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Techno-economic Assessment of a Coupled Solar-photovoltaic Water Heating System for a Residential Complex in Saudi Arabia

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ABSTRACT

Solar energy offers a sustainable pathway to meet residential demands for hot water and electricity. However, comparative community-scale assessments of solar thermal and photovoltaic (PV) systems remain limited. This study presents a techno–economic comparison of solar water heaters and PV systems to meet the combined hot water and electricity needs of a 2000-home residential community in Dhahran, Saudi Arabia. Using Renewable Energy and Energy Efficiency Technology Screening (RETScreen) software, the annual hot water load for a five-occupant household was modeled and a detailed energy audit was conducted to estimate the annual electricity demand. Community-scale requirements were then derived by scaling the results for an individual home by 2000. Two solar water heaters (ThuSolar and SunEarth) and three PV modules (LONGi Solar, Jinko Solar, and REC Solar) were compared in fixed-tilt and one-axis tracking configurations across five metrics: annual energy output, capital expenditure, CO_2 reduction, payback period, and land use. SunEarth water heaters achieved the highest thermal yield of 6.19 million kWh, offsetting 3.44 million kg of CO_2, with a land footprint of 7400 m^2 of land and payback period of 14.6 years. Jinko Solar with one-axis tracking generated the highest electricity output of 63.37 million kWh, offsetting 35.22 million kg of CO_2, with a land footprint of 142568 m^2 and payback period of 12.3 years. These findings highlight that optimized solar thermal and PV technologies can play complementary roles in delivering cost-effective and sustainable energy solutions for large residential communities.

Keywords: solar photovoltaics, solar water heater, net zero homes, payback period, CO_2 reduction

1. INTRODUCTION

Global energy consumption has increased significantly in recent decades, accompanied by a marked increase in fossil fuel consumption. In 2023, the global energy requirements reached approximately 180,000 TWh, an almost six-fold increase from that in 1950 (approximately 30,000 TWh) in Figure 1 [1], with fossil fuels remaining the predominant energy source. This heavy reliance on fossil fuels has detrimental consequences, including oil spills, water and air pollution, resource depletion, and, most critically, climate change. Thus, an urgent global impetus has emerged to transition toward a more sustainable energy paradigm. These challenges are directly linked to the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

In alignment with these global imperatives, Saudi Arabia has boldly committed to achieving net-zero greenhouse gas emissions by 2060 [2]. This strategic vision includes the deployment of carbon capture technologies in both existing and forthcoming gas turbines and the extensive use of combined cycle power plants, which will enhance energy efficiency to curtail fuel consumption, as well as large-scale investments in renewable energy infrastructure. One focal area of this national strategy is the decarbonization of the residential sector. Residential appliances, particularly air conditioners and water heaters, contribute significantly to household energy consumption as shown in Figure 2. To address this demand sustainably, Saudi Arabia is pursuing a multifaceted approach that incorporates solar photovoltaic (PV) systems, solar thermal water heating technologies, wind energy, and improved building insulation along with the optimization of existing thermal processes and energy cycles. Collectively, these measures will contribute to the Kingdom's long-term objective of an energy-resilient and low-carbon future.

A pivotal strategy for decarbonizing residential communities involves replacing conventional electric water heaters with solar thermal water heating systems. These systems are broadly categorized into two primary types: active and passive solar heating. Active solar heating systems, while more complex and costlier, offer superior efficiency owing to the incorporation of pumps and electronic controls that actively circulate the heat-transfer fluids. In contrast, passive systems rely on natural convection and gravity-driven flow, which make them simpler and less expensive as well as less efficient [4]. The residential market offers three primary configurations of solar water heaters: flat-plate collectors, integrated collector storage (ICS) systems, and evacuated-tube solar collectors. These configurations vary considerably in terms of efficiency, cost, and suitability depending on the climate and

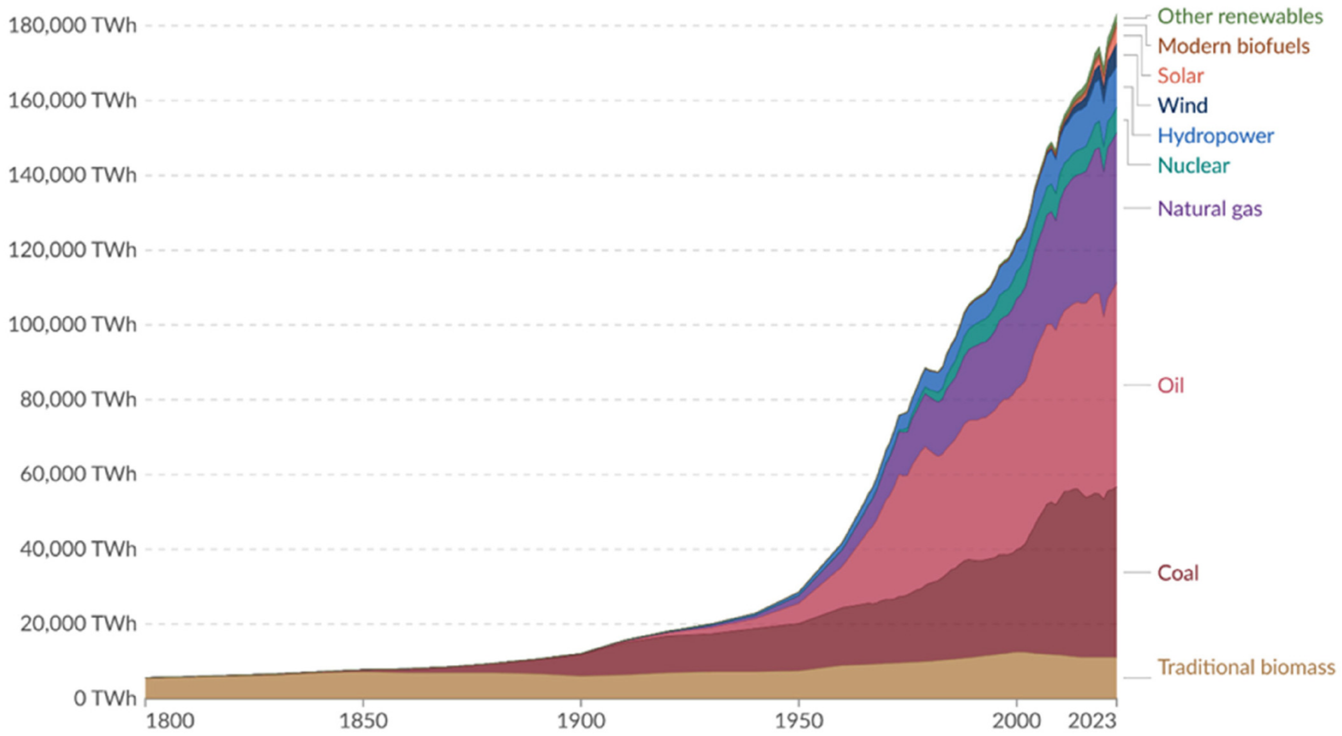


Figure 1. Global primary energy consumption by source

operational conditions[5]. Flat plate collectors are among the most commonly available solar water heaters and were modeled in this study.

Similarly, solar PV technology has emerged as a cornerstone of global energy transition and continues to experience exponential growth driven by decreasing costs and improved efficiency. Solar PV systems are composed of interconnected semiconductor cells, each capable of generating approximately 1–2 watts of electrical power. Solar PV technologies include monocrystalline silicon, polycrystalline silicon, and thin-film modules, each of which differs in terms of efficiency, cost, and application. Monocrystalline silicon PV modules are among the most efficient and thus were modeled in this study[6].

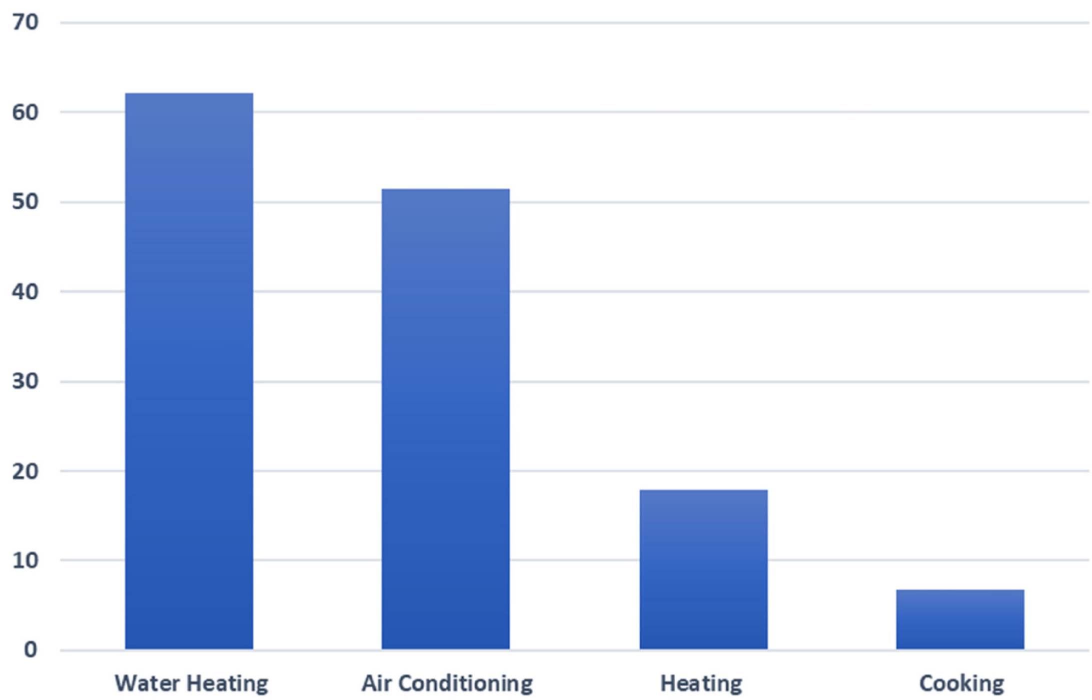


Figure 2. Average weekly operating hours of electrical appliances in the kingdom in 2023[3]

The cost of solar PV technology has drastically declined in recent decades, while its efficiency and scalability have continuously advanced. As illustrated in Figure 3, the average price of solar PV panels in 2023 dropped to approximately \$0.31/watt, which is only 4.8% of the cost in 2000—which stood at \$6.41/watt. This substantial cost reduction underscores the growing economic viability of solar PV systems and strengthens the case for accelerating the transition toward solar energy. However, declining cost alone is not sufficient for nationwide deployment. Comprehensive feasibility studies guided by rigorous data and statistical analyses are essential for governments to assess the reliability and long-term cost-effectiveness of solar PV infrastructure.

A considerable body of research has addressed the technical and economic performance of solar PV and solar thermal technologies. Previous studies have provided critical insights into the optimal deployment of solar technologies in Saudi Arabia. Abd-ur-Rehman and Al-Sulaiman [8], conducted a comprehensive techno-economic evaluation of evacuated tube and glazed flat-plate solar water heater systems across 10 Saudi cities and found significant regional variations in solar viability and economic feasibility. Almohammadia and Allouhi [9] proposed optimal grid-connected PV installations for residential buildings in 19 Saudi cities and highlighted the key trade-offs between renewable fractions and net present costs. Their findings emphasized the need to balance economic viability and renewable energy utilization to achieve sustainable energy transitions. Alanazi [10] explored hybrid renewable energy systems consisting of wind turbines, PV panels, batteries, and diesel generators in rural Saudi Arabia and concluded that despite considerable solar and wind potential, stand-alone renewable systems require supplementary storage or backup generators to ensure a reliable electricity supply. Recent advances in hybrid systems include developing solar PV-powered thermoelectric solar air conditioning and modeling their performance using multiple artificial intelligence models [11]. Other innovative studies have coupled solar PV/thermal collector systems with electrolytic hydrogen production units, and they reported hydrogen production yields as high as 4.41 kg/day [12,13]. Furthermore, the use of solar dish-Stirling systems has also been explored in detail, with reported efficiencies approaching 32% in arid climates; thus, these systems may play a key role in distributed energy systems [14].

While these studies have highlighted the performance potential of solar thermal, PV, and hybrid solar approaches, most of them focused on component-level demonstrations. Thus, community-scale comparative techno-economic assessments of solar thermal and PV systems for meeting heating and electrical loads in regions with high solar insolation such as Saudi Arabia are still limited in scope.

Therefore, this study provides a detailed techno-economic assessment of solar water heaters and PV systems specifically tailored for a 2000-home residential community in Dhahran, Saudi Arabia. The objectives of this study were as follows:

- Comprehensively compare the techno-economic performances of two commercial solar water heaters (ThuSolar and SunEarth) and three widely used PV modules (LONGi Solar, Jinko Solar, and REC Solar).
- Evaluate the influence of fixed-tilt and one-axis tracking configurations across key metrics, including annual energy output, capital investment, CO_2 emission reductions, payback time, and land requirements.
- Identify optimal solar energy solutions capable of sustainably and economically meeting both hot water and electrical energy demands, thus supporting Saudi Arabia's long-term

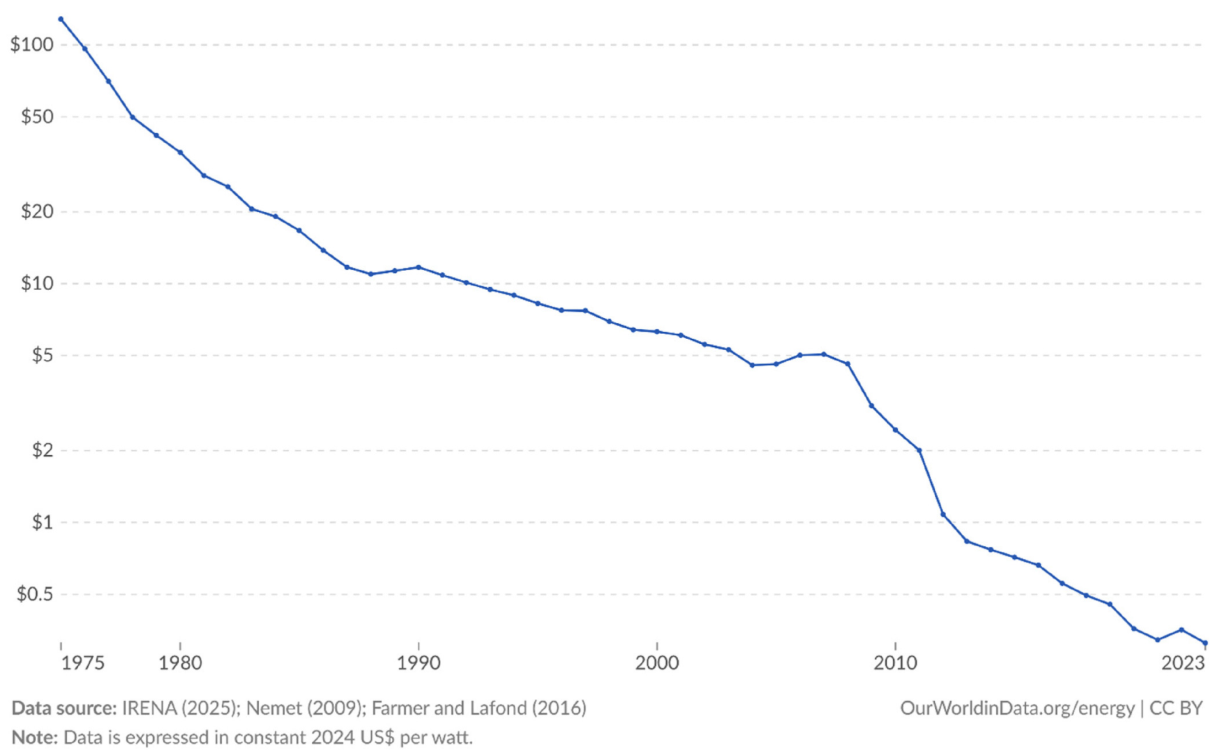


Figure 3. Solar PV panel prices in USD per watt over the years [7]

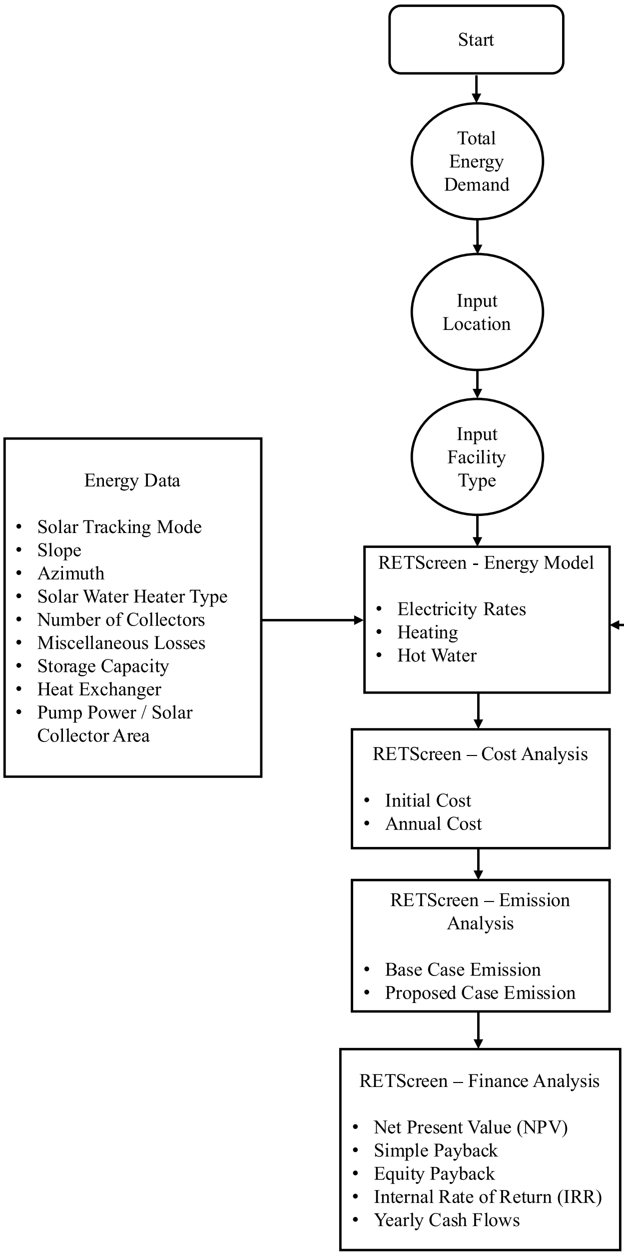


Figure 4. Solar water heater flowchart

decarbonization goals and contributing toward achieving the relevant SDGs (7 and 13).

The findings highlight how optimized solar thermal and PV technologies can play complementary roles in delivering cost-effective and sustainable energy solutions for large residential communities

2. RESEARCH METHODOLOGY

The research methodology used in this study consists of two primary stages. In the first stage, detailed energy demand data were collected from a representative household sample to quantify the hot water and electricity requirements that could be supplied by solar water heater and PV systems. In the second stage, Renewable Energy and Energy Efficiency Technology Screening (RETScreen) software was utilized to identify suitable technologies and conduct comprehensive cost, emission, and financial analyses for the selected location in Dhahran, Saudi Arabia. The overall methodological framework is illustrated in detail in Figures 4 and 5.

Figure 6 shows a simplified 2D schematic of the system. The diagram illustrates the major components, beginning with the solar PV farm located at distance from the community. The PV farm is connected to a direct current (DC) combiner box and inverter, which conditions and converts the generated electricity into alternating current (AC) power. Transmission lines carry electricity to the community, where service disconnects are installed to ensure safety during maintenance and emergency operations.

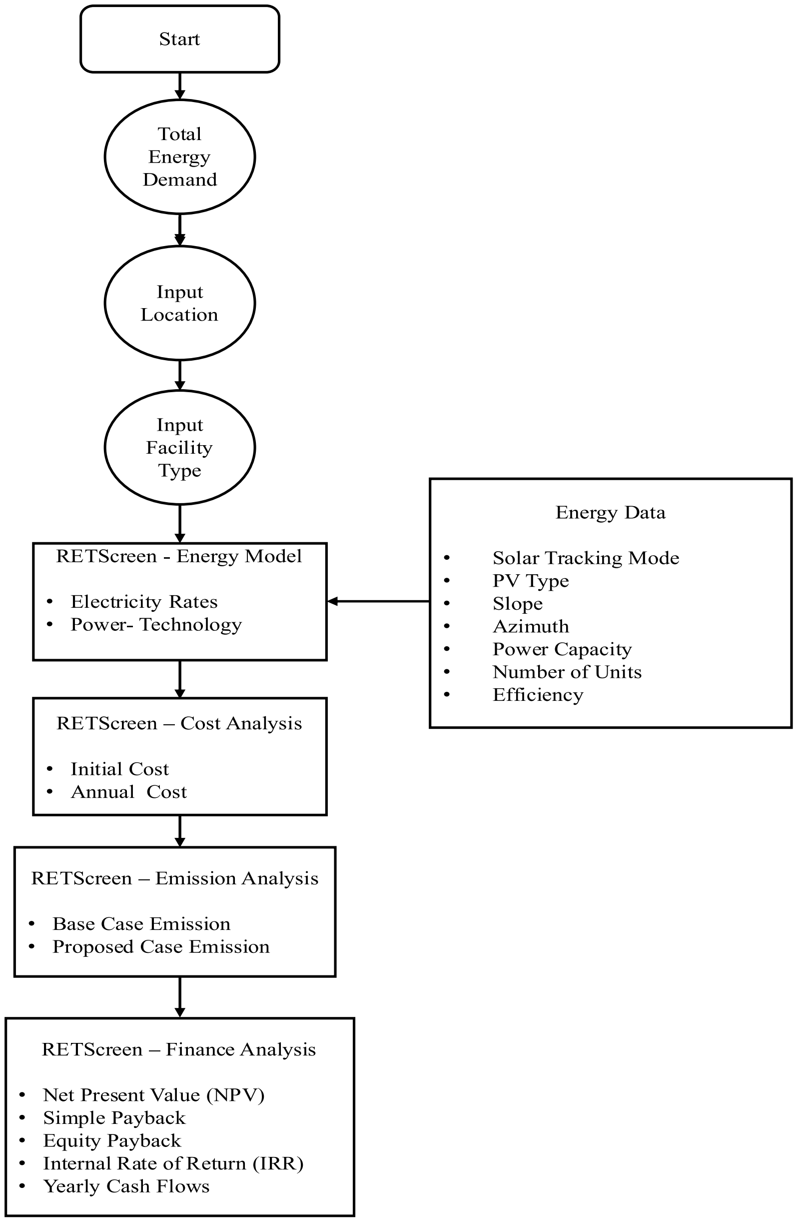


Figure 5. Solar PV flowchart

The schematic highlights the solar water heating system within the community. This includes a solar water heater collector, circulation pump, water storage tank, valves, and piping, all of which are integrated to provide hot water to residents.

2.1. Total Energy Demand. A representative household of five individuals was selected as the basis for estimating the annual energy consumption. The most frequently used appliances were identified, along with their power ratings (in W) and average daily operating hours in both winter and summer. To simplify the analysis, a single representative day from each season was used to represent the overall seasonal demand. The daily energy consumption for each summer and winter day was then calculated using Eq. (1):

$$Consumption\ per\ day\ (kWh) = Usage\ Hours \times Quantity \times Rating \div 1000 \quad (1)$$

Annual energy demand was determined by averaging the calculated daily consumption for summer and winter days and multiplying it by 365.

Table 1 presents detailed energy consumption data calculated for a single representative household. These data served as the basis for determining the required heating and electricity generation from the solar water heating and PV systems. Based on the above data, the total annual energy consumption of the representative households was 45,008 kWh. Assuming that all households consume the same amount of energy, the total annual energy consumption for 2,000 households was calculated as 9, 00, 16, 000 kWh.

As solar water heaters are assigned to meet hot water demand, the energy consumption of water heaters, estimated to be 20,805 kWh per household, was subtracted from the total household load to determine the net energy demand to be met by the solar PV system. The PV system was then sized to generate electricity

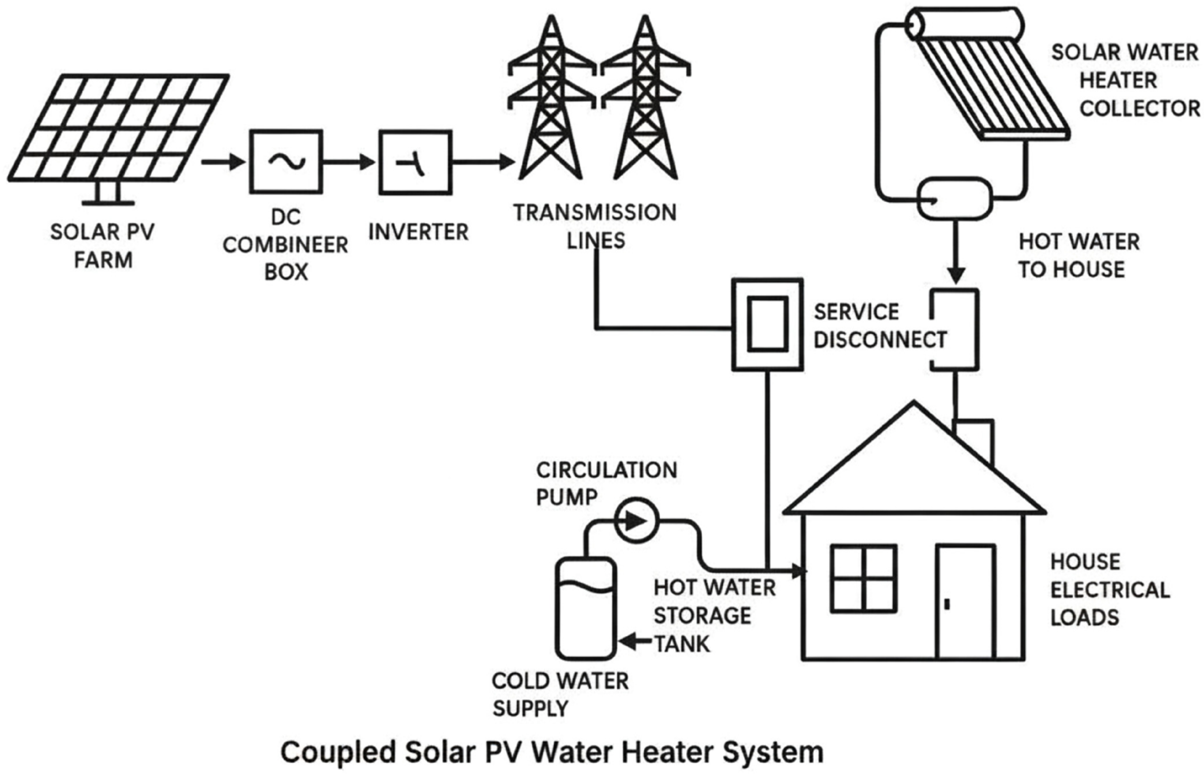


Figure 6. 2D schematic of coupled solar PV water heating system

for this reduced demand of 48, 406, 000 kWh, as calculated using Eq. (2).

$$\begin{aligned} &\textit{Reduced Energy Demand} \\ &= \textit{Annual Energy Consumption for } 2,000 \textit{ Houses} \\ &- \textit{Annual Consumption by Solar Heater} \times 2,000 \qquad (2) \end{aligned}$$

2.2. RETScreen Software. In this study, the RETScreen software was employed to model, analyze, and design both solar water heating systems and solar PV systems. RETScreen is a comprehensive software platform designed to evaluate the technical performance, economic feasibility, and greenhouse gas (GHG) emissions of a wide range of clean energy projects. It has been extensively validated as a reliable tool for predicting the energy yields of solar PV and solar water heating systems. González-Peña et al.[15], evaluated RETScreen, SAM, PVGIS, and other PV software using 12 years of operational data from three PV plants in Castile and León, Spain, and reported that RETScreen's predictions for fixed-, single-axis-, and dual-axis systems showed good agreement with the measured data, with discrepancies remaining below 10%. Similarly, the solar water heater model was validated against both theoretical predictions and experimental data from ten solar water heater systems in Ontario, Canada. For medium to heavy loads approaching 380 L/day, RETScreen overestimated the collector performance by less than 15%, which remained within the acceptable range for feasibility studies[16]. In this study, RETScreen was applied to design and assess the performance, environmental benefits, and financial payback periods of solar water heating and PV systems under the climatic and economic conditions of Dhahran, Saudi Arabia. This approach ensures that the proposed solutions are technically viable and environmentally sustainable, and it offers practical insights into their long-term economic returns.

2.3. Solar Heater System.

2.3.1. Solar water heater theory. In this study, a flat-plate collector in Figure 7 was employed to satisfy the water heating requirements. In this type of system, potable water flows through a network of pipes embedded within a dark-colored absorber plate enclosed in insulated and glazed housing. The absorber plate captures both direct and diffuse solar radiation and converts it into thermal energy, which is transferred to the water circulating through the embedded tubes. The heated water is then stored in a dedicated storage tank for domestic use. Flat-plate collectors are designed to operate efficiently across a wide range of solar conditions; however, their thermal performance is influenced by ambient factors, such as air temperature, wind speed, and cloud cover. This type of solar water heater was selected for this study owing to its wide commercial availability, proven reliability, and compatibility with standard residential water heating systems.

2.3.2. Solar water heater components. A typical solar water heating system consists of several integral components that work together to ensure efficient thermal capture and utilization. The solar collector absorbs solar energy and transfers it to the water, thereby increasing the water temperature. The heated water is stored in a storage tank until it is required for domestic use. A pump circulates the water through the system, maintaining a consistent flow to maximize heat absorption. Controls and sensors are used to activate, deactivate, and monitor the system based on the water temperature and demand. Usually, a heat exchanger is included to transfer heat to the domestic water via a secondary fluid, thereby preventing freezing in colder climates.

Table 1. *Electricity consumption baseline data*

Appliances	Summer Usage (h)	Winter Usage (hours)	Quantity	Rating (W)	Summer Consumption/ day (kWh)	Winter Consumption/ day (kWh)	Annual Energy Consumption (kWh)
Refrigerator	6	6	1	425	2.55	2.55	930.8
Dishwasher	2	2	1	NA	-	-	265.0
Air conditioner	12	2	5	NA	0.00	0.00	11705.0
Electric water pump	2	2	1	1100	2.20	2.20	803.0
Electric heater	0	4	2	2000	0.00	16.00	2920.0
TV	4	3	1	210	0.84	0.63	268.3
Laptop	6	6	2	200	2.40	2.40	876.0
Clothes washer	0.571	0.571	1	NA	0.00	0.00	442.0
Dryer	0.2857	0.2857	1	NA	0.00	0.00	560.0
LED lights	6	8	133	6	4.79	6.38	2038.9
Microwave	1	1	1	900	0.90	0.90	328.5
Electric kettle	1	1	1	2200	2.20	2.20	803.0
Mist fan	12	0	1	100	1.20	0.00	219.0
Oven	2	2	1	2800	5.60	5.60	2044.0
Water heater	1	18	5	1200	6.0	108	20805
						Total	**45,008**

However, the system used in this study did not use antifreeze fluids or heat exchangers, making it well-suited for regions such as Dhahran, where freezing temperatures are rare. Pipes and fittings facilitate water flow and complete the closed-loop system, thereby enabling continuous operation[18].

2.4. Solar Water Heater Methodology.

2.4.1. Location. The city selected for this project was Dhahran, which is located in the Eastern Province of Saudi Arabia, at 26.3° N a latitude and 50.2° E longitude. Monthly weather data for Dhahran are shown in Figure 8.

The facility type selected in RETScreen software is "individual measure," and the type is "solar water heater." All subsequent inputs provided by the software are presented in detail below.

2.4.2. Energy model. The next step involved entering the data for the conventional electric water heater, which served as the baseline system. As this system operates solely on electricity, no fuel cost is involved, and only electricity expenses are considered. In Saudi Arabia, the electricity tariff is 0.18 SAR/kWh, which is 0.048 \$/kWh after converting to US dollars using a conversion rate of 3.75. Therefore, the base technology for water heating was an electric heater using electricity as the fuel type, with a tariff of 0.048 \$/kWh, and a seasonal efficiency of 100%.

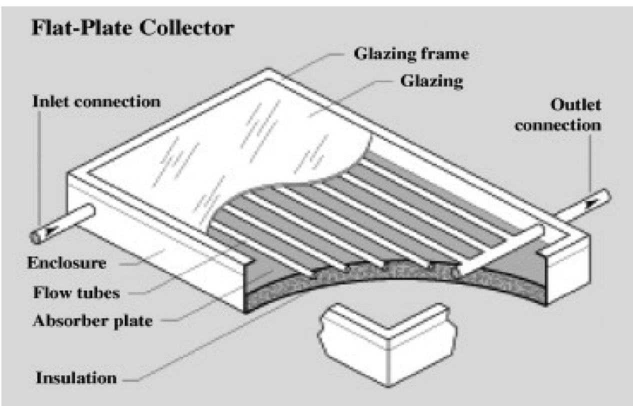


Figure 7. Flat-plate collector[17]

Next, the hot water demand was defined to represent a typical household with five occupants, an occupancy rate of 90%, and a water temperature of 70 °C. These inputs were used to estimate the thermal load that the solar water heater would need to meet.

For the solar water heater configuration, a fixed solar tracking system was selected, with a collector slope of 22° (angle between the tracking axis and the horizontal axis) and an azimuth of 0° (horizontal angle at which the collector is facing, measured clockwise from true north). Glazed flat-plate solar collectors manufactured by ThuSolar and SunEarth were selected and the specifications are shown in Figures 9–11. Miscellaneous losses of 2% were assumed, and the storage capacity was designed to meet a daily demand of 270 L. No heat exchanger or pump power was included because these components are not required under Dhahran's climatic conditions. The thermal efficiency of the solar water heating system was calculated using Eq. (3).

$$\eta_c = F_R \times K_{\tau\alpha} \times \tau \times \alpha - F_R \times U \times \frac{T_{w,in} - T_{air}}{G} \tag{3}$$

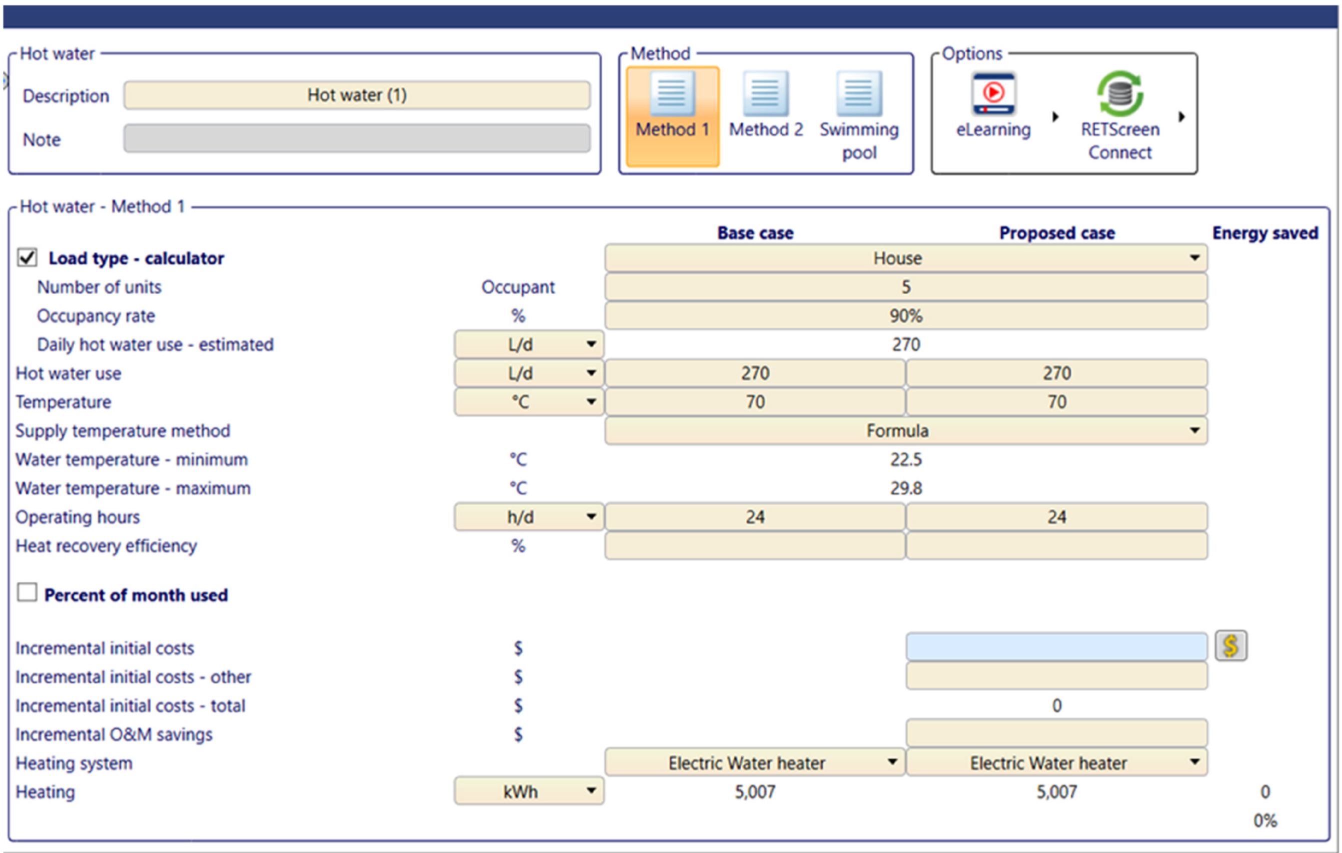
where η_c is the collector efficiency, F_R is the heat removal factor, $K_{\tau\alpha}$ is the incident angle modifier, τ is the transmittance of the cover, α is the absorptance of the absorber plate, U is the overall heat transfer coefficient, $T_{w,in}$ is the inlet temperature of the water, T_{air} is the ambient air temperature, and G is the solar irradiance.

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	15.3	67.5%	12.09	3.57	101.8	4.2	17.8	84	164
February	16.8	64.3%	8.12	4.42	101.5	4.6	18.2	34	190
March	20.3	58.0%	12.09	5.13	101.3	4.7	20.8	0	319
April	25.8	47.4%	2.70	6.03	100.9	4.6	25.3	0	474
May	31.6	36.7%	0.62	7.03	100.5	4.9	30.1	0	670
June	34.7	31.6%	0.00	7.73	99.9	5.4	32.8	0	741
July	35.9	35.6%	0.00	7.26	99.6	4.7	34.9	0	803
August	35.3	44.2%	0.62	6.97	99.8	4.2	35.6	0	784
September	32.4	50.6%	0.00	6.45	100.4	3.9	33.7	0	672
October	28.5	58.2%	0.31	5.33	101.0	3.7	30.2	0	574
November	22.7	62.5%	9.30	4.00	101.5	4.1	25.2	0	381
December	17.5	68.2%	11.78	3.28	101.7	4.2	20.3	16	233
Annual	**26.5**	**52.0%**	**57.63**	**5.60**	**100.8**	**4.4**	**27.1**	**133**	**6,005**
Source	Ground	Ground	NASA	NASA	NASA	Ground	NASA	Ground	Ground
Measured at					m	10	0		

Figure 8. Dhahran monthly weather report

2.5. Solar Photovoltaic. The analysis of the solar PV system followed a workflow similar to that of the solar water heating system; however, the facility type was defined as a power plant with a photovoltaic configuration. The photovoltaic specifications were selected to maximize efficiency, and PV modules from three different manufacturers–LONGi Solar, REC Solar, and Jinko Solar–were used for comparison, as presented in Section 3.2.

2.5.1. Solar photovoltaic theory. This study employed monocrystalline silicon PV modules, which were chosen for their high efficiency and suitability in applications where space is limited. The cells absorb photons from sunlight with energy equal to or greater than the silicon bandgap, whereas photons with lower energies are either transmitted or reflected. The monocrystalline structure was formed from a single, highly purified silicon crystal doped to produce an n-type layer (phosphorus-doped)


Hot water
Description: Hot water (1)
Note:
Method: Method 1 | Method 2 | Swimming pool
Options: eLearning | RETScreen Connect

Hot water - Method 1

	Unit	Base case	Proposed case	Energy saved
Load type - calculator		House		
Number of units	Occupant	5		
Occupancy rate	%	90%		
Daily hot water use - estimated	L/d	270		
Hot water use	L/d	270	270	
Temperature	°C	70	70	
Supply temperature method		Formula		
Water temperature - minimum	°C	22.5		
Water temperature - maximum	°C	29.8		
Operating hours	h/d	24	24	
Heat recovery efficiency	%			
Percent of month used				
Incremental initial costs	$			
Incremental initial costs - other	$			
Incremental initial costs - total	$		0	
Incremental O&M savings	$			
Heating system		Electric Water heater	Electric Water heater	
Heating	kWh	5,007	5,007	0 0%

Figure 9. Hot water data

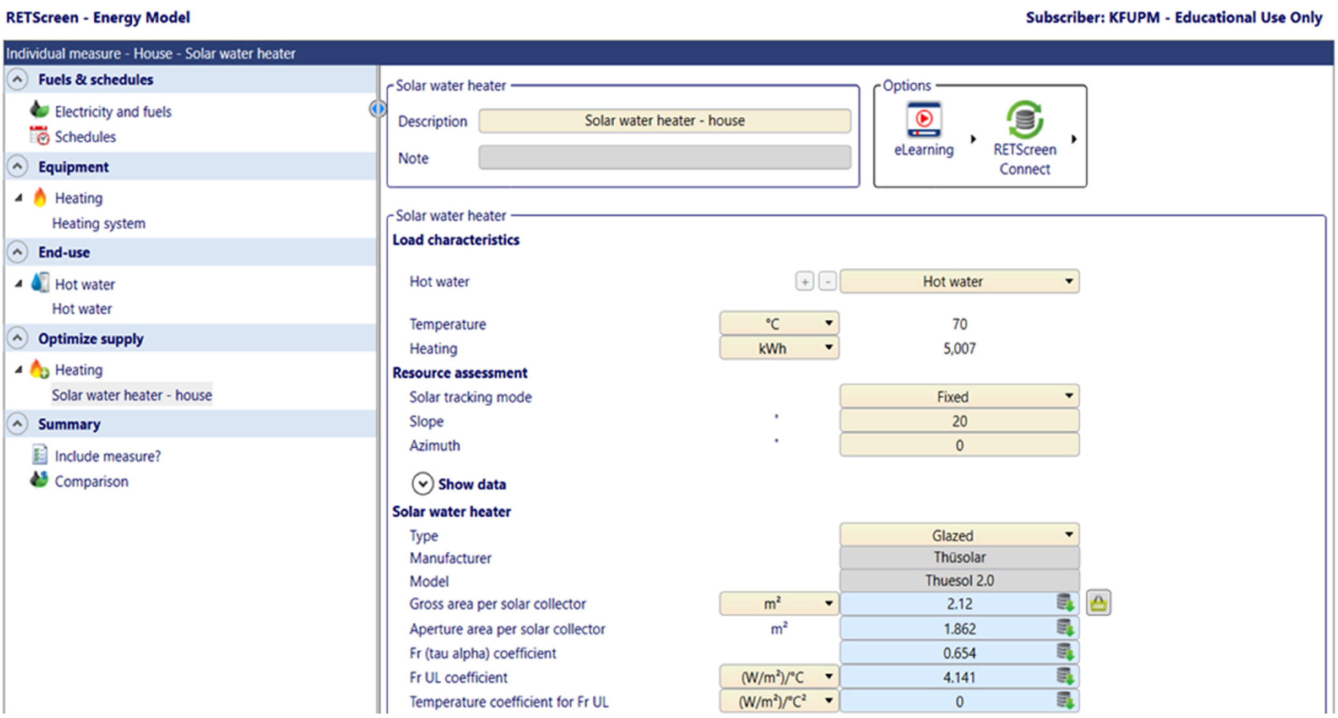


Figure 10. ThuSolar water heater data part 1

and a p-type layer (boron-doped), thereby creating a p–n junction. When photons strike the cell, the electrons in the n-type layer are excited and migrate toward the p-type layer, establishing an electric field across the junction. This process generates DC power, which is then converted into AC power through an inverter for household use or grid integration. With typical efficiencies ranging from 20% to 22%, monocrystalline PV modules deliver excellent performance; however, they also have higher manufacturing costs [19].

2.5.2. Solar photovoltaic components. A standard solar PV system consists of several key components that work together to enable efficient solar power generation and utilization. At the core of the system are solar PV cells, which capture solar energy

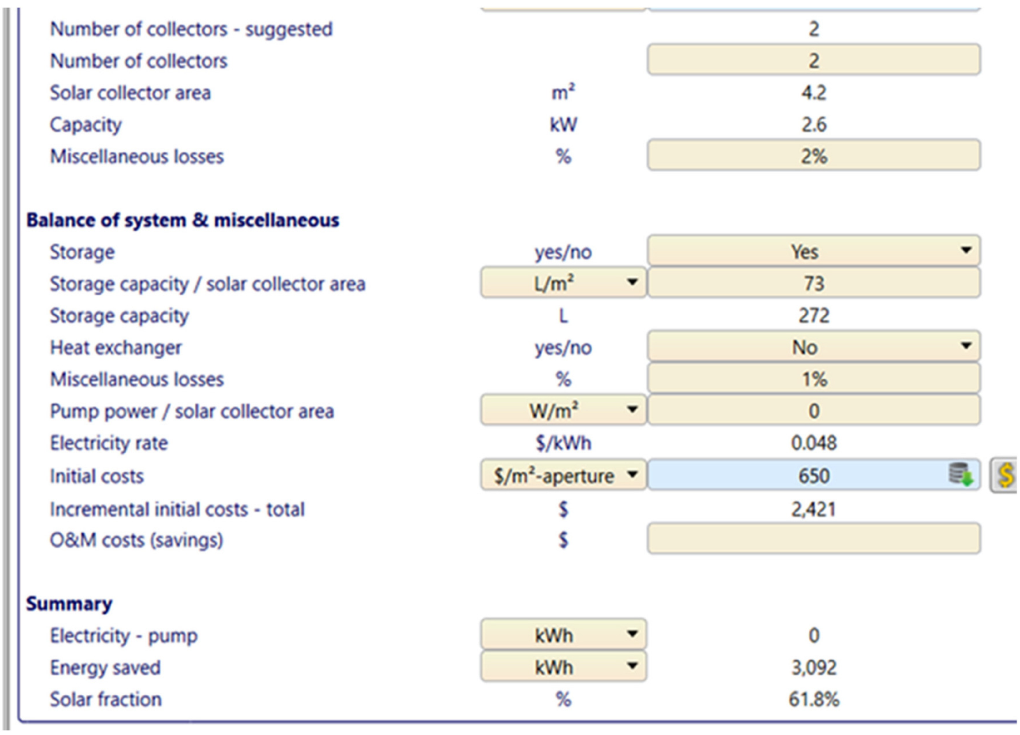


Figure 11. ThuSolar water heater data part 2

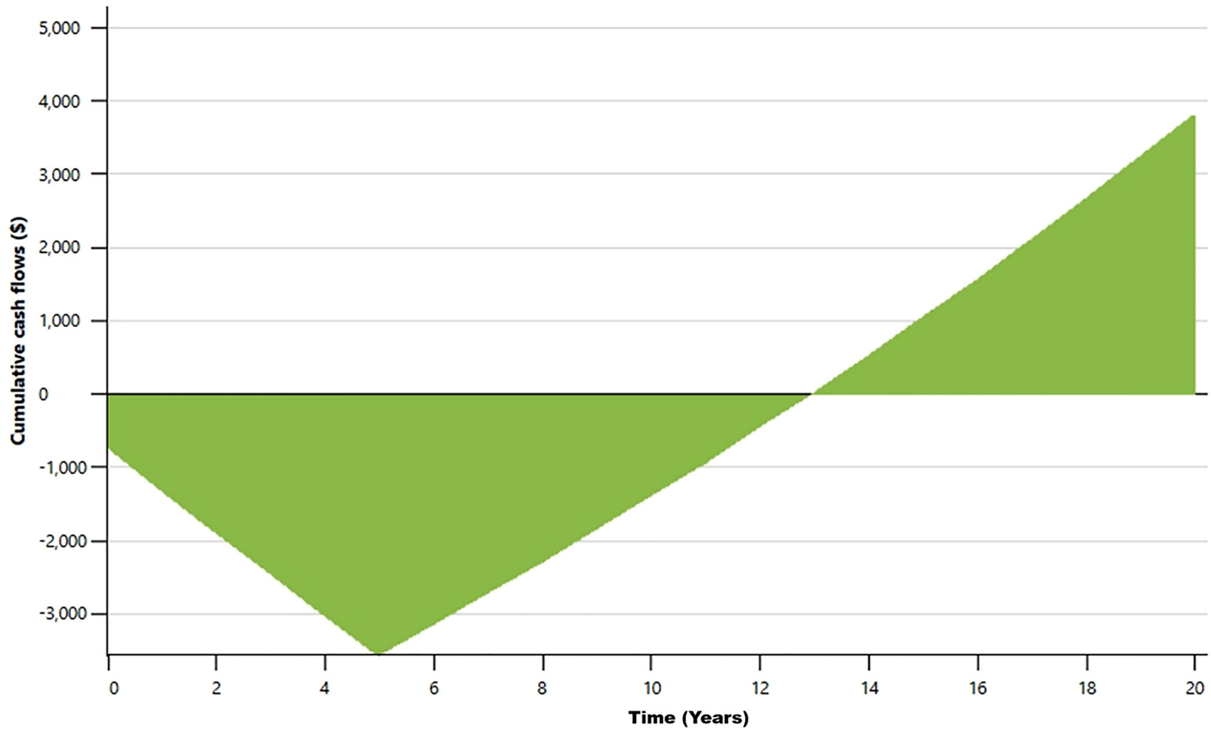


Figure 12. ThuSolar cumulative cash flows graph

and convert it to DC electricity. The cells are secured within a mounting structure to ensure stability and optimal orientation. The generated DC is then converted into AC power by an inverter, making it suitable for residential and commercial use.

A small battery is also typically included to store excess energy for use during periods of low solar power generation. Miscellaneous components, such as cables and connectors, ensure electrical connectivity among all the parts of the system. DC and AC disconnects are incorporated to allow for the safe isolation of the inverter during maintenance. A solar charge controller regulates the current and voltage to prevent battery overcharging, whereas a combiner box aggregates the electrical output from multiple solar panels connected in parallel, simplifying the wiring and improving the overall system efficiency[20].

2.5.3. Solar photovoltaic methodology. A key factor in the solar PV system analysis is the efficiency equation, which relates the power output to the maximum available solar radiation, as expressed in Eq. (4).

$$\eta_{cell} = \frac{P}{AG} \tag{4}$$

where P is the power capacity of the cell, A is the area of the solar collector, and G is the incident solar irradiation.

The methodology for the solar PV system followed steps similar to those outlined in Section 2.4, including the selection of the location, electricity prices, and number of PV panels to meet the required electrical load.

3. RESULTS & DISCUSSION

3.1. Solar Water Heater. Figure 9 presents the hot water demand calculations for a single household of five occupants with an occupancy rate of 90%, which translates to a daily requirement of 270 L of hot water. The water temperature was set to 70 °C, and the water heater was assumed to operate for 24 h per day during winter. With these inputs, the total power required for heating was calculated to be 5,007 kWh.

The device specifications were selected as shown in Figures 10 and 11. The solar tracking type was set to *fixed* because it is the most cost-effective option. The tilt angle (slope) of the collector was determined based on the latitude of the selected location. For Dhahran, which has a latitude of 26.3°, the acceptable range for optimal efficiency is between 20° and 27°. An initial slope of 22° was used and subsequently optimized based on the resulting solar fraction and heating output. The azimuth was set to 0°to ensure an optimal orientation.

The type of solar water heater was *glazed* because it offers higher efficiency than unglazed types and is less expensive than evacuated-tube solar heaters. The selected model was the ThuSolar 2.0, with the specifications shown in Figures 10 and 11. The air temperature and solar irradiation were assumed to have average values of 25.8 °C and 6.03 kWh/m^2 /day, respectively, as obtained from Figure 8. These values resulted in a thermal efficiency of 35% for the ThuSolar 2.0 solar water heater using Eq. (3). Based on the system parameters, two collectors were suggested, which provided a total collector area of 4.2 m^2. For efficient operation, the miscellaneous losses were assumed to be 2% and the storage capacity was assumed to be 73 L/m^2, resulting in a total of 272 L/day, which closely matched the calculated requirement of 270 L/day.

No heat exchangers were included because Dhahran's climate does not present freezing risks. Similarly, no pump power was required. The initial cost was set at \$650/m^2 (aperture area) for a solar water heater with storage, resulting in a total incremental initial cost of $2,421. Under these conditions, the system achieved an output of 3,088 kWh with a solar fraction of 61.7%. The final step involved selecting the optimal slope to maximize the solar fraction and energy savings. After several trials, the optimal slope was determined to be 25°.

The system saved 3,092 kWh out of the 5,007 kWh required, with an initial cost of $2,421. Based on the energy savings of 3,092 kWh for a single home, the total power savings for 2000 homes was 6, 184, 000 kWh. The financial parameters considered for both this module and the SunEarth module included a fuel escalation rate of 3% and an inflation rate of 2.5%. A discount rate of 12% and reinforcement rate of 9% were applied to the analysis. The project life was assumed to be 20 years, with a debt ratio of 85% and a debt term of 5 years. This results in a simple payback period of 13.6 years shown in Figure 12, and an equity payback period of 12.9 years.

The use of the ThuSolar water heating system resulted in a reduction in carbon emissions of 1719.15 kg CO_2 per household, based on a grid emission factor of 0.556 kg CO_2/kWh in Saudi Arabia, and energy savings of 3,092 kWh, as calculated using Eq. (5):

$$Reduction\ in\ CO_2 = Emissions\ factor \times Heating\ Load\ Reduction \quad (5)$$

For 2,000 houses, the total reduction in CO_2 emissions was calculated as 3, 438, 304 kg CO_2.

An additional performance assessment was conducted using a SunEarth solar water heater module featuring different design properties, which achieved a solar fraction of 61.8%. Using the appropriate parameters for the SunEarth module in Eq. (3), the thermal efficiency was calculated as 41%.

To satisfy the hot water demand, the storage capacity per solar collector area was adjusted to 85 L/m^2 as in Figure 13.

The SunEarth module was marginally superior to the ThuSolar module based on its higher thermal efficiency, heating value of 3,096 kWh, initial cost of $2,089, and simple payback period of 12.7 years as shown in Figure 14. The equity payback period was 12.2 years. Following a similar methodology, the CO_2 emissions

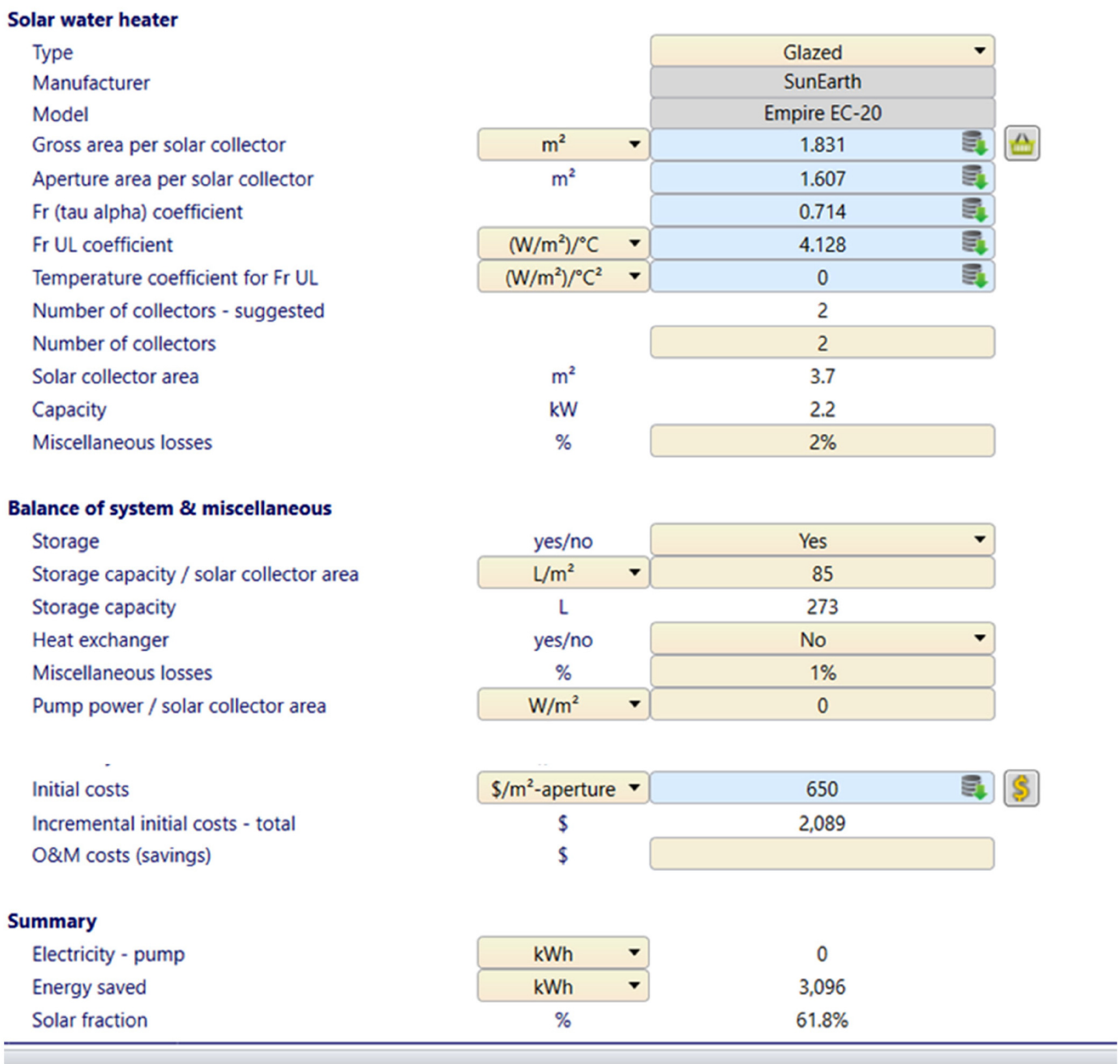


Figure 13. Data for the solar water heater by SunEarth

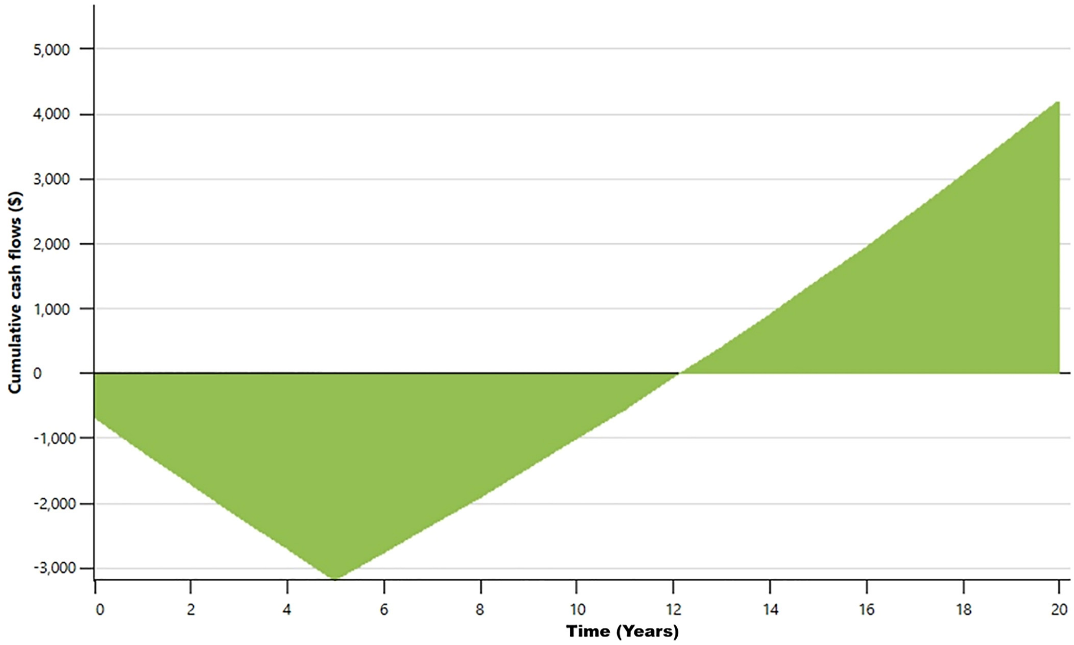


Figure 14. SunEarth cumulative cash flow graph

reduced by this module were calculated as 1,721.376 *kg* CO_2 per household. For a residential community of 2,000 houses, the use of the SunEarth water heating system resulted in an estimated total heating energy savings of 6,192,000 kWh. Therefore, the total reduction in CO_2 emissions was estimated as 3,442,752 kg CO_2, based on the emission factor and energy savings determined for a single household.

Based on the above comparative analysis, the SunEarth module is more suitable for this community because it offers higher power generation, lower costs, and a shorter payback period.

3.2. Solar Photovoltaic Power Plant.

This section presents a comparative performance analysis of the three different solar panels. Figure 15 shows the details of the first solar panel used in this study. A fixed tracking mode was initially selected for the panels, with a slope of 22°and an azimuth of 0°, which provided maximum power generation. The first module was manufactured by LONGi Solar (mono-Si-LR5-72HBD-550M), with a rated power output of 550 W and an efficiency of 21.5%.

The number of units required to generate 484,060,000 kWh was 56,250, which had a total capacity of 30,937.5 kW and a capacity factor of 17.9%. The total area occupied by the panels was 143,895 m^2. The nominal operating cell temperature was 45 °C, which is an appropriate value for a city with hot summer weather such as Dhahran.

The initial cost of a solar PV power plant with a capacity between 10,000 kWh and 100,000 kWh was $1,100. With these parameters, the total power exported to the grid was calculated as 48,643,447 kWh, which generates revenue of $ 2,334,885 as Figure 16 shows. This power plant produces an additional

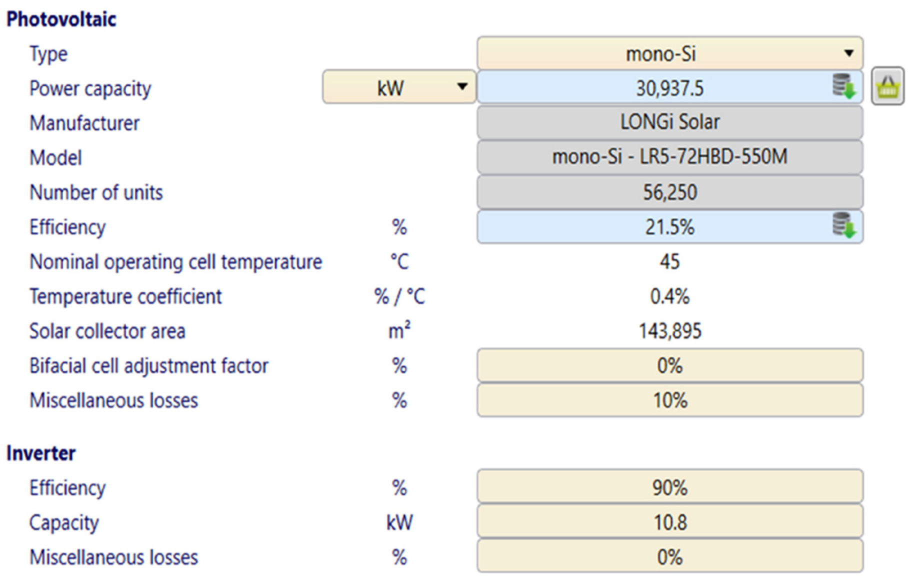


Figure 15. LONGi solar panels specification's part 1

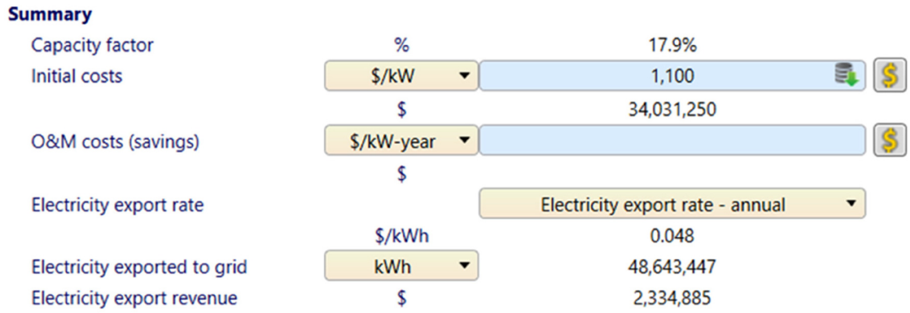


Figure 16. LONGi solar panels specification's part 2

237,447 kWh to compensate for the decrease in power output under poor weather conditions and efficiency degradation over time. The financial parameters for all panels used here included a fuel escalation rate of 2%, an inflation rate of 2%, and a reinvestment ratio of 9%. The project life was assumed to be 25 years, resulting in a net annual cash flow of $2,334,885. Based on the selected financial parameters, the simple payback period for this system was 14.6 years, Figure 17, whereas the equity payback period was 12.7 years. The reduction in CO_2 emissions was calculated using the same methodology as used previously for solar water heaters and based on energy savings of 48,643,447 kWh, which produced a value of $27,045,756.53$ kg CO_2. If one-axis tracking is used for the same number of panels, then the generated electricity would increase to 63,122,098 kWh.

Two additional panels were analyzed in comparison with the panel from LONGi. The second panel was manufactured by REC Solar (mono-Si-REC350NP2 Black 350W), which has a rated power output of 350 W and an efficiency of 19.1%, which were lower than those of the LONGi solar panels. The number of units required to generate the required electrical demand of 484,060,000 kWh was 88,500, with a total capacity of 30,937.5 kW and a capacity factor of 17.9%. The total area occupied by the solar panels was estimated at 162,173 m^2 Figure 18. The total electricity exported to the grid was 48,702,409 kWh, generating a revenue of $2,337,718. This system also produced an additional 296,409 kWh of power.

Based on the same financial parameters applied for the LONGi solar panels, the payback period for the REC PV panel was calculated as 14.6 years as in Figure 19, with an equity payback period of 12.7 years. This was expected because both the cost and revenue were lower than those of LONGi Solar. The net annual cash flow was $2,337,716, and the total reduction in CO_2 emissions for these panels for 48,702,409 kWh of electrical energy was calculated to be $27,078,539.4$ kg CO_2. If one-axis tracking is used for the same number of panels, the generated electricity would increase to 63,198,609 kWh.

The last module analyzed in this study was manufactured by Jinko Solar (mono-Si-JKM615N-78HL4-V 615W), which has a rated power output of 615 W and an efficiency of 22%, making it the most efficient panel among the three considered here. Owing to the larger power output per unit, only 50,500 units were needed to generate the required electrical demand of 484,060,000 kWh with a total capacity of 31,057.5 kW and a capacity factor of 17.9%. These panels also occupied the smallest total area of 141,170 m^2 Figure 20. They

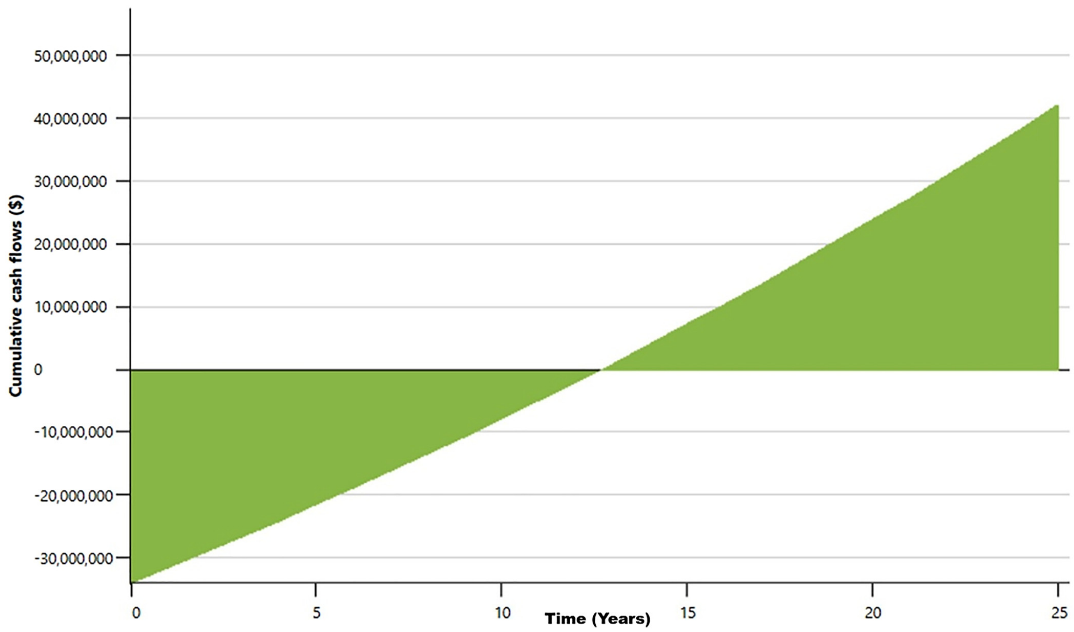


Figure 17. LONGi solar financial analysis

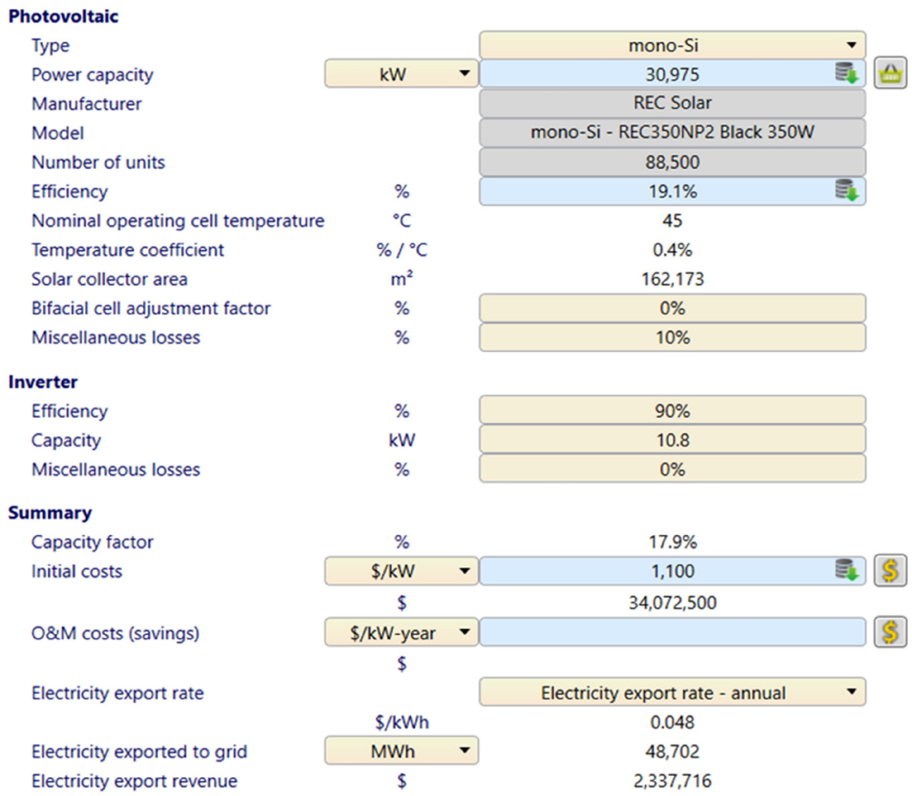


Figure 18. REC solar panels specifications

generated 48,832,125 kWh of electrical energy, with a total cost of $34,163,250 and exported electricity revenue of $2,343,942. The panels also produced an additional electrical energy of 426,125 kWh.

Using the same financial parameters as in the previous panels, the simple payback period for the Jinko solar system was calculated as 14.6 years as in Figure 21, with an equity payback period of 12.7 years and simple payback of 14.6 years, which are consistent with the previous models. The net yearly cash flow was calculated as $2,367,149. The reduced CO_2 emissions for these panels based on their electricity generation of 48,832,125 kWh equaled 27,150,661.5 *kg* CO_2. If one-axis tracking is used for the same number of panels, the generated electricity would increase to 63,366,935 kWh.

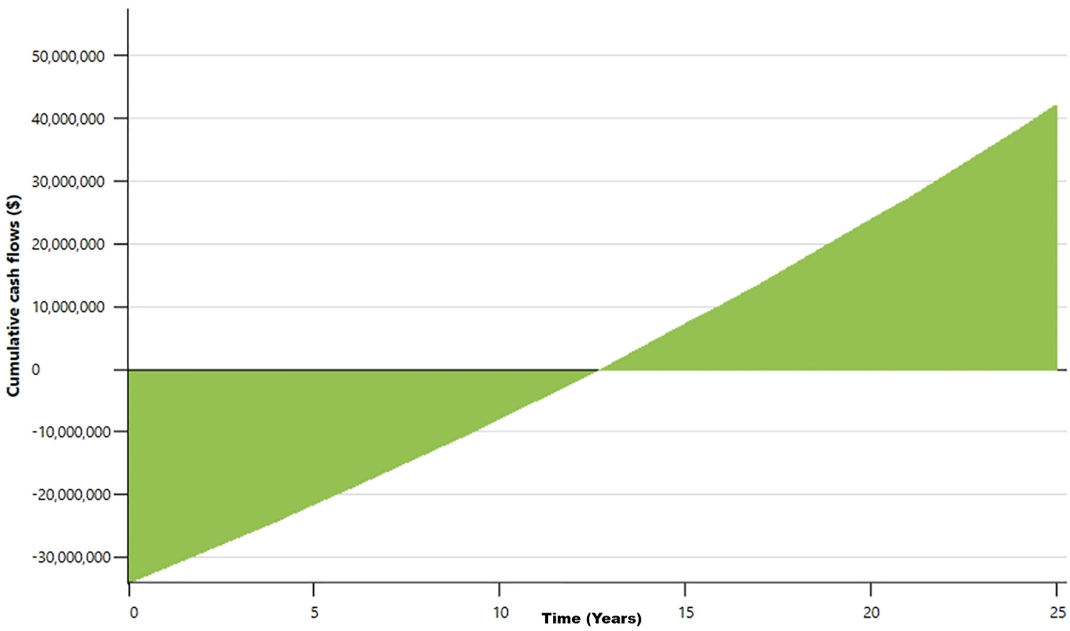


Figure 19. REC solar cumulative cash flows graph

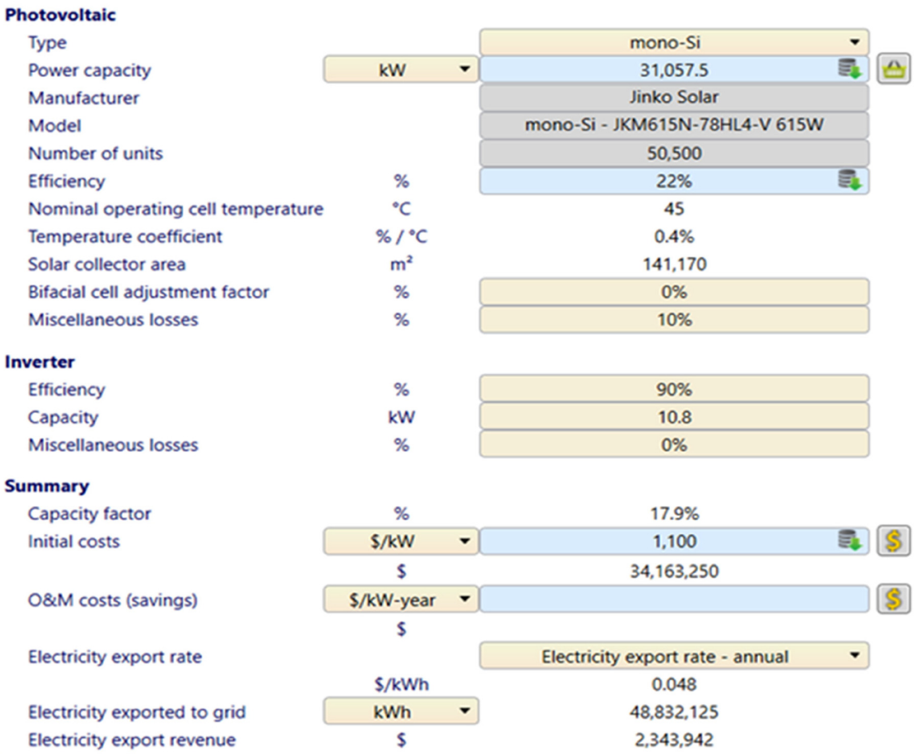


Figure 20. Jinko solar panels specifications

Finally, the performance of all three PV panels was evaluated under both fixed-axis and one-axis tracking configurations, and the results are summarized in Table 2. Although one-axis tracking increases the initial investment, it also enhances energy generation across all modules. The additional output more than offset the higher capital cost, thereby reducing the simple payback period from 14.6 years (fixed-axis) to 12.3 years. Moreover, the higher electrical output from the same number of units resulted in approximately a 30% greater reduction in GHG emissions and 30% increase in electricity export for all panels, with Jinko Solar demonstrating the best performance in both categories.

Based on the above results, Jinko solar panels emerged as the most suitable option for decarbonizing a 2000-home residential community because they offer the highest efficiency and greatest power generation and require the lowest number of panels (51,000 units). Its smaller land footprint and reduced panel requirements also minimize end-of-life waste

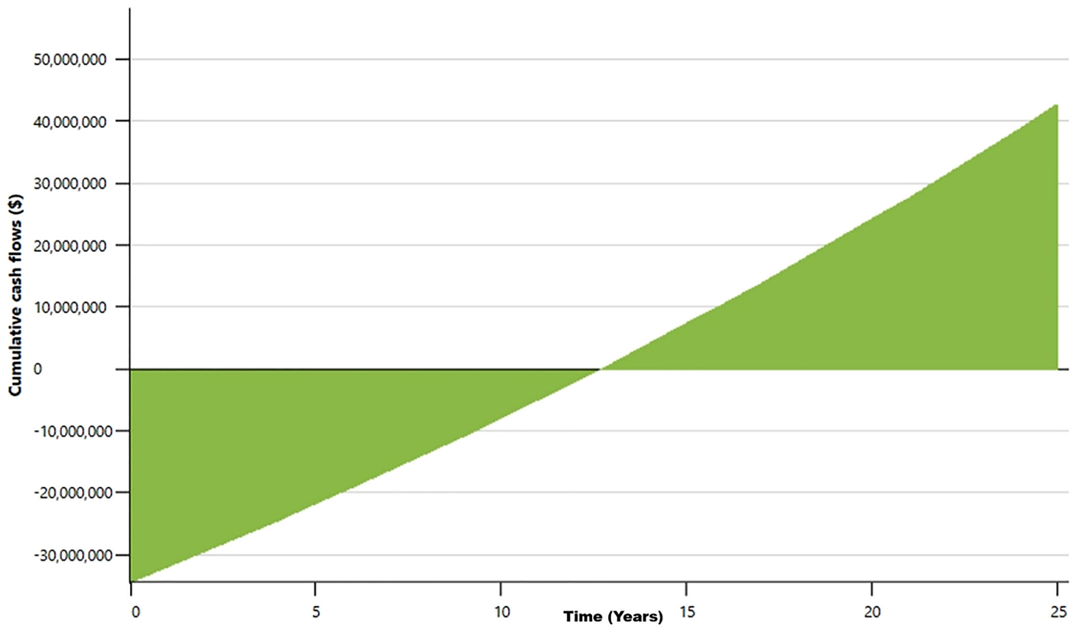


Figure 21. Jinko solar financial analysis

Table 2. *Module tracking mode comparison*

Module	Payback period (years)	Electricity exported (kWh)	Land area needed (m^2)	GHG reduction (kg CO_2)
LONGi Solar (Fixed)	14.6	48,643,447	143,895	27,045,756.5
LONGi Solar (One-axis)	12.3	63,122,098	143,895	35,095,886.5
REC Solar (Fixed)	14.6	48,702,409	162,173	27,078,539.4
REC Solar (One-axis)	12.3	63,198,609	162,173	35,138.427.2
Jinko Solar (Fixed)	14.6	48,832,125	142,568	27, 150, 661.5
Jinko Solar (One-axis)	12.3	63,366,935	142,568	35,215,336

streams, which align strongly with long-term sustainability goals.

Although the detailed comparative analysis conducted using RETSCREEN provides valuable insights, it is important to acknowledge several limitations inherent to the modelling approach. RETSCREEN relies on monthly average climate data and, while it predicts annual energy generation reliably, it may not fully capture hourly solar variability or temperature-dependent performance effects specific to Dhahran. Additionally, community-scale results were derived by scaling a single household model to 2,000 homes, which inherently overlooks variations in household behavior, load diversity, and installation conditions. Financial metrics such as payback period and CO_2 reduction are also based on simplified economic assumptions that do not reflect potential market fluctuations or future policy changes. These limitations suggest that while the present findings are robust at a screening level, more detailed simulations and field-based validation would enhance confidence in the long-term performance projections.

4. CONCLUSIONS

This study presents a comprehensive techno-economic evaluation of solar thermal water heating and solar photovoltaic (PV) systems designed to meet the hot water and electrical energy needs of a 2,000-home residential community in Dhahran, Saudi Arabia. Detailed simulations using RETScreen showed that the SunEarth solar water heater achieved an annual thermal yield of 6.19 million kWh with a land footprint of only 7,400 m^2, corresponding to 836.5 kWh/m^2/year. In contrast, the Jinko Solar single-axis tracking PV system delivered 63.37 million kWh of electrical energy annually over a land footprint of 142,568 m^2, corresponding to 444.5 kWh/m^2 /year. While 100% conversion of PV electricity to heat would produce a comparable thermal energy supply, the solar thermal water heaters demonstrated approximately 88% higher land-use efficiency for water heating applications, which is consistent with their higher conversion efficiencies compared to solar panels. This highlights the complementary roles of these technologies in meeting heating and electrical energy needs and emphasizes the value of dedicated solar water heaters in communities with limited land availability. An optimized hybrid strategy in which land is allocated to each system according to the specific heating or electrical demands could maximize total renewable energy yields and CO_2 mitigation per unit area.

From a carbon abatement perspective, SunEarth's system reduced CO_2 emissions by 3.44 million kg annually, whereas Jinko Solar's PV modules reduced CO_2 emissions by 35.22 million kg annually due to their larger absolute energy output. The payback periods for the SunEarth and Jinko systems were 14.6 years and 12.3 years, respectively, indicating that PV systems retain a marginally faster return on investment. The use of high-performance solar PV panels reduced the total panel count, thereby lowering the end-of-life waste streams. Specifically, Jinko Solar achieved an electrical energy yield of approximately 63 million kWh with 5,250 fewer panels than LONGi Solar and 37,500 fewer panels than REC Solar, reducing both waste and recycling costs at the end of their lifetimes. This aligns well with the United Nations' SDG 12 as well as the broader national goals of minimizing resource consumption and waste generation.

Future work can expand the present analysis across multiple climatic zones in the Kingdom to evaluate performance variations under different solar resource profiles, ambient temperatures, and seasonal demand patterns. Additionally, integrating thermal storage and implementing hybrid PV–thermal technologies could further enhance the practical applicability of these systems. Finally, detailed life cycle assessments, including embodied carbon and end-of-life recycling, should be conducted to strengthen sustainability metrics.

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