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Leveraging Solar Water Heaters in Jordan: A Simulation-Based Analysis of Efficiency, Diesel Savings, and CO_2 Reduction

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ABSTRACT

*With Jordan increasingly relying on solar water heaters (SWHs), optimizing their performance is crucial. This study investigates the performance of solar water heaters (SWHs) in Jordan using T*SOL software to identify the optimal boiler operation schedule for maximizing system efficiency, fuel savings, and CO_2 emission reduction. The research analyzes various scenarios, including boiler operation frequency throughout specific months. The findings reveal that operating the boiler for 2 days per week during December, January, and February (Variant 4) achieves the best results: 36.91% system efficiency, 446.3 liters of diesel saved, and 1,239.2 kg of CO_2 emissions avoided. Conversely, operating the boiler daily from October to April (Variant 1) leads to the lowest efficiency (36.53%) and fuel savings (398.8 liters of diesel, 1,107.4 kg of CO_2 emissions avoided).*

1. INTRODUCTION

Solar energy is one of the most significant renewable fuels [1]. Despite many breakthroughs in this field, widespread adoption of solar water heater devices has been delayed by some factors such as the related high costs [2]. Solar water heaters (SWHs) are the best choice for the residential sector due to their ease of operation and low upkeep needs [2]. These variables and their environmental friendliness have drawn attention to SWHs in both household and commercial stages [3]. The expense of fossil fuels used for water heating and government funding both affect how cost-effective SWH systems are [4]. SWHs are generally easy to operate because they only use sun radiation to heat household water [5]. Builders of domestic structures frequently included solar thermal installations for environmental reasons such as climate change, energy savings, and carbon dioxide (CO_2) reduction. However, in order to expand the market potential for solar thermal installations, more compelling business reasons are needed [6].

However, passive solar heating with energy-efficient construction can cut space heating needs by 30%, while active solar systems can reduce hot water and space heating fuel use by 40-70% and 50-60% respectively. Solar thermal energy has the potential to meet 30-40% of global and 20% of European heat demand [7]. The combination of traditional fossil fuel systems and alternative energy sources will drastically cut energy use and greenhouse gas emissions. Solar energy is one of the most promising options among those suggested to address the global energy crisis from an environmental standpoint [8]. As a result of the world's expanding energy needs, the finite supply of fossil fuels, and the negative environmental and economic effects of the traditional energy system, there has been extensive research and development on renewable energies.

Eslami *et al.* [8] studied the viability of employing a solar hybrid system to provide Tehran, Iran parks with electricity, hot water, and drinking water.

Košičan *et al.* [9] discovered that replacing a standard gas boiler with a solar thermal system results in monthly savings between EUR 140 and EUR 250, with payback periods varying from 2.5-7 years. The life cycle assessment revealed that environmental impacts are manageable, and solar thermal solutions provide all energy requirements.

Jahangiri *et al.* [10] desired to reduce energy consumption in Zambia and promote the use of solar energy as a renewable energy source for residential space heating and drinking water. Providing low-income households with the best SWHs for their homes can save expenses and increase their well-being, particularly in remote places. A study using T*SOL software recommended a solar thermal system for small-medium-sized pasteurizing plants in Budapest and Damascus. The system efficiencies were 14.9% and 17.2%, respectively. The research emphasized the importance of integrating solar thermal technologies in regions like the Middle East and Central Europe, as solar energy is a sustainable solution.

While Ghabour *et al.* [11] demonstrated the cost-saving potential of solar thermal systems for fuel and electricity consumption in small and medium-sized enterprises, they were unable to establish a direct relationship between the two. The authors used the

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modern engineering simulation tool, T*SOL® to optimize the integration of these systems. Furthermore, Gatzka *et al.* [12] suggested that solar thermal systems are a financially feasible option for French households. The study analyzing solar thermal systems in France using T*SOL software found them economically viable, with profitability influenced by factors like irradiation levels and energy price increases. While ecological benefits are important, the study highlights economic factors like solar heat price and pre-tax return on investment for better customer understanding.

Košičan *et al.* [13] discovered that other factors affecting energy consumption include energy production and geographical latitude.

According to the statistics, a gas boiler and combination tank) is the optimal choice for minimizing energy needs, CO_2 emissions, installation energy efficiency, and transmission losses. This should be the optimal priority plan scenario when economic criteria are not much important.

Other financial benefit the nation derives from the use of SWHs is that the gas transportation expenses in the broad and complex municipal gas network can be reduced by reducing household and commercial gas consumption.

As the demand for SWHs increases, as a result of the development of new factories and an increase in the output on the country's market, the cost price of this product will decrease, and hence, the economic efficiency will increase. SWHs will save 7.6 billion cubic meters of natural gas annually in the residential and commercial sectors [14]. Jahangiri *et al.* [15] were the first to undertake dynamic simulations of the solar thermal system for all Canadian provinces over a period of one year. In addition to teaching people about the benefits of SWHs and encouraging to use them, this study demonstrated that private investment is safer.

Ghorab *et al.* [16] analyzed the actual performance of solar domestic hot water systems in relation to a residence in Alberta, Canada, for a home with two adults and two children with a domestic hot water (DHW) load of 246 L/day per year. This closed-loop system consisted of two 7.716 m^2 solar collectors installed on the roof of each home, a 272 L solar tank, and a 172 L auxiliary gas tank. According to the findings, solar radiation and ambient temperature had a significant effect on the temperature of the domestic hot water within the solar tank. It was determined that approximately 91.5% of the solar energy captured by solar tanks was utilized to heat household hot water.

In addition to using the T*SOL® simulation tool for solar thermal heating systems based on site radiation data, the study by Seretse *et al.* compared two methods for analyzing solar thermal heating systems: T*SOL® simulation (based on real-world radiation data) and theoretical/mathematical modeling. The mathematically designed system achieved a 70% higher average efficiency than the 20% efficiency reported using T*SOL®. The effectiveness of the collector was shown to be greater at the start of the test and to diminish over time [17]. Imteaz *et al.* [18] investigated the real-world efficiency of four Australian dwellings in Melbourne and Adelaide. Using real solar energy output and actual incoming solar radiations over a period of time, the efficiency of solar panels installed in the selected households was estimated. A maximum efficiency of 7% was obtained among the four homes being studied.

A study by Siampour *et al.* compared the performance of flat-plate and evacuated tube SWHs in 45 locations across Turkey [19]. Using simulations and rankings T*SOL® and GAMS, respectively, they found that evacuated tube SWHs outperformed flat-plate models at every site. Over a year, evacuated tube SWHs produced roughly 70% more heat (229 MW vs. 133 MW) and prevented 36% more pollution (93.4 tons vs. 68.4 tons) than flat-plate systems. This suggests that evacuated tube SWHs are a more efficient and environmentally friendly option for solar water heating in Turkey [19].

Olimat *et al.* [20] investigated the performance of a thermal storage unit loaded with a commercial phase change material (PCM) using energy/exergy analysis. The study examined the influence of fluid parameters on the effectiveness of the system and found that the latent heat principle is a promising method for achieving high energy and exergy efficiency. The results showed a significant influence of thermal resistance on the performance of the storage unit. Additionally, fluid and PCM temperature differences influenced the rate of energy/exergy transfer and the time needed for melting/solidification [20]. In their study, Giri *et al*. analyze the design and implementation of a solar photovoltaic (PV) system for lighting, water pumping (for drinking and irrigation), at Centurion University (CUTM) in Odisha, India. This technology selection offers several advantages. First, solar energy is abundant and readily available in most locations, making it a sustainable and renewable resource. Second, solar PV systems are known for their ease of installation, operation, and maintenance [21]. In another study, Giri *et al.* [22] analyze a combined solar photovoltaic (PV) and water heating system integrated with turmeric farming (agrivoltaics). This system utilizes an artificial neural network and genetic algorithm to optimize energy and food production while minimizing land usage. Their model achieved high accuracy, predicting good yields for both electricity and turmeric. Economic indicators further suggest the system's profitability and rapid cost recovery, positioning it as a sustainable solution [22]. While research like Vennila *et al.* [23] explores using advanced algorithms to optimize solar integration with traditional power plants, achieving a perfect balance between cost, emissions, and renewable stability remains a challenge. This highlights the need for further analysis of hybrid systems, considering factors like energy storage and diverse renewable sources, to ensure a truly sustainable future [23]. Agyekum *et al.* [24] investigated the potential of solar water heating (SWH) systems to reduce South Africa's high carbon footprint from electricity generation. While no comprehensive national assessment existed, their study modeled flat plate and evacuated tube SWH systems across five diverse locations. The analysis suggests both systems offer payback periods of 3-4 years and levelized costs of energy under 10 cents/kWh. Annual cost savings and CO_2 emission reductions vary by location, with evacuated tubes achieving slightly greater benefits (75-77% CO_2 reduction) compared to flat plates (69-76%). This study adds to the growing body of research supporting SWH as a viable and impactful technology for South Africa's clean energy transition [24]. A study by Agyekum *et al.* assessed the technical, economic, and environmental performance of SWHs in six Chinese cities. They compared water and glycol as working fluids and found Lhasa to be the optimal location due to high solar radiation. An optimized azimuth angle of 190° was identified, and a 25% reduction in outlet water temperature could decrease the capacity factor. The SWH system reduced CO_2 emissions by 1252.87–2014.85 kg/year to 138.20–330.23 kg/year and offered net electricity bill savings of $156–296 depending on location. This analysis highlights the potential of SWHs for both economic and environmental benefit but also emphasizes the influence of location and system parameters [25]. A study done by Odoi-Yorke *et al.* [26] in Ghana found that installing solar water heaters in hotels is financially profitable and environmentally friendly. The heaters would pay for themselves in a reasonable time frame, reduce reliance on fossil fuels, and cut carbon emissions by up to 58.7 tons a year. This can help hotels save money on electricity and meet sustainability goals [26].

Altork *et al.* [27] explored optimizing hybrid thermal systems for domestic heating in Jordan. It investigated evacuated tube solar water heaters (ETSW) combined with conventional boilers or heat pumps across various climates. The researchers used T*SOL and Meteonorm software to simulate energy production and employed various methods to analyze station rankings, technical performance, and environmental impact. Their findings suggest that utilizing ETSW with optimized hybrid systems can significantly reduce energy use, carbon emissions (12.18 tons annually), and overall heating costs, with the largest energy losses identified in the Maan station. This research highlights the potential of solar integration for improved residential heating efficiency and sustainability [27].

In light of a gap in existing research on the optimal usage period of SWHs in Jordan, this study seeks to identify the most suitable time frame for SWH utilization throughout the year in Amman, Jordan. SWHs offer a range of advantages, including environmental friendliness, energy efficiency, and cost-effectiveness. They foster a reduction in reliance on fossil fuels, a decrease in energy consumption, and the promotion of domestic manufacturing. Additionally, SWHs contribute to improving the lives of low-income households, mitigating greenhouse gas emissions, and diversifying energy sources. Their minimal maintenance requirements align with several sustainable development goals. To evaluate the feasibility of solar water heaters (SWHs) across various timeframes, the study employed T*SOL Pro 5.5 software. This method enables the assessment of the project's viability for both private investors and the general public. The utilization of T*SOL Pro 5.5 software to evaluate the feasibility of SWHs across different time periods serves as an appropriate approach, enhancing the study's value.

2. PROBLEM DESCRIPTION

The study simulates a solar water heating system for a house with an average daily hot water usage of 150 liters at 50°C. The system utilizes a 3 m² evacuated tube solar collector facing south (0° azimuth) and works year-round. Two double coil buffer tanks are used: a 1000 L tank for sanitary hot water and a 320 L tank for space heating. A 9 kW gas boiler serves as a backup. As illustrated in Figure 1, three pumps circulate water: one between the solar collector and the sanitary hot water tank, one between the collector and the space heating tank, and one for the radiator circuit. The key design parameters of the considered solar thermal system in Amman, Jordan are summarized in Table 1. The system is designed to provide domestic hot water (DHW) and space heating for a residential building. The current case study was located at Queen Alia International Airport in Amman, Jordan. A warm, temperate climatic zone, sometimes referred to as a Mediterranean climate zone, is included by Queen Alia International Airport in Amman, Jordan [28]. Locations with warm, temperate climates like Amman, Jordan, often see similar CO_2 emission patterns due to shared factors.

These regions tend to require both heating and cooling throughout the year, and conventional methods powered by fossil fuels significantly contribute to their overall CO_2 emissions.

Four variants have been considered and analyzed to determine the best option including diesel savings, CO_2 emissions avoided, heating energy requirement, boiler energy to heating and energy from the boiler. Four scenarios are described for boiler operation: Variant 1: The boiler runs all day from October to April (10, 11, 12, 1, 3, 4). Variant 2: The boiler operates all day during the winter months (December, January, February). Variant 3: The boiler runs for 4 specific days per week in December, January, and February. Variant 4: The boiler operates for 2 specific days per week in December, January, and February. In all scenarios: Domestic hot water (DHW) consumption is assumed to be 150 Liters daily. A solar system is also present to supplement heating.

Table 1. Solar thermal system design parameters.

Variant	Variant 1	Variant 2	Variant 3	Variant 4
Working months	Winter months (10,11,12,1,3,4) all days	Winter colder months (12, 1, 2) all days	Winter colder months (12,1,2) 4 days per week	Winter colder months (12,1,2) 2 days per week
Location	Queen Alia International Airport			
Global radiation	2098.072 kWh/m²			
Site data DHW				
Daily consumption	150 L			
Desired temperature	50°C			
Site data space heating				
Standard heat flow requirement	5 kW			
Design temperatures	40°C/25°C			
Collector array				
Number of collectors	3			
Total gross surface area	3.0 m²			
Inclination (tilt angle)	30.0°			
Auxiliary heating				
Type	Oil-fired boiler			
Fuel	Diesel			
Nominal output	9.0 kW			
Tank 1				
Type	Space-heating buffer tank			
Volume	1 m³			
Tank 2				
Type	Dual coil indirect hot water tank			
Volume	0.32 m³			

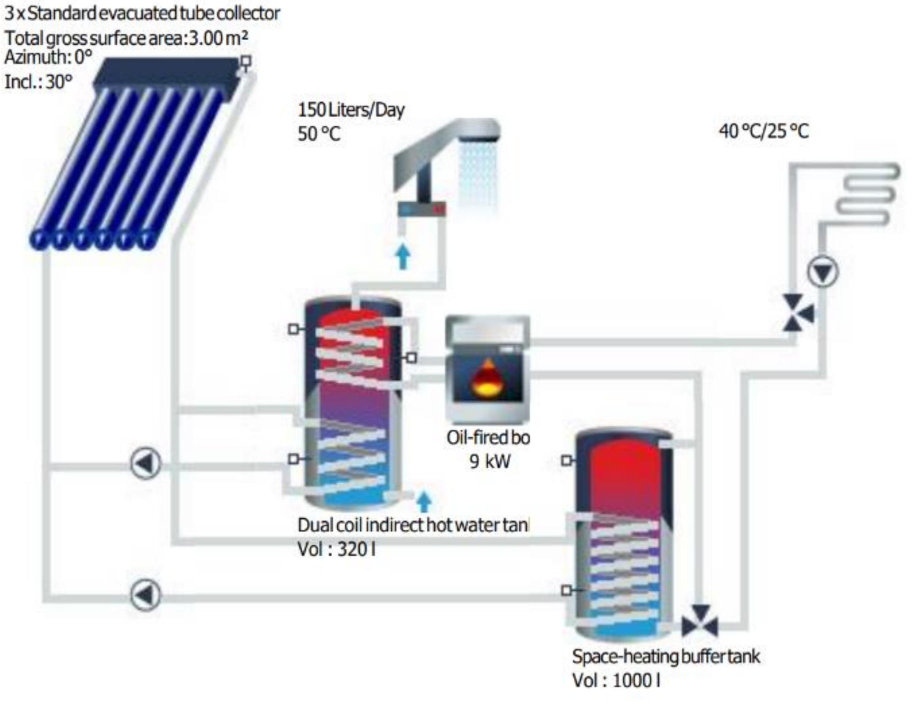

Fig. 1. The simulated system's specifications and parts.

4. RESULTS AND DISCUSSION

The solar energy consumption as KWh of the total energy consumption in Amman, Jordan, in 2022 is shown in Figure 2 from T*SOL software report. It could be seen from this figure that the KWh of solar energy consumption varies throughout the year, but it is generally higher in the summer months when there is more sunlight.

It should be noted that the total energy consumption of the house could be changed by varying the energy consumption values throughout the year. While solar energy use fluctuates throughout the year, it can't entirely replace other sources. To reduce overall building energy use, consider implementing energy-efficient technologies or adopting behavioral changes. This could involve switching to LED lights, improving insulation, or turning off electronics when not in use.

Figure 3 shows the daily maximum collector temperature of a solar thermal collector in Amman, Jordan, throughout the year. As expected, the temperatures are highest during the summer months and lowest during the winter. The average daily maximum temperature for the entire year is around 80°C.

The daily maximum collector temperature is an important factor to consider when designing a solar thermal system. The collector temperature must be high enough to heat the fluid to the desired temperature, but it must not exceed a certain limit which may damage the collector. The energy balance of a solar thermal system in Amman, Jordan, for the year 2022 is illustrated in Figure 4. It depicts the flow of energy from the sun to the collector array, storage tank, buffer tank, space heating, and domestic hot water (DHW) production. The diagram key parameters are described in Table 2.

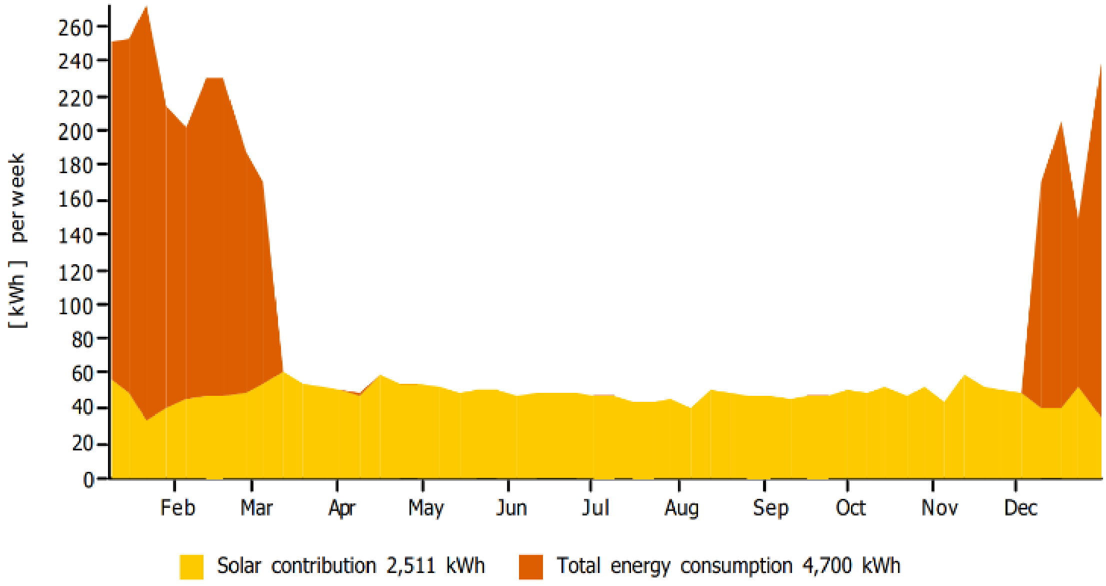

Fig. 2. Solar energy consumption in kWh of total consumption in Amman, Jordan from T*SOL report for our four scenarios.

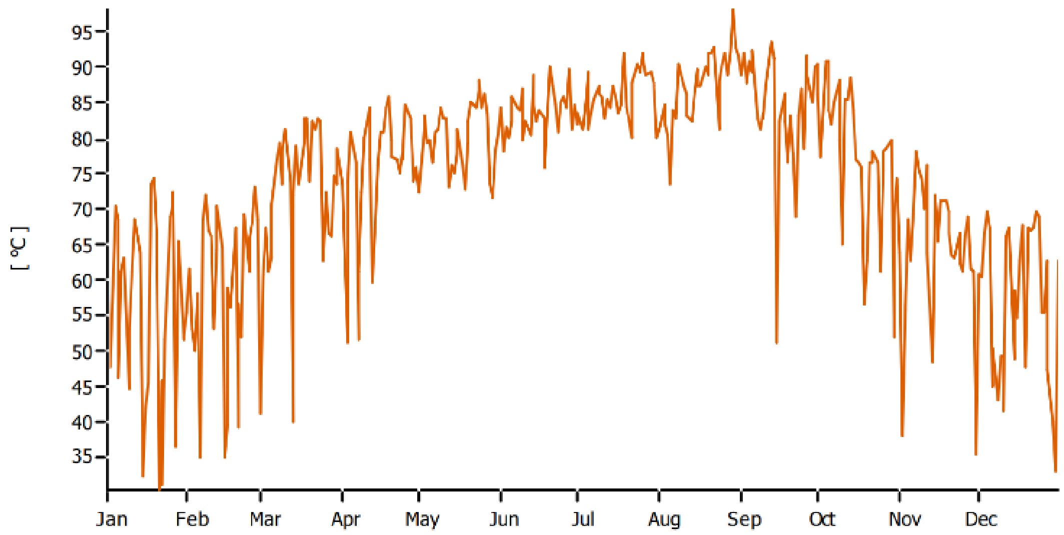

Fig. 3. Daily maximum collector temperature of a solar thermal collector in Amman, Jordan, showcasing the year-long trends in 2022.

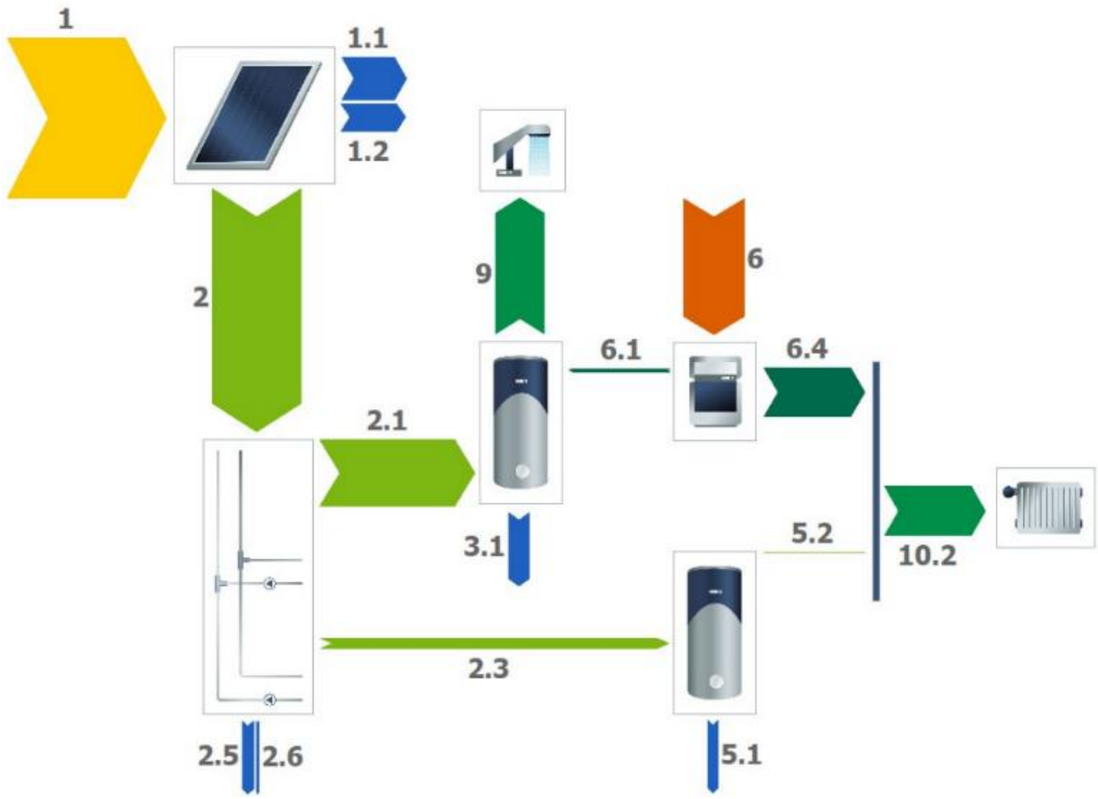

Fig. 4. Energy balance schematic diagram for a solar thermal system in Amman, Jordan in 2022.

The key energy balance parameters of the solar thermal system in Amman, Jordan, across the year 2022 are shown in Table 2. The system was able to provide 2,072 kWh of DHW in 2022, which is equivalent to about 52 L of hot water (desired temperature 50°C) per day. The system also provided enough heat to meet the space heating needs of a small house. Overall, the solar thermal system in Amman, Jordan, was a cost-effective and efficient way to produce domestic hot water and space heating. The system produced a significant amount of energy from the sun and required very little supplementary energy.

The variation of diesel savings for the four variants considered in Amman, Jordan during 2022 is shown in Figure 5. It could be seen from this figure that Variant 4 shows the highest diesel savings, followed by Variant 3, Variant 2, and Variant 1. Variant 4 achieves the greatest diesel savings due to the least boiler operation (2 days per week) compared to the other variants (all days or 4 days per week). Less frequent boiler use translates to lower diesel consumption and consequently, higher diesel savings.

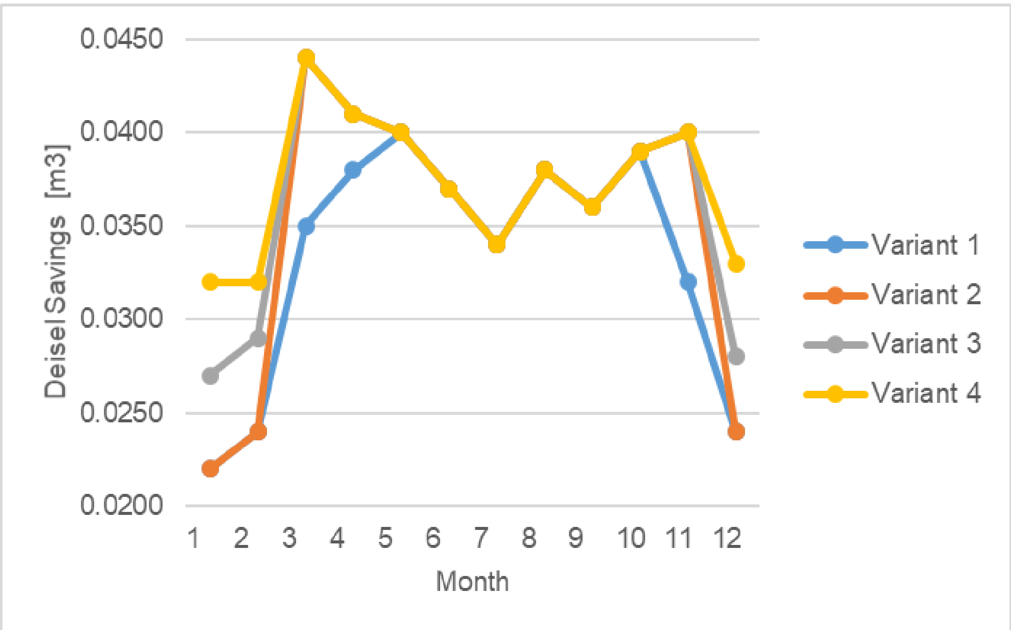

Fig. 5. Diesel savings for our four variants compared to each other in Amman, Jordan during 2022.

Table 2. Solar thermal system energy balance parameters.

#	Parameter	Average value / year (kWh)	Description
1	Irradiation on collector surface (active)	6,849	Total solar radiation incident on the collector surface during the year.
1.1	Optical collector losses	1,830	Losses due to direct reflection and absorption by the collector's cover and fins.
1.2	Thermal collector losses	1,168	Losses due to heat conduction and convection from the collector to the surrounding environment.
2	Energy from collector array	3,852	Total usable energy extracted from the collector array.
2.1	Solar energy to storage tank	2,845	Energy transferred to the storage tank to provide hot water for domestic use.
2.3	Solar energy to buffer tank	440	Energy diverted to a buffer tank for space heating purposes.
2.5	Internal piping losses	498	Losses associated with heat transfer through the pipes connecting the collector array and the storage tank.
2.6	External piping losses	68	Losses due to heat transfer through the pipes connecting the storage tank and the buildings.
3.1	Tank losses	886	Heat losses from the storage tank, mainly due to convection and thermal radiation.
5.1	Buffer tank losses	439	Heat losses from the buffer tank, primarily through conduction and convection.
5.2	Buffer tank to heating	0	No energy transferred from the buffer tank to the space heating system.
6	Final energy	2,577	Total energy delivered to the end-users (DHW and LT heating).
6.1	Supplementary energy to tank	112	Additional energy supplied to the storage tank for DHW production.
6.4	Supplementary energy to space heating	2,077	Additional energy required for space heating beyond the solar-generated energy.
9	DHW energy from tank	2,072	Total amount of hot water extracted from the storage tank for domestic use.
10.2	Heat to LT heating	2,077	Heat delivered to the space heating system.

Figure 6 shows the CO_2 emissions avoided in Amman, Jordan during 2022. It could be shown from this figure that the maximum annual amount of CO_2 emissions avoided is 123.3 metric tons. This is a significant achievement, as it represents a reduction in greenhouse gas emissions that contribute to climate change. The CO_2 emissions avoided are equivalent to the emissions from approximately 22,000 cars driving for one year.

Figure 7 illustrates the varying heating energy demands of different heating system configurations (Variants 1-4). While all variants aim to provide hot water for domestic use and space heating, their efficiency in achieving this comfort level differs. This variation can be attributed to factors like the inherent efficiency of the heating systems themselves, the level of insulation in the building, and the local climate. These factors all play a role in determining the amount of energy required to maintain a comfortable indoor temperature throughout the year.

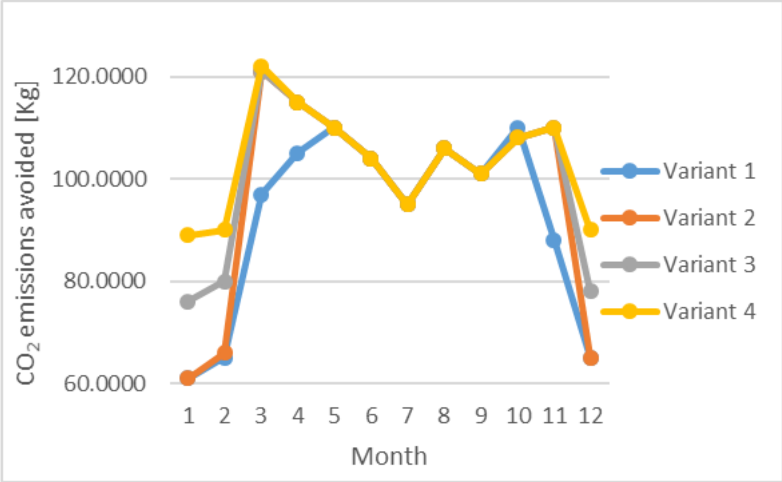

Fig. 6. CO_2 emissions avoided in Amman, Jordan during 2022.

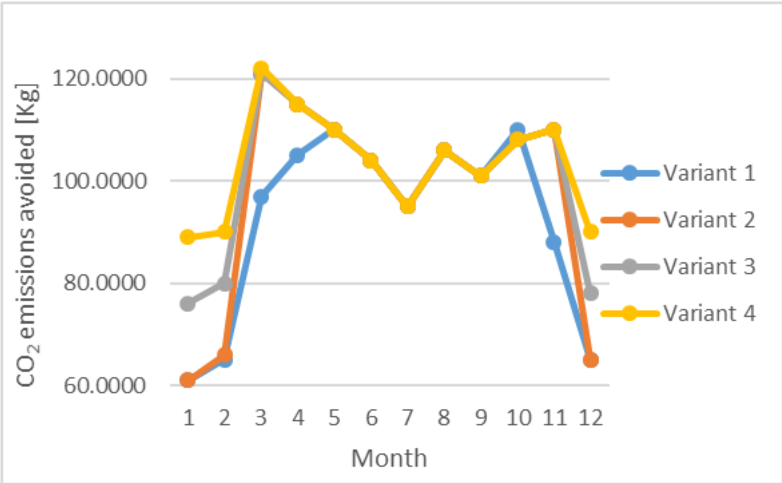

Fig. 7. Heating energy demand for different variants of a heating system in Amman, Jordan during 2022.

Figure 8 depicts the average boiler energy consumption for heating purposes in Amman, Jordan, throughout the year, 2022. The graph indicates that the boiler energy demand peaks during the winter months, particularly from December to February, when temperatures drop significantly. The demand gradually decreases during the spring and summer months as temperatures rise. The graph also shows that there is a significant difference in boiler energy consumption between different variants of heating systems.

Variant 1, which represents the less efficient system, consumes the most energy on average throughout the year considered. Variant 4, which represents the more efficient system, however, consumes the least energy on average throughout the year considered. These findings highlight the importance of using efficient heating systems to minimize energy consumption and reduce greenhouse gas emissions.

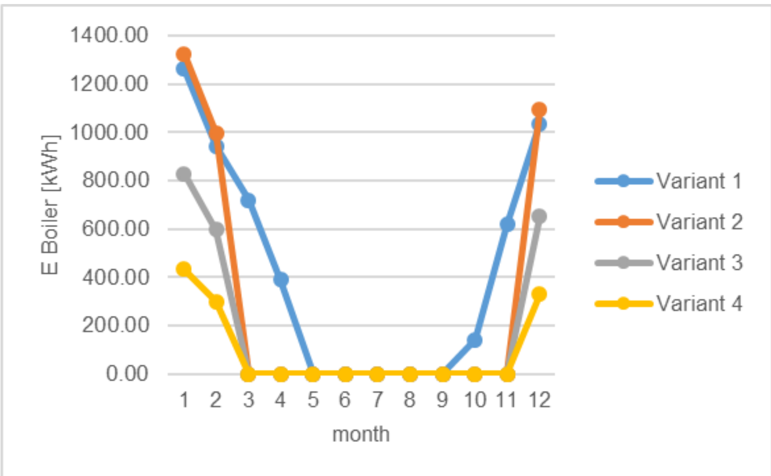

Fig. 8. Boiler energy utilization for heating in Amman, Jordan during 2022.

Figure 9 shows the monthly boiler energy production in Amman, Jordan, for one year (2022). The data was based on the four different variants of heating systems considered. The figure shows that the energy production from the boiler varies throughout the year, with the highest production occurring during the winter months and the lowest production occurring during the summer months.

This is because the boiler is used to provide heat for buildings, and there is a greater demand for heat during the winter months. The figure also shows that there is a significant difference in energy production between the different variants of the boiler. It could be also seen from the figure that Variant 1 produces the most energy on average throughout the year considered, followed by Variant 2, Variant 3, and Variant 4.

The average diesel consumption in Amman, Jordan, from January to December 2022 is presented in Figure (10). It is shown that the highest consumption occurs during the winter months and the lowest consumption occurs during the summer months. This is because the demand for heating is greater during the winter months. The figure also shows that there is a significant difference in diesel consumption between the different variants considered. It could be also seen that Variant 1 consumes the most diesel amount on average throughout the year considered, followed by Variant 2, Variant 3, and Variant 4. The difference in diesel consumption between the different variants is due to a number of factors, including the insulation levels of the buildings, the efficiency of the heating systems, and the size of the buildings.

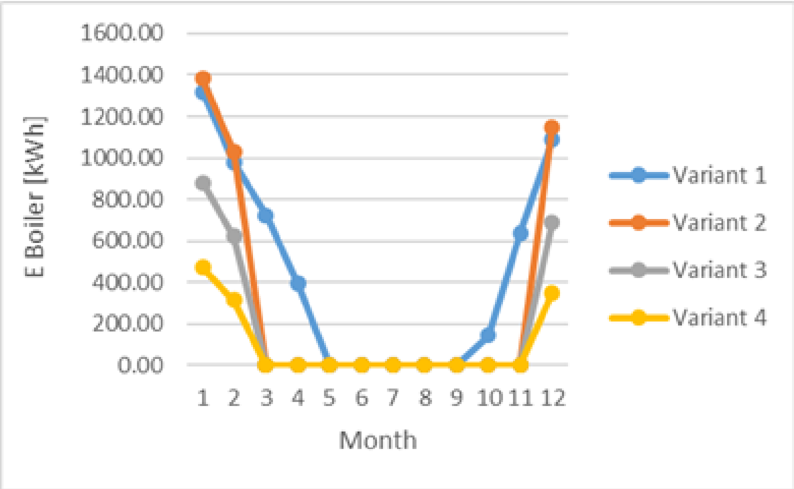

Fig. 9. Energy production from boiler in Amman, Jordan during 2022.

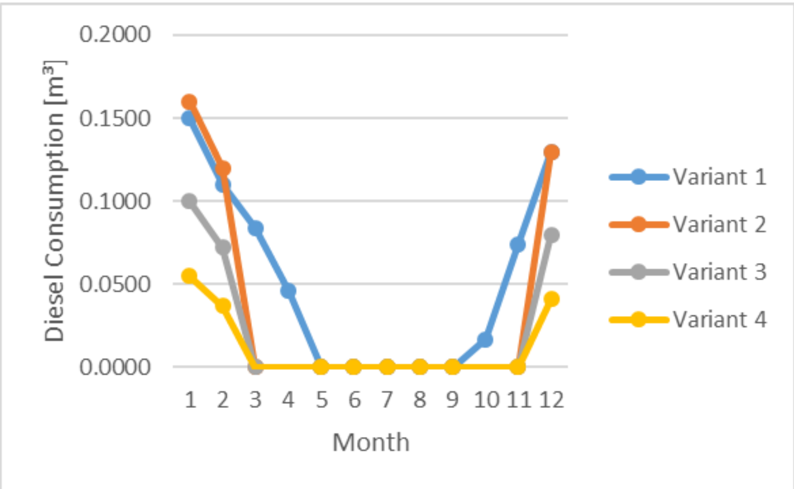

Fig. 10. Diesel consumption in Amman, Jordan, from January to December 2022.

Table 3 summarizes the performance of the four different solar thermal heating systems considered. The systems were evaluated based on the irradiation on the collector area, energy delivered by the collector loop, energy from auxiliary heating, system efficiency, total solar fraction, DHW heating energy supply, DHW solar fraction, solar energy contribution to DHW, space-heating energy supply, fuel savings, and CO_2 emissions avoided.

Solar water heaters have steadily improved their efficiency over time, reflected in a rising solar fraction. This signifies a significant reduction in reliance on conventional backup heating, leading to substantial energy savings.

The table shows that there is a significant difference in the performance of the four systems.

Variant 4, which was the most efficient system, had the highest total solar fraction (68.95%) and consequently, the lowest fuel consumption (446.3 L Diesel). This indicates that Variant 4 achieved the highest reliance on solar energy, minimizing the need for auxiliary heating and thereby reducing greenhouse gas emissions. While Variant 1 achieved the highest fuel savings (398.8 L Diesel), it was the least efficient system overall. This is reflected in its low total solar fraction of 30.47%. This means that Variant 1 heavily relied on auxiliary heating, which increases greenhouse gas emissions.

Variant 2 and Variant 3 fall in between Variant 1 and Variant 4 in terms of performance. Variant 2 had a total solar fraction of 41.19% and fuel savings of 418.2 L Diesel, while Variant 3 had a total solar fraction of 53.42% and fuel savings of 433.5 L Diesel.

The table also shows that the solar energy contribution to DHW is highest for Variant 4 (2,528 kWh) and lowest for Variant 1 (2,478 kWh). This is because Variant 4 is the most efficient system and is able to convert the most solar energy into usable heat. Overall, the table shows that more efficient solar thermal heating systems can significantly reduce the need for auxiliary heating and greenhouse gas emissions

Table 3. Comparison between the performance of different variants of solar thermal heating systems considered.

Variant	Variant 1	Variant 2	Variant 3	Variant 4
Irradiation on collector area – total (kWh)	6,849	6,849	6,849	6,849
Irradiation on collector area – specific (kWh/m²)	2,283.00	2,283.00	2,283.00	2,283.00
Energy delivered by collector loop (kWh)	3,273	3,278	3,285	3,295
Specific energy delivered by collector loop (kWh/m²)	1,090.86	1,092.54	1,095.03	1,098.44
Energy from auxiliary heating(kWh)	5,710	3,567	2,190	1,138
System efficiency (%)	36.53	36.47	36.66	36.91
Total solar fraction (%)	30.47	41.19	53.42	68.95
DHW heating energy supply (kWh)	2,091	2,089	2,072	2,058
DHW solar fraction (%)	93.25	94.34	95.72	97.23
Solar energy contribution to DHW (kWh)	2,478	2,498	2,511	2,528
Space-heating energy supply (kWh)	5,554	3,417	2,077	1,066
Fuel savings (L Diesel)	398.8	418.2	433.5	446.3
CO_2 emissions avoided (kg)	1,107.4	1,161.3	1,203.6	1,239.2

5. CONCLUSION

This study investigated the effectiveness of SWHs in Jordan's climate and identified the optimal utilization strategy to minimize environmental impact. The analysis focused on four variants, each representing a distinct boiler operation schedule throughout the year. The results revealed that Variant 4, employing boiler operation for two days per week during December, January, and February, achieved the most favorable combination of system efficiency (36.91%), fuel savings (446.3 liters of diesel), and CO_2 emissions reduction (1,239.2 kg). This suggests that prioritizing solar water heating during peak sunshine months while strategically utilizing the boiler during colder periods offers the most balanced approach. Conversely, Variant 1, characterized by boiler operation from October to April, exhibited the lowest system efficiency (36.53%) and fuel savings (398.8 liters of diesel) despite achieving the highest avoided CO_2 emissions (1,107.4 kg). This indicates a trade-off between maximizing reliance on solar energy and ensuring sufficient hot water supply during extended periods with lower solar irradiance.

Advantages:

- The study provides a data-driven approach for selecting the optimal boiler operation schedule for SWH systems in Jordan, balancing environmental benefits and system efficiency.
- The findings promote the widespread adoption of SWHs as a sustainable solution for hot water generation, contributing to reduced reliance on fossil fuels and greenhouse gas emissions.

Future studies:

- The investigation could be expanded to incorporate real-time weather data integration with the SWH system for dynamic boiler operation optimization.
- Analyzing the cost-effectiveness of different SWH configurations and boiler types could provide valuable insights for broader economic feasibility assessments.

Further research could explore the integration of SWHs with other renewable energy sources to create a more comprehensive and sustainable hot water heating system.

ACKNOWLEDGEMENT

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NOMENCLATURE

Symbol	Description	Unit
SWHs	Solar water heaters	-
PV	Photovoltaic	-
T*SOL® Pro 5.5	Transient System Simulation Tool (A simulation software for solar thermal heating systems.)	-
Variant 1	Boiler operates all days in October, November, December, January, March, and April	-
Variant 2	Boiler operates all days in December, January, and February	-
Variant 3	Boiler operates 4 days per week in December, January, and February	-
Variant 4	Boiler operates 2 days per week in December, January, and February	-
η	System efficiency	%
ΔD	Diesel savings	L
ΔCO_2	Avoided CO_2 emissions	kg
SWH	Solar water heater	-
DHW	Domestic hot water	-
CO_2	Carbon dioxide	-
Al_2O_3	Aluminum oxide nanoparticles	-
GAMS	General algebraic modeling system	-
ETC	Evacuated tube collector	-
FPC	Flat plate collector	-
LT	Low temperature	-
E	Energy	kWh

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