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A Combination of SWHs and PVs Mounted on the Façade of a Building to Reduce Energy-Consuming

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This study aims to enhance the energy efficiency in cold climates, specifically Shahrekord, by exploring the integration of solar water heater systems and photovoltaic panels into building facades. Employing TSOL 2021 R(3) and HOMER V.2.81 software, this research adopts a novel approach to address the energy efficiency challenge. The placement of solar equipment on the southern facade yields a 44.6% increase in electricity generation and a 59.3% rise in heat production compared to the western facade. This significant difference is attributed to the larger collectors and optimal orientation in Scenario 1, resulting in a remarkable 45% greater reduction in pollutant emissions. The primary losses in the first scenario are associated with optical inefficiencies, whereas thermal inefficiencies in the solar collector drive losses in the second scenario. Despite having more solar panels, electricity costs are 19% lower in the first scenario, contributing to a higher proportion of solar electricity. This research provides valuable insights into optimizing energy efficiency in cold climates through strategic solar equipment placement, emphasizing the economic and environmental advantages of such integrations.

1. Introduction

The building sector is one of the most resource-intensive energy-consuming. In Iran, buildings consume 35% of the total energy-consuming [1, 2]. It's going to be particularly crucial when we consider global warming due to the greenhouse production, the high energy demand of productive industries, the high fossil fuel consumption that is attributed to buildings [3].

The implementation of solar energy harvesting systems in buildings have been known as an alternative way to meet energy-consuming. One of the most common way is the installation of

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photovoltaic systems (PV). In one hand, the building sector is one of the most resource-intensive energy-consuming. For example in Iran, buildings consume 35% of the total energy-consuming [1, 2]. In the other hand, It is going to be more crucial when we consider global warming due to the greenhouse production and the saved energy in this way that can be used in high energy demand of productive industries.

Most of the converted energy from the sun is used for heating and domestic hot water (DHW) loads [4].

Photothermal heating technology can be classified into two main categories, passive and active, based on the methods used to collect heat [5].

PV in buildings primarily falls into two main types: building-attached photovoltaic systems, which involve the installation of PV systems after the building's construction, and building-integrated photovoltaic (BIPV) systems [6-10].

Building Integration of PVs refers to incorporating PV modules into architectural elements. They are not only used as energy converters, but ~~they~~ also can be used as shutters, claddings, and part of the façade, or being utilized as roofing elements. Moreover, PV installed on the building might be used as a dry facade. As a result, the airflow inside the space between the PVs and the building's external envelope acts as a cooling flow of the panels, which enhances the efficiency of the PVs. [11-15]. New approaches usually introduce systems that include a combination of different installations like thermal insulation, modern opening walls, smart and technical HVAC systems and harvesting renewable energy [16].

The other perspective is a building integration of active solar systems, including PV, solar water heater (SWH), solar thermal and hybrid systems which gives a proper design and operation to buildings [17].

Typical SWH systems consist of the following main components: (i) solar collector, (ii) heat exchanger, (iii) heat transfer fluid, (iv) storage tank, (v) circulation pumps, and (vi) valves [18].

The most common heat transfer fluid used in SWH systems is water. However, other fluids like air, hydrocarbon oils, glycol/water mixture, and refrigerants/phase-change liquids can be used [19].

This study aims to consider a residential building in the city of Shahrekord, Chaharmahal and Bakhtiari province, located in the southwest of Iran (Figure 1) to investigate the potensial of solar energy harvesting systems installation on the façade. The ~~study~~ building is located in a main city area. Based on the reports that were classified in Table 1, the simultaneous use of PV and SWH in the facade of buildings is a novel idea and hasn't been considered in the previous studies yet. Moreover, the methodology is completely different ~~as well~~. The geography, the approach, and the location of the building from the point of the weather condition view are completely special as well. Additionally, none of the studies has investigated pool energy-consuming. In addition, the accurate analysis, the updated energy price, and the on-grid PV system assumption make it unique and usable for investigators and authorities in the field of building energy.

in this study, Section 2 shows the geographic location of the study, Section 3 discusses on the methodology, Section 4 presents the needed data, Section 5 exhibits the results and findings and Section 6 reviews the main results of the paper.

Table 1. Previous literature, main findings and differences from the present study

Authors	location	Software and tools	Subject	Main Results	Difference from this study
[20]	Netherlands	in-depth interview	Architectural photovoltaic applications: lessons learnt and perceptions from architects	When applying PV on a facade, it is more important to be careful with design and aesthetics; in an urban area, it is difficult to integrate it as part of the architecture	not used SWH in the facade
[21]	Germany	Review	Review of technological design options for BIPV on roofs and facades	Crystalline silicon-based solar cell technologies currently offer the greatest advantages for BIPV applications. Two options were proposed: the use of PV cells as basic elements of patterns and the use of colour to conceal the PV cells.	not used SWH in the facade

[22]	China	Numerical approach (Mathematica)	Performance evaluation of an active pipe-embedded building envelope system to transfer solar heat gain from the south to the north external wall	The heating load reduction during the heating season is 12.8% for hot summer and cold winter climates. For severe cold climates and cold climates, the heating loads in January are reduced by 4.6% and 8.7%, respectively.	not used PV in the facade
[23]	Cyprus	Review	Building integration of active solar energy systems: A review of geometrical and architectural characteristics	The single façade solutions are followed by the double façade systems since the second one offers a cavity which can be used as an air duct for the BIPV and BIPV/Thermal solutions.	not used SWH in the facade
[24]	Egypt	online questionnaire and semi-structured interviews with Egyptian experts and suppliers	Functionalizing building envelopes for greening and solar energy: Between theory and the practice in Egypt	The main benefits of greening and solar energy systems are identified as enjoying the greenery view (95%) and reducing energy expenses (100%), respectively.	not used local analyzing and special methodology
[25]	Jordan	Simulation by MATLAB/Simulink©	A comprehensive comparison and control for different solar water heating system configurations	The optimal SWH system configuration depends on the dominant nature of the solar radiation in the region at which the SWH system is installed.	not used PV panels in the facade
[26]	China	day-long experiment	Performance comparison of photovoltaic/thermal solar water heating systems with direct-coupled photovoltaic pump, traditional pump and natural circulation	A comparison among the three PV/T systems shows that the system with a PV pump has the best thermal performance. The PV pump can enhance the thermal performance of the PV/T system compared to a traditional pump.	not used SHW in the facade
[27]	Review	Review	integration of solar photovoltaic modules and heat pumps towards decarbonisation of buildings	By using hybrid systems composed of optimal control, PV cells, heat pumps and wind energy, energy saving of more than 50 % is achievable.	not used SHW and PV simultaneously in the facade
[28]	China	MATLAB	A study of an off-grid hybrid structure with two main energy storage systems is implemented to increase energy independence in green buildings.	The PV/battery system in remote areas becomes more economical than the off-grid PV/hydrogen system as reliability decreases and interest rate increases.	not used SHW in the facade
[29]	Iran, Jask and Ramsar	HOMER	Techno–Econo–Enviro Energy Analysis, Ranking and Optimization of Various BIPV Types in Different Climatic Regions of Iran	In the final ranking of cities, Jask is the most suitable and Ramsar is the most unsuitable. -For an angle of 30° at Jask city, 39 MWh of solar electricity is generated annually, The lowest return time of 11.7 years is related to Jask city (30° angle), and the highest return time with more than 25 years is related to Ramsar city (90° angle).	not used SHW in the facade

[30]	10 different locations all over the world	Design-builder software	Energy investigation in buildings applying a solar adsorption chiller coupled with biofuel heaters and solar heating/cooling systems in different climates.	An example is a combination of cooling systems with biofuel heaters. Adding green electricity producers like photovoltaic panels to this system reduces fossil fuel -consuming by up to 50%.	Investigation just the PV panels technology
[31]	Cyprus	Energy Plus	Use of double skin façade with building-integrated solar systems for an energy renovation of an existing building in Limassol	The study also includes the effect of the combination of three main features, a BIPV, glazing system and rambling planting. This combination reduces 63% of the proposed -consuming of the building.	The building is integrated with PV but not SHW
[32]	Nicosia, Cyprus	Energy Plus	Design optimization of a solar system integrated double-skin façade for a clustered housing unit	The study compares a conventional double façade, the conventional double façade system demonstrates lower heating demands than the other systems, whereas the opposites occur for the cooling needs.	The building integrated of PV but not SHW

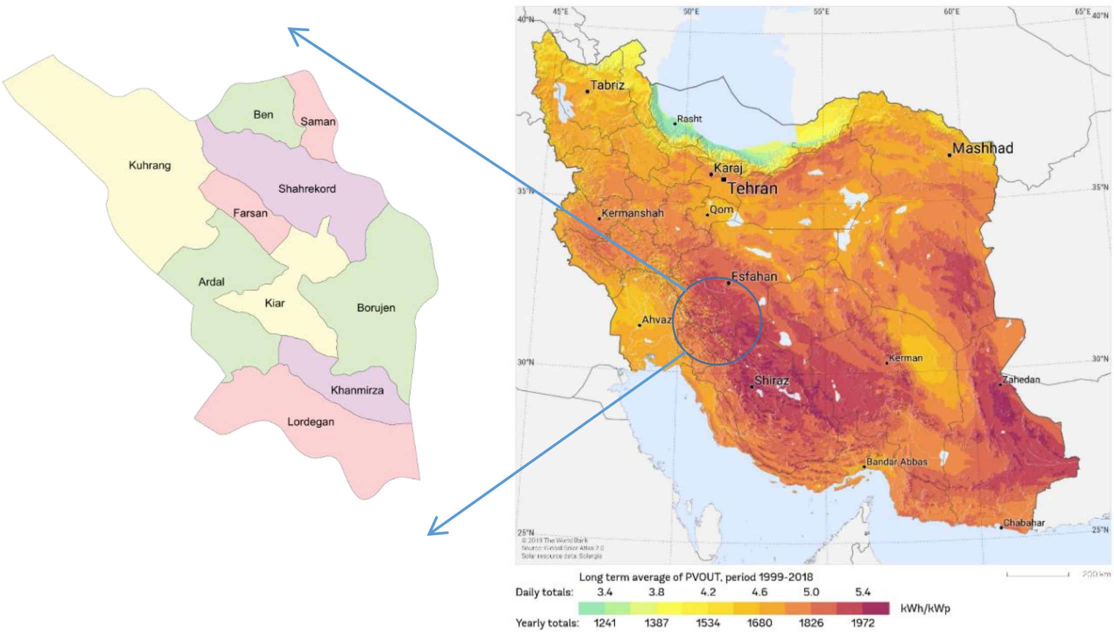


Figure 1. Left; Chaharmahal & Bakhtiari Province, Right; Iran potential of solar irradiation map [33]

a)

b)

Figure 2. Existing building facades (a: West and b: South), the PV and SWH places of installation are hatched on the Façade

2. Geographic location of the study

The considered building (Figure 2) is located in Shahrekord city, the centre of Chahrmahal & Bakhtiari province. Shahrekord is located about 90 km (56 mi) southwest of Isfahan and 512 km (318 mi) of Tehran. It is located in the centre of the Zagros mountain range. The city's altitude is about 2,070 m (6,790 ft) above the sea level; Shahrekord is the highest centre among the 31 centres of Iran and is known as the tourist target, especially during the ~~hot~~ summer, when the temperature is up to 35 degrees centigrade. Based on the 2016 Census in Iran, Shahrekord's population was 190441. With a temperate climate in summer and very cold weather in winter, this city is recognized in the Dsa group from the point of Köppen climate classification. It was first published by German-Russian climatologist Wladimir Köppen (1846–1940) in 1884 [34].

3. Methodology

The TSOL 2021 (R3) software was employed to simulate and investigate the annual performance of SWHs. Initially, TSOL considers governing variables such as solar radiation, air temperature, and heat losses in various components of the system, enabling precise forecasts of system performance [35]. This aids users in fine-tuning the design and dimensions of SWHs to achieve maximum efficiency, Moreover, has got a user-friendly interface. Additionally, it offers preconfigured settings for various SWH types, allowing users to compare different system configurations regarding installation expenses, energy savings, economic viability [36]. Nevertheless, this software comes with limitations, such as its reliance on accurate data for solar radiation and air temperature, which may not always be accessible. For example it does consider fluctuations in weather conditions throughout the day [37]. In terms of methodology, TSOL software relies on mathematical models based on heat transfer principles to replicate the behaviour of SWHs. It computes variables like collector efficiency, heat losses from pipes and hot water storage tanks, and the overall system's performance. Ultimately, TSOL employs iterative algorithms to solve equations and delivers precise outcomes [38]. Figure 3 illustrates the essential data and results that TSOL software can provide.

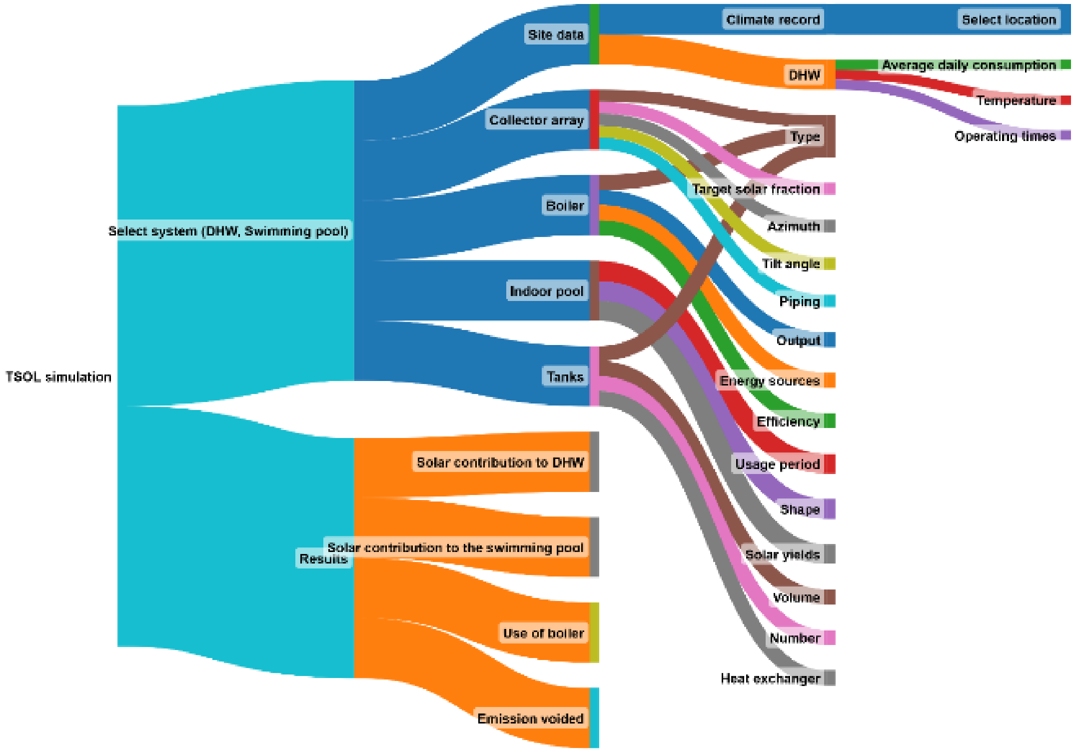


Figure 3. Diagram of required information and presentable results of TSOL software

The HOMER software stands out as a widely used tool for simulating renewable energy systems. One of its key strengths lies in its capability to model intricate hybrid systems, facilitating user-driven system configuration based on energy needs and available resources [39]. By considering equipment costs, maintenance expenditures, fuel prices, and more, the HOMER software offers a thorough economic analysis for the examined system. This aids users in making informed decisions regarding the viability and profitability of their renewable energy projects [40]. Nevertheless, it's worth noting that this software does have some limitations. For instance, it requires precise input data, which can often pose a challenge to acquire. Furthermore, due to the complexity of the issues involved, HOMER's optimization algorithms may not always identify the globally optimal solution. From a methodological standpoint, HOMER relies on a blend of mathematical models and optimization algorithms to simulate renewable energy systems [41]. To determine the most efficient system configuration, aiming to minimize the total Net Present Cost (NPC), various factors like resource availability, system efficiency, and energy demand are taken into consideration [42]. The necessary information and presentable results of the HOMER software are illustrated in Figure 4.

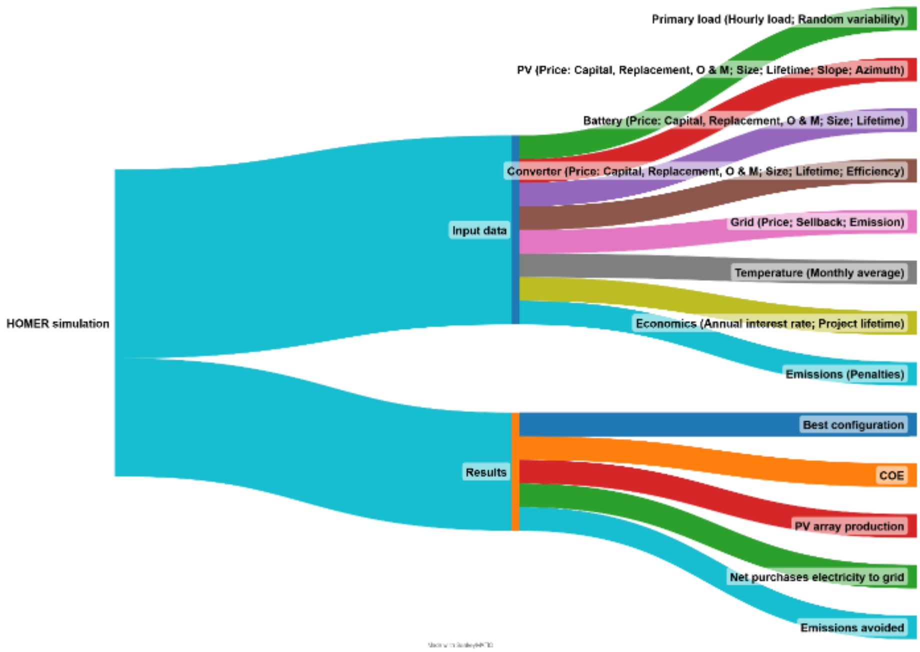


Figure 4. Diagram of required information and presentable results of HOMER software

4. Examined Systems

Figures 5 and 6 illustrate the systems that have been studied, with their respective roles in providing a portion of the required heating for the building and a portion of the building's electricity demand. The simulation of the system in Figure 5 was conducted using TSOL software, while the system in Figure 6 was simulated using HOMER software. The system depicted in Figure 5 is responsible for delivering some or all of the hot water needed for the building's sanitary facilities and the on-site swimming pool. On the other hand, the system shown in Figure 6 is in charge of meeting some or all of the building's electricity needs through the utilization of solar cells.

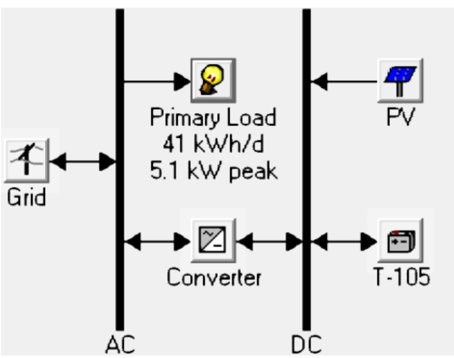


Figure 5. Schematic of the Simulated System in TSOL Software

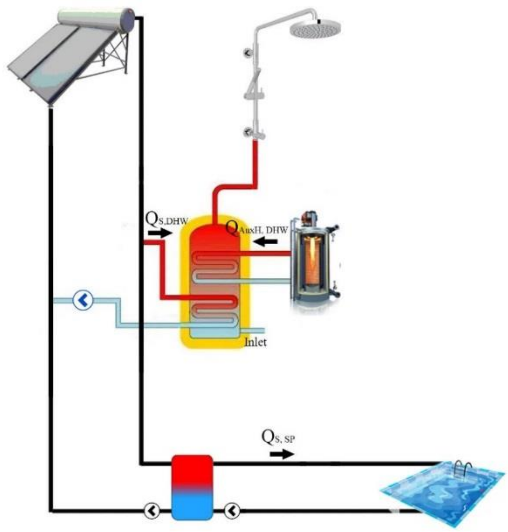


Figure 6. Schematic of the Simulated System in HOMER Software

5. Governing Equations

For energy balance, TSOL software employs the following equation [43]:

$$\rho = G_{dir}.\eta_0.f_{IAM} + G_{diff}.\eta_0.f_{IAM.diff} - K_0(T_{cm} - T_A) - K_q(T_{cm} - T_A)^2 \quad (1)$$

The first sentence on the right-hand side pertains to directly incident solar energy on the collector surface, the second sentence on the right-hand side relates to reflected solar energy incident on the collector surface, and the third and fourth sentences, respectively, concern first-order and second-order thermal losses of the solar collectors.
To calculate the solar fraction for supplying domestic hot water consumption and the solar fraction for supplying pool water heating, TSOL software utilizes equations 2 and 3, respectively [44, 45].

$$\text{DHW solar fracion} = \frac{Q_{S,DHW}}{Q_{S,DHW} + Q_{AUXH,DHW}} \tag{2}$$

$$\text{Swimming pool solar fracion} = \frac{Q_{S,SP}}{Q_{S,SP} + Q_{AUXH,SP}} \tag{3}$$

HOMER software uses equation 4 to calculate the power generated by solar cells [46]:

$$P_{pv} = y_{pv} \cdot f_{pv} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) \tag{4}$$

To calculate the electricity exchanged with the national power grid over the year in both the purchasing phase for required electricity and the selling phase for surplus electricity, HOMER software utilizes equation 5 [47].

$$C_{grid,energy} = \sum_{i}^{rates} \sum_{j}^{12} \begin{cases} E_{net\ grid\ purchases,i,j} \cdot c_{power,i} & \text{if } E_{net\ grid\ purchases,i,j} \geq 0 \\ E_{net\ grid\ purchases,i,j} \cdot c_{sellback,i} & \text{if } E_{net\ grid\ purchases,i,j} < 0 \end{cases} \tag{5}$$

For performing economic calculations, TSOL software uses equations 6 and 7, respectively [48, 49].

$$C = C_0 + \sum_{n=1}^{N} \frac{C_{O\&M} \times (1+e)^n}{(1+d)^n} \tag{6}$$

$$R_t = \frac{Q_u}{\eta_h} \sum_{n=1}^{N} \frac{(1+e)^n}{(1+d)^n} \tag{7}$$

The economic calculations carried out by HOMER software involve calculating the total NPC and the cost per kWh of electricity generated by the system, obtained from equations 8 and 9, respectively [50, 51].

$$\text{Total NPC} = \frac{C_{ann,total}}{\frac{i\,(1+i)^N}{(1+i)^N - 1}} \tag{8}$$

$$LCOE = \frac{C_{ann,total}}{E_{Load\ served}} \tag{9}$$

6. Required data

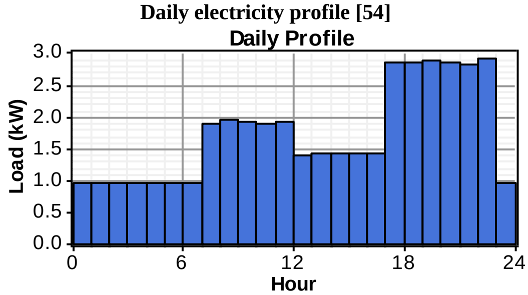
Because accurate input data is essential for simulation, the necessary input information for TSOL and HOMER software is presented in Tables 2 and 3, respectively.

Table 2. Data Needed for Simulating Solar Heating

Parameter	Amount
Daily usage of warm water (L)	495
Temperature of hot water consumption (ºC)	60
Heated floor area (m^2)	1000
Required Range of Hot Water	All months
Volume of Hot Water Storage Tank (L)	600
Total Solar Collector Area (m^2)	84 on the southern facade 65 on the western facade
Azimuth angle (º)	0 for the southern facade 90 for the western facade
Tilt angle (º)	90
Conversion factor (%)	78
Lifetime (Years)	25
Interest on capital (%)	2.5
Reinvestment return (%)	2.5
Fuel cost ($/$m^3$)	0.001
Subsidy (%)	50
Flat plate collector price ($/$m^2$)	200
Allowance ($/kWh)	0.118
Allowance payment duration (years)	25
Running cost (%/year)	0.5
Working fluid	60% water, 40% Ethylene glycol
Solar fraction	Middle
Auxiliary boiler type	Natural gas
Auxiliary boiler capacity (kW)	20
Daily fresh water requirement for the pool (L)	100
Timeframe for pool usage	November, December, January, February
Pool area (m^2)	6×4
Pool depth (m)	1.4

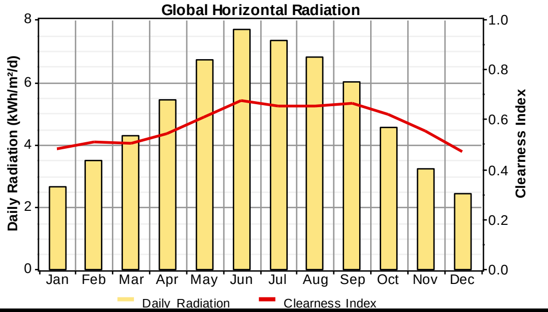
Table 3. Data Required for Solar Power Simulation

PV [52]	Battery [53]
Capital: 350 $/kW Replacement: 350 $/kW O & M: 10 $/year Lifetime: 25 years Azimuth angle: 0, 90 Derating factor: 80% Trackers: No Size to consider: 65 kW, 84 kW Consider the effect of temperature: Yes	Capital: 174 $ Replacement: 174 O & M: 5 $/year Type: Trojan T-105 Size to consider: 0-20 Nominal capacity: 1.35 kWh
Daily electricity profile [54]	



Grid electricity price [55] The average buying and selling price at all times: \$0.02/kWh	**Economic data [56, 57]** Annual real interest rate: 18% Project's useful life: 25 years
Converter [52] Capital: 138 \$/kW Replacement: 138 \$/kW O & M: 10 \$/year Lifetime: 10 years Size to consider: 65 kW, 84 kW	**Penalties for pollutants [59]** Carbon dioxide: \$3.1 per ton Carbon monoxide: \$57 per ton Sulfur dioxide: \$560 per ton Nitrogen oxides: \$184 per ton

Global Horizontal Radiation [58]



7. Results

7.1. Thermal analysis

For this section, two scenarios have been considered. In the first scenario, solar collectors are installed on the southern facade of the building (84 m^2), and in the second scenario, they are installed on the western facade of the building (65 m^2). The results of these two scenarios are provided in Table 4.

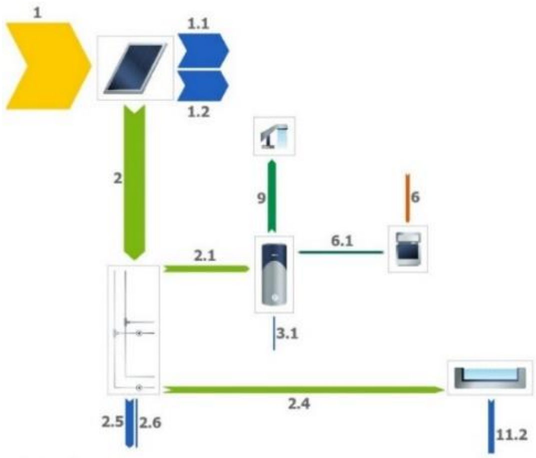
Table 4. Results of SWH simulation

Scenario	Solar contributed to DHW	Solar contributed to pool	Use of auxiliary boiler	CO_2 emission avoided
1	7.7641 kWh/m^2	7.6085 kWh/m^2	3202.7 kWh	3989.6 kg/year
2	7.8583 kWh/m^2	1.7936 kWh/m^2	3272 kWh	2742.4 kg/year

The information from Table 4 reveals that in the first scenario, solar heat production amounts to 15,372.6 kWh, whereas it's 9,651.9 kWh for the second scenario. This difference can be explained by the fact that in the first scenario, there are more solar collectors, and they are oriented towards the south (given that Shahrekord is located in the northern hemisphere), resulting in greater solar radiation capture. Additionally, since both scenarios require supplementary heating through auxiliary boilers due to the inability of solar collectors to meet all heating demands, this was an anticipated necessity. Considering the higher solar heat production in the first scenario, the reduction in preventing pollutant emissions is approximately 45% greater compared to the second scenario.

Figures 7a and 7b depict loss diagrams for the first and second scenarios, respectively. In the first scenario, most of the losses are attributed to optical losses, followed by thermal losses in the solar collectors and losses in the internal piping system. In the second scenario, the majority of losses are due to thermal losses in the collectors, with optical losses and losses in the internal piping system closely following.

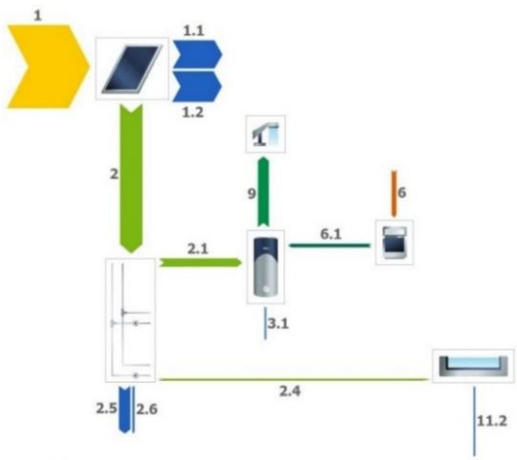
In the economic analysis section, it is evident that the price per kWh of solar heat produced in the first and second scenarios is \$ -0.082 and \$ -0.074, respectively. The negative sign signifies the profitability of the solar heating project in the current context, resulting in savings when considering the average global natural gas purchase price data. The 25-year financial analysis for the first and second scenarios is depicted in Figures 8a and 8b, respectively. The results indicate that the payback period and the profit at the end of 25 years are 4.9 years and \$50,443 for the first scenario, and 6.1 years and \$29,982 for the second scenario, respectively.



Legend

1	Irradiation on collector surface (active)	114,009 kWh
1.1	Optical collector losses	44,879 kWh
1.2	Thermal collector losses	39,700 kWh
2	Energy from collector array	27,211 kWh
2.1	Solar energy to storage tank	7,764 kWh
2.4	Solar energy to swimming pool	7,609 kWh
2.5	Internal piping losses	10,353 kWh
2.6	External piping losses	1,486 kWh
3.1	Tank losses	834 kWh
6	Final energy	4,647 kWh
6.1	Supplementary energy to tank	3,203 kWh
9	DHW energy from tank	10,138 kWh
11.2	Swimming pool losses	6,925 kWh

a)

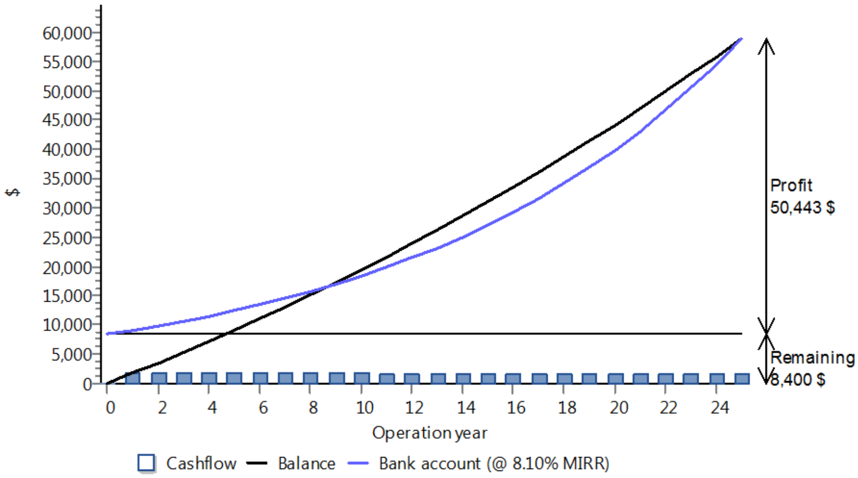


Legend

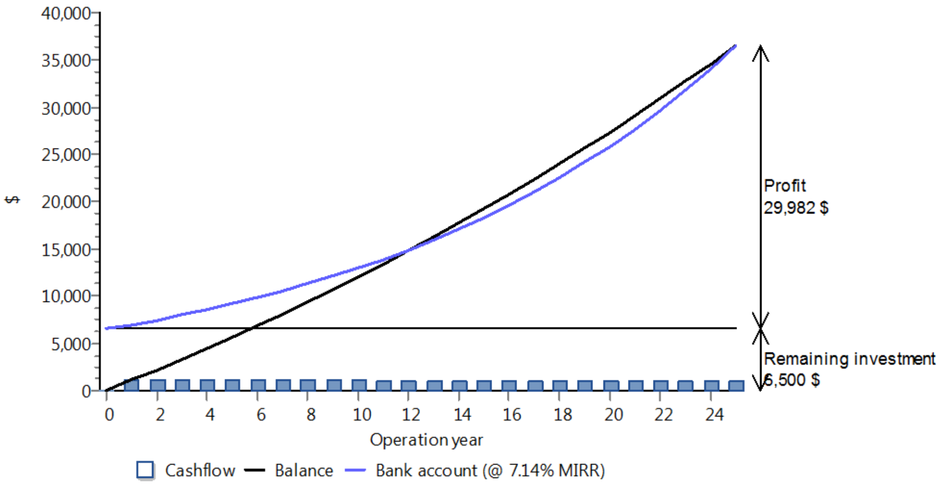
1	Irradiation on collector surface (active)	80,734 kWh
1.1	Optical collector losses	26,960 kWh
1.2	Thermal collector losses	29,902 kWh
2	Energy from collector array	21,618 kWh
2.1	Solar energy to storage tank	7,858 kWh
2.4	Solar energy to swimming pool	1,794 kWh
2.5	Internal piping losses	10,573 kWh
2.6	External piping losses	1,393 kWh
3.1	Tank losses	991 kWh
6	Final energy	4,100 kWh
6.1	Supplementary energy to tank	3,272 kWh
9	DHW energy from tank	10,138 kWh
11.2	Swimming pool losses	1,308 kWh

b)

Figure 7. Energy diagrams of examined systems a) First scenario b) Second scenario



a)



b)

Figure 8. 25-year financial analysis results for the solar heat production a) first scenario b) second scenario

7.2. Electrical analysis

The results of analyzing how electricity is provided for the building in the first and second scenarios can be found in Table 5. As mentioned earlier, the PV system being examined is connected to the national power grid, allowing for surplus electricity to be shared with the grid. Furthermore, because of the grid's electrical support, there was no need to use batteries in the simulation results.

Table 5. Results of PV simulation

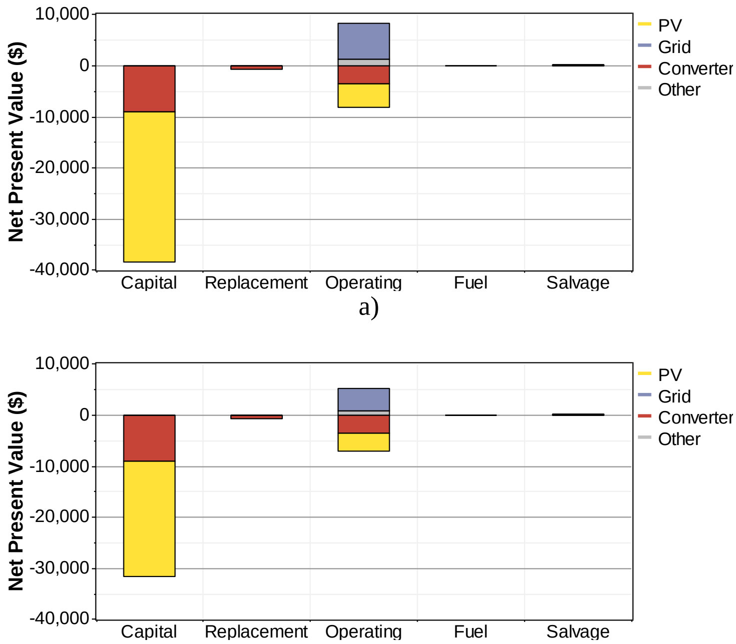
Scenario	Equipment	COE ($/kWh)	Solar production	Surplus electricity	CO_2 emission avoided
1	84 kW PV, 65 kW Converter	0.082	91% of 91.174 kWh/m^2-year	63922 kWh/y	40.4 ton/year
2	65 kW PV, 65 kW Converter	0.101	88% of 65.194 kWh/m^2-year	39345 kWh/y	24.9 ton/year

The information from Table 5 reveals that, despite having a larger number of solar panels, the cost per kWh of electricity in the first scenario is approximately 19% lower at $0.082. This cost reduction is attributed to the surplus solar electricity in the first scenario, which is sold back to the national power grid, leading to a lower overall cost. Additionally, due to the increased number of solar cells in the first scenario, the proportion of solar electricity is higher compared to the second scenario.

Selling excess solar electricity back to the grid helps mitigate pollutant emissions resulting from grid electricity production. The second scenario achieves the minimum reduction in CO_2 emissions, a notable 24.9 tons/year. According to reference [60], the global average residential electricity price stands at \$0.181/kWh, and the findings from both scenarios in this study indicate the cost-effectiveness of utilizing PV for on-building facade electricity generation. It's important to highlight that employing PV on the building facade also contributes to reducing building thermal losses, which is a valuable benefit.

Figures 9a and 9b present the 25-year analysis results for the first and second scenarios, respectively. The results clearly show that the primary expense is related to equipment procurement, totalling \$38,370 in the first scenario and \$31,720 in the second scenario. Additionally, both scenarios incur costs related to replacing the electrical converter in the fifteenth year, as well as ongoing operational expenses for solar cell and electrical converter maintenance and repairs. Selling excess electricity back to the grid generates positive income for the system, which, when combined with the salvage cost, reduces the total system cost. In summary, the first scenario yields a total NPC of -\$38,921, while the second scenario amounts to -\$34,422 when considering the aforementioned costs.

The usage of the PV system on the facade of the buildings would reduce the price of the construction since it can be replaced by common materials and this price reduction should be included in the total price of the solar system.



a)

b)

Figure 9. 25-year economic analysis results for the examined systems a) first scenario b) second scenario

8. Conclusion

Combining SWHs and PVs systems installed on a building's façade is of utmost importance and holds significant potential. This integration enables the simultaneous utilization of solar energy for water heating and electricity generation, leading to a substantial reduction in energy-consuming. This holistic approach not only promotes sustainability but also reduces dependence on conventional energy sources, resulting in cost savings and a more environmentally friendly footprint. In this ground-breaking study conducted in Iran, solar energy application on a 5-story building's façade in Shahrekord is explored for the first time. The primary objectives are to provide electricity through analytical assessments using HOMER V.2.81 software and to meet the hot water demands for sanitary and swimming pool purposes using TSOL 2021 R(3) software. The technical, energy, economic, and environmental evaluations carried out in this study serve as a roadmap for decision-makers and investors in this domain. Two distinct scenarios were analyzed: one with solar collectors on the southern façade (84 m^2) and the other on the western façade (65 m^2). Key findings include:

- Solar heat production:

First Scenario: Achieved solar heat production of 15,372.6 kWh.

Second Scenario: Achieved solar heat production of 9,651.9 kWh.

- Auxiliary boiler usage:

Both scenarios necessitate auxiliary boilers due to inadequate solar heat production. The first scenario, with higher solar heat output, results in a significant 45% reduction in pollutant emissions.

- Loss analysis:

In the first scenario, the most substantial losses are optical, followed by thermal and piping losses.

In the second scenario, solar collector thermal losses are predominant, trailed by optical and piping losses.

- Electricity supply and costs:

The first scenario enjoys a cost advantage with a 19% lower cost per kWh at $0.082, thanks to surplus electricity sales.

- CO_2 emission reduction:

The first and second scenarios effectively reduce CO_2 emissions by 40.4 and 24.9 tons per year, respectively.

- PV cost-effectiveness on façade:

In both scenarios, cost-effectiveness is demonstrated when compared to the global average residential electricity price of $0.181 per kWh.

- 25-Year analysis:

Equipment acquisition represents the primary cost component, totalling $38,370 (first scenario) and $31,720 (second scenario). Additional costs arise from the replacement of electrical converters in the 15th year. The sale of surplus electricity contributes positively to system finances. The total NPC amounts to -$38,921 for the first scenario and -$34,422 for the second scenario.

Moreover, in the proposed future studies it can be investigated in various climates and the effect of different climates on the economic performance results and the new technologies in PV and SWH shall be studied. The proposed installation can be implemented on the building roof as well.

Nomenclature:

NPC	Net present cost ($)
ρ	Collector energy balance (kW)
C	Cost of the SWH system ($)
e	Useful life (year)
n	Number of years (-)
d	Rate of decline (%)
f_{PV}	Derating factor (%)
P_{PV}	Output power of PV cells (kW)
Y_{PV}	Output power of solar cell under standard conditions (kW)
$\overline{G_T}$	Incident radiation on the cell's surface every month (kW/m^2)
$\overline{G_{T.\ STC}}$	Incident radiation on the cell's surface under standard conditions (1 kW/m^2)
$C_{ann,total}$	Total annual cost ($)
$E_{load\ served}$	Real electrical load by system (kWh/year)
O & M	Operating and maintenance (-)
BIPV	Building-integrated photovoltaic (-)
DHW	Domestic hot water (-)
PV	Photovoltaic (-)
SWH	Solar water heater (-)
R_t	Total revenue ($)
$C_{sell\ back}$	The sellback rate ($/kWh)
$C_{grid,\ energy}$	Total annual energy charge (kWh)
LCOE	Levelized cost of energy (-)
T_A	Air temperature (K)
T_{cm}	Average temperature of collector (K)
k_q	Quadratic heat transfer coefficient (W/m^2.k^2)
$Q_{S,\ SP}$	Solar heating for swimming pool (kW)
$Q_{S,\ DHW}$	Solar heating for DHW (kW)
$Q_{Aux,\ DHW}$	Auxiliary heating for DHW (kW)
$Q_{Aux,\ SP}$	Auxiliary heating for swimming pool (kW)
i	Annual interest rate (%)
N	Useful life-time (year)
G_{dir}	Part of solar radiation striking a tilted surface (kW)
η_0	Collector's zero-loss efficiency (%)
f_{IAM}	Incidence angle modifier factor (-)
G_{diff}	Diffuse solar radiation striking a tilted surface (kW)
$f_{IAM,diff}$	Diffuse incidence angle modifier factor (-)
k_0	Simple heat transfer coefficient (W/m^2.k)
C_0	Total purchase cost ($)
$C_{O\&M}$	Total annual operating and maintenance costs ($)
Q_u	Useful energy collected by the solar collectors (kW)
η_h	Efficiency of the auxiliary boiler (%)
C_{power}	The grid power price ($/kWh)
$E_{net\ grid\ purchases}$	The net grid purchases (grid purchases minus grid sales) (kWh)

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