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Evaluation of photovoltaic systems in different building forms in terms of energy and cost efficiency

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Abstract

Being an environmentally clean energy source and with its high potential, solar energy is widely considered as the most efficient alternative energy source. Meeting energy needs of buildings using solar energy is possible by achieving an energy efficient building envelope design through the use of passive and active solar energy systems. Photovoltaics (PV), as the active system, converts solar radiation directly into electricity and can meet part of the total energy loads of a building contributing to the sustainability and energy efficiency of the building. In this study, the goal is to evaluate photovoltaic systems in different building forms in terms of energy and cost efficiency and to identify the most efficient building form and photovoltaic system alternative. Different building forms, with the same volume to building envelope surface ratio (V/A) are developed, and all forms are further fitted and compared with flat, pitched and gabled roofs. Additionally, different tilt angles for photovoltaic panels, different building component on which the panels are mounted and different orientations are used to obtain multiple different alternatives.When comparing annual energy loads and gains obtained in different building forms, the most efficient alternative which provide the lowest energy consumption and the highest energy gain can be identified with its cost. The results of this study can provide guidance for the design of energy and cost efficient building systems to eliminate the negative impact of fossil fuels on the environment.

Keywords
Building form, Photovoltaic, Life cycle cost, Energy efficiency, Cost efficiency.

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1. Introduction

Most of the energy expenditures in Turkey is made to heat and cool residential buildings. The use of alternative energy sources instead of fossil fuels have started to be encouraged with the enactment of the Energy Efficiency Law no '5627'. The sun, the main source of all fuels used in the world except for nuclear fuels, provides an alternative energy source that has the highest potential when compared with other energy sources (Cıtıroglu, 2000). With easy installation and use in buildings;

- solar energy is considered as the only infinite source of energy which is clean and which does not cause any environmental damage,
- can eliminate dependencies for energy,
- does not require any fee or expense except for the costs of installation, maintenance and repair
- and can be used virtually anywhere without any additional transport costs.

In addition to the above, situations such as natural disasters, possible constraints on transport networks and changes in the defense strategies of nations do not have any impact on the sustainability of solar energy. Solar energy does not require any complicated technology and is seen as a major opportunity to meet heating and cooling loads of increasingly popular public housing projects with an alternative energy (Yanardag, 2015). Solar energy does not require any complicated technology and is seen as a major opportunity to meet heating and cooling loads of increasingly popular public housing projects with an alternative energy (Borand, 1997). Since photovoltaic systems can be easily installed on building envelops, cost and energy efficiency analyses of these systems according to the properties of the buildings for which these system are used have become a necessity. Factors affecting energy loads during photovoltaic system installations on buildings can be classified as climate related factors, building related factors and factors affecting PV systems (Yanardag, 2015).

Climate related factors are solar radiation, outside air movement, outside air temperature and outside humidity. Among these factors; solar radiation values and angle of sun radiation, which change throughout the year depending on the location, have a direct impact on the efficiency of PV systems. Higher outside temperature values cause overheating of photovoltaic panels leading to deterioration of the performance of the PV system. In such a situation, prevailing wind in the region can cool down photovoltaic panels with reduced efficiency due to overheating and prevent any further reduction in the efficiency.

Among building related factors, building orientation directly affects energy gain from a photovoltaic system depending on which façade the system is installed. The amount of energy obtained from a PV system depends on the latitude of the building as well as the angle of the PV system panels (Roberts and Guaiente, 2009). Both horizontal and vertical dimensions of a building determine the surface area of the building envelope and thus the amount of energy that can be obtained with a PV system on different façades of the building. However in different building forms, with the same ratio of building volume to surface area of the building envelope (V/A) can have different annual energy loads.

Similarly, since the building envelope areas with different orientations may defer depending on different building forms that in turn may yield same V/A ratio, energy gains obtained with PV systems as well as energy loads could as well be different from each other. On the other hand, tilt angles and orientation of photovoltaic panels change when different roof types are used on buildings and this can have an impact on the energy load and gain balance (Yanardag, 2015).

Photovoltaic System Related Factors include materials, volume and module types of the system, surface areas and tilt angles of panels, connection types which have a direct impact on the energy output of photovoltaic systems.

2. Evaluating photovoltaic systems in different building forms in terms of energy and cost efficiency

This study aims to evaluate the use of photovoltaic systems for heating, cooling and lighting energy loads of buildings in different forms in terms of energy and cost efficiency. The steps of the approach developed for this study are as following.

2.1. Assumptions on climate and building

In this study, all calculations are done under real atmospheric conditions by importing a meteorological data file based on real meteorological data to the selected simulation program (Erdim, 2010).

Climate epw (energy plus weather format) data for Istanbul, the city picked for the simulations, are used for the calculations made in the Design builder simulation program (Saltı, 2015).

Buildings analysed in the study were on a flat land in Istanbul. It is assumed that the buildings are not shaded by nearby buildings. An electrical system is chosen for the heating and cooling system of the building and the required illumination level is set to be 150 lux. It is assumed that the occupants are in the building for 24 hours during the week and the occupant load is accepted as 0.04 person/m^2. 7 different building forms with the same V/A are developed for the study. Each building form is evaluated with a flat roof, pitched roof and a gable roof. Building forms developed for the study and their orientations are shown in Table 1.

During the heating period, the heating system is set to maintain indoor air temperature at 20°C between 07:00 – 23:00 and at 12°C between 23:00 - 07:00 during week days and weekends. During the cooling period, the cooling system is set to maintain indoor air temperature at 26°C between 07:00 – 23:00 and at 28°C between 23:00 - 07:00 during week days and weekends. The transparency ratio for all façades is 30%. The overall heat transfer coefficient of transparent components (double glaze (e2=1) Clr 3 mm/13 mm air) is accepted as U= 1,79 W/m^2-K .

The limit values of the overall heat transfer coefficients of opaque components for Istanbul which is in the second region in accordance with TS-825 are; U_{wall}:0.57 (W/m^2K), $U_{ceiling}$: 0.38 (W/m^2K), U_{floor}: 0.57 (W/m^2K) and U_{window}:1.8 (W/m^2K) (TSE 825, 2013). When these limit values are used, thermophysical properties of the materials that constitute building envelopes of the buildings chosen for the study are shown in Table 2.

2.2. Calculation of annual energy loads (heating, cooling and lighting) of different building forms and the energy gains to be obtained from photovoltaic systems used on building envelopes

Necessary calculations for different building forms with different roof types are made in the Design Builder simulation program. Design Builder is a dynamic thermal building energy

Table 1. Building forms and their orientations.

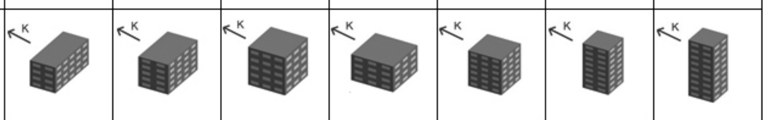
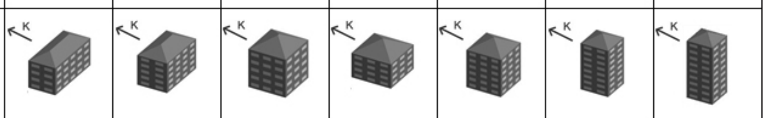
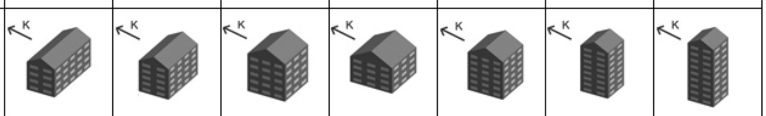
V=4800 m3 (+-%2) A=1760 m2 (+-%2) V/A=2,73 (+-%2)	BF1	BF2	BF3	BF4	BF5	BF6	BF7
FLAT ROOF							
PITCHED ROOF							
GABLE ROOF							
South F. Width (m)	28,8	24	17,7	20	16,6	14,2	12,8
East F. width (m)	12,8	14,2	16,6	20	16,6	14,2	12,8
Height (m)	12,8	14,2	16,6	12	17,7	24	28,8
Building Floor Area(m^2)	369	341	294	400	276	202	164
South F. Area (m^2)	369	341	294	240	294	341	369
East + West F. Area (m^2	328	403	551	480	588	682	737
Total Facade Area (m^2)	1065	1085	1139	960	1175	1363	1475

Table 2. *Thermophysical properties of building envelope materials.*

	Material	Thickness (m)	Thermal Conductivity λ (W/mK)	Overall Heat Transfer Coefficient (U Value) (W/m^{2}K)
Flat Roof	Asphalt	0,01	0,7	0,36
	Cement Plaster Mortar	0,03	0,23	
	EPS Insulation Mat.	0,08	0,04	
	Cement Plaster Mortar	0,03	0,23	
	Cast Concrete	0,12	0,38	
	Gypsum Plaster	0,01	0,4	
Pithced- Gable Roof	Tile Roof	0,025	1	0,36
	Air Gap	0,25	0,19	
	EPS Insulation Mat.	0,09	0,04	
	Cast Concrete	0,12	1,13	
	Gypsum Plaster	0,01	0,4	
Exterior Wall	Cement Plaster Mortar	0,02	0,72	0,57
	XPS Insulation Mat.	0,04	0,03	
	Brick	0,19	0,62	
	Gypsum Plaster	0,02	0,4	
Ground Floor	Rubber Flooring	0,001	0,06	0,54
	EPS Insulation Mat.	0,05	0,04	
	Cement Plaster Mortar	0,03	0,23	
	Cast Concrete	0,1	1,13	
	Blokage	0,15	1,8	

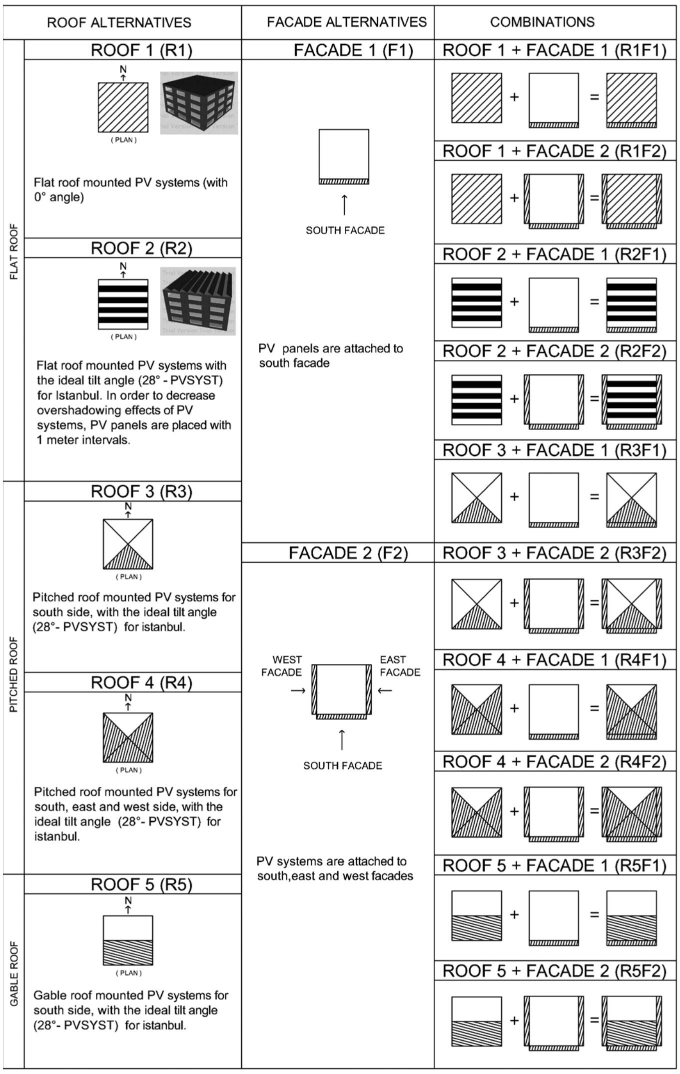


Figure 1. *Roof and façade combinations for PV system installations.*

simulation program developed by the US Department of Energy, which evaluates energy performances of buildings and building systems. The PV system chosen in this study automatically connects to the grid, in case there is a power cut or a lack of sun light. Polycrystalline PV Panels are used for all roof types and Thin Film solar panels are used for all façades. The amount of energy to be obtained from solar panels mounted on building envelopes is calculated with a simulation program called PVSYST. The PVSYST program calculates the electrical energy that can be generated depending on the panel string angle and orientation variables based on the monthly or hourly measured climate data of the region (Mutlu and Turkeri, 2010 and PVSYST, 2016). In the calculations it is assumed that photovoltaic panels are mounted on building envelopes (not integrated) therefore there is no change in the U values of building envelopes and energy loads. Roof and Façade Combination alternatives derived for PV Systems installation are shown in Figure 1.

Annual energy loads and energy gains for each building are shown in Figure 2-4, and at what percentage annual energy gains with PV systems meet annual energy loads of the buildings is shown in Figure 5.

The highest energy gains for all building forms are obtained with;

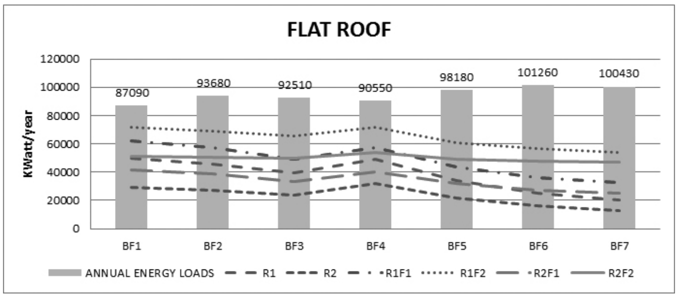


Figure 2. *Annual energy loads and energy gains with photovoltaic systems in different building forms with flat roof.*

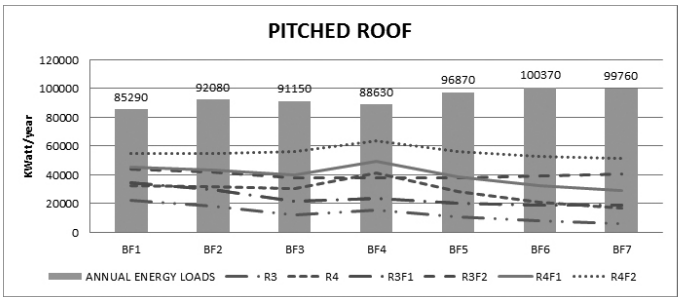


Figure 3. *Annual energy loads and energy gains with photovoltaic systems in different building forms with pitched roof.*

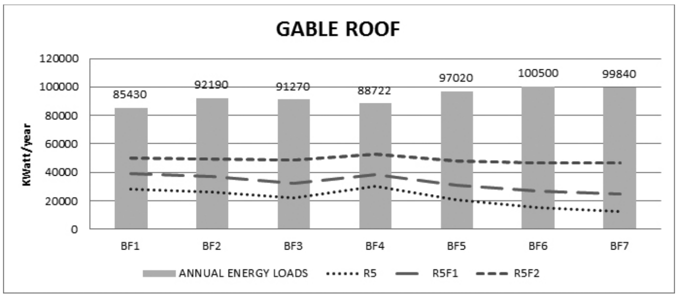


Figure 4. *Annual energy loads and energy gains with photovoltaic systems in different building forms with gable roof.*

- the alternative (R1) where solar panels are mounted with 0° tilt angle to the flat roof; the alternative (R4) where PV panels are mounted on east, south and west sides of the pitched roof and the alternative (R5) where PV panels are mounted on south side of the gable roof, for roof mounted PV systems and,
- the alternative (F2) where the entire east, south and west facades of the buildings are covered with PV panels, for façade mounted PV systems.

Accordingly, when all combinations are compared, the highest energy gain is obtained in BF1 with the R1F2 combination for building forms with flat roofs; in BF4 with the R4F2 combination for building forms with pitched roofs and in BF4 with R5F2 combination for building forms with gable roofs. When all building forms are compared with each other, the highest energy gain is obtained in BF1 with R1F2 combination (Figure 2-4).

Based on the comparisons, the alternative in which annual energy loads of all building forms is met with the highest photovoltaic system efficiency is found to be the alternative R1F2 . The percentage efficiency obtained with PV panels in the alternative R1F2 for the annual energy loads in BF1, BF2, BF3, BF4, BF5, BF6 and BF7 is 82%, 74%, 71%, 79%, 62%, 56% and 54% respectively. (Figure 5).

2.3. Economic evaluation of the alternative with the highest gain for different building forms

Lifecycle cost analysis for the building forms with the highest energy gain in the study is calculated with the formula 1.1 and net present value used for costs is calculated with the formula 1.2

$$LCC = I + M + R + E - S \tag{1.1}$$

I: Initial investment cost (€), M: Maintenance, Repair and Operation Costs (€), R: Refurbishment Costs (€), E: Energy costs (€), S: Salvage value (€) (Manioglu, 2002)

$$P = A.[(1+i)^n -1/I(1+I)^n] \tag{1.2}$$

P: present value of money, F: future value of money, i: escalation rate, n: number of escalation periods, A: uniform series of payments - instalments (Tas, 2014)

Initial investment costs of a PV system consist of construction costs and overhead expenses. Breakdown of the initial investment costs for a polycrystalline Photovoltaic system to be mounted on a building are shown in the Table 3.

Initial turnkey investment cost of photovoltaic systems is 1.5 Euro/WattPeak for the polycrystalline photovoltaic systems that do not require additional construction on buildings; 1.56 Euro/WattPeak for the polycrystalline photovoltaic systems that require additional construction on buildings and 1.4 Euro/WattPeak for the thin film photovoltaic systems that require additional construction on buildings (Meetings with companies, 2015).

For the purpose of the study, photovoltaic panels are assumed to be cleaned

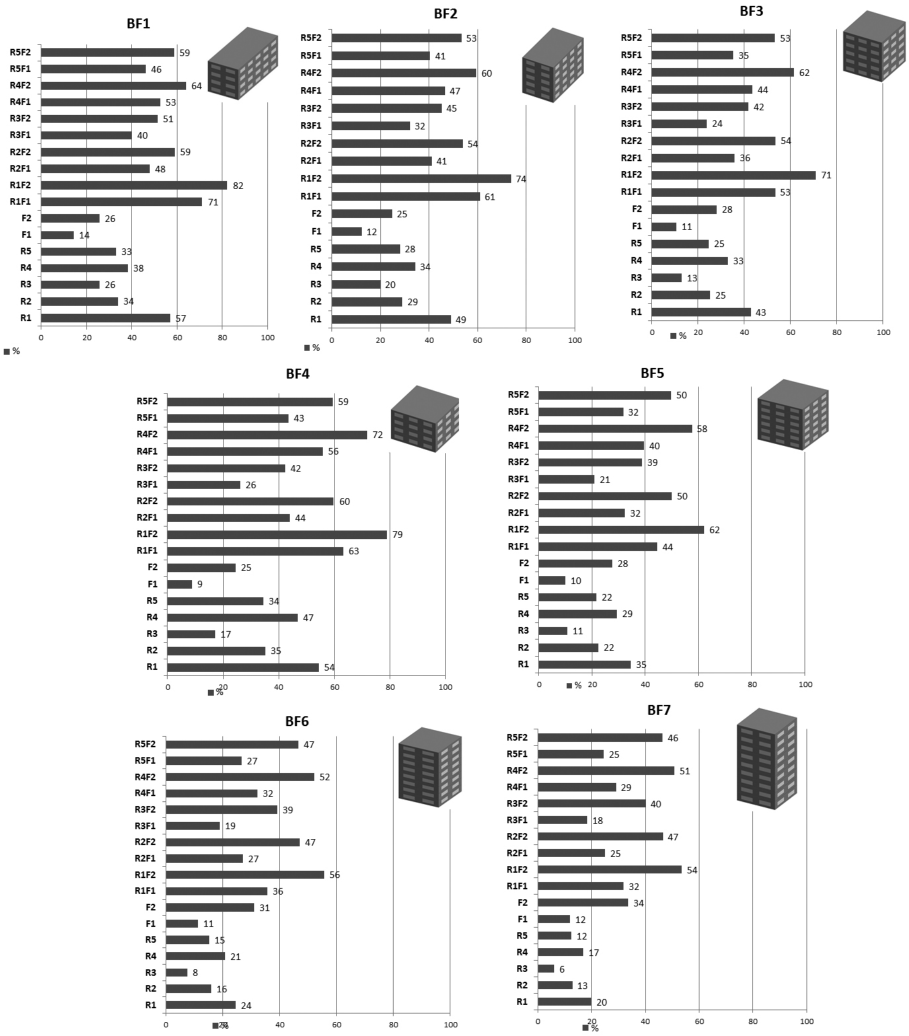


Figure 5. *The ratio of energy gain obtained with photovoltaics in building form 1-7 to the annual energy loads.*

every 2 weeks in summer and every 1.5 months in the other seasons. While 1% of the initial investment cost for roof mounting is sufficient for cleaning, this percentage is taken as 1.5% for façades as cleaning is harder there (Meetings with companies, 2015). Periodic maintenance and inspection costs are assumed to be Euro 500 for only façade or roof mounted systems and Euro 750 for the systems mounted both on the roof and on façades (Meetings with companies, 2015). There are no operating and management costs in the project in this study. Except for the taxes related with the initial investment costs, since the project is considered as "unlicensed electric power generating" systems, it is not subject to regular taxes.

Excess energy generated can be sold to the grid at 0.133$ / kWh. In case the energy generated by PV panels is insufficient, the electricity needed is invoiced at a rate of 0.36 TL/kWH (EPDK, 2015). As there is no energy

Table 3. *The percentages of ınitial investment cost ıtems of a photovoltaic system (meetings with companies, 2015).*

INITIAL INVESTMENT COST							
WORKSITE COSTS						GENERAL EXPENSES	
MATERIAL COSTS				LABOUR COSTS	VEHICLE-FACILITY COSTS	TAX COSTS	ENGINEERING SERVICES COSTS
PANEL COSTS	INVERTER COSTS	CABLE LAYING COST	CONSTRUCTION				
35%	16%	6%	8%	13%	9%	3%	10%

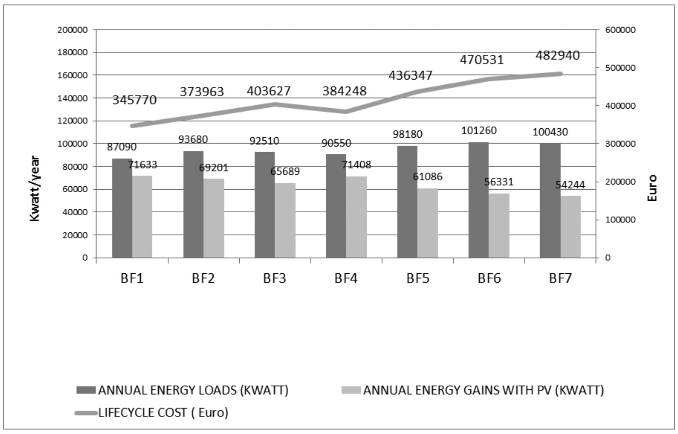


Figure 6. *Annual energy loads, energy gains obtained with photovoltaic panels and lifecycle costs in different building forms for the R1F2 combination.*

consumed for the commissioning of a system, there is no energy cost.

The cost of removal and dismantling, i.e. the disposal cost of the PV system is assumed to be 10% of the initial investment cost (Meetings with companies, 2015). Panels which are the most important components in a photovoltaic system do not have any salvage value however aluminium profiles around panels are assumed to have a salvage value. Thus, the salvage value for the aluminium in one string of panels is TL 4.67 (Euro 1.67) (EPDK, 2015, Gulsan Metal, 2015).

Lifecycle cost analysis is made based on the assumption that average service time of a photovoltaic system is 25 years. The alternative annual rate of investment for EUR is assumed to be 1% (Garanti Bank, 2015). Lifecycle costs of the alternatives where highest gains are obtained in different building forms with photovoltaic systems are calculated using the formulas 1.1 and 1.2 (Figure 6)

By comparing energy gains and energy loads with lifecycle costs, the building form alternative which has the minimum lifecycle cost with the highest energy gain obtained with PV systems is found to be Building Form 1.

3. Conclusion

The increase in the need for the amount of energy due to fast depletion of fossil fuels and increasing human population in the world has led people to resort to alternative energy sources. Solar energy is the alternative energy source with the highest potential and can be used as the infinite source of energy in buildings. In this study photovoltaic systems in different building forms are evaluated in terms of energy and cost efficiency. Overall findings of the study are summarized below.

- When photovoltaic systems on different building forms are used with different roof and façade combinations, although building forms have the same building envelope area (A) and internal volume (V), different annual energy loads are achieved due to the loss and gains from the solar radiation resulting from different façade and roof areas with the same orientation.
- When all roof types and building orientations are reviewed, the roof area of a building and the areas of façades with different orientation, which are the determinant of the building form show different performance depending on solar radiation gain and the selection of the photovoltaic types.
- As the roof and south façade areas increase, annual energy loads are reduced and the efficiency of photovoltaic systems increases and as the roof and south façade areas decrease, annual energy loads are increased and the efficiency of photovoltaic systems decreases.
- When buildings forms are developed horizontally, annual energy loads diminishes while the efficiency of photovoltaic systems increases whereas when building forms are developed vertically, annual energy loads are increased while the efficiency of photovoltaic systems decreases.
- The highest energy gain among all building forms is obtained in the R1F2 combination which combines the alternative with the flat roof (R1) with the alternative where photovoltaic systems are used in east, south and west façades (F2).
- When a flat roof, pitched roof and gable roof alternatives are used on the same roof areas, energy gains are affected both by the area and the tilt angle of photovoltaic panels.
- When a photovoltaic system is mounted on flat, pitched and gable roof, it is seen that the optimum

option which gives the highest efficiency for each building form is different and as roof and façade areas change with different building form , the efficiency also differs.
- Based on cost analysis, the lowest lifecycle cost is achieved in the building form with the lowest energy loads.

As the above approach indicates, solar energy as an alternative source could be used to design energy and cost efficient systems eliminating environmental pollutions caused by fossil fuels .

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