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Energy and Cost Analyses of Solar Photovoltaic (PV) Microgeneration Systems for Different Climate Zones of Turkey

Suzi Dilara Mangan[1], Gül Koçlar Oral[2]

[1]Faculty of Architecture, Istanbul Aydin University, Istanbul, Turkey
[2]Faculty of Architecture, Istanbul Technical University, Istanbul, Turkey
Email: dilaramangan@yahoo.com, kgul@itu.edu.tr

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Abstract

The environmental and energy problems that have arisen in Turkey because of the dramatically increase in energy consumption require the implementation of energy efficiency and microgeneration measures in the building sector which is the main sector of primary energy consumption. Since Turkey is highly dependent on exported energy resources, the basic energy policy approach is based on providing the supply security. In this regard, supporting for *in situ* energy production, encouraging the use of renewable energy sources and the systems such as microgeneration systems in order to meet the energy requirements of buildings would be considered as a key measure for resolving the energy related challenges of Turkey and dealing with the sustainability issues. Turkey's geographical location has several advantages for extensive use of most of the renewable energy sources such as especially solar energy. However, this huge solar energy potential is not being used sufficiently in residential building sector which is responsible for the great energy consumption of Turkey. Therefore, this paper aims to introduce a study which investigates, on a life cycle basis, the environmental and the economic sustainability of solar Photovoltaic (PV) microgenerators to promote the implementation of this system as an option for the renovation of existing residential buildings in Turkey. In this study, main parameters which were related to the distribution of modules to be installed in flat roofs and facades and the evaluation of the PV systems were taken into account. The effect of these parameters on energy generation of PV systems was analyzed in a case study considering different climate zones of Turkey; and the decrease in the existing energy consumption of the reference building was calculated.

Keywords

Residential Building Energy, Photovoltaics, Optimum Design, Energy Performance Analysis, Cost Analysis, Life Cycle Assessment

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1. Introduction

In recent years, as the climate changes have been noticeable, the issues related to energy, economy and environment should be considered as a whole. Within these issues, energy is the key parameter for the environmental impact. In terms of minimizing the energy related environmental impacts and increasing the security of energy supply by reducing the dependence on imported-fuel supplies, the extensive use of renewable energy sources acquires significance. In this respect, Turkey's national vision within the framework of climate change is to become a country fully integrating climate change-related objectives into its development policies, extending the energy efficiency, increasing the use of clean and renewable energy resources, actively participating in the efforts for dealing with the climate change under its "special circumstances", and providing citizens with a high quality of life and welfare with low-carbon intensity [1].

To achieve a low carbon intensity and to develop specific mechanisms to encourage self-sufficiency, buildings have to become a more integrated part of the energy generation system. Microgeneration systems can contribute to a more distributed and efficient system in which buildings can be an element within the energy supply infrastructure. Thus, according to Climate Change Strategy Document of Turkey, which foresees year 2020 to integrate Turkey's future development and environmental plans, the purpose of increasing renewable energy use in buildings was identified as at least 20% of the annual energy demand of new buildings was met via renewable energy resources as of 2017 [1]. At the beginning of 2011, the Law on Utilization of Renewable Energy Resources for the Propose of Generating Electrical Energy was amended to providing price incentives based on resource types, for the electrical energy generated in the energy plants based on the renewable energy resources [2]. Furthermore, Regulation Concerning Unlicensed Generation of Electricity in the Electricity Market was enacted to establish procedures and principles allowing the real and legal persons to engage with generation of electricity without having to establish company; and to obtain license from Energy Market Regulatory Authority [3]. It is essential that the microgeneration systems to be set up with maximum installed capacity of 1 MW without licenses should be established in order to only meet the need of electrical energy [4]. In terms of feed-in tariffs, the highest price incentives are specified for the sale of electrical energy generated from the production facilities basing on solar energy and biomass among the others. Both the specified price incentive and having a high potential for solar energy due to its geographical position of Turkey, getting photovoltaic electricity competitive to harness solar energy is the best implementation of utilization of renewable energy resources in buildings. And also, as direct financial incentives and other types of subsidies for the generation of electrical energy based on renewable energy resource are gradually phased out, grid connection to electricity utility will become an essential feature of the microgeneration system design. Therefore, due to the feature of grid connection to electricity utility, the use of grid connected PV systems can take precedence over the other microgeneration technologies in buildings.

This study is aimed to enhance the performance of grid-connected solar PV systems on the flat roofs and facades, the sensitivity analyses related to tilt angle and row distance of the modules and the impacts of energy generation by PV systems on the energy, economic and environmental parameters were evaluated for different climate zones of Turkey.

2. Methodology

The proposed methodology aims to enhance the building energy efficiency and renewable energy usage by the application of solar PV microgeneration systems in the buildings. To determine the energy, economical and environmental aspects of PV systems concerning the renovation of existing residential buildings in temperate humid, temperate dry, hot humid, hot dry and cold climate zones of Turkey, the calculation procedure consists of the following steps:

- Definition of the reference building,
- Calculation of the heating and cooling energy consumptions,
- Calculation of the overall energy performance indicators (primary energy and CO_2 emissions),
- Definition of the PV systems,
- Sensitivity analyses for the determination of optimum tilt angle and row distance of the modules,
- Calculation of the annual energy generation by PV systems,
- Calculation of the cost performance of PV systems,
- Calculation of the energy and environmental indicators of PV systems.

By this methodology, an integrated approach is discussed to enhance the energy performance of existing residential building; the opportunities for solution oriented application of PV systems are defined; and their impact on energy savings and environmental sustainability of the reference building for different climate zones of Turkey are assessed. Thus, calculation procedure related to the determination of solar energy potential becomes more beneficial. Because the calculation not only contributes to the specific evaluation of building codes requirements, but also helps to develop the future building policies both from a medium and long term perspective for Turkey by providing an outlook on necessary further steps towards an energy effective renovation of existing residential buildings.

2.1. Definition of the Reference Building

In Turkey, Housing Development Administration of Turkey (TOKI) undertakes the significant role on the nationwide investments in building sector and especially in residential buildings. Therefore, existing mass housing project, constructed by TOKI in Istanbul, was selected as a reference building.

This project was designed on 25.312 m^2 as 7 blocks, 408 flats. Specified one block was accepted as the reference building for the calculations (**Figure 1**). The building height is 48.28 m, the floor area is 573 m^2 and it has four apartments per storey (**Figure 2**).

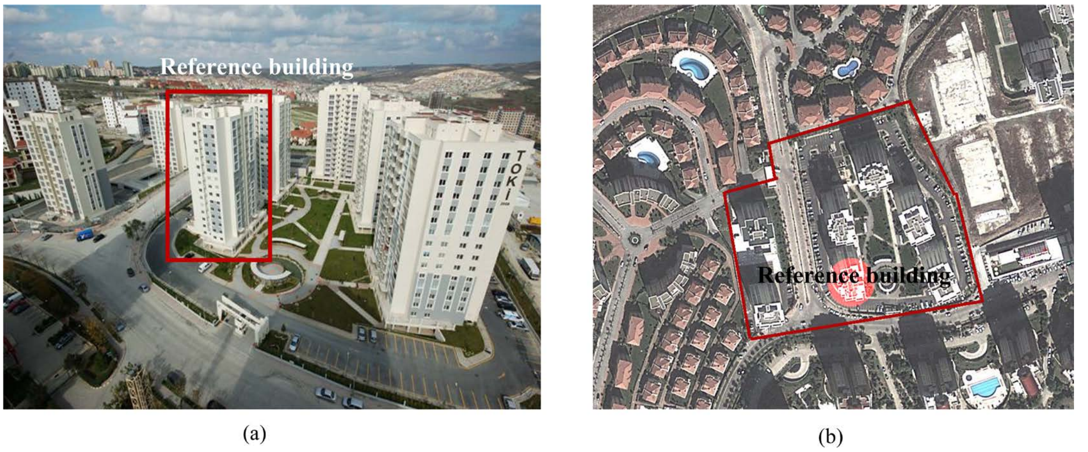
The building envelope is constituted from two types of external wall. Type 1 and type 2 are consisted of 20 cm aerated concrete block, 20 cm reinforced concrete block respectively. Window type is double glazed (4 mm clear glass + 12 mm air + 4 mm clear glass, U: 2.725 W/m^2K) and PVC frame (60 mm, U: 1.912 W/m^2K). The transparency ratios (the ratio of the window area to the facade area) are 14%, 24%, 15%, 30% for the north, east, south and west direction respectively. The characteristics of opaque elements of building envelope are shown in **Table 1**.

The reference building was assumed to be located in different climate zones of Turkey. These climate zones have been classified according to the results of previous scientific research projects carried out in Istanbul Technical University [5]-[7]. The characteristics of climate zones are shown in **Table 2**.

2.2. Calculation of the Heating and Cooling Energy Consumptions

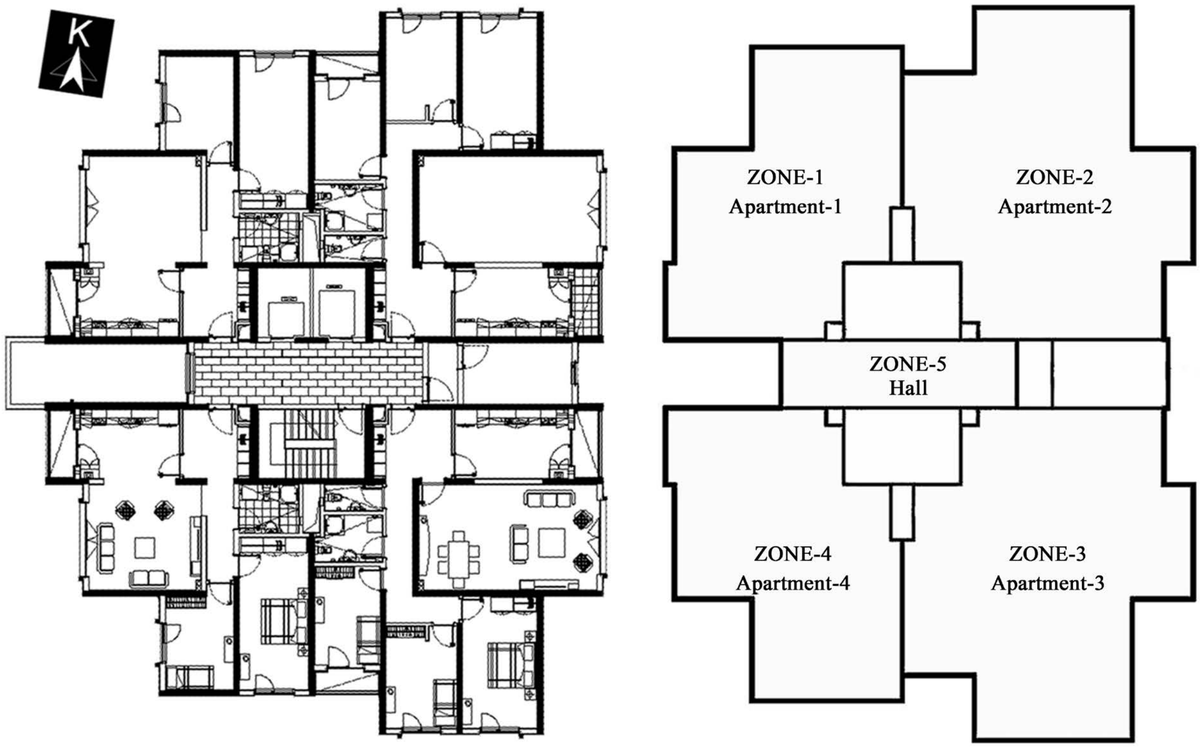
In order to evaluate the energy performance of the reference building, annual heating and cooling energy consumptions were calculated by using dynamic energy simulation program "Design Builder" that is user-friendly visual interface of Energy Plus [8]. To perform energy simulations, outdoor climate data for five climate zones of Turkey is corresponding to a typical meteorological year (TMY).

According to environmental control, each apartment area and hall were accepted as a zone, means heated/cooled area (**Figure 2**). The core units (stairs, elevators, fire stairs) were accepted not conditioned areas. For Zone 1-2-3-4 (apartments), the comfort value for indoor temperature was assumed to be 21˚C for heating period and 25˚C for cooling period. For Zone 5 (hall), heating set point temperature was accepted 18˚C. Natural ventilation was taken into the calculations as minimum fresh air (l/s-person) parameter, accepted value was 10 [9].



(a) (b)

Figure 1. (a) General view of existing mass housing project and (b) site plan.



(a) (b)

Figure 2. (a) Plan view of the reference building and (b) conditioned zone areas.

Table 1. Characteristics of existing opaque elements.

Construction	Material layers (from outside to inside)	U value (W/m^{2}K)
External wall (type 1)	0.03 m cement rendering + 0.05 m extruded polystyrene + 0.2 m aerated concrete block + 0.02 m gypsum plaster	$U_{wall\_1} = 0.371$
External wall (type 2)	0.03 m cement rendering + 0.05 m extruded polystyrene + 0.2 m concrete + 0.02 m gypsum plaster	$U_{wall\_2} = 0.576$
Ground floor	1 m reinforced concrete + 0.03 m concrete + 0.04 m extruded polystyrene + 0.03 m concrete + 0.05 m screed + 0.01 m parquet	$U_{floor} = 0.513$
Flat roof	gravel + roofing felt + 0.05 m expanded polystyrene + EPDM + 0.04 m concrete + 0.14 m reinforced concrete + 0.02 m gypsum plaster	$U_{roof} = 0.547$

Table 2. Characteristics of climate zones of Turkey.

Climate zones	Representative city	Latitude - longtitude (˚)	Heating degree days	Cooling degree days	Global horizontal radiation (kWh/m^{2}a)
Temperate humid	Istanbul	40.97 - 28.82	1886	2152	1465
Temperate dry	Ankara	40.12 - 33.00	3307	1338	1417
Hot humid	Antalya	36.70 - 30.73	972	3345	1798
Hot dry	Diyarbakir	37.88 - 40.20	2086	2843	1718
Cold	Erzurum	39.95 - 41.17	4785	856	1555

Heating system type was hot water radiator central heating system and fuel type was natural gas. $COP_{cooling}$ was accepted 4.50 and fuel type is electricity. According to the cooling demand dates, if the indoor air temperature was higher than 23˚C and the outdoor air temperature was less than the indoor air temperature, natural ventilation would be accepted "on" mode.

2.3. Calculation of the Overall Energy Performance Indicators (Primary Energy and CO_2 Emissions)

In this study, primary energy consumptions and CO_2 emissions related to the heating and cooling energy consumptions were taken into account as the energy performance indicators. The primary energy consumptions were calculated by:

$$E_{\text{cons,primary}} = E_{\text{cons,fuel}} \times f_{p,\text{fuel}} \tag{1}$$

where $E_{\text{cons,primary}}$ is the primary energy consumption; $E_{\text{cons,fuel}}$ is the energy consumption related to the fuel type (kWh/m^2-a) and $f_{p,\text{fuel}}$ is the primary energy conversion factor which corresponds to the typical fuel mix for natural gas and electricity production in Turkey. To convert the annual natural gas consumption for heating and annual electricity consumption for cooling into primary energy, the factors 1.0 and 2.36 were used respectively [10].

The calculation of energy related CO_2 emissions was done according to the Tier 2 approach, an estimation method provided by the IPCC 2006 [11]. Tier 2 method concentrates on estimating the emissions from the carbon content of fuels supplied to the country with the country specific emission factors. The energy related CO_2 emissions were calculated by:

$$CO_2 \text{ Emissions} = E_{\text{cons,fuel}} \times f_{CO_2,\text{fuel}} \tag{2}$$

where $E_{\text{cons,fuel}}$ is the energy consumption related to the fuel type (kWh/m^2-a) and $f_{CO_2,\text{fuel}}$ are the country specific emission factors for the types of fuel (kg eq.CO_2/kWh). For Turkey, the emission factors for natural gas and electricity were taken as 0.2 and 0.55 kg eq.CO_2/kWh respectively [12].

2.4. Definition of the PV System

For the purpose of this study, grid connected PV systems, which have high potential in terms of long term global energy supply and CO_2 mitigation, were considered. As a renovation measure, roof mounted PV systems and PV facades, the two most common types of PV systems, were determined to analyze the energy performance of PV systems related to the irradiation level and climatic conditions of five representative cities shown in **Table 2**.

The global in-plane irradiation was calculated with the global horizontal irradiation database Meteonorm 7.0 [13] and a conversion factor generated for each representative city with PV*SOL Expert 6.0 software [14] is used to convert horizontal irradiation into in-plane irradiation, to carry out the simulation of energy yields and to calculate the economic efficiency according to the defined tariffs for energy supply to and from the grid.

For the roof mounted PV systems, due to the highest efficiency rate and the limitations of space, mono crystalline silicon (m-Si) PV technology was considered. For the PV facades, amorphous silicon (a-Si) thin film PV technology, the most efficient one in poor light conditions, was used. The studied modules and their physical and electrical characteristics are shown in **Table 3**.

The location determined to install the PV systems in the building has to allow to the integration or superposition of the modules avoiding shadows. Therefore, it was assumed that all PV systems were installed in the conditions that facing south and minimum shading effect at any hour of the day in all seasons. The south facade of the reference building is oriented to 9˚ from south to east. PV systems on the blind wall area of south facade were installed parallel to the facade with a tilt angle 90˚. For roof mounted PV system, the orientation of PV modules was facing south. In terms of determining the optimum tilt angle and row distance of the modules which have significant impacts on the annual energy generation by PV systems and consequently on their environmental benefits, existing mass housing project was modeled as 3D.

2.5. Sensitivity Analyses for the Determination of the Optimum Tilt Angle and Row Distance

First analysis was related to the determination of the optimum tilt angle of mono crystalline PV modules by

Table 3. Characteristics of the modules.

Technology	Location	Power (Wp)	Module efficiency (%)	V_{OC} (V)/ I_{SC} (A)	V_{MPP}(V)/ I_{MPP}(A)	Length/ width (mm)	Frame
Monocrystalline	Roof	190	14.9	44.8/5.78	35.80/5.33	1581/809	Aluminium
Amorphous	Facade	340	5.9	191.0/2.88	151.2/2.25	2600/2200	-

evaluating the changes on the PV system performance from the point of the final PV system yield Y_f (kWh/kWp), performance ratio (PR) and PV output (kWp) corresponding to the different tilt angles. The final PV system yield is the ratio of energy generation per year to the unit of peak power installed. The performance ratio is a measurement of the energy losses within the PV system in comparison with the PV system energy generation. By this analysis, the optimum tilt angles regarding to the climate zones of Turkey have been determined. This analysis has been performed firstly for angles from 10˚ to 60˚ with 10˚ intervals. In order to determine optimum tilt angles, detailed analysis was carried out for the angles to the result of first analysis with 1˚ intervals.

Second analysis was carried out to calculate the optimum distance for the rows of the PV modules in order to minimize mutual shading by mounted module rows and thus determine the PV output (kWp) for the available flat roof area. To analyze the effect of row distance, initially minimum distances at the Winter solstice (21/12, 12:00) were calculated for all representative cities. Secondly, minimum distances up to an increase of 50% with 10% intervals were analyzed in terms of the final PV system specific yield and performance ratio.

2.6. Calculation of the Annual Energy Generation by PV Systems

The annual energy generation by PV systems at each location was calculated by the means of simulation program, PV*SOL Expert 6.0.

In Turkey, more than one-third of energy consumed is used for heating and cooling in buildings. In recent years, depending on the increase of outdoor air temperatures in summer, cooling loads and cooling energy costs have been higher than the heating ones. Therefore, in this study, to determine the reduction in the existing energy consumption, the calculated annual energy generation by PV systems were compared with existing cooling energy consumption and total (heating and cooling) energy consumption of the reference building.

2.7. Calculation of the Cost Performance of PV Systems

The cost performance of PV systems was calculated by using the net present value (NPV) and discounted payback period (DPP) method to specify the effectiveness of installing the PV systems on buildings. NPV is a standard method for using the time value of money to appraise long-term projects. By this method, costs in the future are discounted to the present value of today. Discounted payback period is basically the same as the simple payback method, it just takes the time value into account.

To calculate the cost performance of the PV systems, initial investment cost and the energy cost were considered. The NPV was calculated by the following equation:

$$\mathrm{NPV} = \sum_{t=1}^{N} \frac{EC_t}{(1+i)^t} - C_{inv} \tag{3}$$

where EC_t is the energy cost for year t (Euro), i is the discount rate, N is the lifetime of the PV system (year) and C_{inv} is the initial investment cost of the PV system (Euro). The cost of the PV modules and inverter are taken as the initial investment cost. EC_t can be calculated by the following equation:

$$EC_t = p_{pv} \times E_{pv} \tag{4}$$

where p_{pv} is the PV electricity tariff for the PV system (Euro/kWh) and E_{pv} is the amount of the PV energy generation (kWh/a).

The DPP can be calculated by the following equations:

$$\sum_{n=1}^{t} \frac{[\Delta EC_t]}{(1+i)^n} \geq C_{inv} \tag{5}$$

where ΔEC_t is the cost of energy savings for year t (Euro).

In this study, the cost performance of PV systems was calculated also considering:

- a yearly degradation rate in the efficiency of the PV panels during the first ten years equals 1%, until the end of the lifetime of PV 0.5% of the nominal initial value, based on manufacturers' warranties,
- an inflation rate of 3.23% [15],
- a current value of 6% of the discount rate,
- PV electricity selling price 0.10 Euro/kWh [16].

In Turkey feed-in tariff mechanism for different renewable sources including solar energy is applied for the first ten years of the operation, and there is no other guarantee after this period. However, these periods are usually long, covering a significant portion of the working life of the installation [17]. Long-term tariff mechanisms are needed so that an investor can obtain a return on investment without substantial risk and because RETs are typically capital-intensive with long pay-back periods [18]. Therefore, the cash flows for 30 years which is the estimated maximum lifetime of PV systems [19] [20] and also the specified period of time for the assessment of renovation measures related to residential buildings in the Cost Optimality Delegated Regulation [21] were calculated regarding all the above economic factors. The year of 2013 is taken as the base year of analysis. The initial investment costs were calculated in correspondence with the Turkish market prices of components considering the cost for labour and fitter's gain. The value added tax (VAT) was not taken into account for the cost calculation.

2.8. Calculation of the Energy and Environmental Indicators of PV Systems

In this study, the energy payback time (EPBT) and energy return factor (ERF) were used as energy indicators, the potential for CO_2 mitigation was used as environmental indicator to evaluate the sustainability of the PV systems.

The EPBT is defined as the ratio of the total primary energy requirements during the system life cycle and the annual energy generation during the system operation. The ERF is defined as the ratio of the total energy generation during the system operation lifetime and the total primary energy requirements during the system life cycle. The EPBT and ERF indicate the balance of energy generation with regard to the primary energy requirements related to the whole production process. These energy indicators were calculated by the following equation:

$$\text{EPBT} = \frac{E_{in}}{E_{PV}} \tag{6}$$

$$\text{ERF} = \frac{E_{PV} \times N}{E_{in}} = \frac{N}{\text{EPBT}} \tag{7}$$

where E_{in} is the primary energy input required to manufacture the PV system (kWh), E_{PV} is the amount of energy generation by the PV system (kWh/a) and N is the lifetime of the PV system (year).

In this study, energy input is considered as manufacturing of PV modules and balance of system (BOS) components such as inverter, array support and cabling. The PV module itself is not the only item to be considered even though the most energy is required for its production. Thus, the primary energy requirements of a PV system cannot be assessed without considering the effect of BOS components [22]. To carry out these calculations, precise information related to the gross energy requirement (GER) and lifetime is required. The considered gross energy requirements and lifetime related to the PV modules and BOS are shown in **Table 4**.

To be able to compare the annual energy generated by the PV system in operation with the energy required for the manufacturing, it is necessary to express both quantities in the same form as primary energy or final energy by using an average grid efficiency value. For Turkey, an average grid efficiency value has not been estimated in the mix of the generation systems of electricity. In this study, the commonly agreed value for Western Europe.

Mainland medium voltage grid, has been estimated as 31%, was used [19] [20]. This value concretely results in the need to use an average 3.23 kWh of primary energy to supply 1 kWh of electricity through the grid to a medium voltage consumer [19] [27].

The environmental indicator of the potential for CO_2 mitigation is defined as the quantity of greenhouse gas

Table 4. Gross energy requirements and lifetime related to the PV modules and BOS [23]-[26].

Element	Gross energy requirements	Lifetime (year)
Monocrystalline silicon module	3700 MJ/m²	30
Amorphous silicon module	1889 MJ/m²	30
Array support + cabling	100 MJ/m²	30
Inverter	1930 MJ/kWp	30

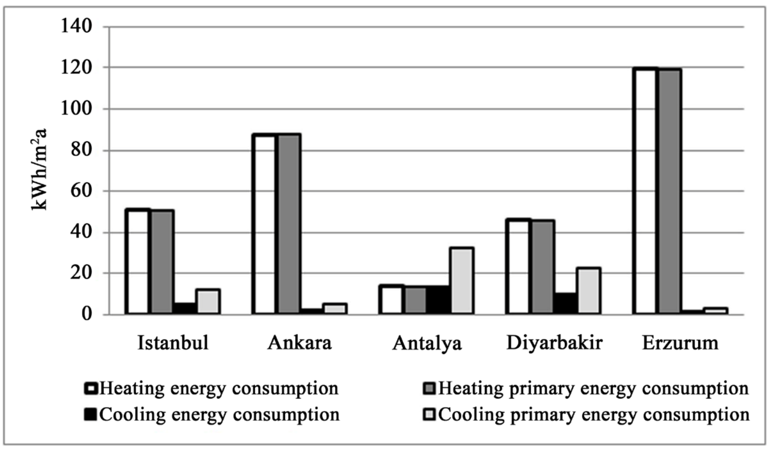
emissions that will be avoided by the PV systems. It is expressed in tons of CO_2 per kWp installed. This environmental indicator can be calculated with the following equation [19]:

$$P_{CO_2} = \frac{E_{PV} \times f_{PV} \times N}{PV_{out}} \quad (8)$$

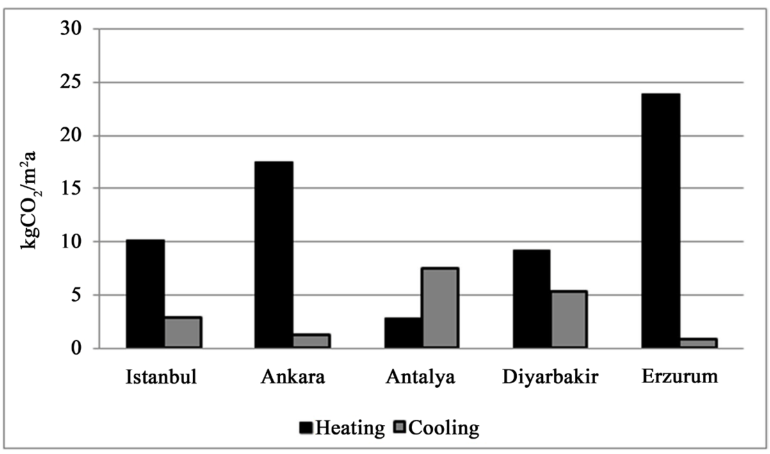
where P_{CO_2} is the potential for CO_2 mitigation (kg eq.CO_2/kWp), E_{PV} is the amount of energy generation by the PV system (kWh/a), f_{PV} is the specific avoided emission factor for the energy generation by the PV system (kg eq.CO_2/kWh), N is the lifetime of the PV system (year) and PV_{out} is the PV system output (kWp).

3. Calculation Results

Figure 3 shows the calculated annual energy consumption, annual primary energy consumption and annual CO_2 emission concerning the heating and cooling energy requirements of the reference building assumed in five climate zones—temperate humid, temperate dry, hot humid, hot dry, cold—of Turkey. From the comparisons among the climate zones, it can be seen that corresponding ranking orders of annual energy consumption, annual primary energy consumption and annual CO_2 emission in the five climate zones are all similar. In Erzurum and Ankara, heating related energy and primary energy consumption and CO_2 emission are more than the other three cities. In terms of cooling related energy and primary energy consumption and CO_2 emission, the values for Antalya and Diyarbakir are more than the other cities. The reason is that more energy consumption for space heating in Ankara and Erzurum is required and more energy consumption for space cooling in Antalya and Diyarbakir is needed.



(a)



(b)

Figure 3. (a) Annual energy and primary energy requirements and (b) annual CO_2 emissions.

The final PV system yield for the different tilt angles with 10˚ intervals is shown in **Figure 4**. As a result of detailed analysis, maximum specific yield and the highest performance ratio were obtained at 31˚ for Istanbul, Ankara and Diyarbakir, 32˚ for Antalya, 30˚ for Erzurum were determined as the optimum tilt angle.

As it is shown in **Figure 5** and **Figure 6**, for Istanbul, Ankara and Erzurum, 20% increased row distance was more effective than the others related to both of the final PV system yield and performance ratio. For Antalya and Diyarbakir, maximum specific yield and performance ratio were achieved by an increase of 30% on row distance. According to the results, yield reduction due to shading was minimized by taking into account the excessive distances among rows. On the other hand, due to the limitations of flat roof area, PV output and also

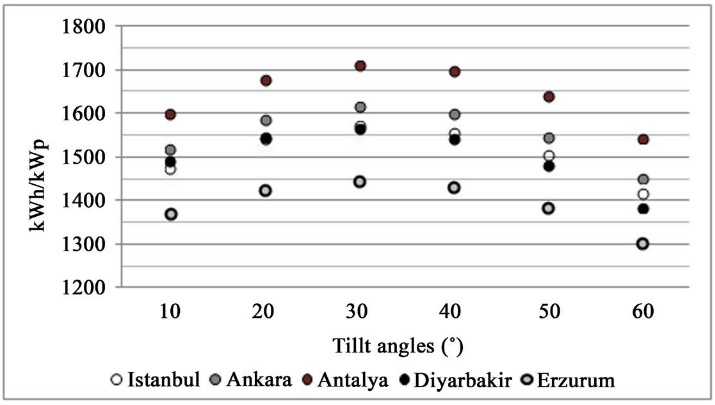


Figure 4. The final PV system yield related to the different tilt angles.

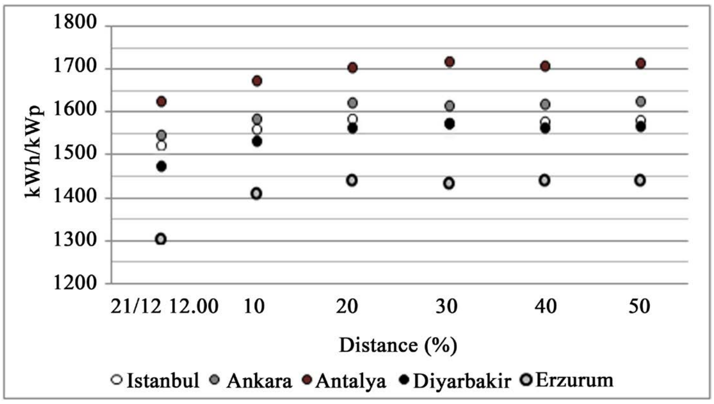


Figure 5. The final PV system yield related to the row distance.

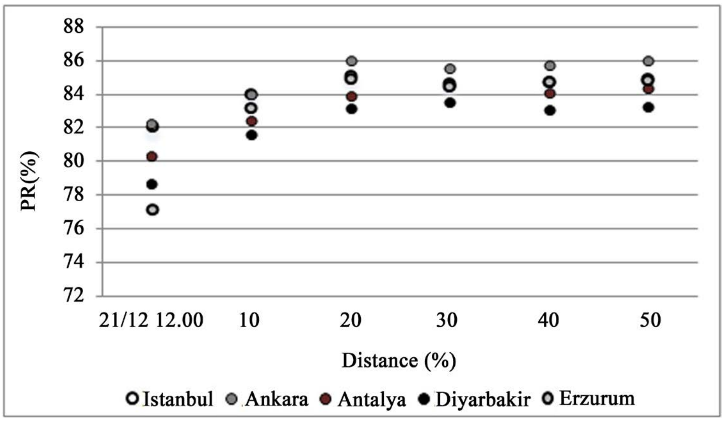


Figure 6. The performance ratio related to the row distance.

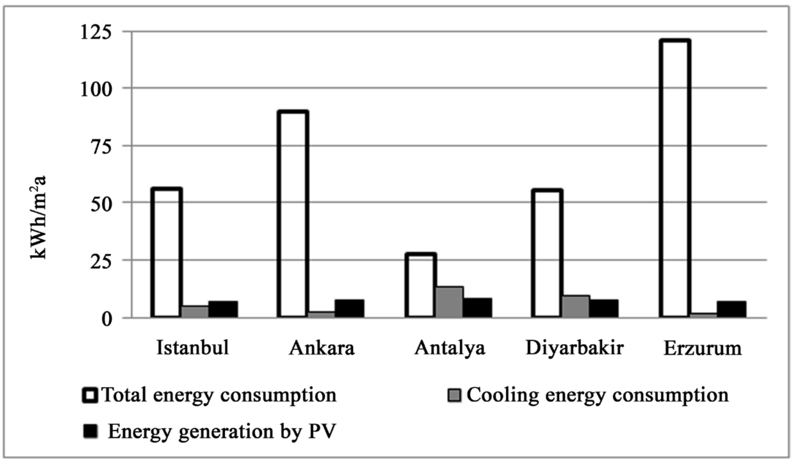
energy generation by the PV system were decreased. For the optimization of solar yield and PV output, in this study 20% increased row distance was assumed as optimum row distances for all representative cities.

The characteristics of PV systems, defined for roof and facade according to the results of sensitivity analyses for the determination of the optimum tilt angle and row distance are shown in **Table 5**.

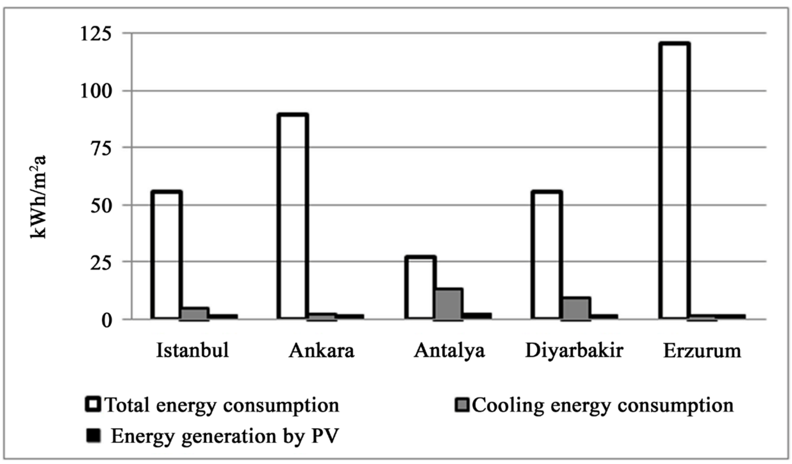
Figure 7 shows the calculated annual PV generation for each of the five climate zones in comparison with the total and cooling energy consumptions (final energy) of the reference building according to the above assumptions and the results of sensitivity analyses. From the comparisons among the climate zones, it can be seen that although higher electricity generation was obtained in Antalya, the representative city of the hot humid climate zone, it depends on a high solar irradiation value, the generated electricity in other climate zones was nearly

Table 5. Characteristics of the PV systems.

Representative city	Roof mounted PV systems			PV facade systems		
	PV output (kWp)	PV surface area (Wp/m²)	Performance ratio (%)	PV output (kWp)	PV surface area (Wp/m²)	Performance ratio (%)
Istanbul	29.26	148.36	85.20	14.28	55.30	84.30
Ankara	29.26	148.36	86.20	14.28	55.30	84.80
Antalya	29.83	148.36	84.10	14.28	55.30	84.50
Diyarbakir	30.78	148.36	83.20	14.28	55.30	83.20
Erzurum	29.64	148.36	85.00	14.28	55.30	84.70



(a)



(b)

Figure 7. (a) Annual energy generation by roof mounted PV systems and (b) PV facade.

similar to the calculated generation value for Antalya and in the cold climate zone was the most outstanding one. From **Figure 7(a)** and **Figure 7(b)**, it can be seen that the annual energy generation by the roof mounted PV system is higher than the annual energy generation by the PV facade. The calculated annual energy generation by the roof mounted PV systems met the annual existing cooling energy consumptions of the reference building which was assumed to be in Istanbul, Ankara and Erzurum. For Antalya and Diyarbakir, the existing annual cooling energy consumptions were met by 58.15% and 77.05% respectively by the roof mounted PV systems. As a result of the comparison of the total energy consumptions and energy generation by the roof mounted PV systems, the total energy consumption can be met by 12.88%, 8.25%, 28.83%, 13.47% and 5.51% for Istanbul, Ankara, Antalya, Diyarbakir, Erzurum respectively. On the other hand, existing annual cooling energy consumptions were met by the PV facades only for Ankara and Erzurum. For Istanbul, Diyarbakir and Antalya, the existing annual cooling energy consumptions were met by 41.90%, 21.43% and 17.50%, respectively by the PV facades. As a result of the comparison of the total energy consumptions and energy generation by the PV facades, the total energy consumption can be met by 3.88%, 2.47%, 8.68%, 3.75% and 1.67% for Istanbul, Ankara, Antalya, Diyarbakir, Erzurum respectively.

The economic convenience of investment of each PV system for the representative cities of the five climate zones is summarised in **Table 6**. Results presented as NPV of investment in Euro and DPP of investment in years show that even though the initial investment cost of PV facade represents approximately half of the initial investment cost of the roof-mounted PV system, negative NPVs are observed and correspondingly the PV facade cannot recover the initial investment in a 30 year calculation period concerning all climate zones. In terms of a roof-mounted PV system, positive NPVs are achieved for all climate zones and DPP varies between 12.9 and 16.8 years. The highest NPV and the lowest DPP are found in Antalya (18,893 Euro, 12.9 years); conversely the lowest NPV and the highest DPP are found in Erzurum (9010 Euro, 16.8 years) among the other cities.

In terms of environmental benefits, energy indicators comprising EPBT, ERF and the potential of CO_2 mitigation as an environmental indicator were calculated using Equations (6)-(8), respectively for simulated on-site performance to show comparative assessment potential value of each PV system in the five climate zones. From **Table 7**, it can be noticed that the lowest value for EPBT, the highest value for both ERF and the potential of CO_2 mitigation can be achieved by the roof mounted PV system compared to overall energy performance indicators of PV facade. It is shown that the potential value of EPBT for the roof mounted PV system is in the range of 4.8 - 5.7 years which is approximately half of the range of EPBT related to the PV facade. In terms of ERF, roof mounted PV systems are expected to produce between 15.2 and 18.0 times the amount of energy required to manufacture during the whole lifetime, which is comparatively higher than obtained with the PV facade. As to the potential of CO_2 mitigation, roof mounted PV systems can avoid during their whole lifetime up to 40 tons

Table 6. The calculation results of the economic performance of each PV systems.

Representative city	Roof mounted PV systems			PV facade systems		
	Initial cost (Euro/kWp)	NPV (Euro)	DPP (year)	Initial cost (Euro/kWp)	NPV (Euro)	DPP (year)
Istanbul	1500	13,969	14.5	1500	−3967	-
Ankara	1500	15,538	13.9	1500	−3609	-
Antalya	1500	18,893	12.9	1500	−2267	-
Diyarbakir	1500	13,927	14.8	1500	−4703	-
Erzurum	1500	9010	16.8	1500	−5240	-

Table 7. The calculation results of the energy and environmental indicators of PV systems.

Representative city	Roof mounted PV systems			PV facade systems		
	EPBT (year)	ERF (number of times)	P_{CO2} (tCO_2/kWp)	EPBT (year)	ERF (number of times)	P_{CO2} (tCO_2/kWp)
Istanbul	5.2	16.7	37.5	11.3	7.6	23.2
Ankara	5.0	17.2	38.5	11.1	7.8	23.7
Antalya	4.8	18.0	40.5	10.3	8.4	25.4
Diyarbakir	5.2	16.5	37.0	11.8	7.3	22.2
Erzurum	5.7	15.2	34.2	12.2	7.1	21.5

of CO_2 for each kWp installed. The corresponding figure for PV facade is limited to 25 tons of CO_2 per kWp installed. Observing **Table 7** it can be inferred that the results concerning the lowest value for EPBT, the highest value for both ERF and the potential of CO_2 emission are found in Antalya (4.8 years, 18 times, 40.5 tCO_2/kWh, respectively), the representative city of the hot humid climate zone.

4. Conclusions

In this paper, a methodology was described for enhancing the building energy efficiency, achieving low carbon intensity and encouraging self-sufficiency of buildings by the application of solar PV microgeneration systems. To determine the energy, economical and environmental aspects of PV systems concerning the renovation of existing residential buildings in temperate humid, temperate dry, hot humid, hot dry and cold climate zones of Turkey, key parameters as final PV system specific yield, performance ratio, energy generation, net present value, payback period, energy payback time, energy return factor and the potential for CO_2 mitigation, which are significant for performing the appropriate design of PV systems, were analyzed.

The existing energy consumption for heating and cooling of the reference building was calculated by the means of simulation program for each representative city of climate zones. Then, the results of energy simulations were used to compare with the energy generation of the specified PV systems for flat roof and facades to determine the share of renewable. According to these calculations, total (heating + cooling) energy consumption can be met with a range of approximately 6% (in Erzurum) and 30% (in Antalya) by roof mounted PV systems. For PV facades, this meeting ratio was calculated up to approximately 9% with the highest value in Antalya. In terms of cost calculations, with the roof mounted PV system, positive NPVs are achieved for all climate zones and DPP varies between 12.9 and 16.8 years. In terms of PV facade, negative NPVs are observed and correspondingly the PV facade cannot recover the initial investment during the calculation period of 30 years for all climate zones. Additionally, each PV system may pay back the primary energy input and the potential for CO_2 mitigation is in the range of 25 - 40 tons of CO_2 per kWh installed. All in all, the assessment of the PV microgeneration system especially underlies the existing potential to achieve a low carbon and low fossil fuel economies target for Turkey.

This study provided an overview of optimum design of solar PV microgeneration systems to promote the implementation of this system not only as an option for the renovation of existing residential buildings but also as a design criteria for the new building construction in different climate zones of Turkey by a complex combination of energy, economic and environmental considerations. The simulation results related to the five different climate zones of Turkey were illustrated graphically to show the potential of solar energy utilization in the buildings to the policy makers, developers and designers. This potential is crucial for the sustainable economic growth in Turkey and other developing countries. Therefore, these studies could be implemented by the adequate legal laws and regulations. In this respect, developing of energy laws, aims on integrating buildings with energy generation systems and taking into account the technical knowledge and criteria leading to the architect/ engineer and building user with a holistic approach, have to be preferential studies for future projects.

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