TECHNO-ECONOMIC ANALYSIS OF A PHOTOVOLTAIC-THERMAL SOLAR COLLECTOR SYSTEM FOR SUSTAINABLE ENERGY PROVISION IN HOTEL FACILITIES

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ABSTRACT

A technoeconomic analysis is conducted on a solar system utilizing hybrid photovoltaic-thermal (PV/T) collectors, deployed within a hotel. The main objective of this study is to evaluate the feasibility and effectiveness of hybrid PV/T collectors in meeting the hotel's annual energy demands for heating and domestic hot water (DHW), and in assessing the system's economic and environmental impacts. The building's annual energy demands are calculated, and the hybrid collectors' capacity to fulfill these demands is determined based on the available roof area. An economic analysis is then conducted to ascertain the system's payback period and economic viability. Additionally, an assessment of the system's environmental impact is included, calculating the reduction in CO_2 emissions resulting from the utilization of the collector system as opposed to existing systems relying on diesel for domestic hot water, along with a Variable Refrigerant Flow (VRF) system for heating and cooling. Finally, a comparative analysis is conducted, contrasting the hybrid system with conventional solar thermal collectors (STC) and photovoltaic (PV) panels. This study is novel in its focus on such an analysis for hotel facilities, a sector not previously extensively examined in this context.

1 INTRODUCTION

In the quest to mitigate climate change impacts and enhance energy sustainability, reducing energy consumption withing the building stock has emerged as a critical pathway. The building sector, a significant consumer of energy resources, faces the dual challenge of satisfying the growing energy demands while attempting to minimize its environmental footprint. In response to this, a variety of retrofitting approaches have been proposed and examined, aiming to enhance energy efficiency and reduce energy consumption across existing buildings.

Bougiatioti et al. (2023) assessed how basic bioclimatic strategies impact the thermal efficiency of a standard single-dwelling homes in Greece, daily, across seasons and throughout the years. Heracleous et al. (2023) examined various retrofitting approaches made to an educational institution in Greece, intended to serve as a model for enhancing energy efficiency in government buildings. Among the studied measures was the installation of PV panels. Pallis et al. (2019) developed a comprehensive strategy for evaluating the cost effectiveness and energy efficiency of intervention packages for nearly Zero-Energy Buildings (nZEB) for the residential sector. These include a broad range of energy-saving measures, such as improvements to building envelopes, solar technologies (like photovoltaics and solar heating), and various heating, domestic hot water (DHW), and cooling systems. They concluded that interventions that combine PV offer significantly enhanced energy efficiency and are crucial for meeting NZEB criteria, particularly when used alongside heat pumps. The same methodologies were applied to office buildings (Pallis et al., 2021), were they stated that the integration of PVs plays a vital role in achieving the nZEB standard, particularly in newly constructed structures, and is also beneficial financially. Dascalaki & Balaras, (2004) developed a methodology for conducting an initial energy audit and evaluate economically energy-saving renovation methods, technologies, and systems for hotels. They stated that utilizing solar energy through thermal systems for generating hot water and

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photovoltaics for creating electrical power represents some of the foremost practices and prospects for harnessing renewable energy sources.

Among the proposed methods in the literature, for improving the energy performance of buildings, the strategy of harvesting solar energy stands out as particularly promising, offering a renewable, abundant, and clean energy source to meet diverse energy needs. As a result, multiple studies have studied the installation of all types of solar systems, PV, solar thermal collectors and PV/T collectors. Bougiatioti & Michael, (2015) studied the architectural installation of active solar systems in Mediterranean region. Uche et al. (2022) investigated a polygeneration system incorporating PV/T and PV technologies in a residential structure. Brottier & Bennacer, (2020) examined a DHW system based on PV/T on different locations. They concluded that for Lyon the designed system can cover 60% of the hot water needs and that the PV/T system generates approximately double the energy compared to an installation that only uses PV. Kalogirou & Tripanagnostopoulos, (2006) also examined numerically and experimentally a PV/T system for DHW and electricity production. They concluded that the system with PV/T has lower payback times compared to PV at al examined locations. Herrando et al. (2018) explored a solar combined heat and power setups that utilize PV/T collectors to concurrently supply power, DHW, and space heating to single-family residences. The system can cover between 29% and 61% of the thermal demands and 64—67% of the electrical demands. Kyriaki et al. (2017) performed a comprehensive assessment of solar thermal system installed in a hotel and its impact on enhancing the energy efficiency and environmental footprint of the building. They stated that the solar system significantly reduces the annual energy consumption and CO_2 emissions.

Barbu et al., (2023) conducted an experimental analysis of a solar collector system, comprising PV panels, STC, and PV/T collectors, under varying weather conditions. Installed at an educational facility in Romania, the research concluded that PV/T collectors are an effective replacement for separate photovoltaic and solar thermal systems, especially in situations where roof space is limited and highly valuable.

Solar energy, encompassing both photovoltaic (PV) systems for electricity generation and solar thermal collectors for heating purposes, offers a versatile solution to the energy challenges faced by the building sector. This approach is especially pertinent to the hotel industry, which is characterized by high energy demands (Farrou et al., 2012; Pieri et al., 2015). While numerous studies have explored the technical feasibility and economic benefits of renewable energy systems in residential settings (Good et al., 2015), comprehensive research analyzing the techno-economic and environmental impacts of PV, solar thermal, and hybrid collectors specifically within the hotel industry remains scarce. This study aims to fill this gap by performing a detailed techno-economic and environmental analysis of the implementation of PV, STC and hybrid systems in a medium-sized hotel located in Greece.

2 METHODOLOGY

This study primary goal is to conduct an annual operational assessment, alongside a comprehensive techno-economic and environmental analysis of various solar collector systems, incorporated within a hotel and compare the results. To obtain the necessary data for the analysis a dynamic energy simulation was established using DesignBuilder, which utilizes the EnergyPlus engine, a scientifically verified calculation tool, and is widely applied in building energy simulation projects (Tsala et al., 2024; Tziritas et al., 2023).

2.1 Examined hotel

The hotel under investigation is located in Athens, Greece (Latitude 37.90°, Longitude 23.73°) and according to ASRHAE belongs to climate zone 3A. It boasts four levels (a ground floor plus three additional floors) with a cumulative floor space of 5485 m^2. The entire internal volume of the building amounts to 18798.63 m^3. Oriented towards the south, the ground level accommodates the reception, restaurant, kitchen, laundry, and offices, whereas the guest rooms are situated on the floors above. The average size of each guest room is 30 m^2, and every room features access to a balcony through glass doors, which also serve as shading solutions. A visual representation of the hotel, as modeled in DesignBuilder, is depicted in Figure 1.

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Additionally, Table 1 outlines the performance indexes of the main construction materials of the building's envelope. It is worth mentioning that the construction materials were selected according to ASHRAE Standard 90.1.

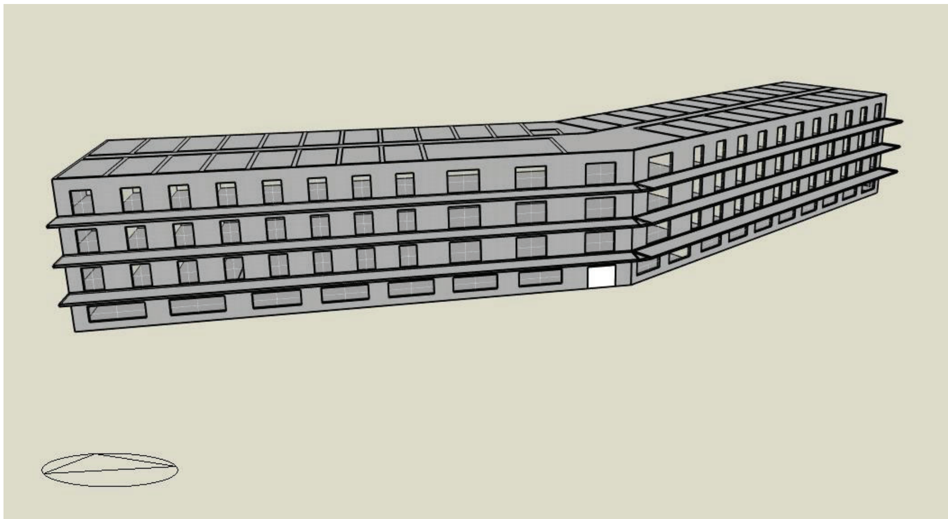

Figure 1: The examined hotel

Table 1: U-values (W/m^2K) of the materials used for the building.

Envelope component	U-values (W/m2K)
External Wall	0.690
Roof	0.229
Floor	0.434

Table 2: Window Properties.

Window Properties	Value
U-value (W/m^2K)	2.260
SHGH	0.251
Visible Transmittance	0.563

2.2 Layout of the systems

The hotel's existing HVAC system comprises of three Variable Refrigerant Flow (VRF) systems for heating and cooling, and a Dedicated Outdoor Air System (DOAS) for each VRF, for satisfying the requirements for outdoor air. Electrical power required to meet the demand is supplied by the grid. Domestic hot water is generated using an oil-fired boiler. Table 3 outlines the primary efficiency metrics that characterize the performance of this system.

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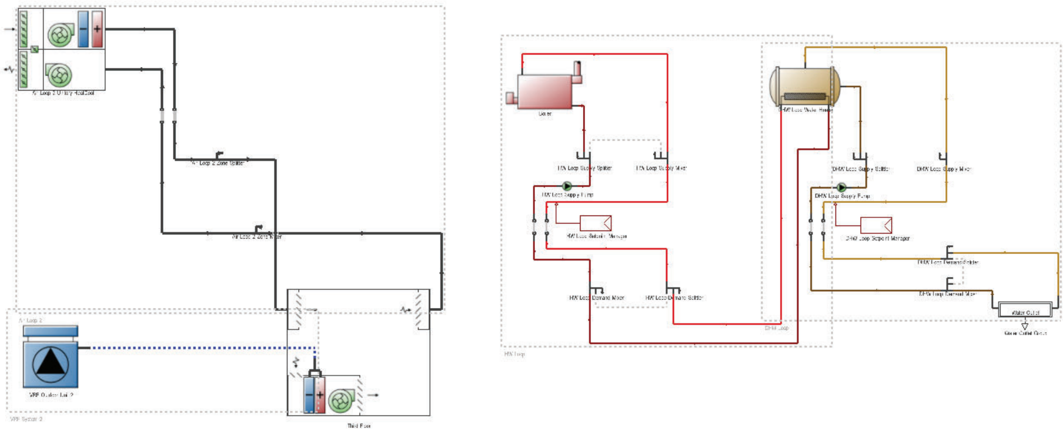

Figure 2: Part of the existing HVAC system of the hotel

The hotel is segmented into three distinct zoning groups: the first group comprises the ground and first floors, while each subsequent floor forms its own separate zone. Notably, the design of the systems accounts for the specific needs arising from the hotel's kitchen and laundry facilities, ensuring that these critical areas receive adequate consideration in the overall energy planning and thermal comfort.
In the initial scenario evaluated, parts of the roof are outfitted with PV cells to generate electricity, fulfilling the building's power requirements while minimizing the reliance on grid-supplied electricity. The subsequent scenario investigates placing solar thermal collectors in the same roof area to produce hot water, aiming to satisfy the domestic hot water needs of hotel occupants. The characteristics of the solar thermal collector are presented at Table 3. The third scenario considers the deployment of hybrid PV/T collectors on the same section of the roof, occupying the identical space. By integrating hybrid PV/T technology, which can concurrently generate hot water and electricity, the system is designed to meet both the electrical and DHW demands of the building. The performance of the PV/T collector was based on EnergyPlus data and models. All collectors were installed with tilt angle of 30^o which is suitable for whole year operation.
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Table 3: Basic efficiencies used in the analysis.

Description	**Value**
VRF COP	3.5
η_{pv}	20%
$\eta_{inverter}$	95%
η_{boiler}	80%
Coefficient 1 of STC	0.6 (-)
Coefficient 2 of STC	-3.8665 (W/m^2-K)
Coefficient 3 of STC	0.0015 (W/m^2-K^2)
$\eta_{el,pv/t}$	15%

2.3 Simulation Parameters

As previously stated, the building and all its components were modeled in DesignBuilder. Four distinct models were developed and analyzed by varying the systems utilized (one for the existing system and three for the different type of solar collector). Beyond the building envelope, which was detailed and examined in earlier sections, the primary factors influencing building performance include the loads from various equipment and lighting, as well as operational schedules. The main parameters of the simulations are presented at Table 4 with accordance with ASHRAE standards.

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Table 4: Basic parameters used by DesignBuilder for the energy simulation.

Parameter	Value
Operating days	365 days
Temperature setpoint for DHW	43°C
Lighting level requirement	300 lux
Lighting power density	4.413 W/m^2
Occupancy density	0.1076 people/m^2
Internal gain from people activity	126 W/person
Internal gain from electrical equipment	10.516 W/m^2
Infiltration	0.4 ac/h

2.4 Economic and environmental analysis

An analysis focusing on the technical, economic, and environmental aspects of running the different types of solar collectors was carried out. This included determining and contrasting the various performance indexes.

The Energy Use Intensity (EUI) is defined as the ratio of the total energy consumption of the building (E_{cons}) to the total area of the building ($A_{building}$) as calculated by the following equation.

$$EUI = \frac{E_{cons}}{A_{building}} \tag{1}$$

The yearly cost reduction (CR) is calculated by considering the total savings in electricity and oil fuel resulting from the electricity and thermal energy needs met each system, in addition to the system's operation and maintenance (O&M) expenses. (Herrando et al., 2018)

$$CR = \sum_{n=1}^{N} \frac{\left(P_{el,covered} \cdot c_{electr} + \frac{Q_{th,covered}}{\eta_{boiler}} \cdot c_{oil} - c_{O\&M}\right) \cdot (1+i)^{n-1}}{(1+d)^n} \tag{2}$$

Where $P_{el,covered}$ is the electricity demand covered by the solar collectors that produce electricity, $Q_{th,covered}$ the thermal demand covered from the solar collectors that produce DHW, c_{electr} and c_{oil} the cost of electricity and oil respectively. $c_{O\&M}$ is the operational and maintenance cost per year.

The calculation of the Life Cycle Cost (LCC) is performed using equation (3) where it is presumed that both the final disposal cost and the residual value are considered to be nil. (Pallis et al., 2019)

$$LCC = C_{inv} + \sum_{n=1}^{N} \left(c_{O\&M} \left(\frac{1}{1+p} \right)^i \right) \tag{3}$$

where C_{inv} is the total investment cost and C_a (Pallis et al., 2019)

The Simple Payback Period (SPP) is calculated by equation (4)

$$SPP = \frac{C_{inv}}{C_{oper,base} - c_{oper,new}} \tag{4}$$

C_{oper} represents the annual operating cost of the building. The subscript new refers to the operating cost after the renovations while the subscript $base$ refers to the base scenario.

The project under evaluation has a forecasted lifespan of 25 years. Financial considerations for the project's LCC are based on a 7% interest rate (p). Additionally, the project accounts for an annual escalation in energy costs at a rate of 2.8% (i), reflecting the expected increase in energy expenses over time. Finally, a market discount rate (d) of 3.5% is taken into account.

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Primary energy (PE) serves as a crucial metric for assessing the system's efficiency. This measure is derived by adding the various energy requirements (E_k) after adjusting each with its corresponding conversion factor for primary energy (pef).

$$PE = \sum_{k=1}^{m} pef_k \cdot E_k \tag{5}$$

In accordance with the guidelines set forth by Greek Technical Chamber (Greek Technical Chamber, 2017), the factor for primary energy is established at 1.1 for oil and 2.9 for electricity.

Table 5: Basic parameters used by DesignBuilder for the economic and environmental analysis).

Component	Value	Unit
PV/T collector	300	€/m^2
PV	130	€/m^2
Solar thermal collector	205	€/m^2
Inverter	180	€/kW
DHW storage tank	500	€/m^3
O&M PV/T	2	%/year
O&M solar thermal	0.6	%/year
O&M PV	1	%/year
Heating oil CO_2 emissions	0.2662	kgCO_2/kWh
Electricity CO_2 emissions	0.41	kgCO_2/kWh
Heating oil	0.133	€/kWh
Electricity	0.235	€/kWh

The above values were taken from relevant studies (Bellos et al., 2022; Herrando et al., 2018, 2019; Pallis et al., 2019; Papoutsis et al., 2017; Uche et al., 2022) and from market analysis.

3 RESULTS

3.1 Base Scenario

The total energy consumption for the Base Scenario amounts to 982,975.39 kWh, with an EUI of 179.21 kWh/m^2. According to DOE and ASHRAE, a typical hotel at the climate zone 3A has an EUI of around 200 kWh/m^2. The simulation results closely mirror the prototypes and statistical data, indicating a high level of accuracy in the modeling process.

To get a clear understanding of the energy performance, the total energy consumption is divided into the following end uses, as it is shown in Table 6. Electricity accounts for the majority of the hotel's energy consumption, comprising 74.13% of the total energy usage. The rest 25.87% of the total energy consumption provides hot water for the building, sourced from Diesel.

Table 6: Breakdown of Energy Usage by End Use.

Energy Type	End Use	Value (kWh)
Electricity	Heating	63,333.33
	Cooling	184,388.10
	Other Electricity Consumptions	480,998.98
	Total	728,720.41
Diesel	Hot Water	254,254.98

3.2 Renovations Results

The installation of solar collectors at the hotel enables a certain proportion of the requirements for electricity and domestic hot water (DHW) to be met with renewable energy, with the specific coverage

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depending on the technology implemented. Table 7 displays the coverage percentages for electricity and DHW provided by the solar collectors that have been installed. All collectors have the same area of 279 m^2.

Table 7: Demands covered by solar collectors.

Demand	**PV/T**	**PV**	**Solar thermal**
Electricity demand covered (%)	10	13.78	-
DHW demand covered (%)	58.96	-	66.92

The data in the preceding table reveals that, within the same collector area, the PV/T collectors provide a smaller percentage of electricity than PV collectors and a smaller percentage of domestic hot water coverage compared to solar thermal collectors.

Table 8: Key performance indexes for the economic and environmental analysis

Performance index	**PV/T**	**PV**	**Solar thermal**
Total investment (C_{inv}, €)	100,366.28	55,015.04	65,810.00
Operation & Maintenance cost ($c_{O\&M}$, €)	2,007.33	550.15	394.86
Cost reduction (CR, k€)	689,441.76	379,574.68	431,509.21
Payback time (SPP, years)	3.71	3.22	3.74
Annual CO_2 emission (tons CO_2 /year)	303.37	334.12	325.41
Primary energy (MWh/year)	2392.97	2036.00	2137.05

The economic analysis and the key performance indexes demonstrate that PV/T systems have the greatest initial investment, as well as higher maintenance and operational expenses compared to the other two scenarios. Nevertheless, due to their dual capacity to generate both electrical and thermal energy—key components for the hotel's operations—the PV/T systems achieve a more substantial reduction in costs over a 25-year period. Additionally, their contribution to decreasing oil consumption and cutting down on electricity imports leads to a more pronounced annual reduction in CO_2 emissions than that offered by standalone PV or solar thermal collector systems.
The payback periods for all considered scenarios are relatively short, rendering each option a feasible investment, particularly in light of the high costs of electricity and diesel. The PV installation leads with the shortest payback time, followed by the PV/T system, while the solar thermal collectors exhibit the longest payback duration of the three.
Finally, the reduction of CO_2 emissions with regard to the base scenario and the primary energy savings also with base scenario are presented at Figure 3 and Figure 4 respectively.

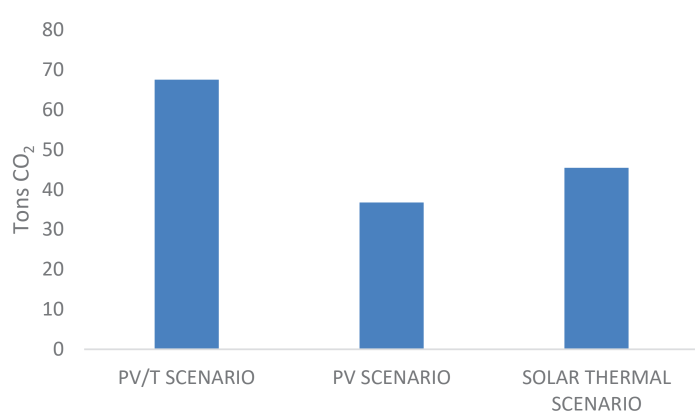

Figure 3: Reduction of CO_2 emissions

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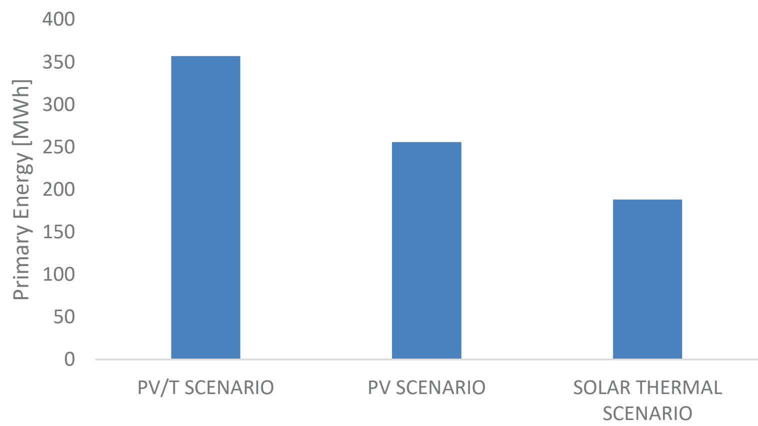

Figure 4: Primary energy savings

4 CONCLUSIONS

Incorporating solar collectors into existing structures is a pivotal strategy for enhancing the utilization of renewable energy and reducing the environmental footprint of the building sector, particularly within the hospitality industry. This study examines the efficiency and environmental consequences of integrating PV/T solar collectors into a pre-existing hotel in Greece. It undertakes a comparative assessment of both the economic and environmental impacts against those of current systems, as well as scenarios involving the installation of PV panels or solar thermal collectors. The evaluation employs critical performance indicators and utilizes DesignBuilder, a software based on EnergyPlus, to conduct the analysis.

The analysis reveals that PV/T systems exhibit superior energy performance relative to both the pre-existing setups and alternative solar solutions like PV and solar thermal collectors, owed to their dual capability to generate electricity and DHW. Despite a higher initial investment cost when compared to other types of solar collectors, the PV/T systems justify their financial expenditure with a payback period of 3.71 years, underscoring their feasibility as an investment. Additionally, the adoption of PV/T systems results in a significant environmental benefit, marked by a reduction of 67.56 tons in CO_2 emissions.

The follow up study proposes to examine the impact of varying tilt angles on the performance of each type of solar collector. It also intends to investigate different configurations, each featuring a distinct number of photovoltaic, solar thermal, and hybrid photovoltaic-thermal collectors.

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