

RESEARCH ARTICLE

Research on improving the energy performance of residential buildings

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Abstract

The research focuses on the improvement of lighting systems and the impact of photovoltaic applications on energy efficiency in buildings, aiming to increase building energy efficiency in response to global challenges such as population growth and urbanization. The study, conducted in Antalya, located in the Mediterranean Climate Zone, evaluates the impact of upgrading the lighting system and integrating photovoltaic panels in three selected blocks within an island-based settlement. Energy efficiency assessments cover a variety of factors such as building location, orientation and energy use scenarios including both natural gas and electricity for heating. Hourly analyses using DesignBuilder simulation and PVsyst software show that by improving the lighting systems, annual energy savings of up to 33.00% in the energy consumption of the lighting system and 7.20% in the total energy consumption of the buildings can be achieved. In addition, it is seen that up to 14% of the energy demands can be met with the integration of PV systems into the buildings. These findings underline the significant potential for reducing energy expenditure and environmental footprints. By demonstrating the effectiveness of an island-based strategy for improving building energy efficiency, this study extends the scope of energy saving initiatives from floors, spaces and buildings to an island-based approach.

1. Introduction

Today, one in two people live in urban areas. This rate is estimated to be 75% by 2050 [1, 2]. The increase in settlements leads to an increase in energy demand. Approximately 40% of the energy consumed in the world, 32% of the resources and 25% of CO₂ emissions are caused by the construction sector [3, 4]. Due to the threat of global climate change, measures have been developed within the framework of international conventions and protocols. In 1992, the United Nations Framework Convention on Climate Change

(UNFCCC) was signed at the United Nations Conference on Environment and Development, and the Paris Climate Agreement signed at the 21st Conference of the Parties 2015 (COP21) held in Paris in 2015 aims to keep global warming below 2°C compared to the pre-industrial revolution by the end of this century and at 1.5°C levels as much as possible [5]. With the Global Renewable Energy and Energy Efficiency Commitment of the 28th Conference of the Parties 2023 (COP28), which was organised in 2023 to discuss the necessary steps to achieve the goals of the Paris Climate

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Agreement, to review the commitments of countries to reduce greenhouse gas emissions and to develop adaptation strategies against climate change, it was decided to limit global warming to 1.5°C. It emphasised that the world will need three times more renewable energy capacity by 2030 to limit the global average annual energy efficiency improvement rate from 2% to more than 4% per year by 2030 [6].

In the PES (Planned Energy Scenario) in the 'World Energy Transitions Outlook 2023: 1.5°C Pathway' report of the International Renewable Energy Agency (IRENA), energy consumption is expected to increase from 120 EJ/year in 2020 to 130 EJ/year in 2030 and 160 EJ/year in 2050, while in the 1.5°C scenario targeted in the Paris Climate Agreement, it is projected to be 130 EJ/year in 2030 and 150 EJ/year in 2050. In terms of CO₂ emissions, emissions are expected to decrease from 2.8 GtCO₂/year in 2020 to 2.7 GtCO₂/year in 2050 in the PES scenario, and up to 0.5 GtCO₂/year in 2050 in the 1.5°C scenario. The share of renewable energy is projected to increase from 35% in 2020 to 54% in 2050 in the PES scenario and to 86% in 2050 in the 1.5°C scenario [7]. According to the 'World Energy Transitions Outlook 2023: 1.5°C Pathway' report, there are difficulties in achieving the 1.5°C global warming target set in the Paris Climate Agreement. The energy efficiency improvement decisions taken at COP28 are considered to be of critical importance to achieve this target.

In order to achieve the targets set by the Paris Climate Agreement, many energy investments are being made in the world. According to the 'Global Landscape of Renewable Energy Finance, 2023' report, annual investments in renewable energy technologies increased from 239 billion USD in 2013 to 499 billion USD in 2022. Solar PV investments have taken the largest share, increasing from 120 billion USD in 2013 to 220 billion USD in 2022, and residences have taken the lead in Solar Home Systems investments with 89%. Renewable energy investments tripled between 2015 and 2022, reaching 839 billion USD in 2022, while energy efficiency investments doubled to 360 billion USD

[8]. In recent years, there has been a significant increase in investments in renewable energy, energy efficiency and other transformation-related technologies in order to achieve the goal of limiting global warming to 1.5°C.

As a party to the Paris Climate Agreement in 2015, Turkey committed to reduce greenhouse gas emissions by 21% by 2030 compared to the ordinary scenario by constructing new residential and service buildings in an energy efficient manner [9]. In this context, in order to achieve energy efficiency targets, with the I. National Energy Efficiency Action Plan (I. NEEAP) covering the years 2017-2023, 8.47 billion USD was invested in energy efficiency in the period between 2017-2023, resulting in a cumulative energy saving of 24.6 Mtoe. With the investments made and savings achieved, 68.62 million tonnes of CO₂ equivalent greenhouse gas reduction was achieved. II. National Energy Efficiency Action Plan (II. NEEAP), which covers the years 2024-2030, aims to invest 20.2 billion USD in energy efficiency, to achieve 37.1 Mtoe cumulative energy savings and to achieve 100 million tonnes of CO₂ equivalent greenhouse gas reduction as a result [10].

In Turkey, the increase in population, rising living standards, new technologies that demand additional energy and the widespread use of consumer products lead to an increase in energy demand. According to the 10-Year Demand Forecasts Report (2023-2032) of the Turkish Electricity Transmission Corporation (TEİAŞ), electricity consumption in 2032 is estimated to be 26.5% in the low scenario, 34.4% in the base scenario and 40.2% in the high scenario compared to 2023 [11]. According to Turkey's National Energy Plan (2020-2035), the share of electricity energy, which was 21.8% of final energy consumption in 2020, is expected to reach 24.9% in 2035, with an average annual increase of 2.3% in residential electricity consumption during 2020-2035. The share of renewable energy sources, which was 42.4% in electricity generation in 2020, is targeted to increase to 54.8% by 2035. In 2053, it is aimed to increase this ratio to 69.1%. In this context, the installed solar power capacity, which

was 6.7 GW in 2020, is targeted to increase approximately 8 times and reach 52.9 GW in 2035. This means that Turkey's solar energy installed capacity, which was 9.32 GW in 2022, will increase by approximately 500% by 2035. Solar energy is targeted to have the highest share in Turkey's total installed electricity capacity in 2035. Solar energy is expected to reach 10% of Turkey's total electricity generation in 2035 [12]. The National Energy Plan of Turkey summarises that the share of households in total energy consumption will decrease until 2035. A general increase in energy consumption is observed. However, it is thought that energy efficiency measures will be effective in decreasing the share of residential buildings in total energy consumption.

The building stock in Turkey has shown a significant growth with approximately 9.6 million buildings as of 2022 and the number of households increasing by 36% from 19.8 million in 2012 to 26.9 million. Residential buildings constitute 87% of this building stock. Due to the rapidly increasing population and decreasing average number of households, an average of 106 thousand new buildings are constructed annually. This situation offers a significant potential in terms of energy efficiency. In this context, II. National Energy Efficiency Action Plan (II. NEEAP) aims to create a sustainable, energy efficient building stock by increasing the amount of credits for buildings with A and B class Energy Identity Certificates, encouraging alternative methods such as thermal insulation campaigns, disseminating smart building designs and making green building certificates in line with international standards. Efforts on energy efficiency in buildings include various strategies such as dissemination of energy efficient buildings, promotion of energy efficiency in existing buildings and dissemination of energy efficient buildings supported by renewable energy [10].

Improvement studies to increase energy efficiency in buildings have a significant role in reducing global energy consumption and carbon emissions. Studies show that buildings with high energy efficiency are more economical in the long term and provide significant savings in energy

consumption. Among the improvements made to increase energy efficiency in buildings, there are many studies on the improvement of thermal insulation [13-21], the use of energy efficient window combinations [19, 22-27], the improvement of lighting systems [28-34], the application of sun shading systems [35-40], smart building automation [41-45] and PV system integration from renewable energy systems [46-49].

Adıgüzel Işıl [50] has realized many applications within the scope of sustainable criteria such as lighting system improvement and photovoltaic panel application based on a block in Antalya. Although the improvement of the lighting system in the Base Block caused a cost increase of 1890.3 TL, it was observed that 71% energy saving was realized in the lighting system. While the application cost of the PV Panel system was 10.286.77 TL, the amount of energy produced was calculated as 3.180.91 kWh/year. It is calculated that the PV system has the capacity to meet 1.5% of the annual electricity consumption of the entire building, and the amortization period of the system is 5.41 years. Mangan ve Koçlar Oral [51] applied the scenarios of retrofitting opaque components, retrofitting transparent components and integrating systems using renewable energy sources in a residential project for moderate humid (Istanbul), warm humid (Antalya) and cold (Erzurum) climate zones of Turkey. For Antalya, the PV system with monocrystalline panels with an installed capacity of 25.08 kW and a system performance of 83.9% meets 48.42% of the electrical energy required by the building. With polycrystalline panels, it is seen that the PV system with 23.54 kW installed power and 83.3% system performance meets 45.13% of the electrical energy required by the building. In their study, Demir et al. [52] calculated that if the existing fluorescent lighting system in Yalova University Faculty of Engineering is replaced with LED luminaires, the payback period is 1.42 years and 2.050.391 TL savings will be achieved in 10 years. They also found that replacing lighting fixtures with LEDs also improves building energy performance. Perdahçı [53] compared energy consumption and lighting efficiency by using LED

luminaires instead of fluorescent luminaires in a metal processing plant. While 11232W energy was consumed with fluorescent luminaires, this consumption decreased to 4315.2W with LED luminaires and 61.5% energy saving was achieved. As a result of this change in the facility, a total annual energy saving of 830.040 Wh was achieved. Karaca and Uçar [54] investigated the electricity generation of photovoltaic (PV) panels applied with different methods in a single-storey house for 4 people in Burdur, located in the Mediterranean climate zone. Four different layouts were evaluated for roof and facade applications. It was found that the roof system produced a maximum daily average of 7.88 kWh and 240 kWh per month; the facade system produced a maximum daily average of 4.82 kWh and 147 kWh per month. In their study, Şanlı and Dilsel [55] installed a photovoltaic cell system with six solar panels with a capacity of 165W in order to meet the daily electricity demand of 4400 Wh of a residence in Mersin, located in the Mediterranean climate zone. During 25 years of operation, the total cost of the photovoltaic system was found to be 61.261.94 TL lower than the grid electricity and they stated that the photovoltaic system is economically advantageous. Kayıkcı [56] conducted an economic and environmental analysis of meeting the electricity demand of a house in Aydın with a grid-connected renewable energy system. The daily electricity demand of the building is calculated as 12.63 kWh. With the addition of a photovoltaic system to the wind turbine, the renewable energy utilization reached 93.10% and the energy unit cost reached -0.0354 TL/kWh. With this hybrid system, emission reduction between 26% and 58% was achieved in the building. The optimum solution for the building is to connect 5 kW photovoltaic and 1.5 kW wind turbine to the grid. In their study, Altınöz and Mıhlıyanlar [57] evaluated energy consumption and environmental impacts through renovation retrofitting of different buildings and integration of active solar systems in Kırklareli. Comparing Scenario 1 (without insulation), Scenario 2 (with insulation) and Scenario 3 (with insulation + active solar energy systems), between Scenarios 1 and 2, 32% to 67%

improvement in annual primary energy consumption and CO₂ emissions and 29% to 64% improvement in total energy consumption were achieved. Between Scenarios 2 and 3, energy consumption improved by 17% to 32% and total energy consumption by 16% to 30%. The results show that even in regions with low solar potential, carbon footprint can be reduced with renewable energy systems and proper building design.

In the literature, there are many studies on the efficient use of energy in buildings. These studies are usually carried out at a specific location, floor or building level. In energy efficiency calculations, only the building heating load is usually taken into account. This study analyses the effect of the improvement of the lighting system and the application of photovoltaic (PV) panel system on the energy performance of the selected base buildings within the scope of energy efficient building design applications in an island-based residential settlement in Antalya, located in the Warm-Humid Climate Zone. The most distinctive feature that distinguishes this study from other studies is that energy efficiency is considered not only at the building, floor or space level, but also at the settlement level on an island basis. Another important feature of the study is that energy-cost analyses are repeated for the case where electricity is used in addition to natural gas in heating and energy efficiency is examined according to the type of fuel used in heating.

2. Methodology

In the study, an island-based residential project in Antalya, which is located in the Mediterranean Climate Zone and classified in the 1st Degree Day Zone according to the Turkish Standards Institute (TS 825), with a hot-humid climate, was selected as a sample. In the buildings selected in the island-based residential project, it was investigated how much the energy need can be reduced by improving the lighting system and how much the energy need can be met by PV system application. In addition, another objective of this study is to find out to what extent the improvement of the lighting system and

PV system application will increase the building cost.

Within the scope of the study; Block B, Block D and Block F were preferred as 'Base Building' in order to improve the lighting system and to examine the effect of PV system application on energy consumption by considering factors such as orientation, location, facade area, number of storeys, Window wall ratio of the buildings in an island-based residential project consisting of 6 blocks. 'Base Building Models' were created by modelling Block B, Block D and Block F according to the current situation. Considering the power densities recommended by the American Society of Heating, Refrigeration and Ventilation Engineers (ASHRAE) according to the spaces, 'Design Building Models' were created by using LED (Lighting Emitted Diodes) bulbs instead of saving bulbs (compact fluorescent bulbs) only in the base buildings so that the lighting fixtures remain constant. By comparing the energy consumption between the Base Building Models and Design Building Models, energy cost, emission and saving rates were obtained separately. The analyses were performed using meteorological database, which is a dynamic thermal simulation programme, and DesignBuilder dynamic simulation tools with 3D modelling capability. The cost of improving the lighting system in the Base Buildings was calculated and cost analysed. Cost information of saving and LED bulbs were obtained from the companies in the market.

There is no PV system to generate electricity from solar energy in the Base Buildings considered in the study. In the study, it is aimed to obtain electricity generation from solar energy by designing PV panels in base buildings. In this context, PV electricity generation report of the base buildings was obtained with the help of PV simulation software provided by CW-Energy Company in order to design solar PV systems. PV system cost was obtained from the companies in the market. Cost analyses were made for each block and presented in tables.

Within the scope of the study, the analyses were repeated by using electric energy as well as natural gas as heating energy in the buildings. In the study, two Base Building models were created for each block according to the type of energy used in heating. In the case where natural gas is used as heating energy, the 'Design Building-1' model was obtained by improving the lighting system and applying PV system to the 'Base Building-1' (heating natural gas; cooling electricity) model. In the case where electricity is used as heating energy, 'Base Building-2' (heating electricity; cooling electricity) model by improving the lighting system and applying PV system to 'Design Building-2' model was obtained. Energy cost, emission and saving ratios between Basic Building and Design Building Models are analyzed and presented in the form of figures and tables. The main work steps followed in the study are shown in Fig. 1.

2.1. Analysis of the study area

The study area is located in the Mediterranean Climate Zone, according to TS 825, the island-based urban regeneration project located in the 1st Degree Day-Hot-Humid Climate Zone has been selected and consists of 6 blocks, 317 houses and a total construction area of 37.647 m². Block B consists of 10 floors and has 76 apartments with a total net usage area of 4743,7 m². Block D has 11 storeys, 41 apartments and a total net usage area of 5102,4 m². Block F has 9 floors, 51 apartments and a total net usage area of 5201,3 m² (Fig. 2).

The architectural design features of the Base Buildings consisting of parameters such as gross volume, orientation, window area, window-wall ratio are shown in Table 1. The optical properties of the windows used in the Base Buildings are presented in Table 2 and the thermophysical properties of the opaque elements forming the building envelope are presented in Table 3. The facade images and floor plans of the Base Buildings are presented in Fig. 3, Fig. 4 and Fig. 5 respectively. The 3D image and photograph of the study area are presented in Fig. 6 and Fig. 7, respectively.

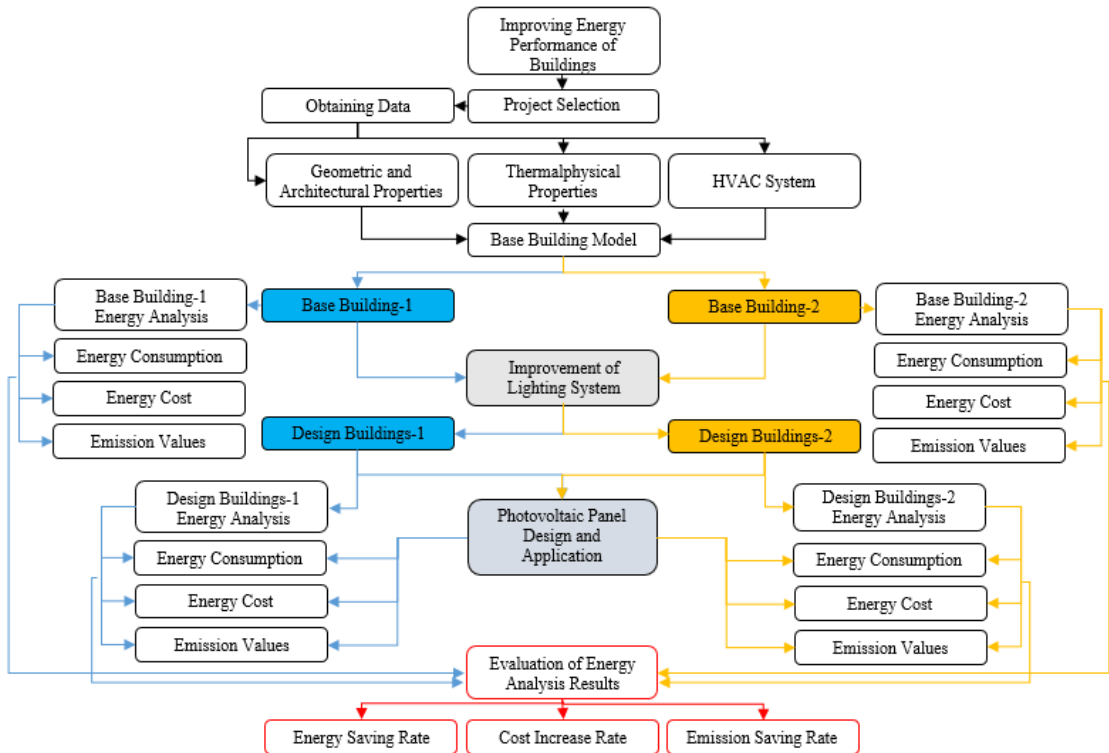


Fig. 1. Flowchart of the process of improving energy performance in residential buildings

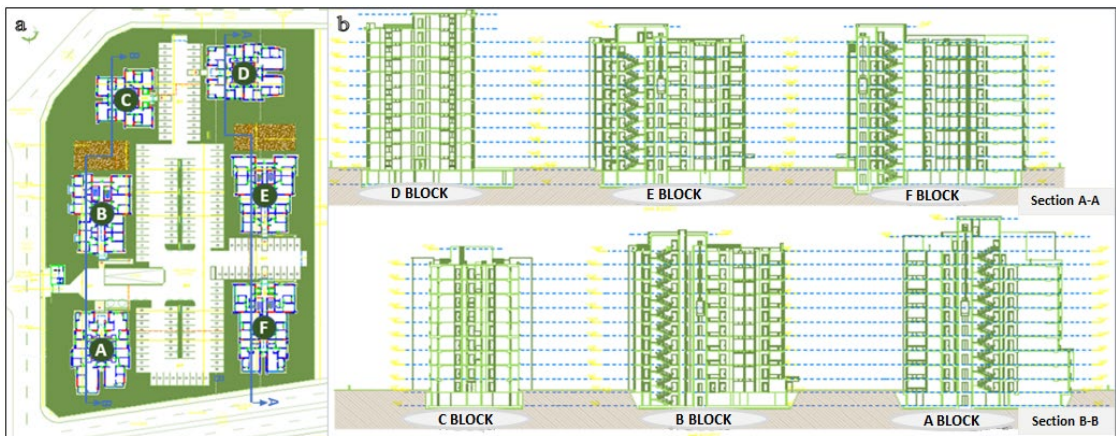


Fig. 2. Island-based settlement project (a) layout plan, (b) sections

2.2. Analysis of base building model

In the study, data on the energy performance of the Base Building and Design Building models were obtained through hourly analyses using the DesignBuilder simulation program. The building models were created based on the climate data

specific to Antalya according to ASHRAE 90.1-2010 standard. Important parameters such as heating and cooling systems, indoor temperatures, ventilation conditions and user profiles are integrated into the models according to ASHRAE standards. In Table 4, the data for these building models are presented in detail.

Table 1. Architectural design features of Base Buildings

Parameters	Base Buildings		
	Block B	Block D	Block F
Number of Floors	10	11	9
Number of Flats	76	41	51
Gross Volume (m ³)	14824	15945	16254
Net Usage Area (m ²)	4743,7	5102,4	5201,3
Building Orientation	east-west	north-south	east-west
	Southern Front	278,7	193,8
	Northern Front	51,7	229,1
Window Area (m ²)	Eastern Front	388,3	309,7
	Western Front	394,1	135,7
	Total	894,7	953,2
Window Wall Ratio (WWR)	30%	32%	39%
A/V Ratio (Total External Surface Area/Building Volume)	22%	20%	16%

Table 2. Optical properties of windows used in Base Buildings

Window combinations	Insulating Glass Series	Daylight (EN 410)		Sun Power (EN 410)		Heat Permeability Coefficient (U) (EN 673)
		Permeability %	Projection %	Total Permeability %	Shading Coefficient	Air
4mm+12+4mm	C	80	14	75	0,86	2,9
4mm+14+4mm	C	80	14	75	0,86	2,7

Table 3. Thermophysical properties of opaque elements forming the building envelope in Base Buildings

Material	Element Thickness of the Structure d (m)	Thermal Conductivity Calculation Value λ_h (w/mK)	Resistance of Thermal Conductor R (m ² K/W)	Thermal Conductivity Coefficient U (W/m ² K)
Hollow brick Wall				
Surface thermal conductivity coefficient (interior)			0,13	
Gypsum mortar, gypsum mortar with lime (interior)	0,03	0,70	0,04	
Hollow brick	0,25	0,22	1,14	
Lime-cement mortar (exterior)	0,03	1,00	0,03	0,73
Surface thermal conductivity coefficient (exterior)			0,04	
Total =			1,38	
Concrete Wall				
Surface thermal conductivity coefficient (interior)			0,13	
Gypsum mortar, gypsum mortar with lime (interior)	0,03	0,70	0,04	
Reinforced concrete	0,25	2,50	0,10	
Extruded polystyrene (XPS)	0,04	0,035	1,14	0,67
Lime-cement mortar (exterior)	0,03	1,00	0,03	
Surface thermal conductivity coefficient (exterior)			0,04	
Total =			1,49	

Table 3. Cont'd

Roof Flooring				
Surface thermal conductivity coefficient (exterior)				0,04
Cement-based mortar	0,05	1,40		0,04
Tyre asphalt coating ≥ 7 mm	0,008	0,70		0,01
Extruded polystyrene (XPS)	0,05	0,035		1,43
Reinforced concrete	0,15	2,50		0,06
Lime-cement mortar	0,03	0,70		0,04
Surface thermal conductivity coefficient (interior)				0,13
Total =				1,75
Earth Contact Flooring				
Surface thermal conductivity coefficient (interior)				0,17
Lime-cement mortar	0,03	1,00		0,03
Metamorphic stones with crystal structure	0,02	3,50		0,01
Cement-based mortar	0,05	1,40		0,04
Extruded polystyrene (XPS)	0,05	0,035		1,43
Reinforced concrete	0,15	2,50		0,06
Surface thermal conductivity coefficient (exterior)				0,17
Total =				1,90

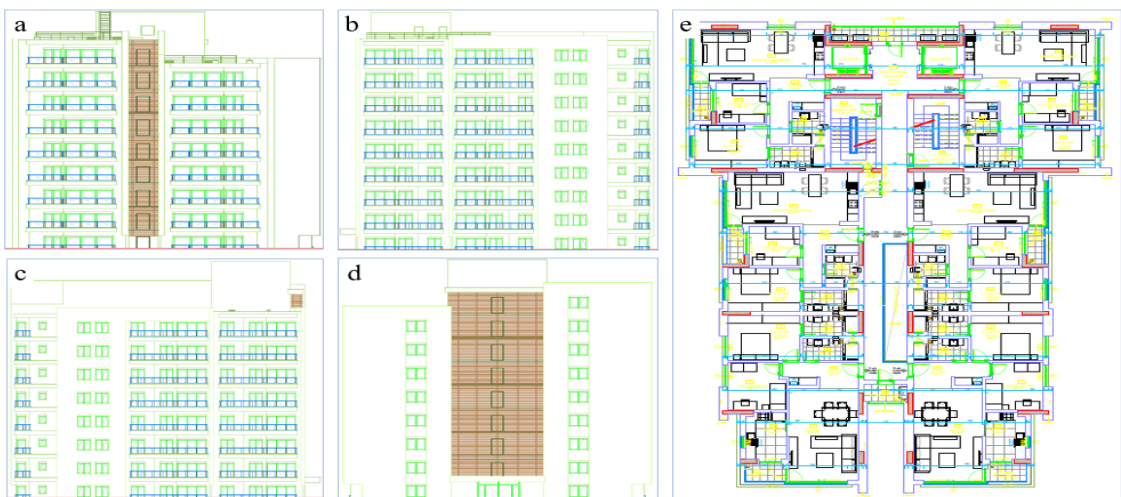


Fig. 3. Block B and its appearance (a) south front, (b) western front, (c) eastern front, (d) north front, (e) regular floor plan

Within the scope of the study; Block B, Block D and Block F were preferred as 'Base Buildings' by considering factors such as orientation, location, facade area, number of storeys, Window wall ratio of the buildings in the island-based settlement. The energy consumption behaviour of the base buildings was modelled to represent the island-based residential settlement (Fig. 8-11).

2.3. Improvement of lighting system

In the study, only the bulb type and lighting power density were changed so that the electrical appliances used in the Base Buildings remained the same.

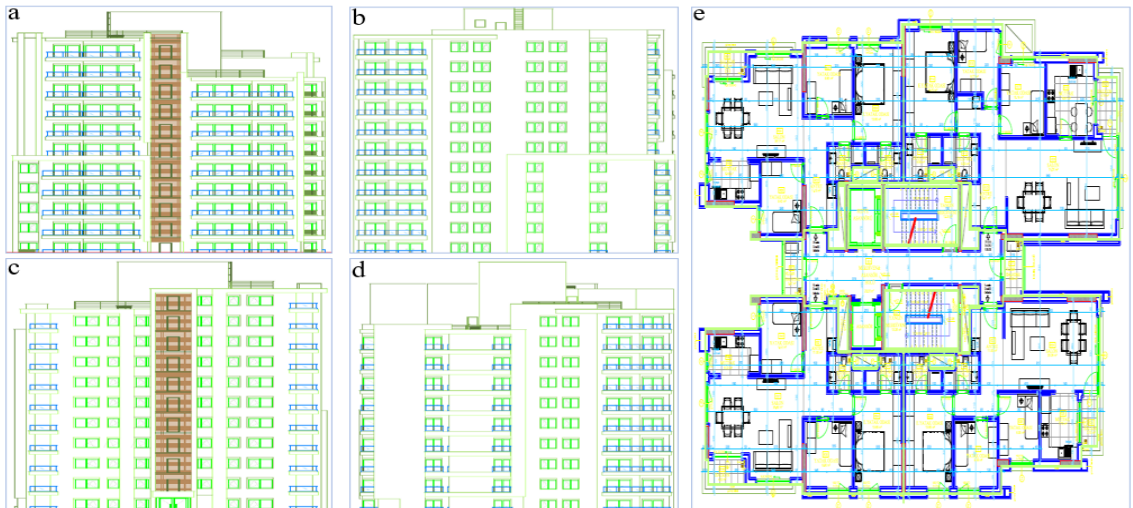


Fig. 4. Block D and its appearance (a) south front, (b) western front, (c) eastern front, (d) north front, (e) regular floor plan



Fig. 5. Block F and its appearance (a) south front, (b) western front, (c) eastern front, (d) north front, (e) regular floor plan



Fig. 6. 3D image of the island-based settlement project study area (a) Block F south facade south facade, (b) Block F south facade east facade



Fig. 7. Photograph of the island-based settlement project study area (a) Block F south facade, (b) Block F south facade east facade

Table 4. Climate and system data for building models

Data Category	Parameters
Building Type	Residential
Location	Antalya
Climate Data	ASHRAE 90.1-2010 Standard, Climate Zone 3A/ TS 825/1. Zone Data file=(ANTALYA-TUR IWEC2 WMO#=173000)
Heating System	Boiler+Radiator/Split Air Conditioner (4800 W, Energy Efficiency Ratio (EER): 3.20)
Cooling System	Split Air Conditioner (4100 W, Energy Efficiency Ratio (EER): 3.00)
Indoor Air Temperatures	Heating period: 22°C; Cooling period: 25°C
Ventilation System	Natural ventilation-Air Exchange Rate (ACH): 0,5 (1/h)
Number of Users	20 m ² /person
Usage Schedules	ASHRAE Residential Use Profile- Hours of use: Continuous-7/24

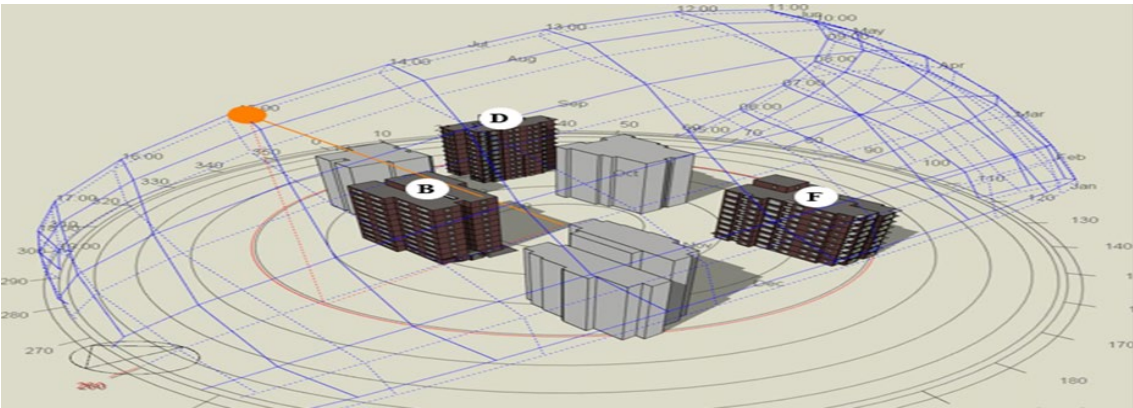


Fig. 8. Model image of the block-based settlement

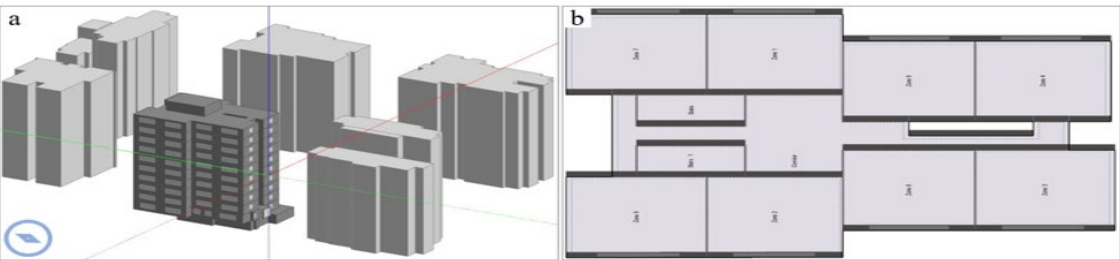


Fig. 9. Block B model; a) site plan, b) floor plan

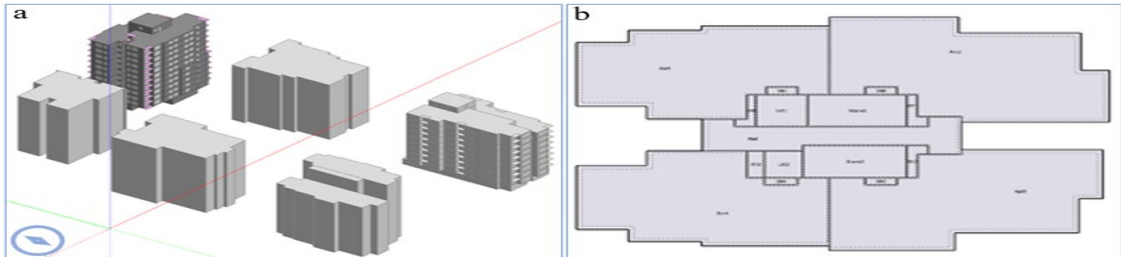


Fig. 10. D block model; a) site plan, b) floor plan

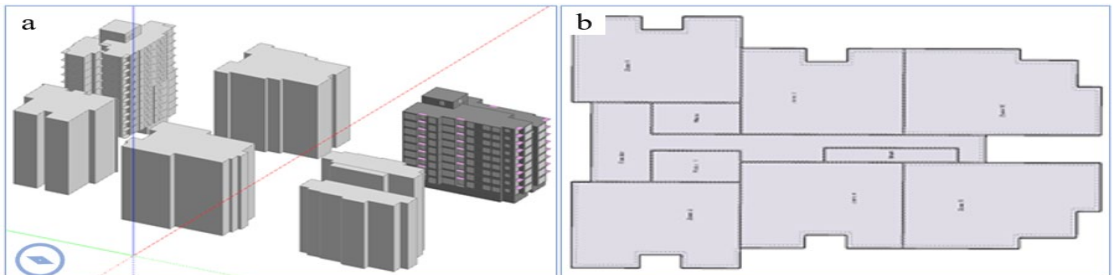


Fig. 11. F block model; a) site plan, b) floor plan

Improvements were made in the lighting system in the base buildings by using 9W and 14W LED (Lighting Emitt Diodes) bulbs, which have approximately equivalent light intensity and more energy efficiency, instead of 12W and 20W saving bulbs (compact fluorescent bulbs). Since there was no change in electrical equipment after the improvement, the electrical equipment power density value did not change. Electrical equipment power density was taken as 6 W/m² as in the Base Buildings. The bulbs used in the lighting system before and after the improvement are shown in Table 5. Energy cost, emission and saving rates were obtained by performing hourly analyses between the existing building models (Base Buildings) and the Design Building models obtained after the improvement with the Design Builder simulation program. Annual energy consumption values, energy saving rates and increase in implementation cost of the Base

Buildings and Design Buildings are presented in separate tables.

2.4. Photovoltaic panel design and application

In the study, it is aimed to generate electricity from solar energy by designing photovoltaic panels in Base Buildings. For the terrace roof PV system applied to the Base Buildings, the optimum design was realised by placing 74 panels in Block B Base Building, 60 panels in Block D Base Building, 64 panels in Block F Base Building with a fixed tilt angle of 30° in the south direction, taking into account the placement and orientation of the panels, the location where the system will be installed and the shading effect (Fig. 12).

The annual amount of energy to be generated by the PV system was calculated using PVsyst simulation software provided by CW-Energy. These calculations include many different data files to accurately evaluate the performance and efficiency of the PV system.

Table 5. Lighting system improvement scenarios

Design Scenario	Bulb Type	Application Areas					
		Parlour	Kitchen	Bedrooms	Antre	Bathrooms	Balcony
Base Buildings	Saving Bulb	20W	20W	20W	20W	12W	20W
Design Buildings	LED	14 W	14 W	14 W	14 W	9 W	14 W

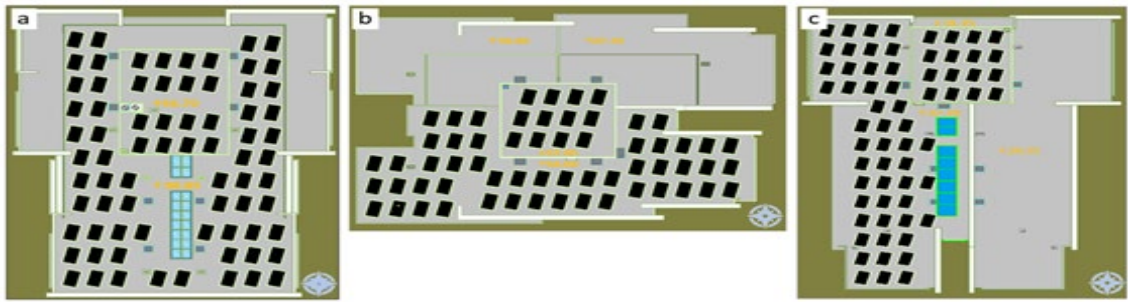


Fig. 12. Photovoltaic panel application in base buildings; a) Block B base building, b) Block D base building, c) Block F base building

The simulation software provides a comprehensive and detailed analysis to estimate the potential energy production of solar energy systems. Firstly, the location of the building is determined and defined as input to the simulation software. Location information is critical for factors such as solar radiation and angular efficiency. Then, the meteorological data of the region where the building is located is included in the simulation as a ready file. These data include weather variables such as solar radiation, temperature, wind speed and humidity in the region throughout the year. Meteorological data is very important to understand how the PV system will perform under different weather conditions. All system components in the simulation software are defined as a ready file input. These components include solar panels, inverters, cables and mounting systems. Taking into account the technical specifications and efficiency values of each component, the overall performance of the photovoltaic panel system applied to the Base Buildings is calculated. In addition, system losses were also evaluated within the PVsyst simulation software. These losses can be caused by cable resistances, shading, pollution and other environmental factors. Finally, 8760 hours, one year, simulation was carried out for each design building separately. By estimating the energy production for each hour of the year with the help of simulation, the total annual energy production amount is calculated and presented in tables. The simulation results, the annual energy production capacity of the PV system, the rate of meeting the annual energy consumption with the solar energy system, depreciation periods are presented in tables.

3. Findings and Discussion

This study analyses the impact of improving lighting systems and integrating photovoltaic (PV) systems in selected buildings in an island-based settlement in Antalya, located in the Mediterranean Climate Zone. Through extensive simulations and analyses, the study aims to quantify the reduction in energy consumption achieved by improving the lighting systems and the extent to which PV systems can meet the energy demands of these buildings. Furthermore, the economic impacts of these energy efficiency measures were assessed in terms of cost increases resulting from electrical system improvements and PV installations. Energy consumption data of heating, cooling, lighting and HVAC systems were analysed in the Design Building Models created after the improvement of the lighting system in the base buildings. The lighting power intensity values of Base Building B, D, and F and the lighting power intensity values of Design Building B, D, and F obtained after improvement are presented comparatively in Table 6. Annual energy consumption values of the buildings, such as heating, cooling, lighting, electrical equipment, common area equipment, HVAC systems, pumps and water heating; annual energy costs, emissions and saving rates are obtained by performing hourly analyses in the Base Building and Design Building models with the Design Builder simulation program and presented in detail in Table 7, Table 8 and Table 9.

Table 6. Lighting power density values of buildings B, D and F before and after improvement

Areas	Base Buildings (W/m ²)	Design Buildings (W/m ²)
Apartment	12	7,8
Corridors/Common Areas	3,2	2,3
Mechanical Room	8	5,6

Table 7. Energy consumption, cost, emission rates before and after lighting system improvement for Block B

System Usage	Energy Source	Unit	Base Building-1	Design Buildings-1	Energy Saving Rate-1	Base Building-2	Design Buildings-2	Energy Saving Rate-2
Heating	Natural Gas/ Electricity	kWh/year	70880,81	77617,40	-9,50%	29031,42	31705,84	-9,20%
Cooling	Electricity	kWh/year	106702,31	103902,37	2,60%	106687,51	103887,85	2,60%
Lighting	Electricity	kWh/year	68714,37	46372,42	32,50%	68714,37	46372,42	32,50%
Electrical Equipment	Electricity	kWh/year	90819,37	90819,37	0,00%	90819,37	90819,37	0,00%
Common Area Equipments	Electricity	kWh/year	2555,00	2555,00	0,00%	2555,00	2555,00	0,00%
Fans-HVAC	Electricity	kWh/year	1124,58	1105,25	1,70%	2811,45	2763,13	1,70%
Pumps	Electricity	kWh/year	484,90	528,00	-8,90%	167,50	167,50	0,00%
Use Water Heating	Electricity	kWh/year	10599,31	10599,28	0,00%	10599,31	10599,28	0,00%
Total Annual Consumption	-	kWh/year	351880,65	333499,09	5,20%	311385,92	288870,39	7,20%
Intensity of Consumption	-	kWh/m ² year	74,16	70,28	5,20%	62,28	57,77	7,20%
Cost	Electricity	\$/year	24178,79	22017,48	8,90%	26793,37	24856,01	7,20%
	Natural Gas	\$/year	1859,90	2036,66	-9,50%	—	—	—
	Total	\$/year	26038,68	24054,14	7,60%	26793,37	24856,01	7,20%
	Unit Area	\$/m ² year	5,49	5,07	7,60%	5,36	4,97	7,20%
Emission Values	Electricity	Kg/year	37091,20	33775,67	8,90%	39005,87	36185,45	7,20%
	Natural Gas	Kg/year	33316,34	36482,76	-9,50%	—	—	—
	Total	Kg/year	70407,53	70258,43	0,20%	39005,87	36185,45	7,20%

Table 8. Energy consumption, cost, emission rates before and after lighting system improvement for Block D

System Usage	Energy Source	Unit	Base Building-1	Design Buildings-1	Energy Saving Rate-1	Base Building-2	Design Buildings-2	Energy Saving Rate-2
Heating	Natural Gas/ Electricity	kWh/year	81871,82	86440,28	-5,60%	31645,58	33759,35	-6,70%
Cooling	Electricity	kWh/year	85321,87	82534,17	3,30%	85313,44	82526,48	3,30%
Lighting	Electricity	kWh/year	57514,60	38521,66	33,00%	57514,60	38521,66	33,00%
Electrical Equipment	Electricity	kWh/year	84824,77	84824,77	0,00%	84824,77	84824,77	0,00%
Common Area Equipments	Electricity	kWh/year	3650,00	3650,00	0,00%	3650,00	3650,00	0,00%
Fans-HVAC	Electricity	kWh/year	769,98	758,58	1,50%	1924,96	1896,46	1,50%
Pumps	Electricity	kWh/year	1115,60	1220,00	-9,40%	167,50	170,00	-1,50%
Use Water Heating	Electricity	kWh/year	10599,28	10599,28	0,00%	10599,28	10599,28	0,00%
Total Annual Consumption	-	kWh/year	325667,92	308548,74	5,30%	275640,13	255948,00	7,10%
Intensity of Consumption	-	kWh/m ² year	65,13	61,71	5,30%	55,13	51,19	7,10%
Cost	Electricity	\$/year	20977,57	19111,45	8,90%	23717,61	22023,19	7,10%
	Natural Gas	\$/year	2148,30	2268,17	-5,60%	—	—	—
	Total	\$/year	23125,87	21379,62	7,60%	23717,61	22023,19	7,10%
	Unit Area	\$/m ² year	4,62	4,28	7,60%	4,74	4,40	7,10%
Emission Values	Electricity	Kg/year	30539,21	27822,50	8,90%	34528,16	32061,42	7,10%
	Natural Gas	Kg/year	36519,87	38557,69	-5,60%	—	—	—
	Total	Kg/year	67059,08	66380,18	1,00%	34528,16	32061,42	7,10%

Table 9. Energy consumption, cost, emission rates before and after lighting system improvement for Block F

System Usage	Energy Source	Unit	Base Building-1	Design Buildings-1	Energy Saving Rate-1	Base Building-2	Design Buildings-2	Energy Saving Rate-2
Heating	Natural Gas/ Electricity	kWh/year	71083,82	77322,97	-8,80%	27957,26	30372,65	-8,60%
Cooling	Electricity	kWh/year	105454,20	102807,81	2,50%	105441,45	102795,48	2,50%
Lighting	Electricity	kWh/year	62026,64	41680,55	32,80%	62026,64	41680,55	32,80%
Electrical Equipment	Electricity	kWh/year	90320,19	90320,19	0,00%	90320,19	90320,19	0,00%
Common Area Equipments	Electricity	kWh/year	2555,00	2555,00	0,00%	2555,00	2555,00	0,00%
Fans-HVAC	Electricity	kWh/year	1111,91	1093,26	1,70%	2779,77	2733,14	1,70%
Pumps	Electricity	kWh/year	646,40	706,10	-9,20%	167,50	167,50	0,00%
Use Water Heating	Electricity	kWh/year	10599,27	10599,28	0,00%	10599,27	10599,28	0,00%
Total Annual Consumption	-	kWh/year	343797,43	327085,15	4,90%	301847,08	281223,79	6,80%
Intensity of Consumption	-	kWh/m ² year	66,11	62,90	4,90%	58,05	54,08	6,80%
Cost	Electricity	\$/year	23465,79	21490,92	8,40%	25972,60	24198,06	6,80%
	Natural Gas	\$/year	1865,22	2028,94	-8,80%	—	—	—
	Total	\$/year	25331,02	23519,86	7,10%	25972,60	24198,06	6,80%
	Unit Area	\$/m ² year	4,87	4,52	7,10%	4,99	4,65	6,80%
Emission Values	Electricity	Kg/year	32847,66	30083,22	8,40%	36356,71	33872,69	6,80%
	Natural Gas	Kg/year	30488,23	33164,23	-8,80%	—	—	—
	Total	Kg/year	63335,89	63247,45	0,10%	36356,71	33872,69	6,80%

The energy consumption values of the Base Building and Design Building models created using DesignBuilder simulation program, simulation results were compared with the average household electricity consumption of Antalya [58]. In addition, the simulation results are compared with the 2023 household electricity consumption values of Greece and Portugal [59], which are in the same climate class as Antalya according to the Köppen Climate Classification System [60, 61], which is widely used in the world, and whose entire country is located in the climate zone of Antalya, and presented in Table 10.

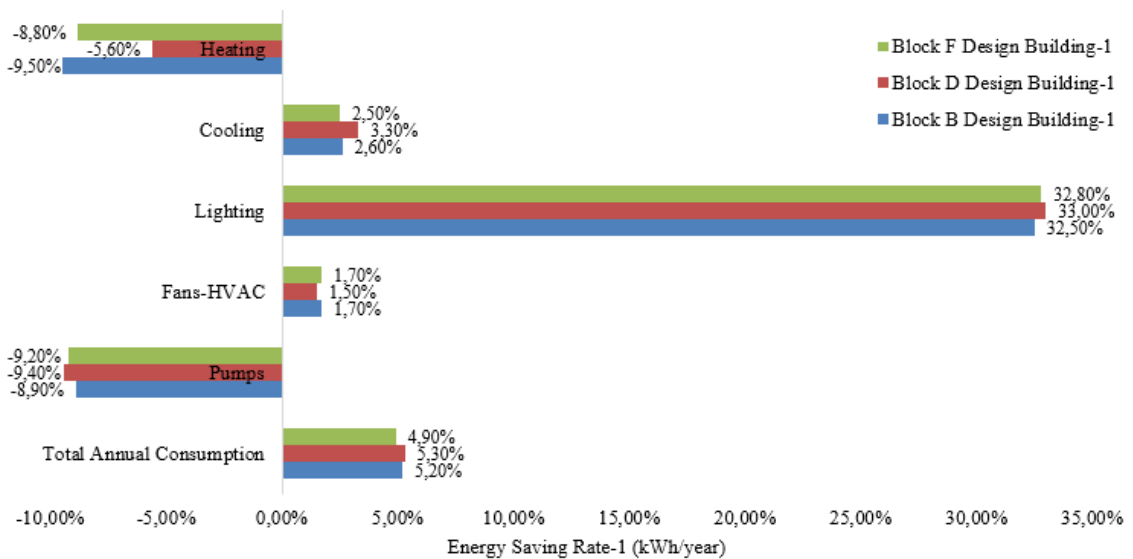
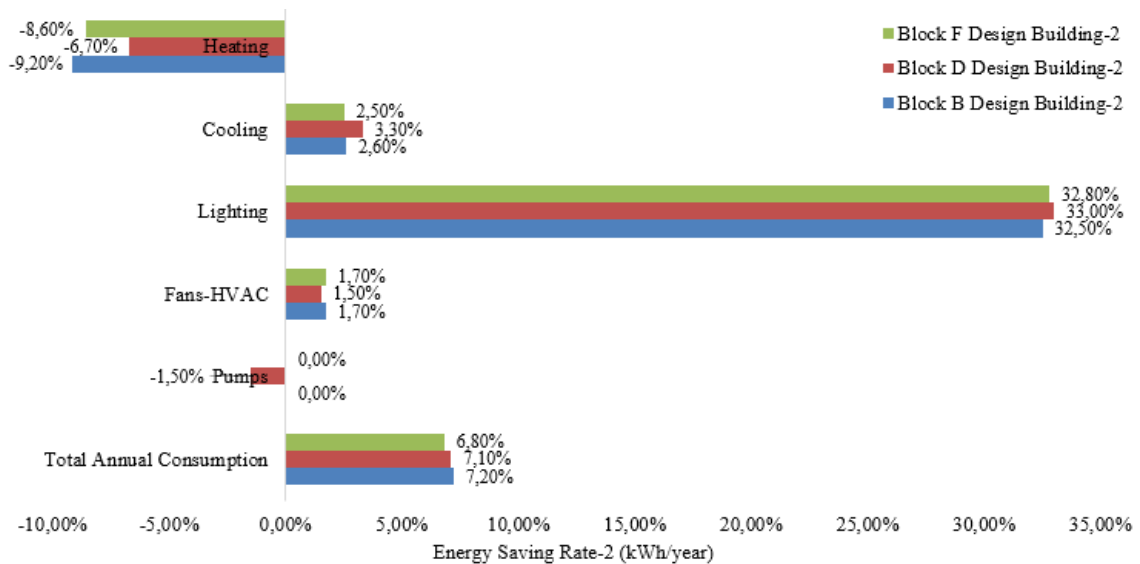
Table 10 presents a comparison of household electricity consumption data from various regions and simulation results for two building models, the Base Building and the Design Building, developed using DesignBuilder simulation software. The energy consumption values of these models are validated with the average household electricity consumption in Antalya, which is in the “Csa” climate classification according to the Köppen Climate Classification System. The simulation results are also compared with the annual household electricity consumption values of Greece and Portugal, which share the same climate zone (Csa) as Antalya according to this classification. Table 10 shows that although the electricity consumption results of the Base and Design Buildings are higher than the average annual household electricity consumption of Antalya, they are closer to the consumption values observed in Greece and Portugal, especially in the range of 2500 kWh-4999 kWh, where a significant portion of the population in these countries resides. This comparison helps contextualize the simulation results within real world consumption data and strengthens the relevance and accuracy of the simulation results despite the lack of direct real-time data from Antalya. The comparison of the annual energy saving rates of Design Buildings-1 and Design Buildings-2 obtained after the lighting improvement is presented in Fig. 13 and Fig. 14, respectively.

In the study, no other parameter was changed except the use of energy efficient light bulbs instead

of energy saving light bulbs. When Tables 7-8-9 and Fig. 13-14 are analysed; it is seen that energy consumption in heating systems in Block B, Block D and Block F Design Building-1s increased by 9.50%, 5.60%, 8.80% respectively. In Design Building-2, these values were calculated as 9.20%, 6.70%, 8.60% respectively. This situation can be explained as energy efficient light bulbs generally produce and emit less heat than energy saving light bulbs. Thus, it may have caused the heating system to work more by reducing the heat gain inside the building. Similar situation can be said for the increased energy consumption in pumps for Design Building-1. Since the heat gain inside the building decreased as a result of the use of energy efficient light bulbs, in this case, the heating system had to work more and the pump systems had to consume more energy. Increased heat loss resulted in the need for more hot water circulation. It can be said that the lack of heat generated by the saving light bulbs increases the need for heating. In cooling systems, it was observed that 2.60%, 3.30%, 2.50% annual energy savings were achieved in cooling systems in Block B, Block D and Block F Design Buildings, respectively. The most significant change was observed in lighting systems, and annual energy savings of 32.50%, 33.00%, 32.80% were calculated in lighting systems in Block B, Block D and Block F Design Buildings, respectively. No change was observed in the amount of energy consumed for electrical equipment, common area equipment and water heating. In fan and HVAC systems, annual energy savings of 1.70%, 1.50%, 1.70% were achieved in Block B, Block D and Block F Design Buildings, respectively. In Block B, Block D and Block F Design Building-1, the total annual energy saving rate was calculated as 5.20%, 5.30%, 4.90% respectively. In Design Building-2, the total annual energy saving rate was obtained as 7.20%, 7.10%, 6.80%, respectively. In the study, in addition to the annual energy saving rates obtained based on energy consumption (kWh/year) in the Design Buildings, energy cost saving rates calculated based on energy cost (\$/year) were also obtained.

Table 10. Comparison of Antalya, Greece and Portugal household electricity consumption values with simulation results

Climate Type Classification	Bsk, Csa, Csb, Cfa, Cfb, Dfa, Dfb, Dfc	Csa	Csa	Csa	Csa	
Household Electricity Consumption (Mid-year)	Türkiye	Greece	Portugal	Antalya	This study	
					Base Buildings	Design Buildings
Less than 1000 kWh	9.8%	5.0%	5.5%			
1000 kWh-2499 kWh	45.9%	25.0%	26.2%			
2500 kWh-4999 kWh	28.9%	44.1%	36.5%	2753.7 kWh	5288.3 kWh	4873.2 kWh
5000 kWh-14999 kWh	8.1%	23.1%	25,00%			
15000 kWh and over	7.3%	2.9%	6.7%			

**Fig. 13.** Comparison of annual energy saving rates of Design Buildings-1 after lighting improvement**Fig. 14.** Comparison of annual energy saving rates of Design Buildings-2 after lighting improvement

These ratios are compared between the Design Buildings and shown in Fig. 15 and Fig. 16.

When the CO₂ emission values are examined as a result of the energy analyses, the annual total CO₂ emission savings rate due to electricity consumption varied between 6.80%-8.90%, while the annual total CO₂ emission increase due to natural gas consumption was between 5.60%-9.50%. This situation is shown in detail in Fig. 17.

The unit price of saving bulbs used in the Base Buildings and LED bulbs used in the Design

Buildings is presented in Table 11. 783 bulbs were used in Block B Base Building, 422 bulbs in Block D Base Building and 524 bulbs in Block F Base Building. The same number of bulbs were used in the Design Buildings as in the Base Buildings and no change was made in the number of bulbs. The cost of saving bulbs used in the Base Buildings, the cost of LED bulbs used in the Design Buildings, and the cost increase caused by the use of LED bulbs instead of saving bulbs in the design buildings are shown in detail in Fig. 18.

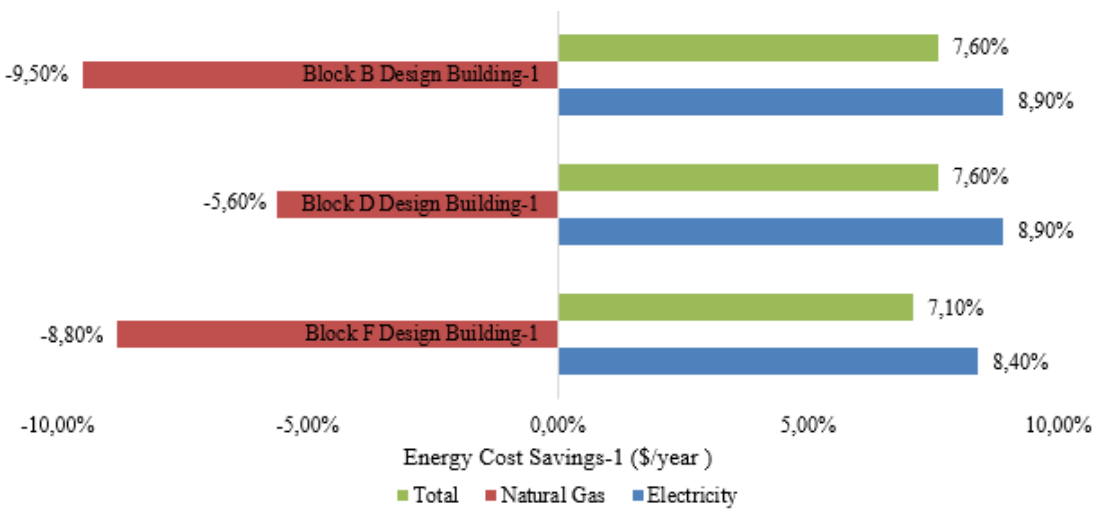


Fig. 15. Comparison of energy cost saving rates of Design Buildings-1 after lighting improvement

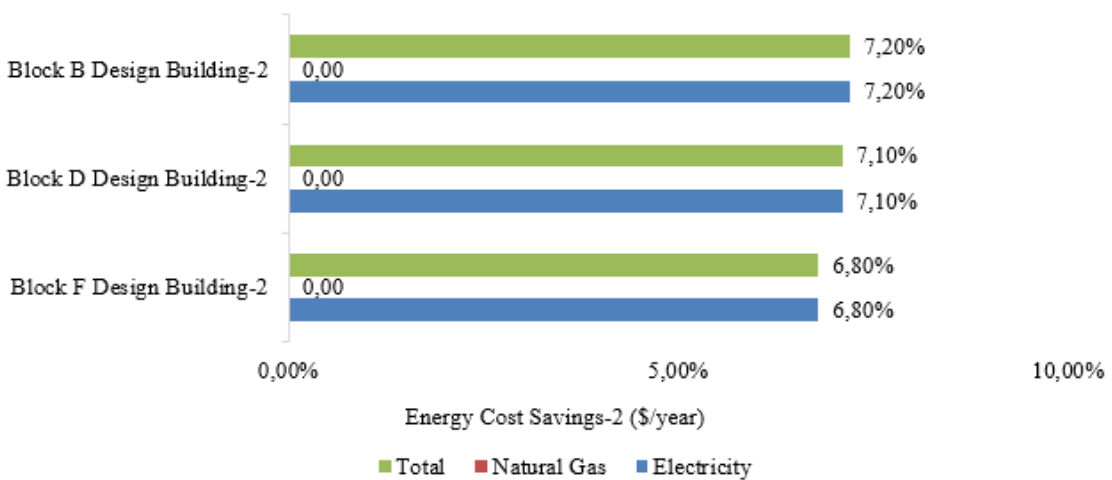


Fig. 16. Comparison of energy cost saving rates of Design Buildings-2 after lighting improvement

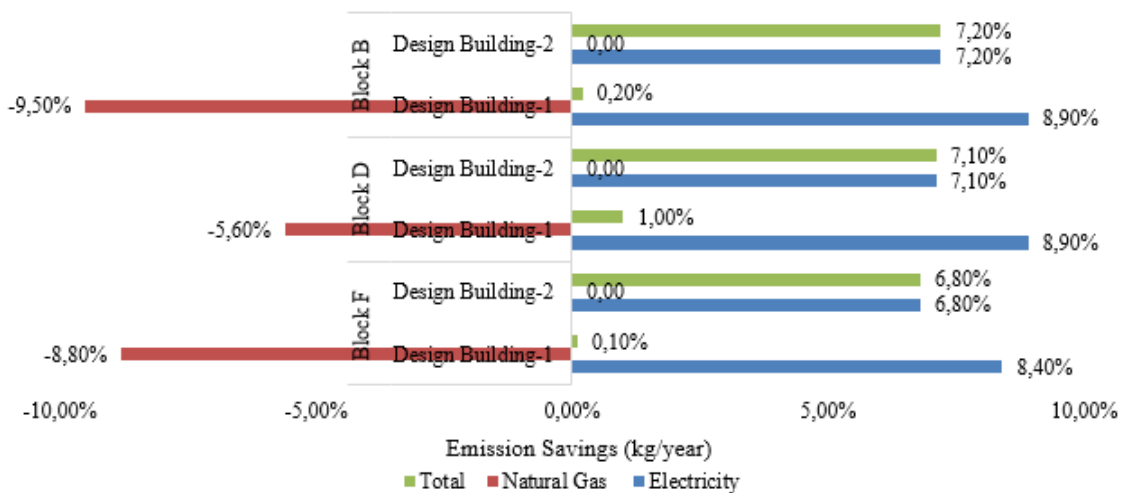


Fig. 17. Comparison of emission saving rates of Design Buildings after lighting improvement

Table 11. Unit price of light bulbs used in Base Buildings and Design Buildings

Bulb Type	Unit Price (\$/pc)
20W-Saving bulb-Philips T3 compact tornado bulb E27 white 20 Watt	3.07
12W-Saving bulb-Philips T2 compact tornado bulb E27 white 12 Watt	2.67
12W-LED bulb-Makel 12 Watt 6500k white led bulb E27 12W	1.54
14W-LED bulb-Philips ESS ledbulb 14 Watt bulb white light	5.48
12W-LED bulb-Makel 12 Watt 6500k white led bulb E27 12W	1.54
9W-LED bulb-Philips ESS ledbulb bulb 9-70 Watt white light	3.34

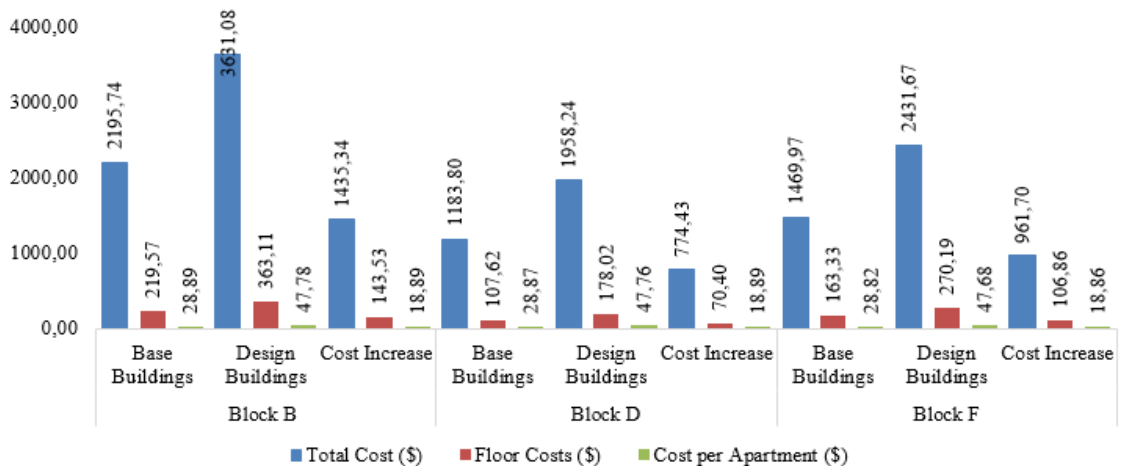


Fig. 18. Lighting cost analysis of Base Buildings and Design Buildings

When Tables 7, 8, and 9 and Fig. 18 are evaluated together, when Design Buildings-1 are analyzed, while the current consumption in Block B was 351880.65 kWh, the consumption decreased to 333499.09 kWh with the use of energy-efficient

light bulbs, and an annual energy saving of 5.20% was achieved. The cost increase of energy efficient light bulbs was 1435.34\$. In Block D, while the energy consumption was 325667.92 kWh in the current situation, this value decreased to 308548.74

kWh in the designed building, resulting in an annual energy saving of 5.30%. The cost increase was calculated as 774.43\$. Similarly, while the current energy consumption in Block F was 343797.43 kWh, with energy efficient light bulbs this consumption decreased to 327085.15 kWh, resulting in an annual energy saving of 4.90%. The cost increase for energy efficient bulbs is calculated as 961.70\$. When Design Buildings-2 were analysed; it was seen that 7.20% more annual energy savings were achieved in Block B, 7.10% in Block D and 6.80% in Block F. Cost increases were the same with Design Buildings-1. The energy-

saving rates obtained as a result of the improvements made in the lighting system and the increase in the related application costs are presented in Fig. 19.

Within the scope of the study, the annual energy amount to be generated by the PV system was calculated with PV simulation software. The location of the building, meteorological data, all system components and system losses were defined as input to the Solar PV programme and 8760 hours of simulation was performed. As a result of the simulation, the amount of electricity produced in the Design Buildings is presented in Table 12.

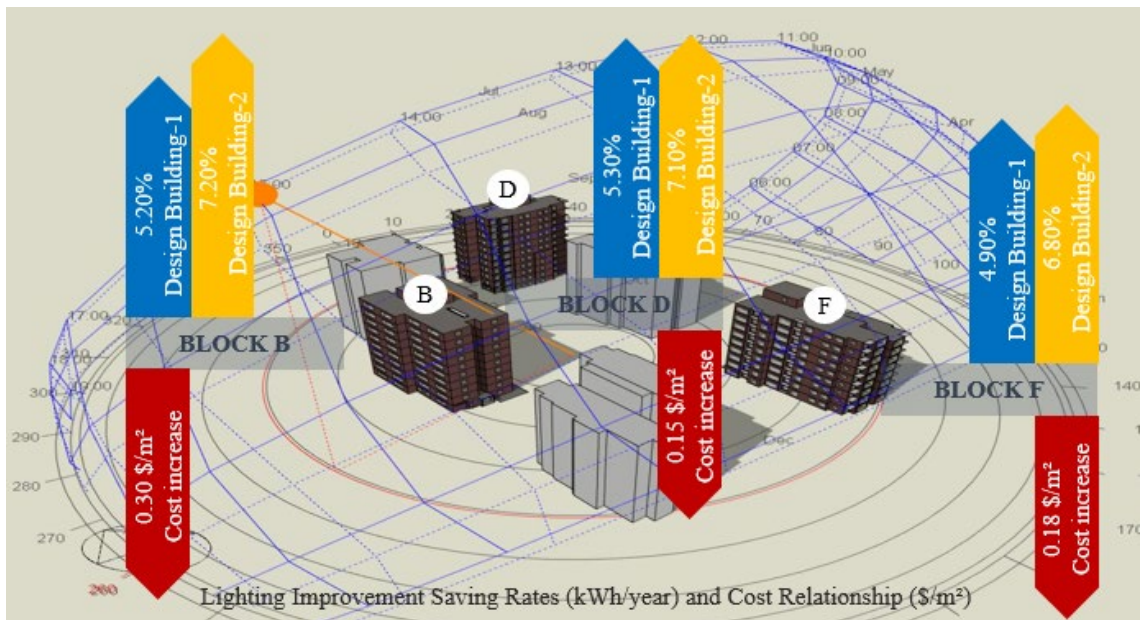


Fig. 19. Energy saving rates and application cost increase rates after lighting system improvement in Design Buildings

Table 12. Photovoltaic panel system information applied to Base Buildings

PV System Information	Unit	B Block Design Building	D Block Design Building	F Block Design Building
Power	kWp	25,4	18,9	20,4
Number of Panels	Quantity	74	60	64
Roof usage area	m ²	220	108	115
Amount of electricity produced with PV	kWh/year	38493,17	28565	30929
Installation cost	\$	25553,90	18963,33	20532,82
Cost increase	\$/m ²	4,9	3,4	3,6
Savings from mains electricity	\$/year	3312,17	2457,89	2661,30
System amortisation time	year	7,7	7,7	7,7

In Block B Base Building-1, heating is provided by natural gas and cooling is provided by electrical energy and annual energy consumption is calculated as 151,880.65 kWh. Electric energy consumption constitutes 280,999.84 kWh of this value. It is calculated that 15.04% of the annual electricity consumption of the Design Building-1 can be met by using PV system. For Design Building-2, which uses electrical energy in heating and cooling systems, this rate was obtained as 13.33%. Similarly, in D-F Design Building-1, where natural gas is used for heating and electrical energy is used for cooling, the rate of meeting the annual energy consumption with PV system is 12.86% and 12.38%, respectively. In D-F Design Building-2, where heating and cooling are met by using electrical energy, these values are 11.16% and 11.00%. In the scope of these rates, the impact of PV system application on building cost increase is calculated as 4 \$/m² on average. In addition, it is observed that with the implementation of the PV system in the blocks, an average of 249,922 Tn CO₂ emission can be prevented in each block. It is known that the lifetime of the photovoltaic panel system is 25 years. In this case, considering the depreciation periods of photovoltaic panel systems, it can be said that with the application of the PV

system, approximately 13% of the electricity used in the buildings can be provided almost free of charge every year for approximately 17 years. These findings show that PV systems have a significant potential in reducing energy consumption and reducing emissions. The Design Buildings obtained by applying PV Systems to the Base Buildings, the rates of meeting the electrical energy consumed in the buildings and the building cost increase rates resulting from the application of PV Systems are shown separately in Fig. 20.

The total energy saving rates and total cost increases in Design Buildings obtained by realising both the improvement of the lighting system and the PV system application together in the study are presented in Fig. 21.

Fig. 21. indicates the energy saving rates and cost increases obtained as a result of the improvement of the lighting system and photovoltaic (PV) system application for Blocks B, D and F. In all three blocks, the improvement of the lighting system and PV system application reduces energy consumption and provides savings. For Block B, annual energy consumption in Design Building-1 decreased by 22.64% to 255,881.69 kWh, while in Design Building-2 it was 288,870.39 kWh with a 19.59% reduction.

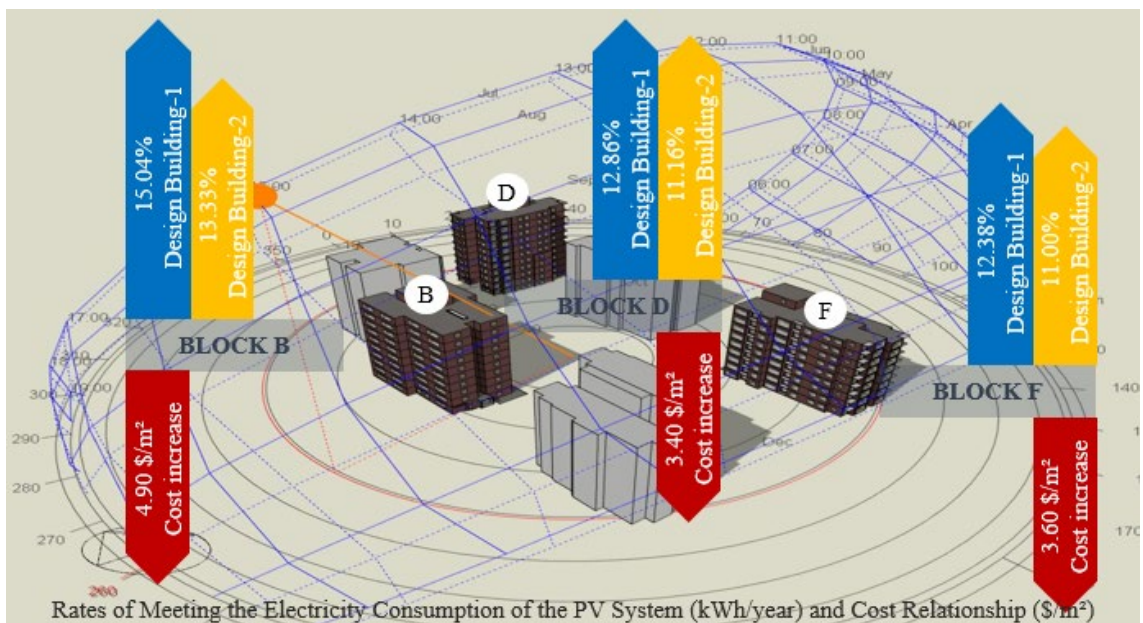


Fig. 20. Electricity meeting rate and cost increase rate in Design Buildings with PV system application

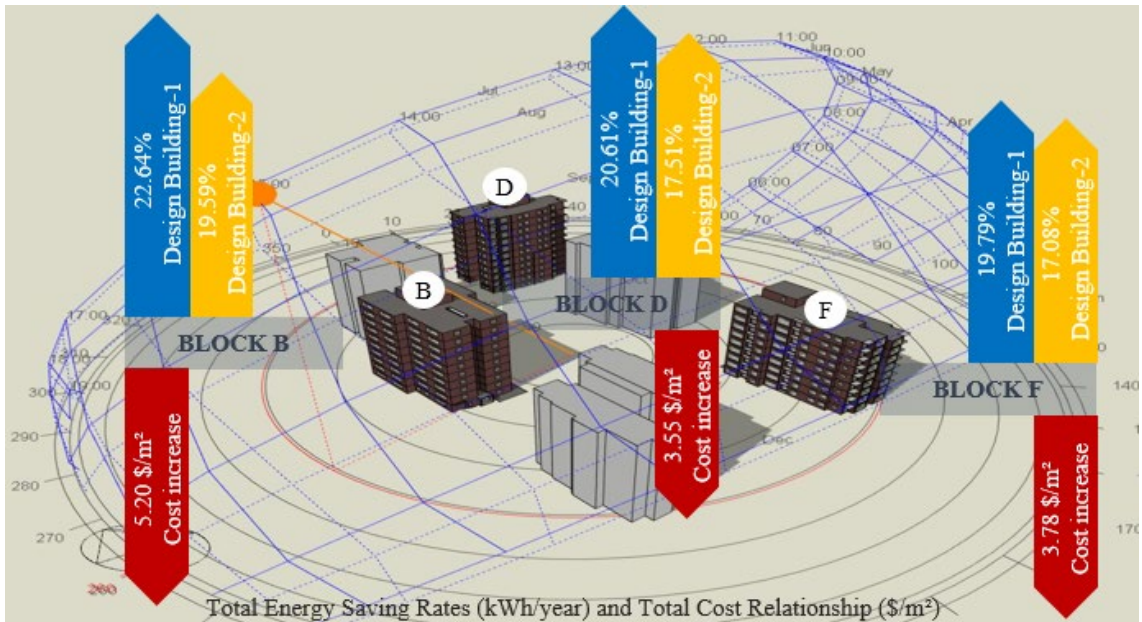


Fig. 21. Energy-cost analysis of lighting system improvement and PV system application in Design Buildings

Similarly, it was observed that Design Building-1 provided more energy savings than Design Building-2 in terms of energy savings in D and F Blocks. In terms of cost increases, although the improvement and implementation cost increases were the same between Design Building-1 and Design Building-2 in all three blocks, it was observed that Design Building-1 had lower energy consumption and higher energy saving rates. This situation reveals that using natural gas in heating is more advantageous in terms of energy efficiency. In the Design Building-2 model, the use of electrical energy for heating increases the total energy consumption and decreases the energy saving rate. For this reason, it is concluded that the use of the Design Building-1 model, in which natural gas is used for heating and electrical energy is used for cooling, is a more advantageous choice in terms of sustainability and cost in the Mediterranean Climate Zone.

4. Results

This study presents a comprehensive analysis aiming to improve the energy performance of buildings in an island-based settlement in Antalya, located in the Mediterranean Climate Zone. It has

been observed that by improving the lighting systems of the buildings and integrating PV systems, energy savings can be achieved in the long term by significantly reducing energy consumption. The simulations and analyses show that by improving the lighting systems, annual energy savings of up to 33.00% in the energy consumption of the lighting system and 7.20% in the total energy consumption of the buildings can be achieved. In addition, it has been observed that with the integration of PV systems into buildings, significant contributions to energy efficiency and environmental sustainability can be achieved by meeting up to 15% of energy demands. When the energy saving and emission rates are analysed, it is concluded that the cost increase rates caused by the improvement of the lighting system and the integration of PV systems in residential projects do not prevent the preference of these energy efficient building criteria.

The findings obtained show that the use of natural gas in heating systems is more advantageous in terms of energy efficiency. In scenarios where electrical energy is used for heating, energy consumption increases and energy saving rates decrease. In this context, it is concluded that the use of natural gas in heating and electrical energy in

cooling is a more suitable option in hot-humid climate regions such as Antalya, which is located in the Mediterranean Climate Zone.

When the study is evaluated from an academic point of view; it will shed light on the studies to be carried out to measure the energy efficiency of island-based settlements within the scope of sustainability. There are many studies in the literature on sustainable buildings, energy efficiency of buildings and sustainable construction cost. However, in these studies, energy efficiency is usually done on a building, floor or a apartment sample. This study is unique in that design parameters such as location, position, orientation and distance between buildings are taken into consideration in order to increase the energy efficiency of buildings in island-based settlements. This research is the most distinctive feature that

distinguishes this study from other studies. Another important feature of the study is that, since the heating needs of buildings in Antalya are widely met with electrical energy, scenarios in which electrical energy is used in addition to natural gas in heating are produced and analysed within the scope of the study. In this context, the study emphasises that the economic and environmental impacts of strategies to improve building energy performance should be carefully evaluated. Accordingly, improvements made in terms of energy efficiency and cost effectiveness can provide significant benefits at both individual and societal levels. It is thought that the study will contribute to the academia and the construction sector by examining the relationship between energy efficient building design criteria and cost, and being sustainable energy oriented.

Declaration

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Author Contributions

A. Kazaz: Conceptualization, Methodology, Investigation, Resources, Supervision, Validation, Writing-Reviewing and Editing; E. Yetim: Methodology, Formal Analysis, Investigation, Data curation, Writing-Original draft, Visualization, Software.

Acknowledgments

Not applicable.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Ethics Committee Permission

Not applicable.

Conflict of Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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