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Evaluation of the Impact of Photovoltaic Systems on Energy and Economic Performances of a Residential Building

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***Abstract—* As the residential buildings have the highest energy consumption, these buildings should be considered as a sub-system of energy generation system in order to provide energy sustainability and capability. In this context, high potential of photovoltaic (PV) system is primarily evaluated both improving the energy performances of existing residential buildings and shaping the energy strategies of the buildings to be constructed. Therefore, designing and integrating the PV systems in residential buildings for maximum energy generation as an active building sub-system have a great importance. Thus, in this study, it is aimed to integrate the PV systems to building envelope intended for improving the energy performance of residential building and evaluate the impact of PV systems on energy and economic performances of residential buildings. In line with this aim, energy and economic analyses were carried out related to the PV systems designed on terrace roof and opaque areas of south facade of a residential building, considered to be located in Antalya representing the hot humid climate zone of Turkey; and the analysis results gained are discussed and presented.**

Index Terms— **Life cycle cost, energy generation, photovoltaic systems, residential energy performance.**

I. INTRODUCTION

Within the framework of sustainable development, renewable energy sources which are alternative to fossil fuels widely used in the world, environment friendly, serve the purpose of producing energy by featuring the energy producing potential of the nature is considered as a priority. Therefore, energy producing systems play an important role in the solutions discussed in transforming natural energy sources to usable energy forms. On the other hand, the costs getting more acceptable for on-site energy generation in the course of time, the specified project dimensions, content and the existing incentives make it more feasible to develop on-site energy generation sources. The renewable energy sources including reasonable payback periods and the possible incentives are firstly taken into account in terms of energy production. Solar, wind, geothermal and biomass fuels are the most researched methods of energy production [1]. Because solar energy is more useful compared to other energy sources among the energy producing methods researched and is the basic component of sustainable development programs, it is primarily taken into account in solving the energy problems in the recent years [2]-[3]-[4]. Also, considering the high amount of energy consuming of the buildings and the production of the consumed energy via complex, costly and polluting systems, it is seen that the reduction of energy delivered to the building is possible with the use of on-site solar energy [5].

From among the various solar energy technologies, PV systems are paid more attention as they don't have CO_2 emission during the usage phase but have the scale flexibility, require less maintenance and don't lead to environmental noise [6]. Continuous drop in the cost of PV industry with the sector activation thanks to the direct implementation of PV systems in everywhere energy utilization is available, and developing PV modules to be integrated to the buildings bring PV systems into the forefront as the most suitable systems to be used in urban areas [7]. In addition, it is indicated that PV systems are the most effective solution for the countries to reduce CO_2 emission and to help achieve their goals in the renewable energy production [8].

In light of the above considerations, PV systems have been primarily dealt with in this study from among the energy producing systems for improving residential energy performance considering the high solar energy potential of Turkey. The aim of the study is to integrate PV systems for improving the residential energy performance to building envelope, and to evaluate the impact of PV systems on energy and economic performances of the residential buildings via the representative province of hot humid climate zone of Turkey, Antalya.

II. METHODOLOGY

A. *Energy Performance Analysis*

1. *Building model*

In this study, an existing mass housing application constructed by the Housing Development Administration of Turkey (TOKI) which has a significant role in dwelling production in Turkey, and including the widely used construction technologies and the design criteria is examined (Figure 1). One of the housing blocks is studied as the example residential building within the scope of the study (Figure 2).

The example residential building is a 17-storey building, and the storey height is 2.79 m. The type of roof is walk able terrace roof. The shape factor (building length / building depth in plan) is 1.37, A / V ratio (total external surface area / building volume) 0.19, and the floor area is 573 m^2 and the total building height is 48.28 m. Within the scope of opaque components of the example residential building, there are two types of external wall component as 20 cm aerated concrete block wall and reinforced concrete block wall. The existing thermal insulation thickness and the total heat transmission coefficient (*U*) values related to the external wall, terrace roof and ground floor are given in Table 1. The plastic joinery double-glazed windows system (4 mm float glass + 12 mm air + 4 mm float glass) was used (U_p:2.60 W/m^2K) as a transparent component .Transparency ratio (total transparent area / total facade area) for north, south, east and west facades are in turn 14%, 15% and 24% and 30%.

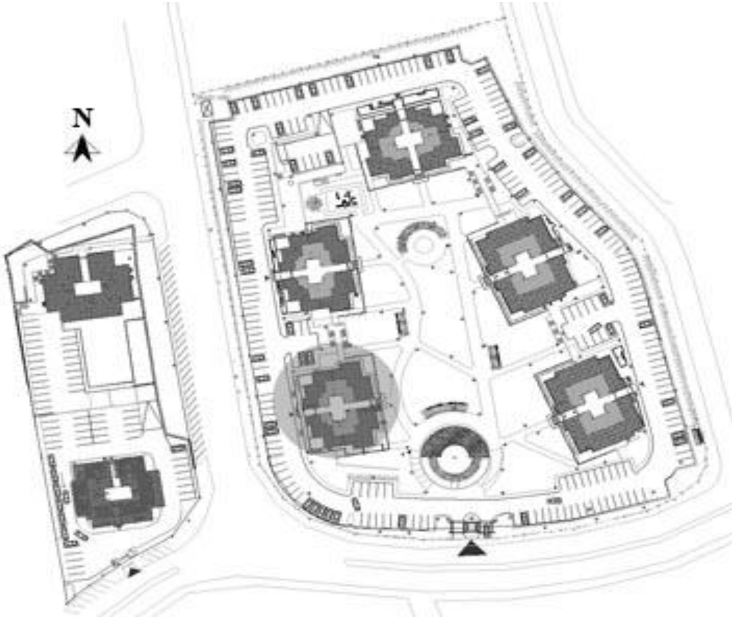

Fig-1: The layout plan of the mass housing application.

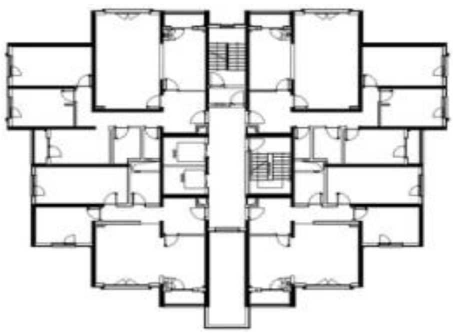

Fig-2: Normal floor plan of the example residential building.

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Table-1: Data of opaque components.

Opaque component	Thermal insulation	U value (W/m^2K)
External wall ($type_1$)	0.05m Thermal insulation (XPS)	U_{wall_1} = 0.37
External wall ($type_2$)	0.05m Thermal insulation (XPS)	U_{wall_2} = 0.58
Ground floor	0.04m Thermal insulation (XPS)	U_{g_floor} = 0.51
Terrace roof	0.05m Thermal insulation (EPS)	U_{roof} = 0.55

There are four residential units on each floor of the example residential building, and each housing unit is considered as a conditioned (area for heating/cooling) single zone. The user activity level in each zone is accepted as 110 W/person. The user clothing type is considered as 1 clo for heating period, 0.5 clo for cooling period. The indoor comfort temperature is accepted as 21ºC for the period required heating, and 25ºC for the period required cooling. The heating system of the residential building is the penthouse condensing boiler type central system and the fuel used is natural gas. It is assumed in the study that there is a cooling system and the electric energy is used for cooling. The hot water system of the residential building is the individual water heater system, and the fuel used is natural gas.

2. *PV system definition*

On the terrace roof and south facade opaque areas of the example residential building, PV systems assumed to be grid connected are designed. For PV systems designed on terrace roof area, the single-crystalline silicon PV cells from crystalline silicon PV cells which can operate at high efficiency are used. The optimum panel tilt angle related to PV system constructed on terrace roof area for Antalya representing hot humid climate zone in the framework of the study has been determined as 32° as a result of the analysis study. PV panels are oriented to the south and the distance ranges reducing the earning lost on panel arrays due to the distance from ghosting to 1% are taken into account as appropriate shading distance between panel arrays. In the southern facade of opaque areas, the amorphous silicon PV cells from thin film PV cells in which the efficiency is less dependent on the solar radiation density are used. PV panels are placed on the south facade of the opaque area of the existing building with the angle of 9° deflection (azimuth angle surface) from south to east and at a 90° tilt angle. Data related to PV modules used on the terrace roof and facade area and the performance data related to both PV systems described are indicated in Tables 2-3.

Table-2: Data of PV modules.

Technology	Power (Wp)	Module Efficiency (%)	Length/ Width (mm)
Single cyrstalline silicon	190	14.9	1581/809
Amorphous silicon	340	5.9	2600/2200

Table-3: The performance data related to the described PV systems.

PV system	PV installed power (kWp)	PV surface area (Wp/m^2)	Performance ratio (%)
Roof PV	29.83	148.36	84.10
Facade PV	14.28	55.30	84.50

3. *The calculation of final energy consumption*

The final energy consumption on the current condition of the example building is calculated using Design Builder simulation program, the comprehensive interface of Energy Plus thermal simulation engine. In the study, for Antalya, data for external climate including external temperature, external humidity, solar radiation and wind is formed in the form of "Typical Meteorological Year (TMY)" format created with Meteonorm 7.0, the program to achieve climate data. Meteonorm 7.0 program is a comprehensive meteorological program which has an extensive database that contains all kinds of data for external climate required for energy applications [9].

4. The calculation of final energy production

The final energy productions of the alternatives described for the implementation of PV systems on the terrace roof and facade areas of the example residential building are calculated by the dynamic simulation program, PV* SOL Expert simulation program which enables to make three-dimensional modelling and the detailed shading analysis. It is very important to determine the solar radiation value falling on PV panels in the calculation of energy amount produced by PV system. In this study, the horizontal irradiance data obtained via Meteonorm 7.0 database related to the province studied was transformed for sloping surface during the simulation by PV * SOL Expert program, and was multiplied by the total active PV surface area, so the energy amount PV system could produce was calculated. The equality stated below is used for the calculation of energy cover factor (C_{PV}) indicating the ratio of the energy amount produced by PV systems to meet the current electricity consumption of the example residential building [10]-[11]:

$$C_{PV}= \frac{E_{pv}}{E_{cons,e}}\ x\ 100 \quad (1)$$

Where E_{PV} is the annual energy amount generated by the PV system (kWh/a) and $E_{cons,e}$ is the electrical energy consumption of the reference residential building (kWh/a).

B. Economic Performance Analysis

1. The calculation of initial investment cost

The initial investment costs related to the defined PV systems are calculated with the help of the equation as follows:

$$C_{inv}=C_{unit,PV}\ x\ PV_{out} \quad (2)$$

where C_{inv} is the initial investment cost related to PV system (TL), $C_{unit,\ PV}$ is the unit cost related to PV system (TL/kWp), and PV_{out} is the PV installed power (kWp). In the study, the unit cost of the PV system applications has been taken 1,5 Euro / Wp.

2. The calculation of operational cost

In the calculation of operational costs, due to the insufficient data related to maintenance and repair costs, only the energy costs are taken into account and calculated by the help of the equation stated below [12]:

$$C_E = \sum\left(E_{cons,fuel} \times C_{unit,fuel}\right) - \sum\left(E_{PV} \times C_{unit,PV}\right) \quad (3)$$

where C_E *is the energy cost* (euro/a), $E_{cons,fuel}$ is the energy consumption per fuel type (kWh/a), E_{PV} is the the energy generated by the PV system (kWh/a), $C_{unit,fuel}$ is the unit cost per fuel type (euro/kWh) and $C_{unit,PV}$ is the unit cost of the electrical energy generated by the PV system (feed-in tariff) (euro/kWh).

The unit price of electricity considered under the study is 0.109108 €/kWh, applied as one-time tariff cost for housing by Turkey Electricity Distribution Company (TEDC) [13]. For the unit price of natural gas, the unit cost applied by the natural gas distribution company in the climate zone studied is considered. It is 0.02894697 €/kWh for Antalya [14]. The unit cost of electricity generated by the PV systems in other words, selling price to the grid, is 0.10 €/kWh (0.133$/kWh) applied to electric energy generation based on solar energy in Turkey [15].

3. The calculation of life cycle cost

In the calculation of life cycle costs related to PV systems, the equation considering the initial investment costs and the current values of life cycle operating costs is used and stated below:

$$LCC = C_{inv} + C_{op,P} \quad (4)$$

Where LCC is the life cycle cost (euro), C_{inv} is the initial investment cost (euro) and $C_{op,P}$ is the present value of the operational cost (euro).

In order to convert the operational costs to the current value, the equation below is used [16]:

$$C_{op,P} = C_E\ x\ \sum_{n=1}^{t}\frac{1}{(1+i)^n} \quad (5)$$

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Where $C_{op,P}$ is the present value of the usage cost (euro), C_E is the energy cost (euro/a), i is the discount rate (%) and n is the analysis period (year).

Within the scope of economic variables, the discount rate as 6% [17]-[18], the evaluation period as 30 years [19], the calculation starting year as 2013 and the current rate as the exchange rate issued by the Republic of Turkey Central Bank (CBRT) [20] are taken into account. Annual degradation values in the performance of PV modules that may occur during the evaluation period are considered as 1% for the first ten years, as 0.5% for the rest [21].

4. The calculation of discounted payback periods

Within the framework of the study, in addition to LCC analysis, the discounted payback period method is taken into consideration. Thus, the payback periods of the initial investment costs related to PV systems can be determined considering the time value of money, and it is calculated by the equation stated below [22]:

$$\sum_{n=1}^{t} \frac{[\Delta C_{op}]}{(1+i)^n} \geq C_{inv} \quad (6)$$

where ΔC_{op} is the total of the saving achieved in the operational cost (euro) and C_{inv} is the initial investment cost (euro) for the measure.

III. FINDINGS

For Antalya, the representative province of hot humid climate zone in Turkey, the impact of PV systems described on the terrace roof and south facade opaque areas of the example residential building on the energy and economic performances of the building has been evaluated utilizing the Figures 3-4 and explained below.

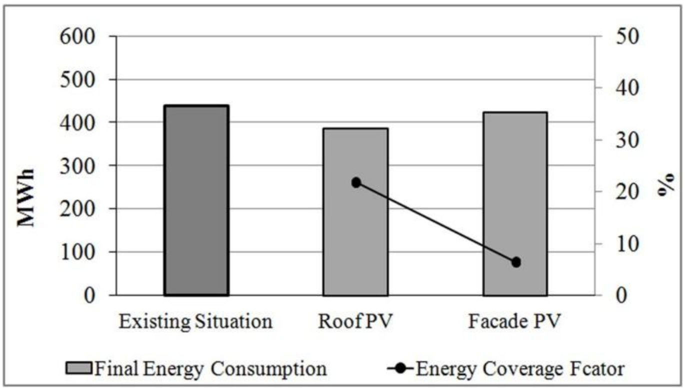

Fig-3: The results of energy performance analysis.

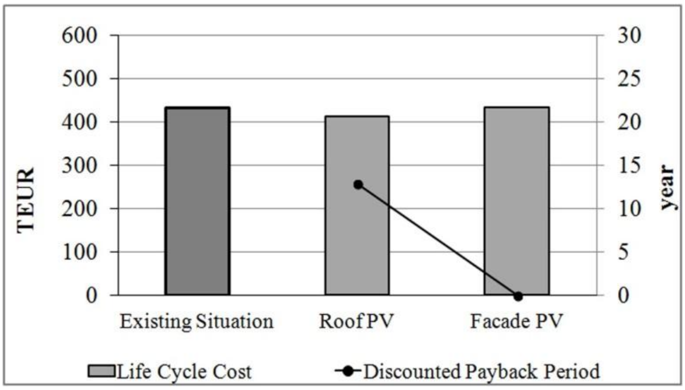

Fig-4: The results of economic performance analysis.

According to the energy performance analysis results, when the roof PV system alternative described for the existing terrace roof area of the example residential building is compared with the situation PV system is absent (in other words, existing situation of example residential building), it is seen that the annual 51.01 MWh energy production by PV, and 12% reduction in the annual final energy consumption have been enabled. The energy

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coverage factor related to the roof PV system, in other words the ratio to meet the current electric energy consumption of the example residential building, is 22%. As the second alternative, when the facade PV system designed on the southern facade of the opaque areas of the example residential building is compared with the situation PV system is absent, it seen that the annual 15.35 MWh energy production by PV, and 4% reduction in the annual final energy consumption have been enabled. The energy coverage factor for the PV facade system is 7%. According to the results of the analysis of economic performance, when roof PV system alternative is compared with the situation PV system is absent, it is seen that 16% reduction in the annual operating cost and 4% reduction in life cycle cost have been enabled. The initial investment cost related to roof PV system alternative could be paid back in 12.9 years with the annual €5,084.91 saving worth provided in the operating costs. When facade PV system alternative is compared with the situation PV system is absent, it is seen that 5% reduction in the annual operating costs and 1% reduction in life cycle costs have been enabled. The initial investment cost related to facade PV system alternative could not be paid back within 30 years of the evaluation period with the annual saving value of €1,530.35 provided in the operating costs.

IV. CONCLUSION

PV system utilizing solar energy is one of today's most promising renewable energy systems. PV systems can enable on-site electric energy production without causing energy supply or environmental damage concerns; can provide the energy supply security with the ability to connect to the grid; and can also be easily integrated into buildings thanks to the modular structure they have.

Therefore, within the scope of this study, it is aimed to evaluate the impact of PV systems on the energy and economic performances of the example residential building by defining an existing housing block as the example residential building including the widely used construction technologies and the design criteria. For this purpose, it has been assumed that the example residential building is in Antalya, the representative province of hot humid climate zone of Turkey, and two types of PV systems have been designed as the roof and the facade PV systems on the terrace roof and the southern opaque areas of the example residential building for improving the residential energy performance. PV systems have been designed in the framework of increasing the energy efficiency delivered to the building; the impact of PV systems on the energy and economic performances of the example residential building has been evaluated via the energy and economic performance analyses. Under the evaluation, it has been calculated that a reduction of 4% and 12% in the final energy consumption of the residential building has been enabled by PV systems, and this reduction has an impact of 1% and 4% on life cycle cost.

Within the framework of the study, an evaluation has been made for PV systems described for improving the energy performance of an example residential building. The results of the study shows the importance of an integrated evaluation of the impacts of PV systems, effective in improving the residential building energy performance, on the energy and economic performances of the residential building on the basis of life cycle. However, the improvement of the energy performances of the residential buildings is a complex process differing from one building to the other and including many requirements. Under this process, in order to achieve acceptable results related to the impact of PV systems on the energy and economic performances of the residential buildings, this kind of studies should be performed and assessed for different kinds of housing. In addition, it is possible to minimize the environmental impacts due to the energy consumption, to reduce the energy costs and so to provide a significant contribution to the national economy with a thorough review of the integrated approaches considering the integration of PV systems to the buildings and the transformation of the buildings to energy producing system components.

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