PV Generator

The layers of a mono or poly crystalline PV module consist of glass, ethylene vinyl acetate (EVA), solar cells and tedlar (Fig 2).

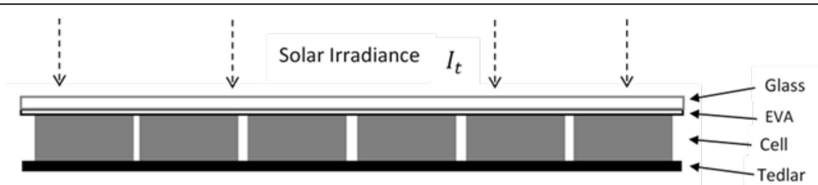

Fig 2. Layers of a PV Module

The energy balance equation for the polycrystalline silicon (Si) PV modules can be written as (Dubey, Sandhu, & Tiwari, 2009; Gaur & Tiwari, 2013).

[Rate of absorbed solar radiation received by solar cells]

=[Rate of thermal energy loss from solar cells]+

Rate of ambient thermal energy loss from solar cells through the top glass surface□

[Rate of electrical energy generated from the solar cells]

$$\tau_g[\alpha_c\beta_c I_t + (1-\beta_c)\alpha_T I_t] = U_t(T_c - T_a) + U_b(T_c - T_a) + \tau_c\eta_c\beta_c I_t \tag{1}$$

Here, U_t and U_b can be defined as

$$U_t = \left[\frac{L_g}{K_g} + \frac{1}{h_0}\right]^{-1} \tag{2}$$

$$U_b = \left[\frac{L_T}{K_T} + \frac{1}{h_i}\right]^{-1} \tag{3}$$

The following equations are obtained by performing the arithmetic operations in Eq. (1) (Dubey et al., 2009; Gaur & Tiwari, 2013):

$$T_c = \frac{\left[\tau_g\{\alpha_c\beta_c + (1-\beta_c)\alpha_T - \eta_c\beta_c\}I_t + U_L T_a\right]}{U_L} \tag{4}$$

Where $U_L = U_t + U_b$

$$\eta_c = \frac{\eta_0\left[1-\beta_0\left\{(T_a - T_0) + \left(\{\tau_g\alpha_c\beta_c + (1-\beta_c)\alpha_T\}/U_L\right)I_t\right\}\right]}{\left[1-\left(\eta_0\beta_0\tau_g\beta_c/U_L\right)I_t\right]} \tag{5}$$

$$\eta_m = \eta_c\beta_c\tau_g \tag{6}$$

The annual electric energy production value of the PV system can be found with:

$$E_{an} = \sum_{d=1}^{365}\sum_{h=1}^{24} H_{i_{d,h}} A_m \eta_{m_{d,h}} C_m \tag{7}$$

where d is the number of day of the year, h is the hour of the day, Hi (Wh/m^2) is the total irradiance on the inclined surface, A_m (m^2) is the module area, η_m is the module efficiency and C_m is the module count.

3.2 Calculation of the Yields, Performance Ratio and Capacity Factor

The data of the grid connected SPP were recorded as hourly averages for 3 years. To determine the performance of the PV system, the following metrics were calculated as defined by IEC Standard 61724 (IEC 61724, 1998) array yield (Y_A), final yield (Y_F), reference yield (Y_R), performance ratio (PR) and capacity factor (CF).

The array yield, which shows the efficiency of the PV array, is calculated as (Ates & Singh, 2021; Ayompe et al., 2011; IEA, Clavadetscher, & Nordmann, 2007):

$$Y_A = \frac{E_{DC}\ [kWh]}{P_{PV_{rated}}\ [kW]} \tag{8}$$

The final yield, which shows the efficiency of the PV SPP with all its components, is given by (Kymakis et al., 2009) and calculated as:

$$Y_F = \frac{E_{AC}\ [kWh]}{P_{PV_{rated}}\ [kW]} \tag{9}$$

The reference yield value is calculated as (R. Sharma & Goel, 2017):

$$Y_R = \frac{H_i\ [kWh/m^2]}{1\ [kW/m^2]} \tag{10}$$

When the reference yield, array yield and system yield are known, capture losses (L_c) can be calculated by subtracting the array yield from the reference yield and system losses (L_s) can be calculated by subtracting the final yield from the array yield (Wittkopf et al., 2012).

Performance ratio (PR) given as a percentage is an indicator of the quality of a PV plant, regardless of location and calculated by dividing final yield to reference yield (Eicker, 2014; R. Sharma & Goel, 2017).

$$PR = \frac{Y_F}{Y_R} \tag{11}$$

The capacity factor (CF) is a parameter that shows the performance of the SPP system according to the installation type and location, and shows how close the electricity produced in the system is to the maximum energy that can be produced (Kazem et al., 2014).

$$CF = 100 \frac{E_{AC,an}}{P_{PV,rated} * 8760} \tag{12}$$

3.3 Economic Income Analysis

A 30-kWp rooftop PV plant was installed in April 2018, and the necessary legal procedures were completed at end of May 2018, when the production of electricity started. The netting method used in Turkey in 2018 is given in (EPDK, 2013), and the applicable fees are given in the Appendix part in the law. According to the regulation, the energy consumed from the grid and the energy fed to the grid by being produced by renewable energy sources is measured on an hourly basis and subsidies are applied for electricity injection into the grid. Within the framework of these subsidies, the electricity injected to the grid is charged at 0.133 USD/kWh for 10 years. The consumed energy from the grid is charged at three different tariffs according to the consumption time. The sales to the grid and the purchase prices, with all taxes included, are given in Table 1.

Table 1. Electricity tariffs and hours

Tariffs and hours	Day (06.00-17.00)	Peak (17.00-22.00)	Night (22.00-06.00)
Selling to the grid Price (SP) (USD)	0.133 (T_s)	0.133 (T_s)	0.133 (T_s)
Purchase Price (PP) (USD)	0.089 (T_1)	0.129 (T_2)	0.056 (T_3)

The monthly consumption bill (CB) is calculated with the following equation, using the consumed energy per hour (CEh) from the grid:

$$CB_{mn} = \sum_{d=1}^{N_d} \left[\left(\sum_{h=6}^{16} CE_h T_1 \right) + \left(\sum_{h=17}^{21} CE_h T_2 \right) + \left(\sum_{h=22}^{24} CE_h T_3 \right) + \left(\sum_{h=1}^{5} CE_h T_3 \right) \right] \tag{13}$$

where N_d is the number of days in the calculated month.

The monthly selling bill (SB) is calculated in the following equation, using the energy delivered hourly (DEh) to the grid:

$$SB_{mn} = \sum_{d=1}^{N_d} \sum_{h=1}^{24} DE_h T_s \tag{14}$$

The monthly net profit (NP) is calculated as the difference between the selling bill and the consumption bill. Here, the annual net profit is calculated as:

$$NP_{an} = \sum_{mn=1}^{12} (SB_{mn} - CB_{mn}) \tag{15}$$

The annual electricity consumption bills of Koprubasi Vocational School were calculated. This value was considered as annual fixed income (FI_a) in this study, since this value would have continued as an annual fixed expense if the PV system had not been installed. 10-year contracts are made for grid connection in Turkey. At the end of 10 years, agreements are renewed according to the grid connection rules of that time. Considering the initial investment cost (IC) of the system, the 10 years' annual cash flow (CF_a) and payback period is calculated as:

$$CF_{an} = -IC + \sum_{y=1}^{10} FI_{an} + NP_{an,y} \tag{16}$$

4. RESULTS

4.2 Measured Radiation and Temperature Values

The monthly total radiation on the modules' surface and the monthly average ambient temperature in Koprubasi, where the PV plant is installed, are given in Fig 3.

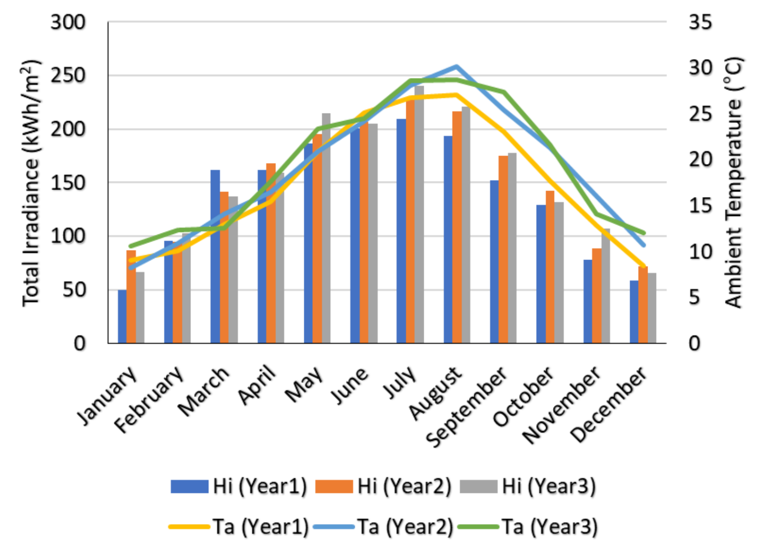

Fig 3. Total İrradiance On Module Surface and Monthly Average Ambient Temperature İn Köprübaşı

In Koprubasi district, the lowest monthly total irradiance on the inclined surface was 49.36 kWh/m² in January of year 1 and the highest value was 240.47 kWh/m² in July of year 3. While there were imbalances in the amounts of radiation between years in January and March, it was observed that the values were closer to each other in the other months. The lowest average monthly temperature was 8.17°C in January of year 2, and the highest was 30.15°C in August of year 2.

4.2 Comparison of Simulation Results and Measured Values

To examine the closeness of the simulation results to the measured energy output values of the modules, the 3-year values are compared and given in Fig 4. The year 1 in which measurements were made had 365 days, year 2 had 366 days and year 3 had 365 days. In Figure 4, it is seen that while the simulation values are high, the measured values are low and sometimes there is no electricity production at all. This shows that PV SPP was not producing due to the power outage in the region, although the solar radiation was suitable during the daytime hours.

A total of 26,304 hours of measurements for these three years were compared with the simulation results using the IBM SPSS Statistics software. The Pearson Correlation coefficients between measured and simulated power output of the modules was calculated as 0.993 (Table 2). These results showed that the measured values were in perfect harmony with the simulation results.

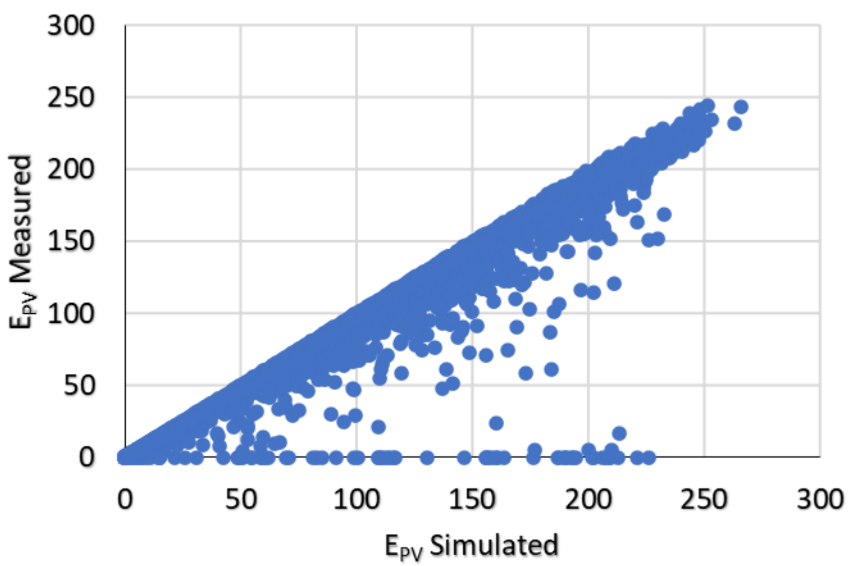

Fig 4. Correlation of its Measured Values with the Simulation of the Energy Generated by the Module

Table 2. Correlation Coefficients

		Simulated	Measured
Simulated	Pearson Correlation	1	,993**
	Sig. (2-tailed)		,000
	N	26304	26304
Measured	Pearson Correlation	,993**	1
	Sig. (2-tailed)	,000	
	N	26304	26304
**. Correlation is significant at the 0.01 level (2-tailed)			

4.3 Performance of the PV System

The total radiation measured on the module surface over a 3-year period and the AC energy values produced by the PV GES were recorded in 15-minute periods and the results are given in Table 3.

While the monthly total radiation on the module surface varies between 49.36 kWh/m^2 and 240.47 kWh/m^2, it has been observed that the monthly total values of the generated electric energy vary between 1.422.58 kWh and 5.896.28 kWh. The 3-year performance values of the PV SPP system are also given in Table 4 on an annual basis.

Table 3. Measured Total İrradiance on the Module's Surface and Generated AC Energy Values by PV SPP

Months	H_i (kWh/m^2)			$E_{Generated}$ (kWh)		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
January	49.36	86.87	65.99	1,422.58	2,483.27	1,848.08
February	95.76	94.63	102.98	2,725.27	2,623.21	2,841.14
March	161.44	141.64	137.21	4,323.43	3,791.08	2,997.07
April	161.66	167.78	159.42	4,246.93	4,385.29	4,189.77
May	186.56	195.61	214.36	4,896.83	5,027.56	5,382.69
June	200.58	206.60	204.99	5,044.99	5,254.98	5,196.41
July	209.02	227.51	240.47	5,660.97	5,685.16	5,896.28
August	193.11	216.07	220.55	5,260.55	5,332.09	5,430.16
September	152.30	174.93	177.83	4,227.01	4,426.45	4,403.60
October	128.69	142.60	131.62	3,663.39	3,746.99	3,413.46
November	77.58	88.05	106.83	2,202.56	2,341.11	2,909.68
December	58.52	71.67	65.57	1,675.91	1,955.72	1,828.90
Annual	1,674.57	1,813.98	1,827.82	45,350.42	47,052.91	46,337.25

Table 4. Annual Yield and Performance Values

	Year 1	Year 2	Year 3
H_i (kWh/m²)	1,674.57	1,813.98	1,827.82
$E_{Generated}$ (kWh)	45,350.42	47,052.91	46,337.25
Array Yield (h/d)	4.23	4.38	4.32
Final Yield (h/d)	4.14	4.29	4.23
Reference Yield (h/d)	4.59	4.96	5.01
Capture Losses (h/d)	0.36	0.58	0.68
System Losses (h/d)	0.09	0.09	0.09
Performance Ratio (%)	90.27	86.46	84.50
Capacity Factor (%)	17.26	17.86	17.63

When table 4 is examined, it is seen that the total in-plane solar insolation increases every year, but the production amount decreases in year 3 compared to year 2. The same situation is observed in array yield and final yield values. When the values of capture losses and system losses are examined, it is seen that the value of capture losses increases every year, while the value of system losses remains constant. This situation can be explained by two reasons. The area where the school is located is an agricultural area. A large amount of dust is spread around during agricultural activities. The first reason may be that the dust dispersed abundantly during agricultural activities covers the surface of the modules. It has been said that dust can reduce the output power of photovoltaic modules by 21.57% (Lasfar et al., 2021). The second reason may be that there are occasional power cuts in the region. When the recorded data were examined, it was seen that the power outages were more common in year 3 compared to other years. In this case, it can be said that both factors influence the capture losses. However, the weights of both factors can be examined separately in another study.

4.4 Economic Results and Payback Period

The energy produced, the energy injected to the grid, the energy withdrawn from the grid, the energy consumed by the school were recorded on an hourly basis to make the economic analysis of the system and given in Table 5.

During the daytime (T1) tariff, PV SPP produced a total of 1,584.97-1,725.74 kWh of electricity annually. The school, which consumed 23,778.17 kWh of electrical energy in the year 1, consumed 20,056.84 kWh in the year 2, with the effect of the Covid-19 pandemic that started in April, and 14,881.41 kWh in the year 3. In the T1 tariff range, the electrical energy injected to grid and withdrawn from the grid was evaluated and

Table 5. Irradiance and Produced Energy of the SPP in Koprubasi

Year	FIT	Hi (kWh/m²)	Generated (kWh)	Given to grid (kWh)	Taken from grid (kWh)	School Consumption (kWh)	Net Energy (kWh)
1	T1	1,584.97	42,871.45	28,005.76	8,912.48	23,778.17	19,093.28
	T2	88.88	2,475.78	1,301.60	3,539.12	4,713.30	-2,237.52
	T3	0.72	3.18	0	7,361.28	7,364.46	-7,361.28
2	T1	1,711.67	44,423.07	29,926.40	5,560.17	20,056.84	24,366.23
	T2	101.98	2,628.31	1,623.60	3,234.24	4,238.95	-1,610.64
	T3	0.33	1.52	0	7,322.19	7,323.71	-7,322.19
3	T1	1,725.74	43,723.67	31,256.94	2,414.68	14,881.41	28,842.26
	T2	101.42	2,611.61	1,785.84	2,299.84	3,125.61	-514.00
	T3	0.66	1.97	0	5,754.14	5,756.11	-5,754.14
Total		5,316.37	138,740.58	93,900.14	46,398.14	91,238.58	47,502.00

the annual net amount of energy injected to the grid was measured as 19,093.28 kWh, 24,366.23 and 28,842.26 kWh, respectively. During peak hour (T2), only in summer, there was very low electricity production due to weak radiation. Despite this low production, since the working hours are over and only cleaning, maintenance-repair activities are carried out in the school building, electricity consumption is also low. The amount of energy withdrawn from the grid during this (T2) period was measured as 2,237.52 kWh, 1610.64 kWh and 514 kWh, respectively. At night (T3), only infrastructure systems such as security, lighting and network consume energy in the school building. During this period, only a very low amount of electricity was produced on some days due to the very weak radiation falling on the module surface in the very early hours of the morning. The decrease in energy consumption in year 3, when the effect of the pandemic increased and schools were not opened almost all year, was also seen in this T3 period.

The 3-year electricity production of the PV SPP system, the electricity consumption of the school, the costs of the electricity supplied to and drawn from the grid according to the tariffs are given in the Table 6. The standard bill line in the table represents the annual total electricity bill that the school would pay if the PV system was not installed. Sales invoices lines represent the income from the electricity injected to the grid, the purchase payment line represents the money paid for the electricity drawn

Table 6. Economic Table

Years		Year 1	Year 2	Year 3	Total	Average
Generated (kWh)		45,350	47,053	46,337	**138,741**	**46,247**
School Consumption (kWh)		35,856	31,620	23,763	**91,239**	**30,413**
Standard Bill ($)		3,416	2,987	2,233	**8,636**	**2,879**
Sales Invoices	T1 ($)	3,725	3,980	4,157	**11,862**	**3,954**
	T2 ($)	173	216	238	**627**	**209**
	T3 ($)	-	-	-	**-**	**-**
	Total ($)	3,898	4,196	4,395	**12,489**	**4,163**
Purchase Payment ($)		1,809	1,438	906	**4,153**	**1,384**
Net Income ($)		2,089	2,758	3,489	**8,336**	**2,779**

from the grid, and the net income line represents the annual income as a result of the purchase and sale transactions.

The bill of 8,636 dollars that had to be paid in a 3-year period was eliminated with the established PV GES. In this period, an electricity bill of $4,153 was paid, while

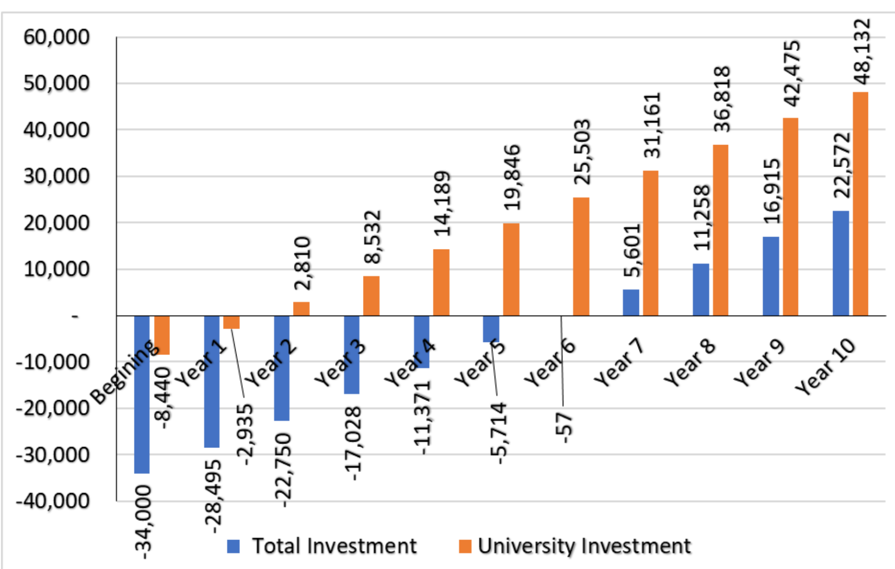

Fig 5. 10-Year Cash Flow

an income of $12,489 was achieved from the surplus electricity injected into the grid. The annual average electricity bill that the school was saved from paying was calculated as $2,879 and was called fixed income in the calculations. The initial investment cost of the system was $34,000, of which $8,440 was paid by the university, while the remaining 25,560 was paid by the Zafer development agency. The graph drawn by calculating the 10-year cash flow of the PV system is given in Fig 5.

According to these calculations, the university, which initially invested $ 8,440, started to make a profit by recovering this investment cost in the middle of the second year. According to the calculations, it was seen that the payback period of the PV system installed at a cost of $ 34000 is approximately 6 years.

5. CONCLUSION

In this study, the energy performance and economic income analysis of a 30 kWp rooftop PV system in Köprübaşı Vocational School in Turkey for 3 years were evaluated. The PV module's electricity output was modelled by writing the energy balance equations, and the electricity production was calculated hourly. Measured results were compared with simulation results using the IBM SPSS Statistics software, and the Pearson Correlation coefficient between them was found to be 0.993. These results showed that the measured values were in perfect harmony with the simulation results.

On the module surface of the PV SPP installed with a slope of 12 degrees, the annual total radiation between July 2018 and June 2021 was recorded as 1.674.57 kWh/m2, 1.813.98 kWh/m2, and 1.827.82 kWh/m2, respectively. The annual total electrical energy generated under this radiation was measured as 45.350.42 kWh, 47.052.91 kWh, 46,337.25 kWh. When the annual yields and losses are analysed, especially the rapid decrease in capture losses draws attention. Although it is thought that the reason for this decrease is the pollution on the module surface or the frequent power cuts in the region, the effect of these factors should be examined in another study.

The calculated annual performance ratio values are 90.27%, 86.46% and 84.50%, respectively. The effect of capture losses on the performance ratio is also clearly seen here. According to the calculations made by Fraunhofer ISE in 1994, 1997 and 2010 to compare the performance of PV systems, it was observed that the performance ratios were around 70% in the 1990s, while in the 2000s it ranged from 80% to over 90% (Fraunhofer ISE, 2020). Thus, this PV system, which produces electrical energy with a performance ratio of over 80% in three years, has met performance expectations.

The annual capacity factor values of the system were calculated as 17.26%, 17.86% and 17.63%. In a study done in Tamil Nadu, South India in 2019, the capacity factors of systems using polycrystalline silicon (p-Si) and copper indium selenium (CIS) modules were calculated as 17.99% and 19.57%, respectively (Ramanan et al., 2019).

In a 6-month study conducted at the Universiti Kebangsaan Malaysia, the monthly average capacity factor of a 3kW PV system was 15.70% (Farhoodnea et al., 2015). Research has shown that PV systems operate under a very wide range of capacity factors, depending on the region where they are installed. In the literature, capacity factors were found to be 7.91% in Southern Algeria (Necaibia et al., 2018), 9.27% in Khatkar-Kalan, India (V. Sharma & Chandel, 2013), 15.21% in Chandigarh, India (Kumar et al., 2020), 15.6% and 14.4% in southwestern Malaysia (Humada et al., 2016), 14.84% in Tangier, Morocco (Attari et al., 2016), 21% in Sohar, Oman (Kazem et al., 2014) and 12.88% in Niš, Republic of Serbia (Milosavljević et al., 2015). Compared to those results, it can be said that Koprubasi PV SPP performs well according to its location.

If this PV system were not installed, the school would pay electricity bills of $3,416, $2,987 and $2,233 each year, respectively. The decrease in the bill is due to the covid-19 pandemic that emerged in April 2019. Without the pandemic, this electricity bill would have averaged around $3,400 per year. In this case, the average annual electricity bill is $2,879. In this 3-year period, an electricity bill of $4,153 was paid, while an income of $12,489 was achieved from the surplus electricity injected into the grid. The initial investment cost of the system, which was established in 2018 with a 10-year purchase guaranteed connection agreement, was $34,000, of which $8,440 was covered by the university and $25,560 by Zafer Development Agency. According to the measurements made in the 3-year period and the electricity bills, the first investment fee paid by the university was taken back in the middle of the second year. Considering the 3-year average net profit and the average electricity bill, the payback period of the total initial investment cost was calculated as approximately 6 years according to the simulation made from the fourth to the tenth year.

NOMENCLATURE

A_m Area of module (1.63 m^2)

h_0 Heat loss coefficient from the top (W/m^2K) (5.7+3.8v (Duffie & Beckman, 1991))

h_i Heat loss coefficient from the bottom (W/m^2K) (2.8 + 3.0v (Cole & Sturrock, 1977))

I_t Incident solar intensity (W/m^2)

H_i The total radiation on an inclined surface during a period (Wh/m^2).

K Thermal conductivity (W/mK). (0.033 for tedlar, 1.1 for glass (Gaur & Tiwari, 2013))

T Temperature (K)

U_t Overall top loss heat transfer coefficient from solar cell to ambient (W/m^2 K)

U_b Overall bottom loss heat transfer coefficient from solar cell to ambient ($W/m^2 K$

U_L Overall loss heat transfer coefficient from solar cell to ambient ($W/m^2 K$)

L Length (m). (0.0005 for tedlar, 0.003 for glass)

v Air velocity.

Subscripts

a Ambient

c Solar cell

g Glass

m Module

T Tedlar

d Day

h Hour

an Annual

Greek letters

α Absorption factor (0.5 for tedlar, 0.9 for cell)

β_0 Temperature coefficient of the material (0.0049 for p-Si)

β_c Packing density

η Efficiency

η_0 Solar cell efficiency at STC (17.8% from module catalogue)

τ Transmissivity (0.95 for glass)

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REFERENCES

Adaramola, M. S. (2015). Techno-economic analysis of a 2.1 kW rooftop photovoltaic-grid-tied system based on actual performance. *Energy Conversion and Management,* 101, 85–93. https://doi.org/10.1016/j.enconman.2015.05.038

Adaramola, M. S., & Vågnes, E. E. T. (2015). Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions. *Energy Conversion and Management,* 90 (2015), 458–465. https://doi.org/10.1016/j.enconman.2014.11.028

Al-Otaibi, A., Al-Qattan, A., Fairouz, F., & Al-Mulla, A. (2015). Performance evaluation of photovoltaic systems on Kuwaiti schools' rooftop. *Energy Conversion and Management,* 95, 110–119. https://doi.org/10.1016/j.enconman.2015.02.039

Ates, A. M., & Singh, H. (2021). Rooftop solar Photovoltaic (PV) plant – One year measured performance and simulations. *Journal of King Saud University - Science,* 33(3), 101361. https://doi.org/10.1016/j.jksus.2021.101361

Ates, A. M., Yilmaz, O. S., & Gulgen, F. (2020). Using remote sensing to calculate floating photovoltaic technical potential of a dam's surface. *Sustainable Energy Technologies and Assessments,* 41(July), 100799. https://doi.org/10.1016/j.seta.2020.100799

Attari, K., Elyaakoubi, A., & Asselman, A. (2016). Performance analysis and investigation of a grid-connected photovoltaic installation in Morocco. *Energy Reports,* 2 (December 2015), 261–266. https://doi.org/10.1016/j.egyr.2016.10.004

Ayompe, L. M., Duffy, A., McCormack, S. J., & Conlon, M. (2011). Measured performance of a 1.72 kW rooftop grid connected photovoltaic system in Ireland. *Energy Conversion and Management,* 52(2), 816–825. https://doi.org/10.1016/j.enconman.2010.08.007

BP. (2019). *Statistical Rewiev of World Energy.* London, UK.

Cherfa, F., Hadj Arab, A., Oussaid, R., Abdeladim, K., Bouchakour, S., Arab, A. H., … Bouchakour, S. (2015). Performance Analysis of the Mini-grid Connected Photovoltaic System at Algiers. *Energy Procedia,* 83, 226–236. https://doi.org/10.1016/j.egypro.2015.12.177

Cole, R. J., & Sturrock, N. S. (1977). The convective heat exchange at the external surface of buildings. *Building and Environment, 12* (4), 207–214. https://doi.org/https://doi.org/10.1016/0360-1323(77)90021-X

Cory, K., Couture, T., & Kreycik, C. (2009). Feed-in Tariff Policy: Design, Implementation, and RPS Policy Interactions. *United States.* https://doi.org/10.2172/951016

Couture, T. D., Cory, K., Kreycik, C., & Williams, E. (2010). Policymaker's Guide to Feed-in Tariff Policy Design. *United States.* https://doi.org/10.2172/984987

Couture, T., & Gagnon, Y. (2010). An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy,* 38(2), 955–965. https://doi.org/10.1016/j.enpol.2009.10.047

Dabou, R., Bouchafaa, F., Arab, A. H., Bouraiou, A., Draou, M. D., Neçaibia, A., & Mostefaoui, M. (2016). Monitoring and performance analysis of grid connected photovoltaic under different climatic conditions in south Algeria. *Energy Conversion and Management,* 130, 200–206. https://doi.org/10.1016/j.enconman.2016.10.058

Datta, U., Kalam, A., & Shi, J. (2020). The economic prospect of rooftop photovoltaic (PV) system in the commercial buildings in Bangladesh: a case study. Clean Technologies and *Environmental Policy,* 22(10), 2129–2143. https://doi.org/10.1007/s10098-020-01963-3

Decker, B., & Jahn, U. (1997). Performance of 170 grid connected PV plants in northern Germany - Analysis of yields and optimization potentials. *Solar Energy,* 59(4-6–6 pt 4), 127–133. https://doi.org/10.1016/S0038-092X(96)00132-6

Defaix, P. R., van Sark, W. G. J. H. M., Worrell, E., & de Visser, E. (2012). Technical potential for photovoltaics on buildings in the EU-27. *Solar Energy,* 86(9), 2644–2653. https://doi.org/10.1016/j.solener.2012.06.007

Dondariya, C., Porwal, D., Awasthi, A., Shukla, A. K., Sudhakar, K., Murali, M. M., & Bhimte, A. (2018). Performance simulation of grid-connected rooftop solar PV system for small households: A case study of Ujjain, India. *Energy Reports,* 4, 546–553. https://doi.org/10.1016/j.egyr.2018.08.002

Dubey, S., Sandhu, G. S., & Tiwari, G. N. (2009). Analytical expression for electrical efficiency of PV/T hybrid air collector. *Applied Energy,* 86(5), 697–705. https://doi.org/10.1016/j.apenergy.2008.09.003

Duffie, J. A., & Beckman, W. A. (1991). *Solar Engineering of Thermal Processes* (2nd ed.). Newyork: John Wiley & Sons Inc.

Ebhota, W. S., & Tabakov, P. Y. (2021). Assessment of solar PV potential and performance of a household system in Durban North, Durban, South Africa. *Clean Technologies and Environmental Policy,* (0123456789). https://doi.org/10.1007/s10098-021-02241-6

Eicker, U. (2014). Solar Thermal Technologies for Buildings. *In Solar Thermal Technologies for Buildings* (1st ed.). West Sussex, England: John Wiley & Sons Ltd. https://doi.org/10.4324/9781315074467

Eke, R., & Demircan, H. (2013). Performance analysis of a multi crystalline Si photovoltaic module under Mugla climatic conditions in Turkey. *Energy Conversion and Management,* 65, 580–586. https://doi.org/10.1016/j.enconman.2012.09.007

Emziane, M., & Al Ali, M. (2015). Performance assessment of rooftop PV systems in Abu Dhabi. *Energy and Buildings,* 108, 101–105. https://doi.org/10.1016/j.enbuild.2015.08.057

EPDK. Unlicensed Electricity Generation Regulation in the Electricity Market. Electricity Market Law § (2013). Turkey: TR Official Newspaper - 28783.

Farhoodnea, M., Mohamed, A., Khatib, T., & Elmenreich, W. (2015). Performance evaluation and characterization of a 3-kWp grid-connected photovoltaic system based on tropical field experimental results: New results and comparative study. *Renewable and Sustainable Energy Reviews,* Vol. 42, pp. 1047–1054. https://doi.org/10.1016/j.rser.2014.10.090

Fraunhofer ISE. (2020). Photovoltaics Report. *Freiburg*, Germany.

Gaur, A., & Tiwari, G. N. (2013). Performance of Photovoltaic Modules of Different Solar Cells. *Journal of Solar Energy,* 2013, 1–13. https://doi.org/10.1155/2013/734581

Humada, A. M., Hojabri, M., Hamada, H. M., Samsuri, F. B., & Ahmed, M. N. (2016). Performance evaluation of two PV technologies (c-Si and CIS) for building integrated photovoltaic based on tropical climate condition: A case study in Malaysia. *Energy and Buildings,* 119, 233–241. https://doi.org/10.1016/j.enbuild.2016.03.052

IEA, Clavadetscher, L., & Nordmann, T. (2007). Cost and performance trends in grid-connected photovoltaic systems and case studies, *Report IEA-PVPS T2-06:2007.* In L. Clavadetscher & T. Nordmann (Eds.), Report IEA-PVPS T2-06:2007. Erlenbach, Switzerland: International Energy Agency. Retrieved from International Energy Agency website: https://iea-pvps.org/wp-content/uploads/2020/01/rep2_07.pdf

IEC 61724. (1998). *Photovoltaic system performance monitoring - guidelines for measurement, data exchange and analysis.* Geneva, Switzerland.

Jahn, U., & Nasse, W. (2004). Operational performance of grid-connected PV systems on buildings in Germany. *Progress in Photovoltaics: Research and Applications*, 12, 441–448. https://doi.org/10.1002/pip.550

Kazem, H. A., Khatib, T., Sopian, K., & Elmenreich, W. (2014). Performance and feasibility assessment of a 1.4 kW roof top grid-connected photovoltaic power system under desertic weather conditions. *Energy and Buildings, 82,* 123–129. https://doi.org/10.1016/j.enbuild.2014.06.048

Kumar, N. M., Yadav, S. K., Chopra, S. S., Bajpai, U., Gupta, R. P., Padmanaban, S., & Blaabjerg, F. (2020). Operational performance of on-grid solar photovoltaic system integrated into pre-fabricated portable cabin buildings in warm and temperate climates. *Energy for Sustainable Development, 57,* 109–118. https://doi.org/10.1016/j.esd.2020.05.008

Kymakis, E., Kalykakis, S., & Papazoglou, T. M. (2009). Performance analysis of a grid connected photovoltaic park on the island of Crete. *Energy Conversion and Management, 50(3),* 433–438. https://doi.org/10.1016/j.enconman.2008.12.009

Lasfar, S., Haidara, F., Mayouf, C., Abdellahi, F. M., Elghorba, M., Wahid, A., & Kane, C. S. E. (2021). Study of the influence of dust deposits on photovoltaic solar panels: Case of Nouakchott. *Energy for Sustainable Development, 63,* 7–15. https://doi.org/10.1016/j.esd.2021.05.002

Leloux, J., Narvarte, L., & Trebosc, D. (2012). Review of the performance of residential PV systems in France. *Renewable and Sustainable Energy Reviews, 16(2),* 1369–1376. https://doi.org/10.1016/j.rser.2011.10.018

Milosavljević, D. D., Pavlović, T. M., & Piršl, D. S. (2015). Performance analysis of A grid-connected solar PV plant in Niš, republic of Serbia. *Renewable and Sustainable Energy Reviews, 44,* 423–435. https://doi.org/10.1016/j.rser.2014.12.031

Mondol, J. D., Yohanis, Y., Smyth, M., & Norton, B. (2006). Long term performance analysis of a grid connected photovoltaic system in Northern Ireland. *Energy Conversion and Management, 47,* 2925–2947. https://doi.org/10.1016/j.enconman.2006.03.026

Necaibia, A., Bouraiou, A., Ziane, A., Sahouane, N., Hassani, S., Mostefaoui, M., … Mouhadjer, S. (2018). Analytical assessment of the outdoor performance and efficiency of grid-tied photovoltaic system under hot dry climate in the south of Algeria. *Energy Conversion and Management, 171(March),* 778–786. https://doi.org/10.1016/j.enconman.2018.06.020

Njoku, H. O., & Omeke, O. M. (2020). Potentials and financial viability of solar photovoltaic power generation in Nigeria for greenhouse gas emissions mitigation. *Clean Technologies and Environmental Policy, 22(2),* 481–492. https://doi.org/10.1007/s10098-019-01797-8

Pietruszko, S. M., & Gradzki, M. (2003). Performance of a grid connected small PV system in Poland. *Applied Energy, 74,* 177–184. https://doi.org/10.1016/S0306-2619(02)00144-7

Ramanan, P., K., K. M., & Karthick, A. (2019). Performance analysis and energy metrics of grid-connected photovoltaic systems. Energy for Sustainable Development, 52, 104–115. https://doi.org/10.1016/j.esd.2019.08.001

REN21. (2019). Global Status Report. Paris, France.

Rughoo, D., & Ramasesha, S. K. (2020). Predicting the performance of a photovoltaic system in the island nation, Mauritius. *Clean Technologies and Environmental Policy, 22(7),* 1579–1587. https://doi.org/10.1007/s10098-020-01894-z

Sharma, R., & Goel, S. (2017). Performance analysis of a 11.2 kWp roof top grid-connected PV system in Eastern India. *Energy Reports, 3,* 76–84. https://doi.org/10.1016/j.egyr.2017.05.001

Sharma, V., & Chandel, S. S. (2013). Performance analysis of a 190kWp grid interactive solar photovoltaic power plant in India. *Energy, 55,* 476–485. https://doi.org/10.1016/j.energy.2013.03.075

Tırmıkçı, C. A., & Yavuz, C. (2020). Environmental impact of a 290.4 kWp grid-connected photovoltaic system in Kocaeli, Turkey. *Clean Technologies and Environmental Policy, 22(9),* 1943–1951. https://doi.org/10.1007/s10098-020-01927-7

Wittkopf, S., Valliappan, S., Liu, L., Ang, K. S., & Cheng, S. C. J. (2012). Analytical performance monitoring of a 142.5kW p grid-connected rooftop BIPV system in Singapore. *Renewable Energy, 47,* 9–20. https://doi.org/10.1016/j.renene.2012.03.034

WNA. (2011). Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources. In *World Nuclear Association.* London, UK. Retrieved from http://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/comparison_of_lifecycle.pdf

Yadav, S. K., & Bajpai, U. (2018). Performance evaluation of a rooftop solar photovoltaic power plant in Northern India. *Energy for Sustainable Development, 43,* 130–138. https://doi.org/10.1016/j.esd.2018.01.006

Yamamoto, Y. (2012). Pricing electricity from residential photovoltaic systems: A comparison of feed-in tariffs, net metering, and net purchase and sale. *Solar Energy, 86(9),* 2678–2685. https://doi.org/10.1016/j.solener.2012.06.001