

Article

Performance Evaluation of a Novel Solar Thermal Water Heating System Integrated with Thermal Energy Storage: A New Zealand Case Study

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Abstract

This study evaluates a solar thermal water heating system integrated with thermal energy storage (TES) for domestic hot water supply in New Zealand. A conventional system without TES was first assessed as the baseline case and then compared with a TES-integrated system using Paraffin RT60 as the phase change material and Therminol 55 as the heat transfer fluid. The analysis was based on three selected seven-day periods in 2025, representing summer, winter, and intermediate weather conditions. The simulation results show that TES improves the stability of the water temperature inside the tank, the effective energy usage, and overall system performance when excess solar energy is available for storage. The performance enhancement is most obvious in summer, moderate under intermediate weather conditions, and relatively limited in winter due to less availability of solar radiation. Based on the simulation, annual energy production increased to 6746.93 kWh with TES compared to 5342.88 kWh without using TES, which shows a 26.28% increase. Notably, useful energy consumption increased from 1274.55 kWh to 2327.59 kWh, an 82.62% increase. The produced-to-used energy ratio decreased from 4.19 to 2.90, which shows a 30.85% improvement in energy utilization. The consumption-based LCOE decreased from 0.4825 NZD/kWh to 0.4016 NZD/kWh, while the production-based LCOE increased from 0.1151 NZD/kWh to 0.1386 NZD/kWh. Overall, the solar thermal system with TES improves useful heat delivery and economic performance when evaluated based on actual energy consumption.

Keywords: solar thermal water heater; thermal energy storage; phase change material; New Zealand weather conditions; accumulated system performance



Academic Editor: Ioan Sarbu

Received: 30 July 2026

Revised: 19 September 2026

Accepted: 23 September 2026

Published: 25 September 2026

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1. Introduction

The growing energy demand of the global population is accelerating the depletion of fossil fuel resources and contributing significantly to environmental pollution. While the environmental impacts of fossil fuel consumption raise serious concerns, economic costs also play a crucial role in providing reliable and affordable energy worldwide. As a result, the rapid reduction in renewable energy costs has made renewable technologies a cheaper and more sustainable alternative to fossil fuel-based energy sources [1]. New

Zealand possesses one of the most renewable-based energy systems in the world. In 2024, renewable sources supplied about 45.5% of total primary energy and 85.5% of electricity generation [2]. Solar power is an increasingly promising option to help diversify New Zealand's mix of renewable energy sources. Due to favorable levels of solar irradiation across many regions, with the country receiving an average of 1460 kWh of solar energy per square meter annually [3], there is increasing interest in solar thermal technologies, particularly in solar thermal water heating systems for residential applications. This is especially important given that approximately 30% of all domestic energy use in New Zealand is for heating water [3]. Therefore, improving the performance and reliability of solar thermal systems can be an important part of reducing energy consumption and greenhouse gas emissions in the residential sector.

Among different renewable energy technologies, solar thermal water heating systems are considered one of the most efficient low-emission systems for households. A solar water heating system converts solar radiation into thermal energy to heat the water flowing within the system [4]. Hence, solar thermal systems offer great direct conversion of sunlight into usable heat, achieving thermal efficiency of up to 75% [5], making them well suited for domestic hot water applications. However, conventional solar thermal systems work effectively only when sufficient solar radiation is available; therefore, their ability to supply adequate hot water is limited by the availability of solar radiation and the low irradiance periods during nighttime and cloudy weather conditions [6]. To address this challenge, thermal energy storage (TES) has become a necessary addition to solar water heating, which allows the system to store excess heat during peak solar hours and release it when solar radiation is not sufficient [7]. Without TES, solar thermal systems become inherently intermittent and non-dispatchable, as their operation is restricted to periods of direct solar availability. Consequently, power generation frequently drops to zero when direct intermediate irradiance (DNI) is insufficient [8]. Additionally, studies on TES systems demonstrate that latent heat storage using phase change materials can reduce storage volume requirements by approximately 27% compared to conventional molten salt systems [9]. This highlights that the performance of TES is not only about storing heat, but also about selecting the right storage material to optimize size and efficiency. A study has shown that without thermal storage, an evacuated tube collector's annual solar fraction was 20.5% lower than that of an otherwise identical system with PCM-based storage integrated [10].

While PCM-based TES integration has been studied for solar thermal systems in various climates, there has been limited research into their performance in the particular climate of New Zealand, where solar irradiance and seasonal variation are significantly different from those in more commonly studied regions (e.g., Mediterranean, tropical, or continental climates). Most existing studies also tend to focus on a single season or annual average performance, rather than directly comparing system behavior across representative summer, winter, and intermediate weather weeks within the same evaluation framework. Furthermore, few studies combine performance comparison (with and without TES) with a detailed analysis of hourly and cumulative energy production, consumption, and water tank temperature profile across these distinct seasonal regimes. The present study seeks to fill this gap by evaluating a PCM-based TES-integrated solar thermal water heating system against a conventional baseline system, under New Zealand-specific weather conditions, across three representative seven-day periods (summer, winter, and intermediate), to provide a clearer understanding of how and when TES integration offers the greatest performance benefit. The key objectives of this research are as follows.

1. Design and evaluate a PCM-based TES system integrated with a secondary heat transfer fluid and compare its performance against a conventional non-TES solar thermal water heating system under New Zealand weather conditions.

2. Evaluate the effect of TES integration on water tank temperature stability, and analyze hourly, daily, and cumulative weekly thermal energy production and consumption for both systems across three representative seasonal periods (summer, winter, and intermediate weather).
3. Determine the extent to which TES integration improves the utilization of available solar energy by storing excess heat during high-irradiance periods and releasing it during low-solar or nighttime periods, thereby reducing the system's dependence on direct solar radiation.
4. Assess the annual energy performance and economic feasibility of the TES-integrated system by comparing it with the baseline system.

2. System Configurations

2.1. Schematic Diagram

As illustrated in Figure 1, the proposed system operates as a solar thermal water heating configuration integrated with a TES unit that enables efficient energy utilization during both daytime and nighttime. The system consists of three operational cycles.

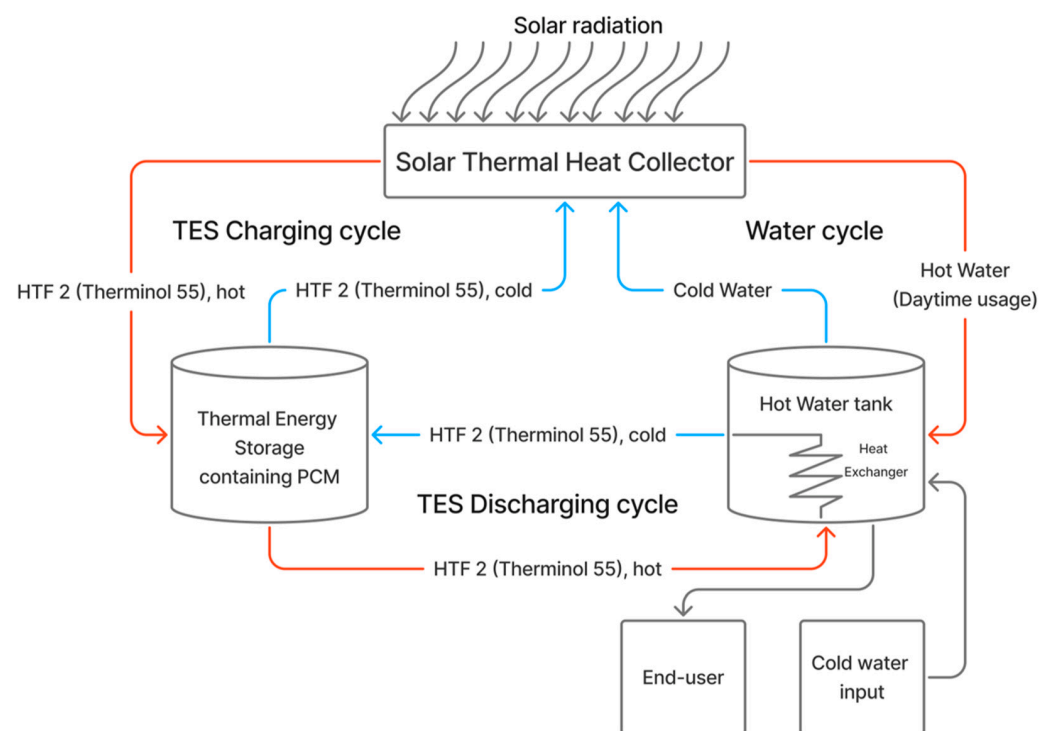


Figure 1. System configuration of solar thermal water heater integrated with TES.

1. The water cycle, which circulates water between the domestic storage tank and the solar thermal collector.
2. The TES charging cycle, which operates between the TES unit and the solar thermal collector.
3. The TES discharging cycle, which operates between the TES unit and the domestic hot water tank.

During daytime operation, when sufficient solar radiation is available, the system initially operates in the water cycle. Water from the domestic storage tank is circulated through the solar thermal collector, where it absorbs solar energy and its temperature gradually increases. This process continues until the entire water volume in the tank reaches the preset temperature range of approximately 50–60 °C depending on the season.

Once the desired temperature is achieved, the control system automatically stops the circulation of water through the collector to prevent overheating and switches to the HTF loop.

In the subsequent stage, the system operates in the TES charging cycle using a secondary working fluid (Therminol 55). The HTF circulates through the solar collector, absorbs thermal energy, and is then directed to the TES unit. The TES tank is designed as a concentric or encapsulated configuration, where the outer region contains the circulating Therminol 55 and the inner compartment contains a phase change material (PCM). The PCM selected for this study is Paraffin RT60, which has a melting temperature of around 60 °C. As the heated Therminol 55 flows through the TES unit, thermal energy is transferred to Paraffin RT60. Initially, the PCM undergoes sensible heating until it reaches its melting temperature, followed by a phase change during which a significant amount of latent heat is stored. After complete melting, further sensible heating of the liquid PCM may occur. This multi-stage process enables efficient thermal energy storage, with latent heat playing a dominant role.

During daytime operation, if the water temperature in the storage tank drops significantly, the HTF discharging cycle can be activated to supply heat indirectly. In this case, the HTF transfers thermal energy to the water, thereby maintaining the desired water temperature even after the primary heating cycle has been completed.

During nighttime or periods of low solar radiation, the system operates entirely in the TES discharging cycle, as solar input is unavailable. The HTF absorbs stored thermal energy from Paraffin RT60 and then circulates between the TES unit and the domestic hot water tank. When the PCM temperature decreases to its solidification point, it begins to crystallize and releases a substantial amount of latent heat, ensuring a stable and sustained heat output. The heated HTF then flows through the surroundings of the water tank, transferring heat to maintain the required temperature. After releasing heat, the cooled HTF returns to the TES unit, where it is reheated by the PCM, and the cycle continues until the stored energy is depleted.

The system operation is further governed by a predefined daily hot water consumption schedule, with withdrawals occurring at 09:00, 13:00, and 19:00, where approximately 50 L of hot water is extracted from the storage tank at each interval. Following each withdrawal event, the tank is replenished with cold inlet water, whose temperature varies seasonally, typically around 25 °C in summer, 20 °C under intermediate conditions, and 15 °C in winter. The introduction of cold water causes a significant drop in the overall tank temperature, thereby triggering a response from the control system. When this temperature drop is detected, the HTF charging cycle is temporarily paused, and the system reactivates the water cycle to restore the tank temperature. During this phase, water is circulated through the solar thermal collector and heated directly until the tank reaches the preset seasonal temperature. Once the desired temperature is achieved, the water circulation is stopped, and the system automatically switches back to the TES charging cycle. This ensures that priority is given to meeting immediate hot water demand before resuming thermal energy storage in the TES unit.

2.2. Control Logic

The control logic illustrated in Figure 2 determines the operating mode of the solar thermal water heating system at every hour. The first decision is based on solar radiation availability. During daytime, when solar radiation is available, the controller first checks the water tank temperature. If the tank temperature is below the seasonal target temperature, the system remains in the water heating cycle and solar heat is used directly to raise the water tank temperature. This loop continues until the water tank reaches the required

target value, and after that, if solar radiation is still available, the system switches from the water heating cycle to the TES charging cycle. In this mode, HTF absorbs heat from the solar thermal collector and transfers it to PCM in the TES unit. During a scheduled hot water draw event at 09:00, 13:00, and 19:00, 50 L of hot water is removed and replaced with cold water, which causes the tank temperature to drop, so the controller pauses TES charging and returns the system to the water heating cycle until the tank temperature is restored.

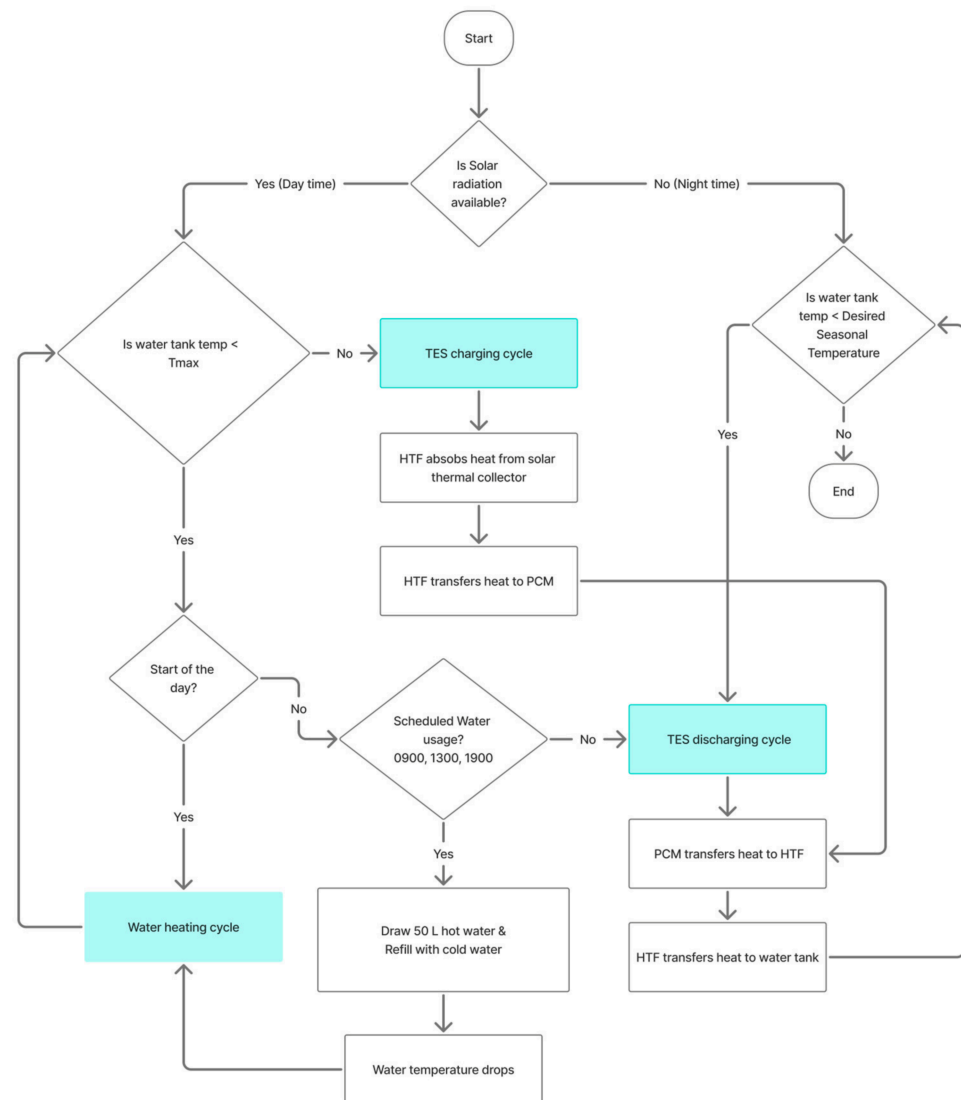


Figure 2. Control logic of solar thermal water heater integrated with TES.

When solar radiation is not available, such as during nighttime or low-solar periods, the controller checks whether the tank temperature is below the desired seasonal temperature. If the temperature is low and stored thermal energy is available in the PCM, the TES discharging cycle is activated. In this cycle, the PCM transfers stored heat to the HTF, and the HTF then carries this heat to the water tank. This loop continues until the tank temperature is restored or the stored energy in the TES unit is depleted. If the tank temperature is already sufficient, the system remains inactive. Therefore, the control logic gives priority to direct water heating, uses TES charging only after the tank demand is satisfied, and activates TES discharging only when solar radiation is unavailable and the tank requires heat.

3. Numerical Model

The research model was developed to represent the hourly thermal behavior of the solar thermal water heating system and to evaluate how TES changes the system response under different New Zealand weather conditions. The key assumptions used in the model are as follows.

1. Solar radiation is assumed to be uniformly distributed over the collector surface, and shading effects are neglected.
2. Heat loss from the water tank to the surrounding air is included in the model, while heat losses from pipes and fittings are neglected.
3. The collector heat removal factor, Fr , is used only for the water heating cycle between the collector and the water tank.
4. TES efficiency is 0.75.
5. The TES unit is assumed to be well insulated, so heat loss from the TES tank to the surroundings is neglected.

3.1. Solar Thermal Heating

The flow characteristics inside the collector tubes are evaluated using the Reynolds number, defined as [11]:

$$Re = \frac{\rho v D}{\mu} \quad (1)$$

where ρ is the fluid density, v is the fluid velocity, D is the tube diameter, and μ is the dynamic viscosity.

The Prandtl number is given by [11]:

$$Pr = \frac{\mu C_p}{k} \quad (2)$$

where C_p is the specific heat capacity and k is the thermal conductivity.

For turbulent flow conditions ($2300 < Re < 5 \times 10^6$), the Nusselt number is determined using [12]:

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \quad (3)$$

where the friction factor is expressed as [13]:

$$f = \frac{1}{(1.82 \ln Re - 1.64)^2} \quad (4)$$

The convective heat transfer coefficient (h_{fi}) between the fluid and the tube wall is [12]:

$$h_{fi} = \frac{Nu \cdot k}{D} \quad (5)$$

The fin efficiency of the absorber plate is given by [14]:

$$F = \frac{\tanh [m(W - D)/2]}{m(W - D)/2} \quad (6)$$

where the fin parameter m is defined as [14]:

$$m = \sqrt{\frac{U_L}{k_{plate} \delta}} \quad (7)$$

Here, W is the distance between tubes, k_{plate} is the thermal conductivity of the absorber plate, U_L is the overall heat loss coefficient, and δ is the plate thickness.

The collector efficiency factor is expressed as [14]:

$$F' = \frac{1}{U_L W \left[\frac{\pi D_i}{h_{fi}} \right]} \quad (8)$$

where D_i is the inner tube diameter.

The heat removal factor is [15]:

$$F_r = \frac{\dot{m} C_p}{U_L A_c} \left(1 - \exp \left(\frac{F' U_L A_c}{\dot{m} C_p} \right) \right) \quad (9)$$

where $\dot{m}$ is the mass flow rate and A_c is the solar collector area.

The solar irradiance incident on a tilted surface is calculated as [16]:

$$G_t = G \cos \theta \quad (10)$$

where G is the horizontal solar radiation and θ is the tilt angle.

The useful heat gain from the collector is determined by [17]:

$$Q_u = A_c F_r [G_t (\tau_\alpha) - U_L (T_i - T_a)] \quad (11)$$

where τ_α is the transmittance-absorptance product, T_i is the inlet temperature and T_a is the ambient temperature.

3.2. Water Storage Tank

The water storage tank is modeled using an unsteady energy balance that accounts for water usage, solar energy input, thermal energy storage discharge, and heat losses to the environment. During hot water withdrawal, instantaneous mixing is assumed, and the resulting tank temperature is given by [5]:

$$T_{use} = \frac{(M - m_{use}) T_{f,i-1} + m_{use} T_{cold}}{M} \quad (12)$$

where M is the total mass of water in the tank, m_{use} is the mass of water withdrawn, $T_{f,i-1}$ is the tank temperature at previous hour, and T_{cold} is the inlet cold water temperature.

The heat loss from the storage tank to the surrounding environment is expressed as [18]:

$$Q_{loss} = U_{tank} A_{tank} (T_{use} - T_a) \quad (13)$$

where U_{tank} is the overall heat transfer coefficient of the tank, A_{tank} is the tank surface area, and T_a is the ambient temperature.

The final tank temperature is obtained from the transient energy balance [18]:

$$T_f = T_{use} + \frac{(q_i - Q_{loss})}{M C_p} \quad (14)$$

where q_i represents the hourly thermal energy supplied to the tank from either direct solar heating or thermal energy storage discharge.

3.3. Thermal Energy Storage (TES)

The heat transfer fluid (HTF) acts as the energy transport medium between the solar collector, TES system, and the water tank. Its temperature is governed by an energy balance [18]:

$$T_{htf,i} = T_{htf,i-1} + \frac{Q_{htf}}{M_{htf} C_{p,htf}} \quad (15)$$

where $T_{htf,i}$ is the HTF temperature at current hour, $T_{htf,i-1}$ is the HTF temperature at previous hour, M_{htf} is the mass of the HTF, $C_{p,htf}$ is its specific heat capacity, and Q_{htf} is the net heat exchanged during charging or discharging.

During operation, the HTF absorbs heat from the solar collector during the charging phase and releases stored thermal energy to the water tank during the discharging phase. The phase change material stores thermal energy in both sensible and latent forms depending on its temperature relative to the melting point. The stored energy is represented in three distinct thermal stages.

For temperatures below or equal to the melting temperature $T \leq T_{melt}$, the PCM stores energy as sensible heat [19]:

$$E_{pcm} = M_{pcm} C_{p,pcm} (T_{melt} - T_{pcm,i}) \quad (16)$$

where E_{pcm} is the energy absorbed or released by the PCM, M_{pcm} is the mass of the PCM, $C_{p,pcm}$ is the specific heat capacity of the PCM, T_{melt} is the melting temperature of the PCM, $T_{pcm,i}$ is the initial temperature of the PCM.

At the melting temperature $T = T_{melt}$, the PCM absorbs latent heat while maintaining a constant temperature [19]:

$$E_{pcm} = M_{pcm} L \quad (17)$$

where L is the PCM latent heat of fusion.

For temperatures above the melting temperature $T > T_{melt}$, additional energy increases the temperature of the fully melted PCM [19]:

$$E_{pcm} = M_{pcm} C_{p,pcm} (T_{pcm,f} - T_{melt}) \quad (18)$$

where $T_{pcm,f}$ is the final temperature of the PCM.

The phase change material temperature is evaluated from its stored energy state, which depends on whether the material is in the sensible heating region, phase change region, or fully melted region. For temperatures below or equal to the melting temperature $T_{pcm} \leq T_{melt}$, the PCM remains in the solid phase, and its temperature is directly proportional to the stored sensible energy [19]:

$$T_{pcm} = T_{pcm,i} + \frac{E_{pcm}}{M_{pcm} C_{p,pcm}} \quad (19)$$

At the phase change region $T_{pcm} = T_{melt}$, the temperature remains constant while latent heat is absorbed.

For temperatures above the melting point $T_{pcm} > T_{melt}$, the PCM is fully melted, and additional energy increases its temperature linearly [19]:

$$T_{pcm} = T_{melt} + \frac{E_{pcm}}{M_{pcm} C_{p,pcm}} \quad (20)$$

3.4. Economic Performance

The economic performance of the system is assessed using the levelized cost of electricity (LCOE), which represents the average cost of generating electricity over the system's operational lifetime. The LCOE is calculated as [20]:

$$\text{LCOE} = \frac{\sum_{t=0}^T (I_t + O_t + D_t) / (1+r)^t}{\sum_{t=0}^T S / (1+r)^t} \quad (21)$$

where T is the project lifetime, t is the annual time index, I_t is the capital investment cost, O_t represents operation and maintenance expenses, D_t is the decommissioning cost or residual value at the end of the project, r is the discount rate based on the country, and S denotes the annual electricity generated by the system.

4. Case Study

This case study aims to evaluate the thermal and economic performance of a solar thermal water heating system integrated with PCM-based TES under representative New Zealand weather conditions. The performance of the proposed TES-integrated system is compared with that of a conventional solar thermal water heating system without TES to quantify the benefits of using thermal energy storage. The summer period was selected from 1 January to 7 January 2025, the winter period from 1 July to 7 July 2025, and the intermediate weather period from 1 October to 7 October 2025. These periods represent typical weather conditions in Auckland, New Zealand, representing high, low, and moderate solar energy availability, respectively. The weather data included ambient temperature and solar radiation that were obtained from the Albany monitoring station, located in North Shore, Auckland, New Zealand [21].

4.1. Initial Operating Conditions

This study uses Therminol 55 as the HTF and Paraffin RT60 as the PCM in the thermal energy storage unit. Therminol 55 was selected as the HTF because it is suitable for low- to medium-temperature heat transfer and can circulate between the solar collector, TES unit, and water tank without phase change. Paraffin RT60 was selected as the PCM because its melting range is close to the desired water temperature range. When the tank reaches the target temperature, Paraffin RT60 can store the extra heat as latent heat. Later, it can release this stored heat during nighttime or low-solar periods. If the melting temperature of the PCM is higher, available solar radiation will not be able to melt the PCM and store energy as latent heat. The PCM within the TES unit is modeled using a lumped-parameter approach, assuming a uniform temperature throughout the PCM.

Hourly climate data for 2025 were used in the numerical analysis. Three representative seven-day periods were selected based on the annual solar radiation profile. The domestic hot water tank volume was set to 200 L. Hot water was consumed three times per day at 09:00, 13:00, and 19:00, with 50 L withdrawn at each event. After each withdrawal, the same volume of cold water was assumed to enter the tank immediately. The inlet water temperature was set to 25 °C in summer, 20 °C under intermediate conditions, and 15 °C in winter. The target tank temperature was set to 50 °C for summer, 55 °C for intermediate conditions, and 60 °C for winter, respectively. These conditions were used to represent the seasonal variation in domestic hot water demand and solar thermal operating difficulty. A flat-plate solar thermal collector was selected for this study because it is suitable for domestic hot water heating in the low to medium temperature range. The collector size was based on the demand of one household, represented by a 200 L storage tank and three daily hot water draws of 50 L. A 10 m² collector area was used to provide sufficient heat for

direct water heating and to allow excess solar energy to be supplied to the TES unit when the tank reached the target temperature. The operating parameters of the TES system and the solar thermal collector are shown in Tables 1 and 2, respectively.

Table 1. Operating parameters of the TES system.

Parameter	Value	Justification
Water density	1000 kg/m ³	Constant
Specific heat capacity of water $C_{p,water}$	4186 J/kgK	Constant
Tank surface area A_{tank}	3.2 m ²	Selected design value
Tank heat loss coefficient U_{tank}	1.5 W/m ² K	[5]
Paraffin RT60 volume	180 L	Selected design value
Therminol 55 volume	50 L	Selected design value
Paraffin RT60 density (solid)	0.88 kg/L	[22]
Paraffin RT60 density (liquid)	0.77 kg/L	[22]
Therminol 55 density	868 kg/m ³	[23]
PCM mass	158.4 kg	Calculated from volume
Initial PCM temperature	30 °C	Chosen by author based on average ambient temperature
Initial HTF temperature	20 °C	Chosen by author based on average ambient temperature
PCM melting start temperature	55 °C	[22]
PCM melting end temperature	61 °C	[22]
Specific heat capacity of PCM	2.0 kJ/kgK	[22]
Latent heat of PCM	214.4 kJ/kg	[22]
Specific heat capacity of HTF	2.4 kJ/kgK	[23]
TES efficiency	0.75	Assumed

Table 2. Solar thermal collector and simulation parameters.

Parameter	Value	Justification
Solar thermal collector area A_c	10 m ²	[5]
Spacing between collector tubes W	0.12 m	[5]
Outer diameter of collector tube D	0.01 m	[5]
Inner diameter of collector tube D_i	0.008 m	[5]
Absorber plate thickness δ	0.0005 m	[5]
Thermal conductivity of absorber plate k_{plate}	200 W/mK	Constant
Thermal conductivity of water k_{fluid}	0.64 W/mK	Constant
Bond conductance between tube and absorber plate C_b	300 W/mK	[5]
Collector tilt angle θ	19°	Chosen by author
Dynamic viscosity of water μ	1.002×10^{-3} Pas	Constant

4.2. Performance Analysis

Figure 3 shows the annual ambient temperature and solar radiation profiles for Albany, New Zealand in 2025. As shown in the annual solar irradiance profile, solar radiation is highest during summer, lowest during winter, and moderate during the intermediate season. Accordingly, three representative seven-day periods were selected for the analysis: 1–7 January 2025 to represent summer, 1–7 July 2025 for winter, and 1–7 October 2025 for intermediate conditions. These periods capture typical high, low, and moderate solar energy availability in New Zealand. Figure 4 shows the weekly ambient temperature and solar radiation profiles for three selected periods. Summer has the highest temperature and radiation levels, with radiation peaks reaching about 1000 W/m². The intermediate

period shows moderate temperature and radiation, while winter has the lowest radiation and generally lower temperature.

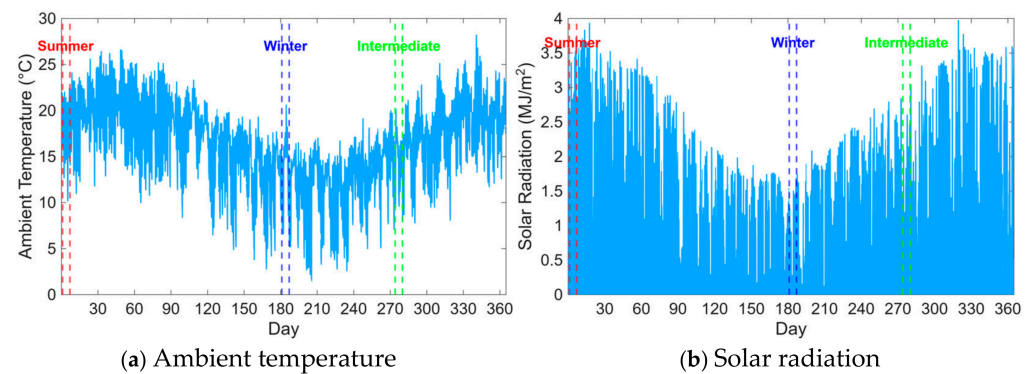


Figure 3. Annual temperature and radiation profile of 2025.

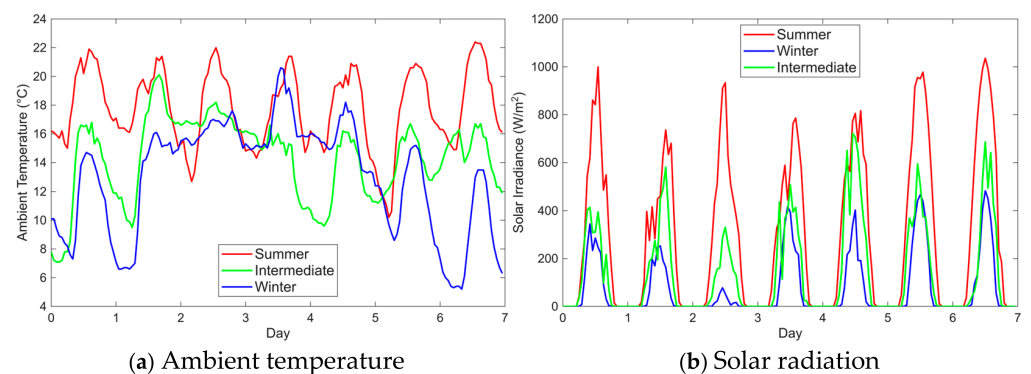


Figure 4. Weekly ambient temperature and radiation profile under three seasons.

4.2.1. Accumulated Hourly Profiles

Figure 5 compares the water tank temperature profiles of the solar thermal water heating system with and without TES under summer, intermediate, and winter conditions. The initial tank temperatures are 25 °C, 20 °C, and 15 °C for summer, intermediate, and winter, respectively, while the target temperatures are 50 °C, 55 °C, and 60 °C. During summer, after the water temperature reaches 50 °C, it stays around there for most of the week in the TES-integrated system, and the three daily draw events at 09:00, 13:00, and 19:00 cause only short drops, usually to around 43 °C, which is recovered almost immediately. In contrast, the system without TES also reaches about 50 °C during the day, but after the 19:00 draw, the temperature drops much more during the night, typically falling to around 37 °C by the following morning at 06:00. Under intermediate conditions, the effect of TES is not visible at the beginning of the week due to low solar radiation. On Day 1 and Day 3, the tank does not reach the 55 °C target, so both systems behave the same. For example, after reaching about 49 °C on Day 1, the temperature falls to 35 °C overnight in both cases, then on the second day drops even further to 32 °C after the 09:00 draw event. On Day 4, the tank reaches the target only briefly, so the TES effect is still limited. From Day 5 onward, the difference becomes more noticeable. The system with TES reaches about 55 °C and remains around 52 to 54 °C until the 09:00 draw event of Day 6, while the system without TES drops further to 38 °C at 05:00. On Day 6, the excess radiation is not enough for the TES to be fully charged, so the temperature drops gradually at night and reaches 46 °C at 08:00 on Day 7, without TES, which would have been 37 °C. In winter, both systems show identical temperature profiles because the 60 °C target is never reached and TES charging does not occur.

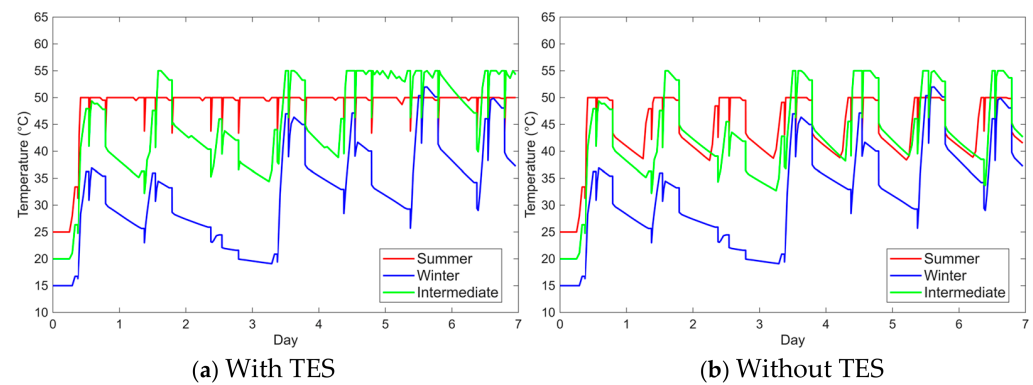


Figure 5. Variation of water temperature inside the storage tank with and without TES under three typical weather conditions.

Figure 6 presents the hourly thermal energy production of the solar thermal water heating system with and without TES over the selected seven-day periods. In this study, energy production refers to the amount of thermal energy captured by the system from solar radiation. In the system without TES, energy production stops once the water tank reaches the desired temperature, because no further heat can be usefully absorbed. In the system with TES, energy production can continue after the tank reaches the target temperature because the excess solar heat is absorbed by Therminol 55 and transferred to the PCM in the TES unit. The production profile follows the solar radiation pattern, with energy mainly generated during daytime and falling to zero at night. Summer shows the highest hourly production because of stronger solar irradiance, followed by the intermediate-weather period, while winter gives the lowest production due to limited solar availability. In the TES-integrated system, summer production reaches the highest values, with peaks of about 6.0 to 6.2 kWh on Days 1, 6, and 7. These values are higher than the system without TES, where the maximum summer peak is about 5.0 kWh. Under intermediate weather conditions, hourly production is lower and more irregular. The system without TES mostly produces peaks between about 1.0 and 3.0 kWh, while the TES-integrated system reaches about 3.5 to 4.2 kWh during the later part of the week when excess heat becomes available. However, on low-radiation days such as Day 1 and Day 3, both systems show similar behavior because the available solar energy is mainly used for direct water heating and not for storage. In winter, both systems have the lowest hourly production, with most peaks below 2.0 kWh. Curves for both with and without the TES system remain identical because the tank does not reach the 60 °C winter target temperature, so TES charging is not activated.

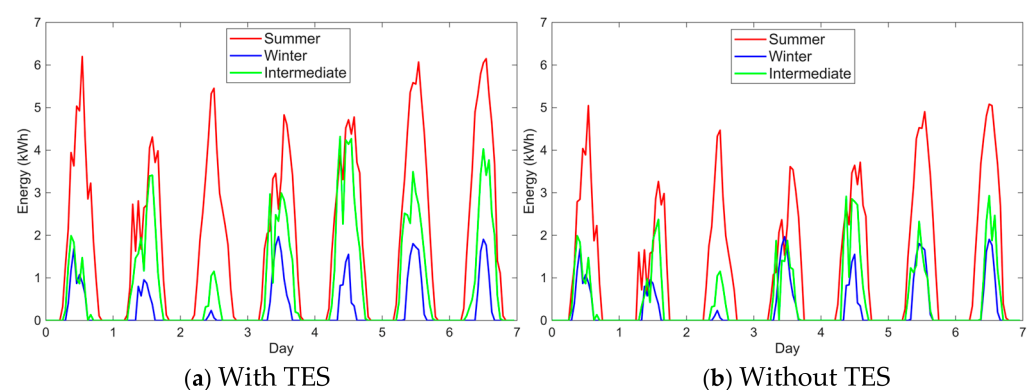


Figure 6. Hourly energy production with and without TES over a week under three typical weather conditions.

Figures 7 and 8 show the hourly thermal energy consumption of the solar thermal water heating system with and without TES under summer, intermediate, and winter conditions. In summer, for the system with TES, the maximum hourly consumption reaches about 2.8 kWh at the beginning of the week, and several repeated consumption events remain around 1.5 to 1.7 kWh during the rest of the week. Without TES, the main daytime consumption events are similar but less continuous, with peaks mostly around 1.5 to 1.8 kWh. The comparison shows that TES adds small but repeated useful heat delivery during nighttime and low-solar periods, when the system without TES falls close to zero. Under intermediate conditions, the TES effect is less uniform because solar radiation changes more strongly from day to day. With TES, the highest hourly consumption reaches about 3.0 kWh on Day 5, with other peaks of about 2.2 kWh on Day 2 and about 2.5 kWh near Day 6. Without TES, the highest value is slightly lower, close to 2.9 kWh, and the profile has fewer useful consumption periods between the main peaks. From Day 5 to Day 7, the system with TES shows more additional low-level consumption between the main draw recovery events, indicating that stored heat is being supplied back to the tank after TES charging. In winter, both systems show the same consumption profile because the tank does not reach the 60 °C target, so TES charging does not occur. The maximum hourly consumption is around 1.7 kWh near the end of the week, while on Day 3, it is almost zero due to very weak solar radiation.

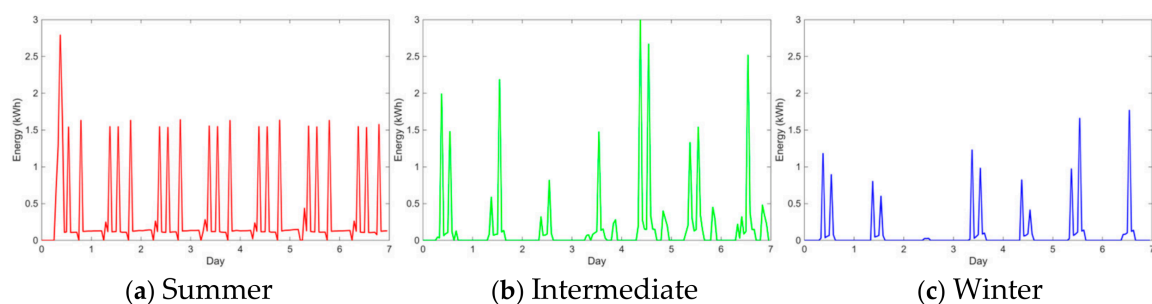


Figure 7. Hourly energy consumption with TES under three typical weather conditions.

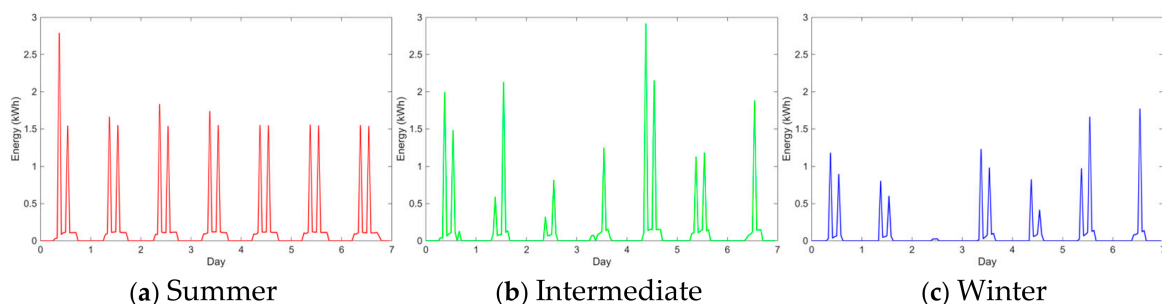


Figure 8. Hourly energy consumption without TES under three typical weather conditions.

4.2.2. Periodical Energy Profiles: Daily and Weekly

Figure 9a,b shows the daily thermal energy production of the solar thermal water heating system with and without TES. Summer gives the highest daily production for both systems because of strong solar radiation during the selected week. The TES-integrated system produces more energy than the baseline system on every summer day, increasing from 40.75 kWh on Day 1 to 52.29 kWh on Day 7, while the without-TES system ranges from 28.87 kWh to 38.46 kWh. Under intermediate weather conditions, daily production is lower and more variable because solar radiation changes from day to day. On low-radiation days, such as on Day 3, both systems show the same production because the tank does not reach the 55 °C target and TES charging is not activated. On higher-radiation days, especially on

Day 4 and Day 5, the TES-integrated system produces more energy because surplus heat becomes available for storage in Paraffin RT60 after the water heating demand is satisfied. In winter, both systems show the lowest daily production because of weak solar radiation and the higher target temperature of 60 °C. Graphs for both systems remain identical throughout the week, with production ranging from 0.40 kWh on Day 3 to 8.94 kWh on Day 4.

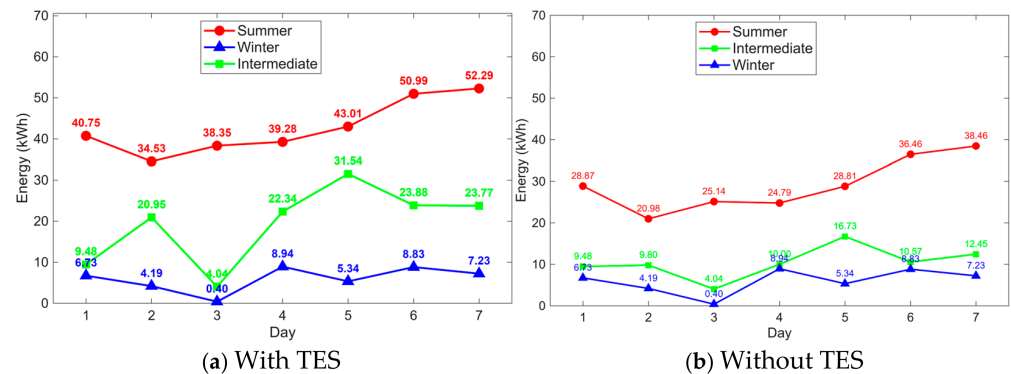


Figure 9. Daily energy production with and without TES.

Figure 10 shows the cumulative weekly thermal energy production with and without TES. With TES, the system produces 299.19 kWh in summer, 136.00 kWh under intermediate conditions, and 41.65 kWh in winter, while the corresponding values without TES are 203.5 kWh, 73.1 kWh, and 41.7 kWh. Compared with the system without TES, the TES-integrated system increases weekly production by about 47% in summer and 86% under intermediate conditions. In winter, both systems give almost the same cumulative value.

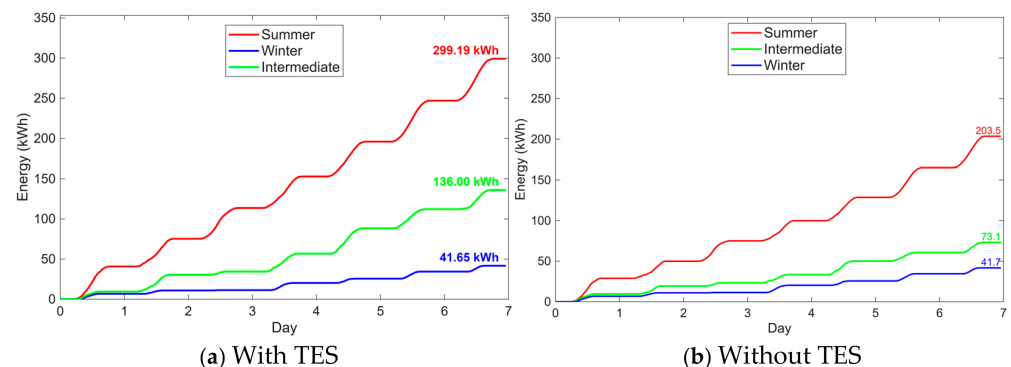


Figure 10. Cumulative weekly energy production with and without TES.

Figure 11 presents the daily thermal energy consumption of the solar thermal water heating system under summer, intermediate, and winter conditions. In summer, the benefit of TES is clearly observed. The daily consumption with TES is 12.98 kWh on Day 1, decreases to 11.10 kWh on Day 2, and then increases toward the end of the week, reaching 15.20 kWh on Day 6 and 15.55 kWh on Day 7. In comparison, the system without TES remains much lower, mostly between 4.18 and 5.14 kWh per day. Under intermediate conditions, daily consumption with TES varies from day to day because solar radiation is less consistent. It increases from 4.06 kWh on Day 1 to 6.31 kWh on Day 2, drops to 1.46 kWh on Day 3, and reaches the highest value of 11.64 kWh on Day 5. Without TES, the consumption is lower, with a maximum of 6.06 kWh on Day 5. In winter, both systems show the same daily consumption values, starting at 2.34 kWh on Day 1, decreasing to 1.64 kWh on Day 2, and then becoming almost zero on Day 3. It reaches the maximum value of 3.19 kWh on Day 6.

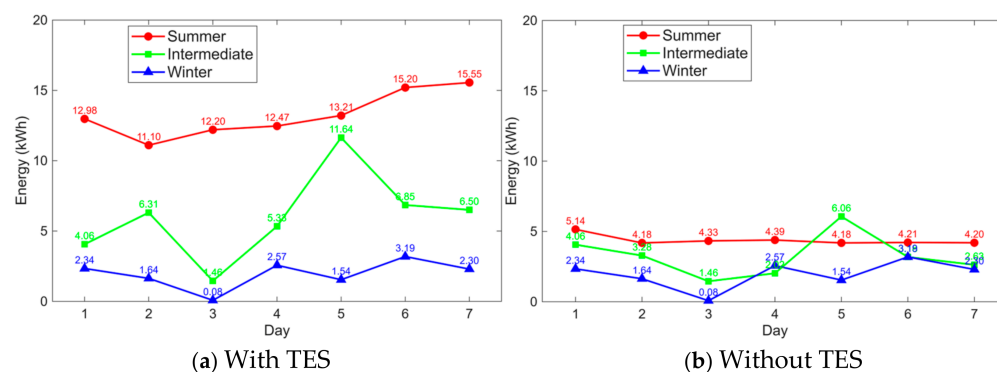


Figure 11. Daily energy consumption with and without TES.

Figure 12 shows the cumulative weekly energy consumption with and without TES. With TES, the cumulative consumption reaches 92.72 kWh in summer, 42.16 kWh under intermediate conditions, and 13.65 kWh in winter. Without TES, the corresponding values are 30.64 kWh, 22.69 kWh, and 13.65 kWh, respectively. Compared with the system without TES, the system with TES increases cumulative weekly consumption by 202.6% in summer and 85.8% under intermediate conditions.

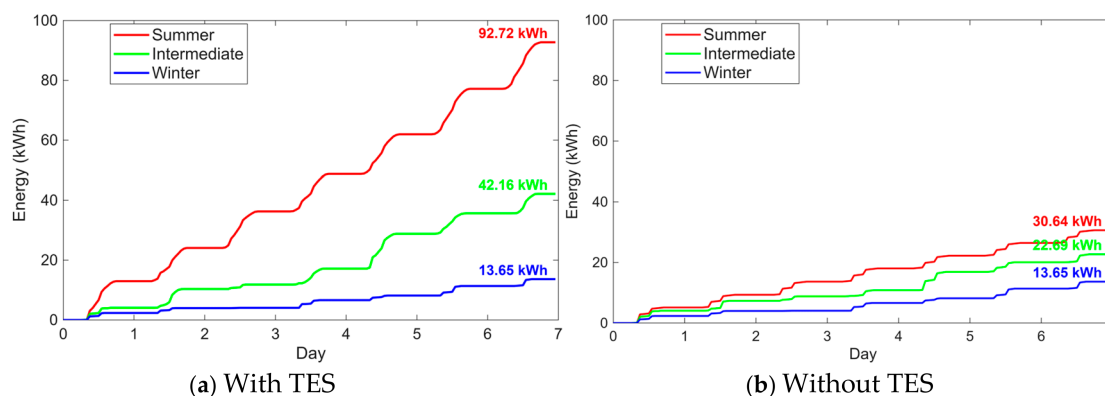


Figure 12. Cumulative weekly energy consumption with and without TES.

4.2.3. TES Charging and Discharging Profiles

Figure 13 shows the TES charging and discharging behavior under summer, intermediate, and winter conditions. In summer, the system switches from water heating to TES charging more frequently because the tank water reaches the 50 °C target very early. Charging occurs every day of the week and usually lasts for about 1 to 4 h. On Day 1, the peak value reaches the highest of about 2.5 kWh. After the draw event at 13:00, the TES charging is halted, and water is redirected to the thermal collector for quick heat gain. Then TES charging resumes, and the peak reaches about 1.6 kWh. Discharging starts after evening and continues for several hours until the radiation is available again on the following day. Initially, the system discharges 1.6 kWh for 1 to 3 h, and after that it supplies 0.3 kWh steadily for the rest of the night. Under intermediate conditions, the system switches to TES charging less often because the tank does not always reach the 55 °C target. Charging is limited during the early part of the week but becomes more visible from Day 5 to Day 7, with values close to 2.0 kWh. Discharging also occurs less frequently, reaching about 2.1 to 2.2 kWh from Day 5 to Day 7. In winter, no TES discharging occurs because Paraffin RT60 does not store useful excess heat during the day.

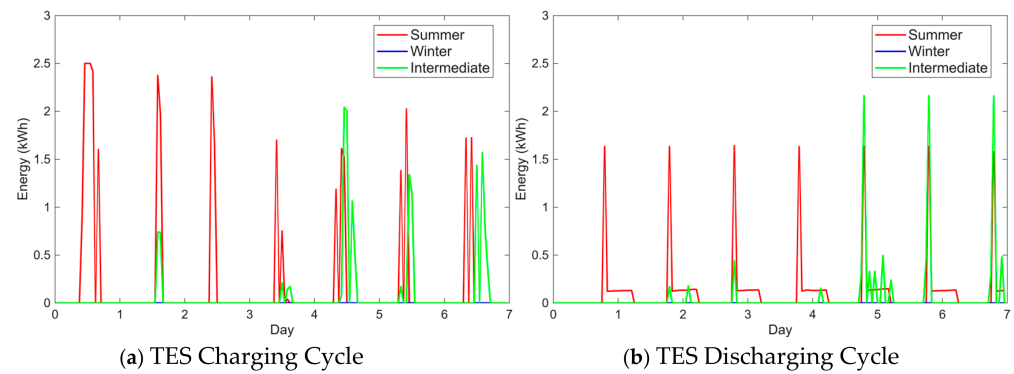


Figure 13. TES charging and discharging energy under three typical weather conditions.

Figure 14 presents the temperature variation of Paraffin RT60 under summer, intermediate, and winter conditions. In summer, Paraffin RT60 receives sufficient excess solar heat after the water tank reaches the 50 °C target temperature. Its temperature rises to the melting range, stores heat mainly as latent energy during phase change, and then increases further once melting is completed. The highest temperatures occur during strong charging periods, reaching above 110 °C on Day 1, around 130 °C on Day 3, and about 115 °C on Day 4. These peaks show that Therminol 55 transfers a large amount of surplus heat from the collector to the TES unit during high-radiation periods. At night and during low-solar periods, the temperature decreases as stored heat is released back to the water tank, but it does not fall below the melting range during the selected summer week. This indicates that Paraffin RT60 remains mostly in the liquid state and does not fully solidify. Under intermediate weather conditions, the temperature response is weaker and more irregular because solar radiation is moderate. Paraffin RT60 reaches about 55 °C near Day 2, showing sensible heating below the melting range, but little or no charging occurs on low-radiation days when the tank does not reach the 55 °C target. From Day 5 onward, stronger solar input allows Paraffin RT60 to enter the melting range and store part of the excess heat as latent energy. The stored heat is then used during nighttime to support the water tank, causing the temperature to decrease during discharge periods. In winter, the temperature remains almost unchanged because the tank never reaches the 60 °C target temperature. Therefore, no useful excess heat is available for TES charging, and Paraffin RT60 does not take part in heat storage during the selected winter week.

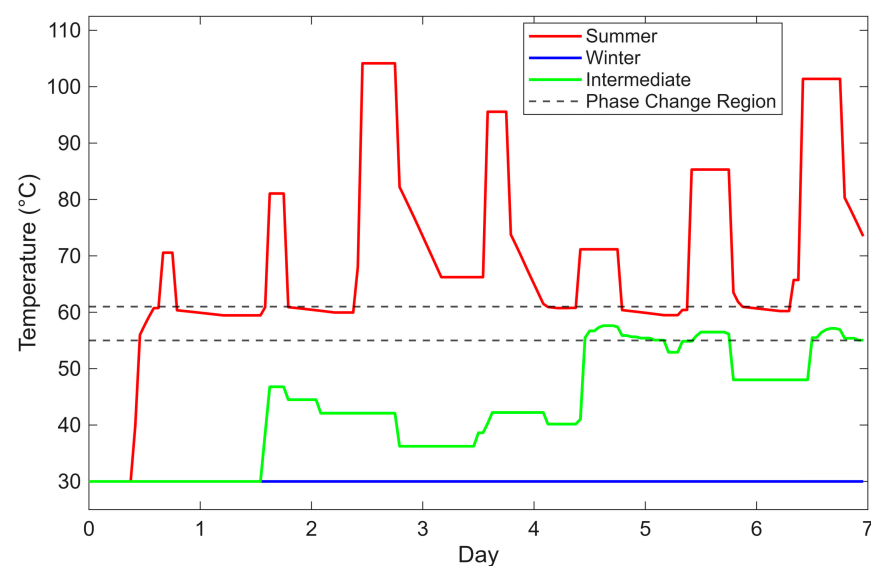


Figure 14. PCM temperature under three typical weather conditions.

4.2.4. Annual Performance and Economic Analysis

Figure 15 shows the annual useful energy and annual produced energy for the solar thermal system with and without TES. Without TES, the annual useful energy is 1274.55 kWh, while the system with TES increases it to 2327.59 kWh. This gives an 82.62% increase in annual useful energy due to TES. For annual produced energy, the system without TES produces 5342.88 kWh, while the TES-integrated system produces 6746.93 kWh, giving a 26.28% increase. The produced-to-used energy ratio decreases from 4.19 without TES to 2.90 with TES, showing that the TES-integrated system uses a larger share of the produced thermal energy. This represents a 30.85% improvement in the produced-to-used energy ratio with TES. These results show that the TES unit improves the overall annual performance by allowing more of the available solar thermal energy to be stored and later used, instead of being lost after the water tank demand is satisfied.

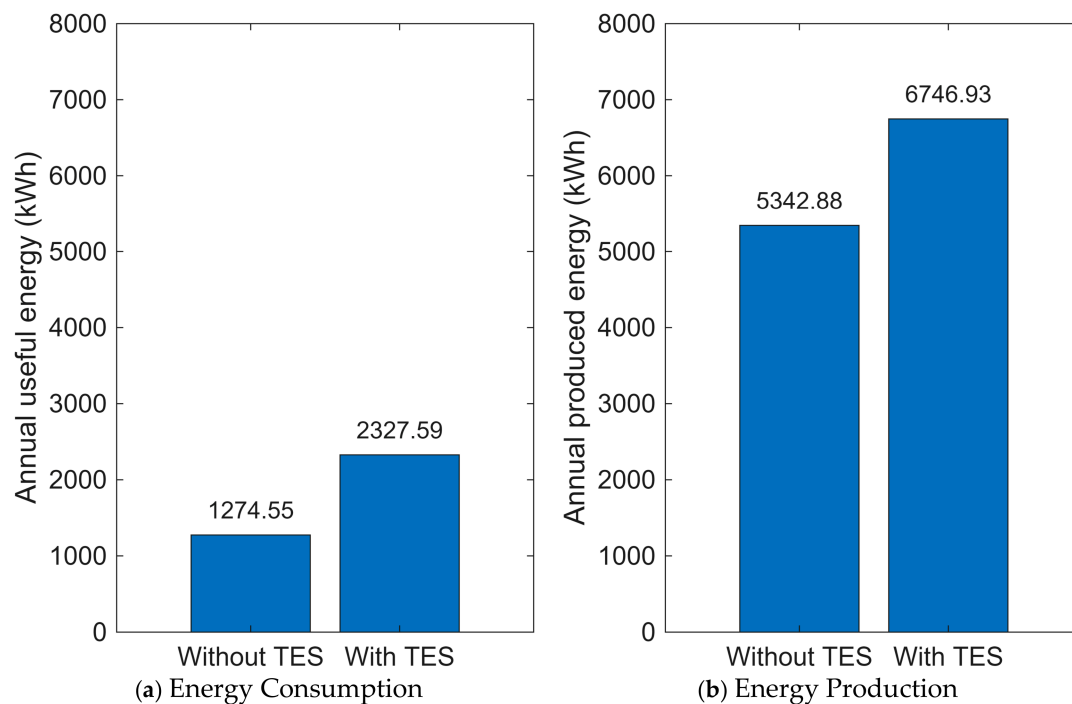


Figure 15. Annual energy production and consumption with and without a TES system.

Figure 16a,b present the levelized cost of energy for the solar thermal water heating system with and without TES, based on annual useful energy consumption and annual energy production, respectively. The calculation was carried out using a 25-year system lifetime [24], a 5% discount rate, annual operation and maintenance cost equal to 1% of the investment cost, and decommissioning cost equal to 5% of the initial investment [25]. The investment cost of the baseline system without TES was taken as 7500 NZD. For the TES-integrated system, the additional TES cost was calculated by considering the material cost and other supporting costs. Therminol 55 was used as the heat transfer fluid, with a cost of 800 NZD for 50 L. Paraffin RT60 was used as the phase change material. Since the model used 180 L of PCM and the PCM density was 0.88 kg/L, the PCM mass was 158.4 kg. Using a PCM cost of 12 NZD/kg, the RT60 cost was approximately 1900 NZD. Therefore, the total TES material cost was 2700 NZD. An additional 1200 NZD was included for other TES-related costs, giving a total TES cost of 3900 NZD. As a result, the total investment cost of the TES-integrated system was 11,400 NZD.

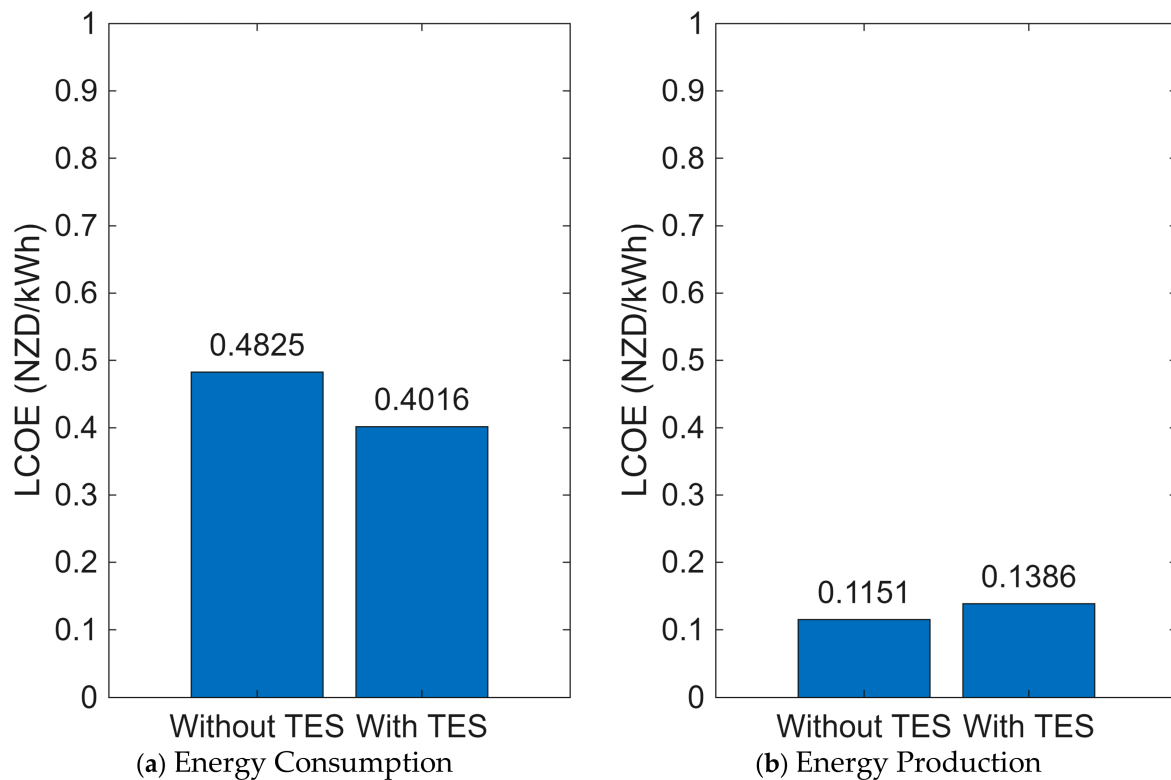


Figure 16. LCOE with and without a TES system.

As shown in Figure 16a, the consumption-based LCOE decreased significantly from 0.4825 NZD/kWh for the system without TES to 0.4016 NZD/kWh for the system with TES, corresponding to a 16.77% reduction. This result is more important for the present study because useful energy consumption represents the actual thermal energy delivered to the water tank and used to meet hot water demand. TES increased the annual useful energy consumption from 1274.55 kWh to 2327.59 kWh, representing an 82.62% increase. Therefore, although the TES unit increased the investment cost, the larger improvement in useful energy delivery reduced the life-cycle cost per unit of useful heat. Figure 16b shows that the production-based LCOE increased from 0.1151 NZD/kWh without TES to 0.1386 NZD/kWh with TES, corresponding to a 20.37% increase. This occurs because the annual produced energy increased from 5342.88 kWh to 6746.93 kWh, giving a 26.28% increase. However, produced energy alone does not directly represent system benefit, because part of the produced heat will not be used by the water tank. For this reason, the consumption-based LCOE provides a more meaningful economic indicator for the TES-integrated system.

5. Conclusions

This study evaluated a solar thermal water heating system integrated with thermal energy storage under New Zealand weather conditions. A conventional solar thermal system without TES was used as the baseline and compared with a TES-integrated system that uses Paraffin RT60 as the phase change material and Therminol 55 as the heat transfer fluid. The main conclusions are summarized as follows.

1. The TES-integrated system improved water tank temperature stability when excess solar heat was available. The greatest improvement occurred in summer, where stored heat reduced temperature drops during nighttime and low-solar periods.

2. Under intermediate weather conditions, the TES benefit was moderate and depended on daily solar availability. TES charging occurred only when the tank reached the 55 °C target temperature, while low-radiation days showed limited storage contribution.
3. In winter, TES provided no additional benefit because the available solar radiation was not sufficient to raise the tank to the 60 °C target temperature. Therefore, TES charging was not activated, and the system with TES behaved the same as the system without TES.
4. TES integration increased annual energy production from 5342.88 kWh to 6746.93 kWh, representing a 26.28% increase. Useful energy consumption increased more significantly, from 1274.55 kWh to 2327.59 kWh, corresponding to an 82.62% increase.
5. Annual useful energy consumption increased from 1274.55 kWh without TES to 2327.59 kWh with TES, corresponding to an 82.62% increase. The produced-to-used energy ratio also decreased from 4.19 to 2.90, which showed a 30.85% improvement in solar energy utilization.
6. The cumulative weekly results showed clear seasonal variation in both energy production and useful consumption. With TES, summer production was 120.0% higher than intermediate conditions and 618.3% higher than winter, while intermediate production was 226.5% higher than winter. Moreover, for useful consumption, the TES-integrated system had 119.9% higher consumption in summer than in intermediate conditions, while intermediate consumption was 208.9% higher than winter.
7. The economic analysis showed that TES integration is economically favorable when the system is evaluated based on useful energy consumption. The consumption-based LCOE decreased significantly from 0.4825 NZD/kWh without TES to 0.4016 NZD/kWh with TES, while the production-based LCOE increased only slightly from 0.1151 NZD/kWh to 0.1386 NZD/kWh. The consumption-based LCOE provides a more practical measure of economic feasibility for the TES-integrated system, as it reflects the actual useful thermal energy delivered to the water tank.

Future work will extend the present study by comparing the TES-integrated solar thermal water heating system with a solar PV water heating system coupled with electrical energy storage. This would allow comparison between thermal storage and battery-based storage under the same New Zealand weather conditions.

Author Contributions: Conceptualization, M.A.H. and J.W.; methodology, M.A.H., D.D., and B.A.; software, M.A.H. and W.L.; formal analysis, M.A.H., D.D., J.W., and M.A.; investigation, M.A.H., J.W., and M.A.; resources, M.A.H. and B.A.; data curation, J.W.; writing—original draft preparation, M.A.H. and J.W.; writing—review and editing, M.A.H., W.L., B.A., and J.W.; visualization, M.A.H.; supervision, J.W.; project administration, J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: I, Manam Ahmed, am employed by ECS Mid-Atlantic, LLC. However, ECS Mid-Atlantic, LLC was not involved in this research and did not provide any financial support, funding, sponsorship, or other resources for this study. My contribution to this research was made independently and in my personal academic capacity. Therefore, my employment with ECS Mid-Atlantic, LLC has no financial or commercial relationship with this research that could be construed as a potential conflict of interest. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TES	Thermal energy storage
DNI	Direct normal irradiance
COP	Coefficient of performance
HTF	Heat transfer fluid
PCM	Phase change material
NIWA	National Institute of Water and Atmospheric Research
PV	Photovoltaic
NZD	New Zealand dollar

Nomenclatures

The following nomenclatures are used in this manuscript:

A_c	Solar thermal collector area (m ²)
A_{tank}	Surface area of water tank (m ²)
C_p	Specific heat capacity of water (kJ/kgK)
$C_{p,pcm}$	Specific heat capacity of PCM (kJ/kgK)
$C_{p,htf}$	Specific heat capacity of HTF (kJ/kgK)
C_b	Bond conductance between tube and absorber plate (W/mK)
D	Outer diameter of collector tube (m)
D_i	Inner diameter of collector tube (m)
D_t	Decommissioning cost (NZD)
E_{pcm}	Energy absorbed or released by the PCM (kWh)
f	Friction factor
F	Fin efficiency
F'	Collector efficiency factor
F_r	Collector heat removal factor
G	Horizontal solar radiation (W/m ²)
G_t	Solar irradiance incident on tilted collector surface (W/m ²)
h_{fi}	Convective heat transfer coefficient (W/m ² K)
i	Hour index
I_t	Investment cost (NZD)
k	Thermal conductivity of water (W/mK)
k_{plate}	Thermal conductivity of absorber plate (W/mK)
L	Latent heat of PCM
m	Fin parameter (m ⁻¹)
$\dot{m}$	Mass flow rate of water (kg/s)
m_{use}	Used water mass (kg)
M	Total mass of water in the tank (kg)
Nu	Nusselt number
O_t	Operation and maintenance cost (NZD)
Pr	Prandtl number
q_i	Hourly energy supply to the water tank (kWh)
Q_{all}	Total solar energy received by the collector (kWh)
Q_{eff}	Useful thermal energy delivered to the water tank (kWh)
Q_{loss}	Heat loss from the water storage tank (kWh)
Q_u	Useful heat gain from the solar collector (kWh)
r	Discount rate
Re	Reynolds number
S	Annual energy output (kWh)
t	Year index
T	Project lifetime

T_a	Ambient temperature (°C)
T_{cold}	Cold water temperature during draw event (°C)
T_f	Final water tank temperature (°C)
$T_{f,i-1}$	Water temperature of previous hour (°C)
T_i	Inlet water temperature (°C)
T_{melt}	Melting temperature of the PCM (°C)
$T_{pcm,i}$	Initial temperature of the PCM (°C)
$T_{pcm,f}$	Final temperature of the PCM (°C)
T_{max}	Maximum water tank temperature (°C)
W	Spacing between collector tubes (m)
δ	Absorber plate thickness
θ	Collector tilt angle
μ	Dynamic viscosity (Pa · s)
τ_α	Transmittance-absorptance

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