Journal of Sustainable Development Indicators

http://www.sdewes.org/jsdi

Year 2026, Volume 2, Issue 1, 2030673

Original Research Article

Design and Assessment of a Hybrid Domestic Hot Water System Using Molten Salt and Concentrated Solar Energy for Smart Buildings: A Case Study in Ankara, Turkey

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Cite as: Kiriş, N., Bal, U., Bulanık Durmuş, G., Turhan, C., Design and Assessment of a Hybrid Domestic Hot Water System Using Molten Salt and Concentrated Solar Energy for Smart Buildings: A Case Study in Ankara, Turkey, J. sustain. dev. indic., 2(1), 2030673, 2026, DOI: https://doi.org/10.13044/j.sdi.d3.0673

ABSTRACT

Concentrated solar power plants, a well-established technology, employ efficient thermal energy storage systems, utilizing molten salts. This study endeavours to diminish energy consumption in conventional residential hot water systems through the utilization of solar energy and the molten salt's thermal storage capacity. To achieve this objective, a pioneering hybrid domestic hot water system is proposed, integrating solar power for application within smart building contexts. This hybrid configuration encompasses solar heliostats to amplify solar irradiance, a dedicated molten salt reservoir for efficient thermal energy storage, and a heat exchanger facilitating the heating of domestic hot water. A specific molten salt mixture, comprising 60% of Sodium Nitrate ($NaNO_3$) and 40% of Potassium Nitrate (KNO_3), is meticulously selected for its superior thermal capacity. Solar energy is effectively harnessed to leverage renewable and environmentally sustainable energy sources, focusing sunlight onto the molten salt reservoir within the smart building infrastructure. Subsequently, the stored thermal energy within the reservoir is efficiently utilized to heat water through the heat exchanger. The performance evaluation of this hybrid system is meticulously conducted through rigorous experimentation within a test building located in Ankara, Turkey.

KEYWORDS

Concentrated Solar Power, Domestic Hot Water, Hybrid Systems, Solar Power.

INTRODUCTION

Energy has become essential in numerous aspects of life with technological advancements driving an increased demand [1]. In this context, Turhan et al. [2] demonstrated that the effectiveness of data-driven control strategies significantly enhance thermal system performance by optimizing operational efficiency and adaptive response under varying boundary conditions. Similarly, Turhan et al. [3] investigated the impact of climate change on indoor environmental quality, revealing that dynamic thermal control approaches are increasingly necessary to maintain occupant comfort in Mediterranean and comparable climate zones.

Initially, fossil fuels were utilized to meet this demand, but their combustion led to severe atmospheric damage through the greenhouse gas effect [4]. For instance, Fayyazbakhsh et al. [4] systematically analyzed the contribution of engine-related emissions to air pollution and global warming, highlighting the dominant role of fossil fuel–based energy systems. Turhan et al. [5] demonstrated that building-integrated green wall and roof applications can mitigate energy consumption and associated emissions, offering nature-based alternatives to conventional systems. Furthermore, Chen et al. [6] quantified the potential of solar thermal integration combined with thermal energy storage to significantly reduce residential greenhouse gas emissions. Together, these studies emphasize the urgent need to transition from fossil fuel–dependent energy systems toward sustainable and low-carbon thermal solutions, directly supporting the motivation of the proposed hybrid solar and molten salt Domestic Hot Water (DHW) system. To mitigate this, researchers have focused on identifying clean and renewable energy sources. For instance, Zhou et al. [7] examined the role of renewable energy technologies and international technology transfer in reducing carbon footprints while supporting industrial growth. Turhan et al. [8] demonstrated the potential of renewable energy–based recycling and reuse strategies to support sustainable post-disaster and urban energy solutions. Similarly, Turhan and Saleh [9] evaluated the energy-saving potential of building-integrated small-scale wind energy systems, emphasizing the importance of decentralized renewable technologies for the built environment. Among these alternatives, solar energy stands out due to its abundance, environmental compatibility, and versatility, making it particularly suitable for both industrial-scale and residential energy applications, including domestic hot water production systems.

In regions with cold winters, heating requirements are the primary driver of energy consumption in the building sector. In the residential sector, the DHW systems account for a significant portion, the DHW accounts for 40% of the total energy demand in the residential sector, while the remaining consumption is attributed to space heating, cooling, lighting, and household appliances [10]. According to data provided by the International Energy Agency (IEA) for 2020, around 13.2% of the energy consumed by buildings worldwide (of total global building energy consumption) is for the DHW, total 0.39 gigatonnes of oil equivalent (Gtoe) or 16.2 exajoules (EJ) [11]. The share of energy used for the DHW from solar thermal energy systems varies across regions and building types. Considering the distribution of solar thermal systems globally, with 86% comprising large DHW systems such as used in multi-family houses, tourism, and public sector (51% of 86%) and the DHW systems for single-family houses (35% of 86%), along with the 1.6 EJ (0.038 Gtoe) of solar thermal heat consumption in buildings in 2020 [12]. Currently, solar thermal energy covers only 8.4% of the global DHW demand, indicating that a further 12.1% of total building energy could potentially be saved by maximizing solar thermal integration.

A significant portion of this thermal energy is dedicated to space heating, which can be notably decreased through enhancements in the thermal efficiency of building envelopes and heating/ventilation systems. To enhance system energy efficiency and reduce operational energy consumption, numerous researchers have been focusing on identifying clean and renewable energy sources [13]. Solar energy, a prominent renewable option, offers significant advantages such as being pollution-free, abundant, and easy to harness. Consequently, leveraging solar energy is crucial for restructuring energy systems and achieving carbon neutrality. Solar photovoltaic thermal (PVT) technology, which enables simultaneous photovoltaic and photo thermal utilization, is gaining increasing interest as a low-energy consumption heat source for domestic hot water [14]. Consequently, there is a widespread tightening of national building regulations aimed at reducing the space heating demand of both newly constructed and renovated buildings, moving them closer to nearly Zero Energy Building standards [15]. Solar power emerges as a viable solution, offering both environmental benefits and economic feasibility for reducing building energy consumption. Over the past few decades, energy consumption for heating buildings has steadily decreased, but the energy demand for producing the DHW has remained relatively stable. As a result, the proportion of energy used for the DHW in the overall energy balance of buildings is becoming increasingly prominent [16]. Given these trends, it is evident that enhancing the energy efficiency of the

DHW production and system operation is a pivotal area for further research and technological advancements. Understanding the current state-of-the-art and exploring new avenues in this domain is imperative. Although existing review articles concentrate on particular the DHW technologies like solar systems, heat storage tanks, and domestic hot water recovery solutions, they frequently overlook a comprehensive viewpoint [17-20].

The International Standards of EN 15316-3-1 and EN 15316-3-2 describe the method of energy use calculations in the DHW systems. The standards also aim to reduce energy consumption of these systems by evaluating the system with three main sections; building the DHW needs, distribution and generation. Recent studies have revealed a surprisingly low energy efficiency in the DHW systems, with significant heat loss occurring before the hot water reaches its point of use. The efficiency of the DHW production and distribution varies greatly depending on key parameters such as plumbing layout, pipe size and location, level of pipe insulation, size of the water storage tank, amount of hot water usage, and the time-varying profile of DHW consumption [16]. A significant portion of energy loss occurs within the distribution system of the DHW systems. Depending on whether the DHW system incorporates a circulation loop, distribution loss can occur in both circulation and distribution pipes or solely in distribution pipes, extending from the DHW source to the points where water is drawn. According to the research distribution heat loss across various building types, including apartment buildings, detached houses, and commercial buildings. Findings revealed that in buildings with circulation loops, up to 73% of energy is lost due to the dispersed locations of taps and the considerable distance from the technical room, where the district heat connection point is situated [19]. Accordingly, the whole system should be taken into consideration in design process of the building. For instance, Xi et al. [21] developed a solar-assisted ground-coupled heat pump system for DHW supply purposes. The authors simulated the developed system in a globally recognized, flexible component-based software package used by engineers and researchers to simulate the behaviour of transient systems, particularly in the fields of renewable energy, solar thermal processes, and building energy performance (TRNSYS) [22] for a 20-year lifetime and concluded that 20% of the total energy was saved by using the hybrid system. On the other hand, thermal energy storage systems play an important role in designing energy-efficient systems for the smart buildings. For instance, Mazman et al. [23] used Phase Change Materials (PCMs) in solar domestic hot water systems by adding a PCM module at the top of the water tank. The authors stated that PCM increased the temperature of the water by 3-4 °C.

The potential for energy savings through solar integration remains a critical pillar for achieving Nearly Zero Energy Buildings (NZEB). In this context, Tsalikis and Martinopoulos [24] emphasize that the optimization of solar thermal systems can significantly reduce the dependency on fossil fuels for domestic heating. To this aim, on the other hand, in the literature, $NaNO_3$ and KNO_3 are used due to their high heat transfer performances [25]. However, the application of highly efficient thermal energy storage systems in the smart buildings is quite limited. Despite significant advancements in solar thermal technologies, a review of the state of the art reveals three critical gaps. First, while low-temperature systems are well-documented, the integration of high-temperature CSP for residential DHW remains under-researched. Second, the use of binary molten salts (60% of $NaNO_3$ and 40% of KNO_3) as a thermal buffer in building applications is rarely explored compared to industrial scales. Finally, there is a lack of dynamic simulations evaluating the synergy between these technologies in cold-dry climates. To this aim, the novelty of the study is to develop a hybrid system by combining traditional DHW system with solar energy and energy storage systems. The proposed system is simulated and tested for a real building in Ankara/Turkey. It is worth to remind that the findings of this study directly align with the United Nations Sustainable Development Goals (SDGs), specifically targeting Goal 7 (Affordable and Clean Energy) and Goal 11 (Sustainable Cities and Communities). Therefore, this research addresses two critical challenges in the transition to sustainable urban environments: the high carbon dependency of the DHW production in high-density residential buildings and the technical difficulty of scaling down industrial-grade concentrated solar power (CSP) for urban applications. Moreover, while conventional solar thermal systems often struggle to meet the massive energy demands of multi-story buildings during winter periods, this study proposes a high-temperature molten salt configuration to overcome these limitations.

MATERIALS AND METHODS

The evaluation of the proposed solar thermal system requires a multidisciplinary approach that integrates thermodynamic modelling, site-specific meteorological data, and architectural requirements. This section details the fundamental framework of the study, beginning with the selection of the case study building and the specific environmental variables of the location, which serve as the primary inputs for the system's performance simulation.

Scope and Geographical Context

A hybrid system is designed for DHW supply for an existing building which is located in Ankara-Turkey. Ankara is the capital city of the Turkey while the location is on Csa Climate Zone according to the Köppen-Geiger Climate Classification [26]. Global irradiance values are depicted for the building in Figure 1 [27]. The figure indicates that global irradiance is around 350 W/m^2 and 50 W/m^2 per day for summer and winter months, respectively. Daily average global irradiance value is 185.16 W/m^2 throughout the year. Therefore, it is logical to note that solar energy can be used for the case building.

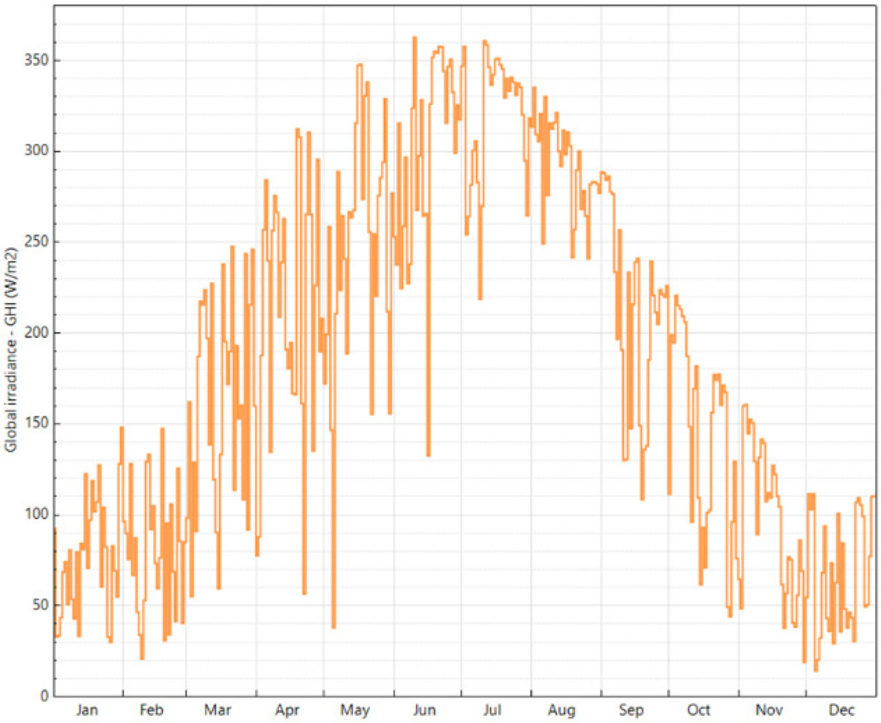

Figure 1. Daily global irradiance chart of Ankara, Turkey [27]

Case Study

The case building has 17 stories with 34 apartments. 2 apartments are included in each floor. Total construction area of the building is 1784 m^2 while it has a total floor area of 6812 m^2. In addition, average area per person is 50.1 m^2. Figure 2 shows the AutoCad [28] Drawing of the case building. According to the details in AutoCad Drawings, the case building is also designed in a 3D sketch program [29]. The energy consumption of the building is 154 kWh/m^2 year while each apartment consumes 100 liters water per day for DHW purpose. Average annual DHW energy consumption is 34% of the total energy consumption of the building. The existing DHW system in the building is a traditional hot water boiler.

The system design revolves around key components, namely the Molten Salt Tank, Water Tank, Heliostats, and Salt Mixture. All calculations and analyses have been carried out according to the specifications and characteristics of these components. Each plays a crucial role in the overall functionality and efficiency of the system. The Molten Salt Tank serves as a crucial reservoir for storing molten salt, ensuring continuous heat transfer within the system. The Water Tank, on the other hand, functions as a storage unit for water, facilitating the generation of steam for power generation. Heliostats, comprising mirrors or reflective surfaces, are pivotal in directing and concentrating sunlight onto the receiver for thermal energy collection. Lastly, the Salt Mixture serves as a medium for storing and transferring thermal energy within the system. Together, these components form the backbone of the system, enabling effective harnessing and utilization of solar thermal energy. The proposed system also includes a recirculation loop to ensure that hot water is immediately available at the taps and to maintain the required temperature throughout the building's distribution network. This recirculation is a critical component of the simulation, as it accounts for a significant portion of the thermal losses in the pipes (estimated at 5 kW in the new model). Table 1 indicates the specifications of the molten salt tank, water tank, heliostats, water pump, salt mixture. The equipment listed in Table 1 was selected based on their proven compatibility with high-temperature molten salt applications and their commercial availability for the scale of the proposed smart building system. These specific components (heliostats, molten salt pump, heat exchanger) represent a balance between high-performance industrial standards and the requirements of a residential-scale CSP integration. The specific binary mixture was selected because it is considered the industry standard for the CSP applications. It offers the most reliable, safe, and cost-effective solution for high-temperature thermal storage compared to other alternatives.

Table 1. Specification of system components

Component	Specifications
Molten Salt Tank	Floor Space: 1 m^2, Height: 2 m
	Volume: 2000 L (2 m^3)
	Surface area: 9.1 m^2
	Material: Stainless AISI316
Water Tank	Floor Space: 2.4 m^2, Height: 1.66 m
	Volume: 4000 L (4 m^3)
	Surface Area: 13.91 m^2
	Material: Stainless AISI316
Heliostats	The system has 45 mirrors.
	Area of each system: 6.2 m^2

Salt Mixture	$NaNO_3$: %60 = 1200 L = 1.2 m^3 If 1 m^3 = 2260 kg, 1.2 m^3 =2712 kg KNO_3: %40 = 0.8 m^3 = 800 L If 1 m^3 = 2110 kg, 0.8 m^3 = 1688 kg

It is worth to note that the system components and specifications listed in Table 1 were selected based on commercially available products, industry-standard design values for molten salt based CSP systems, and their suitability for residential-scale applications.

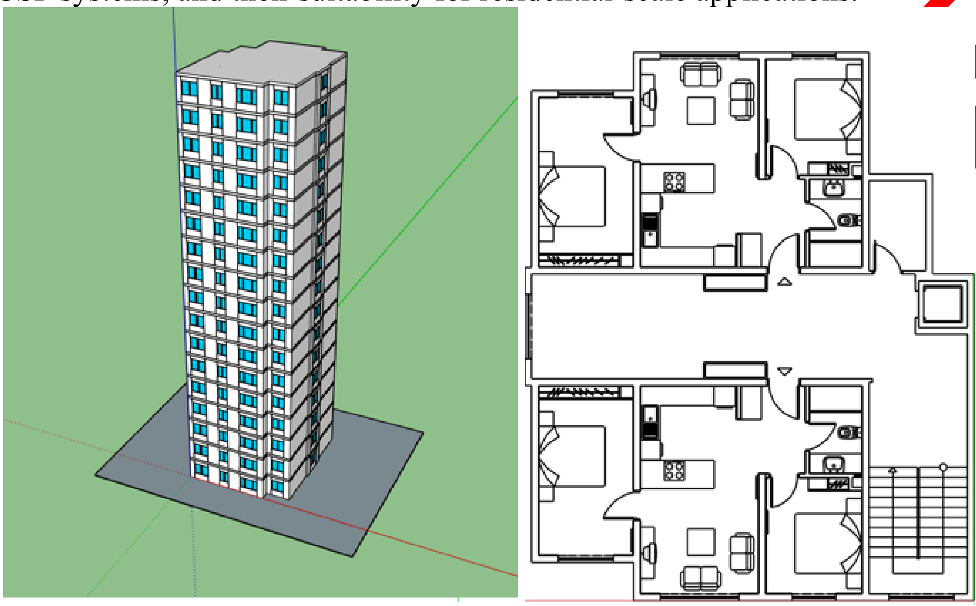

Figure 2. The 3D model (left) and architectural plan (right) of the case building

The system sizing was performed using a "Critical Month" approach (typically January for Ankara), ensuring that the heliostat field provides sufficient thermal energy to the molten salt loop even during the lowest solar radiation periods. The storage tank acts as a thermal buffer to bridge the 24-hour demand cycle. The system was designed based on dynamic simulation across a full meteorological year, rather than a static average. However, the sizing of the heliostat field and the molten salt storage capacity was specifically optimized to ensure a high solar fraction even during the low-radiation winter months. Alongside the traditional boiler system, the proposed hybrid DHW system consists of 45 heliostats with tracking system (6.2 m^2 area for each), each includes flat mirror in order to reflect sunlight toward molten salt tank, a molten salt tank with a capacity of 2000 liters and a hot water tank with a capacity of 4000 liters (Figure 3). Heliostats are designed to follow the angle and direction of the sun, therefore, the loss of solar radiation is aimed to decrease in the study. Reflected radiation from heliostats reaches the molten salt tank and heat the molten salt. The molten salt consists of 60% $NaNO_3$ and 40% KNO_3 mixture and molten salt tank is placed over the hot water tank. Heat coming from the heliostats is stored in molten salt tank and the heat is transferred to the water, which has an average temperature of 12.3 °C, by a heat exchanger. The reason of using molten salt is to store heat for longer hours than water. Thus, the energy consumption can be decreased sufficiently. General overview of the system is given in Figure 4.

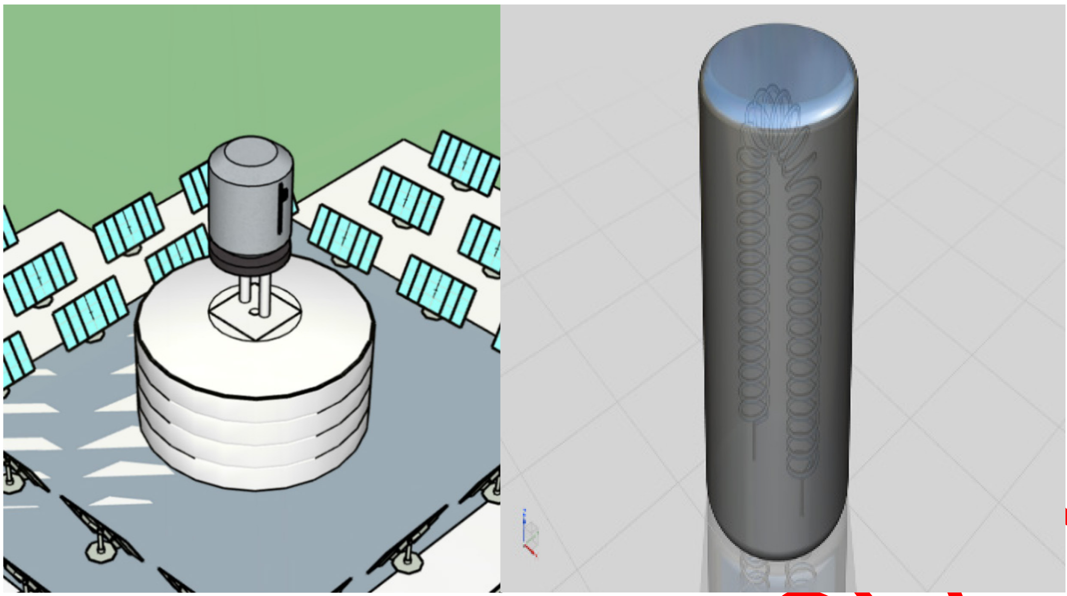

Figure 3. Modelling of the molten salt and hot water tank (left) and heat exchanger in molten salt tank (right)

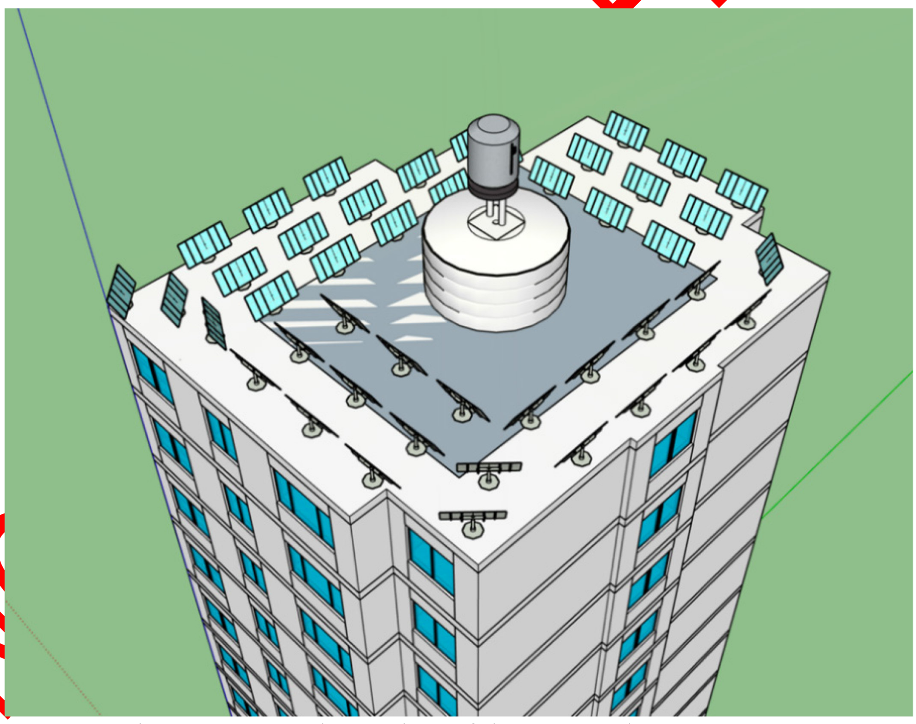

Figure 4. General overview of the proposed DHW system

Thermodynamic analysis

A thermodynamic analysis of the proposed system was conducted by formulating mass and energy balances for the control volumes. Several assumptions were considered as the system operates steadily, turbines and pumps operate under isentropic conditions, negligible pressure drop occurs in the pipeline, the condenser produces saturated liquid, while the evaporator outputs saturated steam and any changes in potential and kinetic energies are deemed insignificant.

Energy analysis from 1st law of thermodynamics for the system:

$$\dot{Q} - \dot{W} + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gZ_i\right) - \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gZ_e\right) = \frac{dE_{cv}}{dt} \quad (1)$$

The net output power of the system is obtained as:

$$W_{net} = W_{turbine} - W_{pump} \quad (2)$$

From the heliostats to the receiver, the rate of heat transfer is expressed as [30]:

$$Q_{sun} = A_h \; N \; DN \quad (3)$$

$$Q_h = n_h \; Q_{sun} \quad (4)$$

where A_h,N,DNI, n_h, Q_{sun} are heliostat surface area, number of heliostats, direct normal irradiance, heliostat efficiency and heat transfer rate from sun respectively. The receiver doesn't completely transfer heat because of losses from convective, conductive, and radiative heat transfer mechanisms. These losses were quantified as [31]:

$$Q_{losses} = h_a A_h (T_r - T_0) + \sigma \, \varepsilon \, (T_r^4 - T_0^4) \quad (5)$$

where h_a, T_r, T_0, σ, ε are convective heat transfer coefficient, solar receiver surface temperature, ambient temperature, Stefan–Boltzmann constant and emissivity of the receiver, respectively.

The instantaneous efficiency of the heliostat field is calculated considering the cosine effect, shadowing, and blocking factors:

$$\eta_{field} = \rho_{mirror} \cdot \cos(\theta_{inc}) \cdot f_{att} \cdot f_{shadow} \cdot f_{block} \quad (6)$$

The field efficiency, η_{field}, represents the overall optical performance of the solar collector field and is defined as the product of several loss factors. The term ρ_{mirror} denotes the mirror reflectivity, indicating the fraction of incident solar radiation reflected by the heliostat surfaces. The cosine term, $\cos(\theta_{inc})$, accounts for cosine losses associated with the angle of incidence of solar radiation on the mirror surface. The attenuation factor, f_{att}, represents atmospheric losses due to absorption and scattering of solar radiation as it travels from the mirrors to the receiver. The shadowing factor, f_{shadow}, accounts for the reduction in effective reflecting area caused by mutual shading among heliostats, while the blocking factor, f_{block}, represents losses occurring when reflected rays are physically obstructed by neighbouring heliostats. Together, these factors determine the fraction of incident solar energy that is effectively delivered to the receiver.

Furthermore, the energy balance for the molten salt storage tank, accounting for the thermal losses mentioned in Table 2, is expressed as the follow.

$$M_{salt} C_p, salt \frac{dT_{salt}}{dt} = \dot{Q}_{solar}, in - \dot{Q}_{load}, out - UA_{tank}(T_{salt} - T_{amb}) \quad (7)$$

System Assumptions and Design Parameters

To ensure the accuracy and reproducibility of the thermodynamic analysis, the following technical assumptions were integrated into the TRNSYS and SAM models. These values are based on industry standards for central receiver systems using molten salt storage. The modelling assumptions and parameter values in Table 2 are based on established literature for molten salt thermal storage systems and standard design practices adopted in TRNSYS and CSP-related simulations [21,25, 30].

Table 2. Assumptions for the calculations.

Parameter	Symbol	Value	Unit
Heliostat Reflectivity	ρ	0.88	-
Receiver Solar Absorptivity	α	0.94	-
Intercept Factor (Annual Avg)	γ	0.89	-
Molten Salt Heat Capacity	C_p	1.51	kJ/kg·K
Heat Exchanger Effectiveness	ϵ	0.85	-
Tank Insulation Conductivity	k	0.04	W/m·K
Pipe Thermal Losses (Assumed)	Q_{pipe}	5	kW
Storage Tank Losses (Assumed)	Q_{tank}	20	kW

Economic Analysis

The economic analysis of the system entails a comprehensive evaluation of the costs associated with its components, as outlined in Table 2. This table provides a detailed breakdown of the expenses incurred for each component, allowing for a thorough understanding of the financial implications of the system's implementation. By scrutinizing these costs, stakeholders can assess the feasibility and profitability of investing in the proposed system, thus informing decision-making processes regarding its development and deployment.

The overall cost of the system was determined by adding up the costs of its individual subsystems.

$$Z_{total} = Z_{moltensalttank} + Z_{watertank} + Z_{heliostats} + Z_{waterpump} + Z_{saltmixture} \tag{8}$$

Using Equation 8, the total cost of the system is calculated to be $52,955.85, and considering the workmanship as 20%, total cost of the system is:

$$52955.85\ \$ + 20\%\ (\text{workmanship}) = 63547.02\ \$ \tag{9}$$

Table 3. Costs of system components

Component / Parameter	Unit Cost	Reference / Data Source
Heliostat Field	\$150 - \$200 / m^2	IRENA (2023) / CSP Industry Reports [32]
Molten Salt (60%/40%)	$2.5 / kg	Chemical Market Reports [33]
Storage Tank & Insulation	$35 - $50 / kWhth	CEPCI Adjusted [34]
Heat Exchangers	$25,000 (Total)	CEPCI Adjusted
Operation & Maintenance	2% of CAPEX	Standard Industry Practice [34]
Discount Rate	5% - 8%	Central Bank of Turkiye / Economic Forecasts [35]

Component	Cost
Molten Salt Tank	1 m^2 = 20 kg, Cost : 6.57 $/kg 9.1 m^2 ,182 kg => 1195.74 $
Water Tank	1 m^2 = 20 kg , Cost: 6.57 $/kg 13.91 m^2 , 278.31 kg => 1828.55 $
Heliostats	1 m^2 = 9.98 $, 279 m^2 = 2784.42 $ One of the trackers stand system = 976.876 $ 976,876 x 45 = 43,959.42 $ Total Heliostat Cost: 46,743.84 $
Water Pump	717.80 $
Salt Mixture	$NaNO_3$: 1000 kg = 450 $, 2712 kg = 1220.4 $ KNO_3: 1000 kg = 740 $, 1688 kg = 1249.12 $

The simple payback period (PBP) of the proposed system is calculated as the ratio of the total initial investment cost to the annual energy cost savings, and it is expressed as:

$$PBP = \frac{Ctotal}{Sannual} \quad (10)$$

Where C_{total} is the total capital investment cost of the system (USD) and S_{annual} is the annual energy cost savings achieved by reducing conventional energy consumption.

The unit costs for the system components were derived from 2024 market data, supplier quotes for CSP materials, and standardized cost indices for solar thermal installations. These figures were calculated based on the insulation coefficients of the materials used in the system. The heat losses were integrated into the model to move beyond an idealized/theoretical scenario and to ensure a realistic representation of the system's operational performance. To ensure a realistic economic evaluation, the capital cost of the system components was estimated using a combination of direct supplier quotes and literature-based scaling. For components where current market prices were not directly available (e.g., heat exchangers and pumps), historical cost data were adjusted to the 2024 price level using the Chemical Engineering Plant Cost Index (CEPCI). The cost escalation was calculated using the following equation:

$$C_{new} = C_{ref}\left(\frac{CEPCI_{new}}{CEPCI_{ref}}\right) \quad (11)$$

Where C_{new} refers estimated cost in the current year, C_{ref} is cost of the component in the reference year, $CEPCI_{new}$ is the average index value for 2024 (assumed as 815 based on recent trends).

RESULTS AND DISCUSSIONS

In this section, the results of the study on the development and evaluation of a hybrid DHW system integrating a molten salt-dependent solar system is explained. This investigation aimed to assess the feasibility and performance of this innovative system. Through comprehensive simulations conducted for a real building located in Ankara, Turkey, obtained valuable insights into the energy savings potential and economic viability of the proposed system are presented. Additionally, a critical discussion on the implications of the findings, considering factors such as geographical location, solar radiation availability, and the broader context of smart building applications are given.

The global irradiance (W/m^2) value and other data are taken from the SAM (System Advisor Model) and the software of NREL (National Renewable Energy Laboratory). The meteorological data (Typical Meteorological Year) is also taken from the Geographical Information System of European Commission (Figure 5).

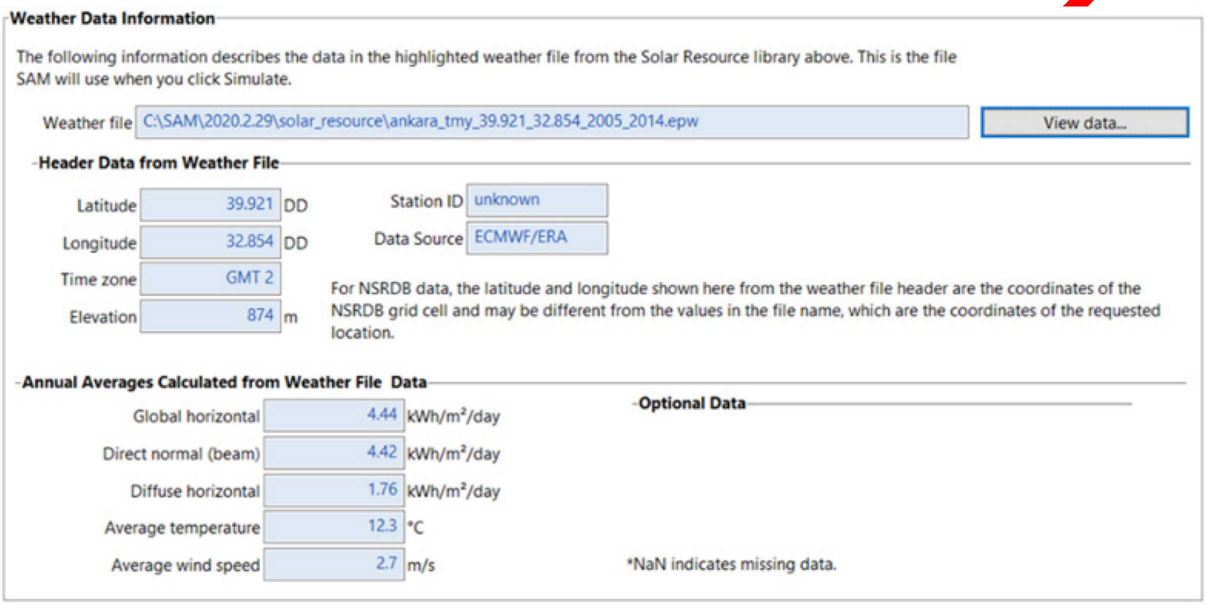

Figure 5. A sample software used for calculations

All calculations on the heat losses of tanks and pipes are conducted in the TRNSYS software [22]. Considering the average insolation is 10 hours per day in Ankara, 516.6 kW is required to heat the water from 12.3°C to 40°C. The total heat losses are calculated as 20 kW and 5 kW from the tank and pipes, respectively. Heliostat efficiency is calculated as 55%. By adding these values, total required energy is 541.6 kW for the proposed system. According to the calculations, one can easily conducts that this value can be obtained from the solar power by heating the molten salt to 260°C. Therefore, the flow rate of the water is calculated as 0.01 kg/s. Since the temperature of the molten salt is lower than its similar applications in industry, the inlet temperature of the water at traditional boiler inlet is 40°C. Thus, total energy consumption of DHW system is decreased by 72% compared to the single boiler system.

Financial Overview of the System

In this section, the investment and installation costs, as well as the payback time of the proposed system, are analyzed. The costs for each component are detailed as follows: the Salt Mixture incurs an investment of $1249.1 with a payback time of 1.7 years, the Water Tank involves an investment of $1828.5 with a payback time of 1.9 years, the Molten Salt Tank requires an investment of $1195.7 with a payback time of 1.6 years, while the Heliostats represent the most significant investment at $46,743.8 with a payback time of 8.7 years. Additionally, the Water Pump necessitates an investment of $717.8 with a relatively shorter payback time of 1.1 years. Collectively, the total investment and installation costs amount to $63,547, with an estimated payback time of 4.8 years. This analysis provides valuable insights into the financial feasibility and return on investment of the proposed system, aiding decision-making processes for potential stakeholders.

Table 4. Financial overview of the proposed DHW system

Name of the Equipment	Investment Cost ($)	Pay-back period (years)
Salt mixture	1249.1	1.7
Water Tank	1828.5	1.9
Molten Salt Tank	1195.7	1.6
Heliostats	46,743.8	8.7
Water Pump	717.8	1.1
Total	63,547*	4.8

**V.A.T and labor charges are included in the calculation*

The calculated payback period of 4.8 years is remarkably competitive when compared to traditional renewable energy investments. Generally, payback periods under 5 years are considered highly attractive for commercial and residential energy projects. This relatively short duration is attributed to the system's ability to cover 72% of the DHW demand, significantly offsetting high electricity and natural gas costs.

The parametric analysis highlights a significant correlation between the system's physical dimensions and its operational feasibility. The results indicate that while increasing the heliostat field area directly enhances the annual solar fraction, the rate of improvement follows a diminishing returns curve. Beyond a certain threshold, the additional thermal energy collected during peak summer months leads to storage saturation, which does not contribute to the domestic hot water (DHW) demand. Therefore, the selected collector area represents a calculated optimum that maximizes winter performance without incurring unnecessary capital costs.

Similarly, the sensitivity study on storage tank volume demonstrates that the system's reliability is heavily dependent on thermal inertia. A larger molten salt volume effectively bridges the gap during consecutive low-radiation days; however, it also increases the thermal losses to the environment due to the larger surface area of the tank. The identified storage capacity of the current model is optimized to maintain the discharge temperature required for DHW while keeping the 20 kW tank losses within a manageable limit. This balance between heat gain, storage density, and economic recovery (4.8 years) confirms that the proposed system is not only technically robust but also commercially competitive for residential applications in climates similar to Ankara.

Several feasible alternatives exist for residential domestic hot water production, including decentralized air-source heat pumps, flat-plate solar collectors, and water tanks integrated with Phase Change Materials (PCM). While these technologies have lower initial capital costs, they present significant limitations for high-density, 17-story buildings. Heat pumps rely heavily on the electrical grid and suffer efficiency drops in cold climates like Ankara, while conventional solar collectors and PCM modules often face 'thermal depletion' during peak morning loads due to their lower energy density. The primary advantage of adopting the Concentrated Solar Power (CSP) with Molten Salt approach in this case is its high thermal inertia and superior energy density. Finally, to validate the superiority of the proposed CSP-molten salt configuration, a comparative analysis was conducted against a standard PCM-integrated DHW storage system (e.g., paraffin-based modules at the top of the tank) for the same 17-story building. The proposed system outperforms PCM-based storage primarily due to the higher temperature gradient, which allows for a more compact storage volume to meet the massive DHW demand of 34 apartments. While PCM systems are effective for small-scale applications, the molten salt loop ensures that the 12.3°C mains water is consistently heated to the target temperature without the rapid depletion issues often seen in domestic PCM modules during peak morning hours [36-40].

The proposed system design is highly implementable for various multi-story buildings with centralized energy needs, such as hospitals, hotels, and large-scale residential complexes, where high-volume hot water demand is consistent. By utilizing a centralized solar receiver and a molten salt loop, the system achieves an economy of scale that individual heating units cannot match. However, practical applicability in diverse urban contexts is subject to specific spatial and structural limitations. The heliostat field requires a significant, unobstructed rooftop or adjacent land area to avoid shading from neighboring structures, which may be a constraint in high-density city centers. Additionally, the high density of the molten salt mixture imposes substantial structural loads on the building's foundation or roof, potentially requiring reinforcement in retrofitting projects. Furthermore, while the system is ideal for new "Smart City" developments featuring centralized piping, its implementation in older buildings with decentralized distribution networks may involve higher installation costs. Despite these challenges, the system's ability to maintain stable discharge temperatures for 34 apartments during peak morning hours makes it a technically robust solution for modern, sustainable urban architecture.

The environmental superiority of the proposed CSP-integrated molten salt system is evaluated by its potential to displace conventional fossil fuel consumption. In the current case study, a standard natural gas-fired boiler system, the most common heating solution for residential buildings in Ankara, is used as the baseline for comparison. Based on the simulation results, the system delivers approximately 210 MWh of clean thermal energy annually. Using a standard emission factor for the natural gas, the proposed design prevents the emission of approximately 42.4 tons of CO_2 per year. Over a projected operational lifespan of 25 years, the total carbon mitigation is estimated at 1,060 tons of CO_2. This significant reduction is primarily attributed to the high solar fraction and the high-density storage capability of the molten salt, which allows the system to remain active even during periods of low solar radiation. Compared to conventional decentralized systems, this centralized approach not only reduces direct greenhouse gas emissions but also minimizes the urban heat island effect by consolidating thermal energy conversion at the central receiver, aligning the building with net-zero emission targets for sustainable urban development.

CONTRIBUTION TO THE UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS

The outcomes of this paper directly contribute to several United Nations Sustainable Development Goals through quantifiable and data-driven indicators. In alignment with *SDG 7 (Affordable and Clean Energy), Target 7.3*, the proposed hybrid CSP–molten salt domestic hot water system achieves a 72% reduction in conventional energy consumption, significantly improving energy efficiency at the building scale. This corresponds to a substantial decrease in reliance on fossil fuel–based boilers for domestic hot water production.

The system further supports *SDG 11 (Sustainable Cities and Communities), Target 11.6*, by reducing the environmental impact of residential buildings. Based on the simulation results, the system delivers approximately 210 MWh of renewable thermal energy annually, leading to an estimated 42.4 tons of CO_2 emission reduction per year, or 1,060 tons over a 25-year operational lifespan. These reductions contribute directly to improved urban air quality and climate resilience. From a community well-being perspective, the proposed centralized high-temperature DHW system ensures a reliable and continuous hot water supply for 34 apartments, even during peak morning demand periods in winter. This enhances occupant thermal comfort, reduces energy costs, and provides a scalable solution for multi-story residential buildings, hotels, and hospitals. By demonstrating technical feasibility, economic viability (4.8-year payback period), and measurable environmental benefits, the proposed system offers a replicable pathway toward low-carbon and energy-efficient urban infrastructure.

CONCLUSIONS

The integration of solar power systems holds significant importance for engineers and architects, yet their application in smart building contexts remains relatively limited. Consequently, this study endeavours to address this gap by proposing the development of a hybrid DHW system incorporating a molten salt-dependent solar system. The envisaged system comprises key components such as a molten salt tank, water tank, and heliostats. Findings from the study indicate that the hybrid DHW system yields a noteworthy 72% reduction in total energy consumption compared to conventional boiler systems. The calculated payback period for implementing the system stands at 4.8 years. It is noteworthy that this study is conducted as a simulation for a real building situated in Ankara, Turkey. It is plausible that the economic viability of the proposed system may exhibit even more promising results in regions characterized by higher solar radiation availability, such as İzmir, Turkey, and Athens, Greece. Furthermore, it is emphasized that conducting feasibility and reliability studies holds paramount significance for the practical application of the proposed system in future installations. Such investigations are essential for ensuring the effectiveness and sustainability of the system once deployed in real-world scenarios. This study collectively contributes to a deeper understanding of the practical implications and future prospects of integrating solar power systems into the DHW solutions for sustainable building environments.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGEMENTS

This study is based on the valuable contributions of all authors.

NOMENCLATURE

Symbol / Abbreviation	Description	Unit
A	Heliostat surface area	m²
CEPCI	Chemical Engineering Plant Cost Index	–
C_p	Specific heat capacity of molten salt	kJ/kg·K
CSP	Concentrated Solar Power	–
DHW	Domestic Hot Water	–
DNI	Direct Normal Irradiance	W/m²
N	Number of heliostats	–
PCM	Phase Change Material	–
PBP	Payback Period	year
PPD	Predicted Percentage of Dissatisfied	–
PMV	Predicted Mean Vote	–
Q	Heat transfer rate	W
Q_{pipe}	Heat loss from distribution pipes	kW
Q_{tank}	Heat loss from storage tank	kW
T	Temperature	°C
α	Receiver solar absorptivity	–
ε	Heat exchanger effectiveness	–
η	Heliostat field efficiency	–
ρ	Heliostat reflectivity	–

REFERENCES

1. Pandiyan, P., Saravanan, S., Usha, K., Kannadasan, R., Alsharif, M. H. and Kim, M. K., Technological Advancements Toward Smart Energy Management in Smart Cities, *Energy Reports*, Vol. 10, pp 648–677, 2023, https://doi.org/10.1016/j.egyr.2023.07.021.
2. Turhan, C., Simani, S., Zajic, I. and Akkurt, G. G., Performance Analysis of Data-Driven and Model-Based Control Strategies Applied to a Thermal Unit Model, *Energies*, Vol. 10, No. 1, p 67, 2017, https://doi.org/10.3390/en10010067.
3. Turhan, C., Arsan, Z. D. and Akkurt, G. G., Impact of Climate Change on Indoor Environment of Historic Libraries in Mediterranean Climate Zone, *International Journal of Global Warming*, Vol. 18, No. 3-4, pp 206-220, 2019, https://doi.org/10.1504/IJGW.2019.101083.
4. Fayyazbakhsh, A. et al., Engine Emissions with Air Pollutants and Greenhouse Gases and Their Control Technologies, *Journal of Cleaner Production*, Vol. 376, p 134260, 2022, https://doi.org/10.1016/j.jclepro.2022.134260.
5. Turhan, C., Carpino, C., Chen Austin, M., Özbey, M. F. and Akkurt, G. G., Impact of Green Wall and Roof Applications on Energy Consumption and Thermal Comfort for Climate Resilient Buildings, *Urban Science*, Vol. 9, No. 4, p 105, 2025, https://doi.org/10.3390/urbansci9040105.
6. Chen, L., Zhang, Y. and Wang, J., Decarbonizing the Residential Sector: Synergistic Impacts of Solar Thermal Integration and Thermal Energy Storage on Reducing Greenhouse Gas Emissions, *Renewable and Sustainable Energy Reviews*, Vol. 212, p 115240, 2025.
7. Zhou, Q., Wu, J., Imran, M., Nassani, A. A., Binsaeed, R. H. and Zaman, K., Examining the Trade-offs in Clean Energy Provision: Focusing on the Relationship Between Technology Transfer, Renewable Energy, Industrial Growth, and Carbon Footprint Reduction, *Heliyon*, Vol. 9, No. 10, p e20271, 2023, https://doi.org/10.1016/j.heliyon.2023.e20271.
8. Turhan, C., Durak, M., Saleh, Y. A. S. and Kalaycı, A., Recycling Decommissioned Wind Turbine Blades for Post-Disaster Housing Applications, *Recycling*, Vol. 10, No. 2, p 42, 2025, https://doi.org/10.3390/recycling10020042.
9. Turhan, C. and Saleh, Y. A. S., A Case Study for Small-Scale Vertical Wind Turbine Integrated Building Energy Saving Potential, *Journal of Building Design and Environment*, Vol. 2, No. 1, p 24174, 2024, https://doi.org/10.18311/jbde/2024/24174.
10. Jahanbin, A., Semprini, G. and Goni, M., Techno-economic Analysis of a Novel Retrofit Solution for the Domestic Hot Water System: A Comparative Study, *Energy Conversion and Management*, Vol. 292, p 117363, 2023, https://doi.org/10.1016/j.enconman.2023.117363.
11. International Energy Agency (IEA), Global Energy Review 2021 – Analysis, https://www.iea.org/reports/global-energy-review-2021, [Accessed: 27-March-2024].
12. International Energy Agency Solar Heating and Cooling Programme (IEA SHC), Solar Heat Worldwide, https://www.iea-shc.org/solar-heat-worldwide, [Accessed: 27-March-2024].
13. Verma, S., Yang, C. K., Lin, C. H. and Jeng, J. Y., Additive Manufacturing of Lattice Structures for High Strength Mechanical Interlocking of Metal and Resin During Injection Molding, *Additive Manufacturing*, Vol. 49, p 102463, 2022, https://doi.org/10.1016/j.addma.2021.102463.
14. Mi, P., Ma, L. and Zhang, J., Integrated Optimization Study of Hot Water Supply System with Multi-heat-source for the Public Bath Based on PVT Heat Pump and Water Source Heat Pump, *Applied Thermal Engineering*, p 115146, 2020, https://doi.org/10.1016/j.applthermaleng.2020.115146.
15. Marszal, A. J. et al., Zero Energy Building-A Review of Definitions and Calculation Methodologies, *Energy and Buildings*, Vol. 43, pp 971–979, 2011, https://doi.org/10.1016/j.enbuild.2010.12.022.

16.Pomianowski, M. Z., Johra, H., Marszal-Pomianowska, A. and Zhang, C., Sustainable and Energy-Efficient Domestic Hot Water Systems: A Review, *Renewable and Sustainable Energy Reviews*, Vol. 128, p 109900, 2020, https://doi.org/10.1016/j.rser.2020.109900.
17.Hohne, P. A., Kusakana, K. and Numbi, B. P., A Review of Residential Hot Water Consumption Patterns and Solar Thermal System Sizing Methods, *Journal of Cleaner Production*, Vol. 213, pp 387-400, 2019.
18.Buker, M. S. and Riffat, S. B., Solar Assisted Heat Pump Systems for Low Temperature Water Heating Applications: A Systematic Review, *Renewable and Sustainable Energy Reviews*, Vol. 55, pp 809-820, 2016.
19.Pomianowski, M. Z. et al., A Review of Thermal Energy Storage Technologies for Buildings, *Renewable and Sustainable Energy Reviews*, Vol. 128, p 109900, 2020.
20.Bøhm, B., Schrøder, F. and Bergsøe, N. C., Varmt brugsvand: Måling af forbrug og varmetab fra cirkulationsledninger (in Danish, Domestic Hot Water: Measurement of Consumption and Heat Loss from Circulation Pipes), Danish Building Research Institute (SBI) forlag, 2009, https://vbn.aau.dk/en/publications/varmt-brugsvand-m%C3%A5ling-af-forbrug-og-varmetab-fra-cirkulationsled, [Accessed: 26-March-2024].
21.Xi, C., Lin, L. and Hongxing, Y., Long Term Operation of a Solar Assisted Ground Coupled Heat Pump System for Space Heating and Domestic Hot Water, *Energy and Buildings*, Vol. 43, No. 8, pp 1835–1844, 2011, https://doi.org/10.1016/j.enbuild.2011.03.033.
22.University of Wisconsin-Madison, Transient System Simulation Tool (TRNSYS) - Official Website, https://sel.me.wisc.edu/trnsys/, [Accessed: 26-March-2024].
23.Mazman, M., Cabeza, L. F., Mehling, H., Nogues, M., Evliya, H. and Paksoy, H. Ö., Utilization of Phase Change Materials in Solar Domestic Hot Water Systems, *Renewable Energy*, Vol. 34, No. 6, pp 1639–1643, 2009, https://doi.org/10.1016/j.renene.2008.10.016.
24.Tsalikis, G. and Martinopoulos, G., Solar Energy Systems Potential for Nearly Net Zero Energy Residential Buildings, *Solar Energy*, Vol. 115, pp 743–756, 2015, https://doi.org/10.1016/j.solener.2015.03.037.
25.Turrini, S., Bettonte, M., Eccher, M., Grigiante, M., Aiotello, M. and Brusa, R. S., An Innovative Small-scale Prototype Plant Integrating a Solar Dish Concentrator with a Molten Salt Storage System, *Renewable Energy*, Vol. 123, pp 150–161, 2018, https://doi.org/10.1016/j.renene.2018.02.053.
26.Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F., World Map of the Köppen-Geiger Climate Classification Updated, *Meteorologische Zeitschrift*, Vol. 15, No. 3, pp 259–263, 2006, https://doi.org/10.1127/0941-2948/2006/0130.
27.Aksoy, B., Solar Radiation Over Turkey and Its Analysis, *International Journal of Remote Sensing*, Vol. 32, No. 21, pp 6261–6272, 2011, https://doi.org/10.1080/01431161.2010.508056.
28.Autodesk, AutoCAD LT 2024 Official Website, https://www.autodesk.com.tr/products, [Accessed: 26-March-2024].
29.Trimble Inc., SketchUp - 3D Design Software, https://www.sketchup.com/, [Accessed: 26-March-2024].
30. Dincer, I. and Rosen, M. A., Exergy: Energy, Environment and Sustainable Development, 3rd Edition, Elsevier, Oxford, UK, 2024.
31.Bahar, A., Ozcan, H. G. and Gunerhan, H., Thermodynamic Analysis and Optimization of Molten Salt Based Solar Thermal Systems for Residential Applications, Energy Conversion and Management, Vol. 302, p 118112, 2025, https://doi.org/10.1016/j.enconman.2024.118112.
32.International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2022, (Technical) Report, Abu Dhabi, UAE, 2023.
33.Chemical Market Reports, Global Nitrate Salts Market: Industrial Pricing and Supply Chain Analysis (2023-2025), (Technical) Report, 2024.

34. Chemical Engineering Magazine, Chemical Engineering Plant Cost Index (CEPCI): Annual Average and Monthly Indicators, https://www.chemengonline.com, [Accessed: 22-December-2025].
35. Central Bank of the Republic of Türkiye (CBRT), Inflation Report and Medium-Term Economic Forecasts, (Technical) Report, Ankara, Turkey, 2024.
36. Liu, X. et al., Thermal Energy Storage and Solar Energy Utilization Enabled by Novel Composite Sodium Acetate Trihydrate/Sodium Dihydrogen Phosphate Dihydrate Phase Change Materials, *Solar Energy Materials and Solar Cells*, p 111938, 2022, https://doi.org/10.1016/j.solmat.2022.111938.
37. Demir, M. E. and Dincer, I., Development of a Hybrid Solar Thermal System with TEG and PEM Electrolyzer for Hydrogen and Power Production, *International Journal of Hydrogen Energy*, Vol. 42, No. 44, pp 27011-27022, 2017, https://doi.org/10.1016/j.ijhydene.2017.09.001.
38. Sarbu, I. and Sebarchievici, C., A Comprehensive Review of Thermal Energy Storage, *Sustainability*, Vol. 10, No. 1, p 191, 2018.
39. Zhang, H., Li, X. and Tan, Y., Optimization of High-temperature Thermal Energy Storage Systems for Net-zero Energy Buildings: A Comparative Study of Molten Salts and Advanced Phase Change Materials, *Energy Conversion and Management*, Vol. 310, p 118450, 2025.
40. Al-Qirimli, H. F. and Al-Abidi, A. A., Advancements in Solar Thermal Energy Storage: A Technical and Economic Comparison Between Sensible, Latent, and Thermochemical Storage for Residential Sectors, *Applied Energy*, Vol. 378, p 124592, 2025.