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An Analytical View of a Water Heating System Through the Integration of Phase-Change Materials and Artificial Intelligence (Case study: Amman)

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ABSTRACT. *This study aims to provide an analytical perspective on the feasibility of designing a solar water heater by integrating phase-change materials and artificial intelligence (AI) in a residential solar heating system. The analysis includes an analytical study of the target area using calculations related to solar radiation and temperatures, an examination of the appropriate characteristics for designing solar storage tanks, and the identification of phase-change materials within suitable temperature ranges. To achieve this, a comprehensive review of relevant research on solar storage systems was conducted, along with the development of concepts and proposals for integrating the systems. Numerical simulations of the system were also performed to generate calculations demonstrating the efficiency of integrating the system with AI using a three-tank solar system, connected to a control unit that selects the appropriate material based on the ambient temperature. The survey highlights the effectiveness of integrating phase-change materials and AI in the design of solar water heating systems. The results show that the integrated system achieves an efficiency ranging from 72% to 88%, while the conventional system achieves an efficiency ranging from 35% to 55%, taking into account logical temperature variations within the time and spatial scope of the study.*

Keywords: Solar Water Heating System, Phase Change Materials, Artificial Intelligence.

1. **Introduction**. The use of solar energy for heating is not limited to contemporary history, it extends far beyond that. Wherever the sun shines, warm water shines. Solar water heating (SWH), on the other hand, is one of the applications of solar energy that has drawn great attention among researchers in this field [1]. SWH is one of the oldest methods of heating water. Today, the uses of SWH are not limited to specific purposes, but rather extend to various domestic and industrial applications. Solar heating systems are divided into two main types: active systems and passive systems, each of which operates directly or indirectly. Active systems are more efficient than simple systems, with performance ranging from 35% to 80%; they are also more complex and expensive, making them more suitable for industrial use, or for systems requiring more than one solar collector [2]. These systems are also used in high-energy processes. Passive systems, on the other hand, are simpler, less expensive, and easier to use, making them suitable for domestic use where heating demand is lower and within the scope of

individual use [2, 3]. A review of previous studies has shown that SWH is an effective method to convert solar energy into heat. This is significantly more efficient than solar-electric systems, which rely on converting solar energy into electricity and then heating it through electrical devices. These systems have an average efficiency of 17% [4]. Researchers are working to improve system efficiency through convection heat transfer techniques, and are focusing on survey into designs and materials that support the convection heating process [4]. WHS has evolved according to the energy source used, such as burning wood or plant waste, to produce the heat needed to heat water since ancient times. Later, coal, diesel, and gas were used, and nuclear power was also employed Each of these sources faces limitations in terms of cost, availability, and safety. SWH offers a solution to overcome these limitations, as its heating system relies on solar radiation. Temperature requirements are determined based on the intended use, geographical location, and climate. They are not only environmentally friendly, but also require lower maintenance and operating costs compared to other solar energy applications [5]. Therefore, analisys in the field of water heating has focused on solar energy for several reasons, the most important of which is improving the efficiency of solar water heating systems. It is essential to design solar water heating systems according to the aforementioned criteria to ensure they are a viable alternative to other heat sources [6, 7, 8, 9]. This work presents a vision and simulation of a system that integrates solar energy into water heating, supported by Phase Change Materials (PCMs) and artificial intelligence (AI)-based control logic, within an environment that simulates the climate of Amman, the capital of Jordan, during the autumn and winter seasons. This survey incorporates improvements to heating systems using phase-change materials and AI technology to enhance the efficiency of SWH.

2. Earlier Research. Heating water using solar energy is a natural phenomenon, as warm beaches extend over areas with high solar radiation and high temperatures. Stagnant water in hot areas is directly exposed to solar radiation, and thus undergoes a gradual heating and evaporation process. This natural phenomenon has shown since ancient times that the sun has the ability to heat water and that water has the ability to absorb heat. Methods of heating water have developed according to uses, from the need for washing, drinking, or cooking to industrial applications. From this standpoint, survey in the field of SWH has expanded, and this expansion has prompted researchers to publish many analyses aimed at developing and improving renewable energy-based water heating systems, including solar energy [1, 8, 9].

Other studies confirm that solar water heating is one of the most widespread applications of solar thermal energy for several reasons: cost, ease of installation, and versatility. Solar water heating technology has proven effective in both domestic and industrial applications [9, 10].

In this context, many works suggest modifications to solar water heaters to enhance the efficiency of solar energy utilization [3, 5]. Countries suffering from a scarcity of oil and gas resources are in dire need of turning to alternative energy sources, including solar power. Jordan is one of these countries, and it needs to diversify its energy sources and utilize renewable resources effectively [11]. Analysis on improving the efficiency of solar systems using PCMs, is a prominent area of focus in numerous works and represents an ongoing field of inquiry [7, 12, 13].

Other analysis and research have provided solutions to ensure energy storage beyond periods of solar radiation through the use of PCMs. The results of these analysis indicate that there is a variation in the effectiveness of these materials [14, 15, 16]. In recent years, there has been a trend towards a wider integration of artificial intelligence into SWH for the for prediction and control purposes. Earlier Investigations have indicated this, as the capabilities of artificial neural network modeling have been integrated into the process of solar thermal energy storage, which involves the use of PCMs [17]. To ensure higher system effectiveness, artificial intelligence is considered an entry point for further improvement in SWH.

Based on preceding experimentss, we can review the following key points:

- The Evolution of Solar Water Heating Systems

It is undeniable that water heating systems have gone thorough multiple stages of development. The survey by Kalogirou (2009) outlines the historical evolution of solar water heating systems, from primitive, uninsulated models to modern, highly efficient systems [18]. This experiment demonstrates that these systems have become an effective economic and environmental option, especially given the increasing energy consumption associated with the development of human civilization. This indicates continuoued growth in both consumption and development rates.

- Classifications of Solar Water Heating Systems

Many studies have classified solar water heating systems, including: The first classification includes active systems that rely on pumps and controllers, and is further divided into open and closed systems. The second classification includes passive systems that rely on natural convection, such as thermosiphon systems and integrated storage systems. Analysis indicate that passive systems are characterized by their simplicity and low maintenance requirements, while active systems offer greater control and efficiency in cold environments [1].

- Main Components of Solar Water Heating Systems

Previous works have addressed the main components of solar water heating systems, including the following:

2.1 Solar Collector

This includes non-concentrating types such as flat plate collectors and evacuated tube collectors, and concentrating types such as parabolic trough collectors and parabolic dish collectors. Past investigations have shown that concentrating collectors, especially parabolic dish collectors, achieve the highest thermal efficiency [19, 20, 21, 22]. Figure 1 roughly represents the types and shapes of solar collectors that have been previously studied.

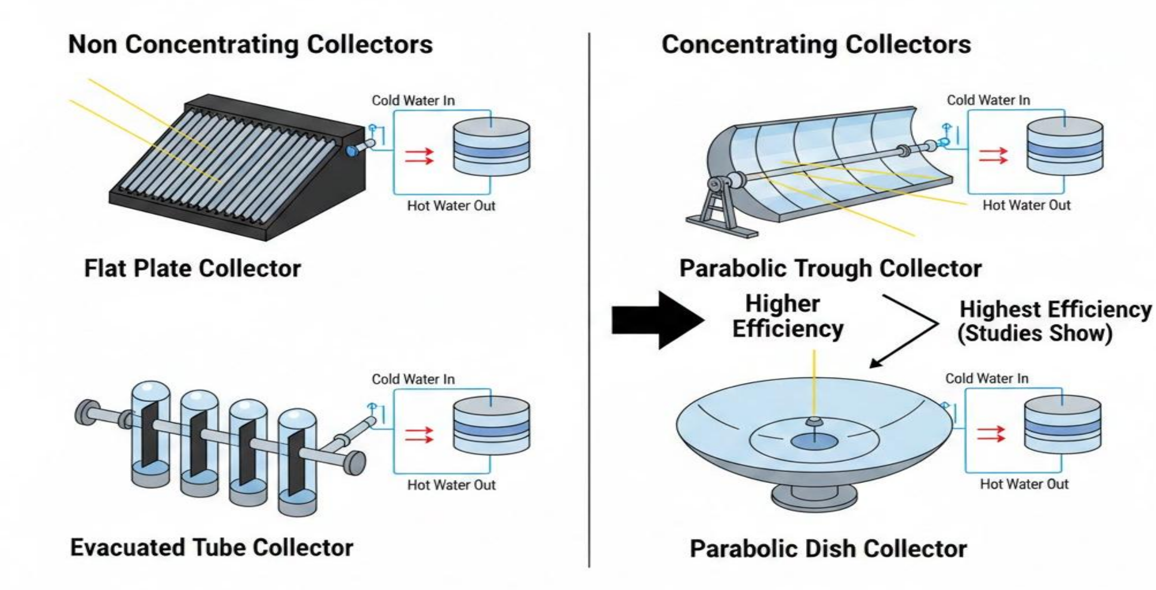

FIGURE1. Solar Collectors Diagram

2.2 Storage Tank

Preceding analysis emphasize the importance of thermal insulation and improving the thermal layering within the tank, as this directly impacts the overall system efficiency [23, 24, 25]. Figure 2 represents approximately the types and shapes of solar tanks that have been referred to in some previous survey [24, 25, 26, 27].

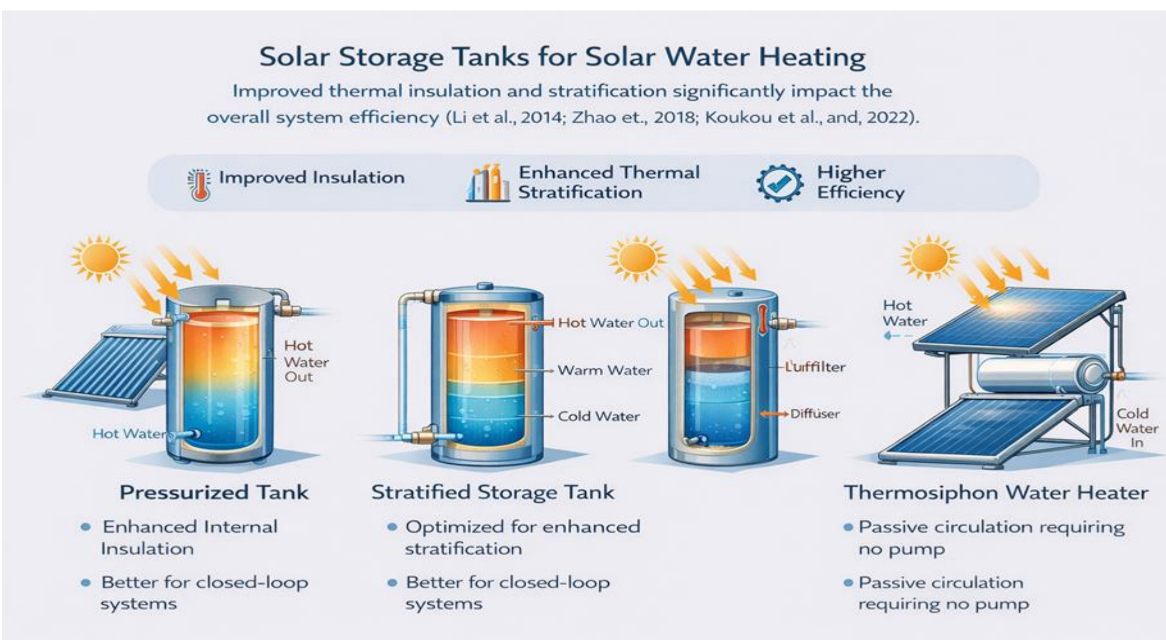

FIGURE 2. Solar Tank Designs According to Previous Search

Figure 3 illustrates the integration of solar storage tanks according to the types of solar collector systems and storage tank.

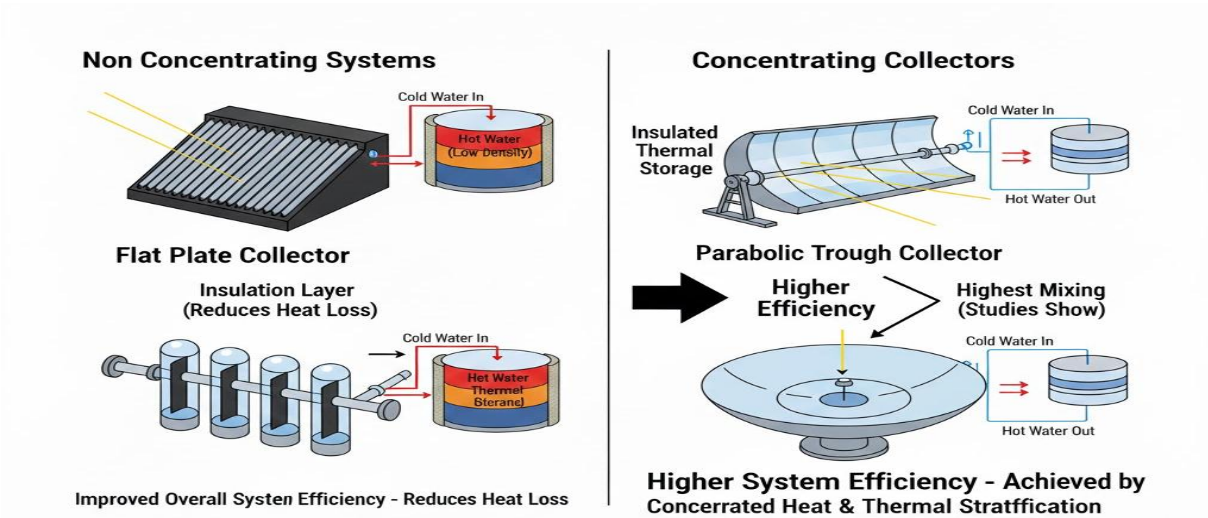

FIGURE 3. Integrating Solar Collection Systems with Storage Systems

2.3 Heat Transfer Fluids

Prior research have indicated the use of water, glycols, and nanofluids, and have shown that nanofluids have demonstrated a significant improvement in heat transfer, despite their limited commercial application to date [28, 29].

Figure 4 shows some types of additives used to improve heat exchange and reduce losses, according to some prior surveys.

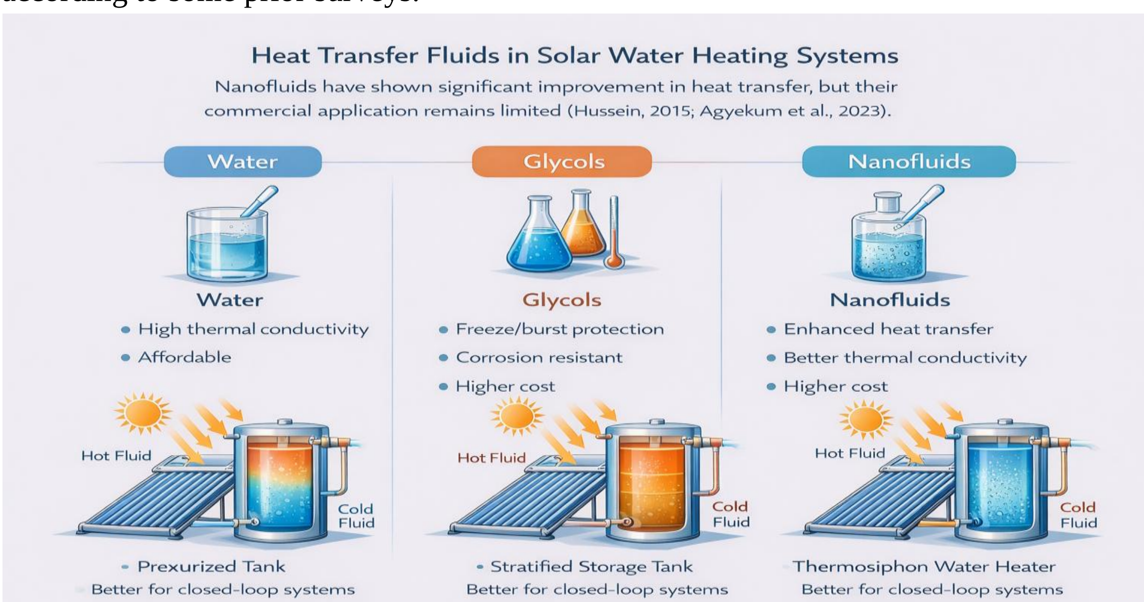

FIGURE 4. Different Heat Transfer Systems

From existing studies [28, 29, 30, 31, 32, 33], we can conclude the following key points:

- Solar water heating systems, both active and passive, are capable of achieving high thermal efficiency when properly designed and operated.
- The type of solar collector and thermal storage tank directly affects the overall system performance, with concentrated solar power (CSP) and evacuated tube collectors achieving higher efficiency under certain conditions.
- Improving thermal insulation and storage properties enhances system stability and reduces heat loss.

2.4 Phase change materials

PCMs are attracting significant attention from researchers in the field of thermal energy storage applications. Their unique properties allow them to absorb and release large amounts of heat during melting and freezing at natural temperatures. Unlike conventional thermal storage systems that rely on high temperatures, PCMs store energy as latent heat, enabling the storage of more energy in a relatively smaller volume, comparable to that of water. Numerous experiments [34, 35, 36] have demonstrated that incorporating these materials into solar heating systems, particularly water heating, improves temperature stability, reduces heat loss during periods of low solar radiation, and increases overall system efficiency throughout the day. Organic materials such as paraffin wax and fatty acid mixtures are among the most commonly used due to their chemical stability, non-corrosive nature, and suitable melting points for domestic applications. Their suitability and low pollution rates have also contributed to the ongoing development of these materials and the refinement of the design of thermal systems based on them. Therefore, the following can be concluded:

- The use of advanced materials such as PCMs including RT32, RT42, and RT55 and Nano fluids represents a promising survey direction for increasing heat transfer and storage efficiency.
- The application of AI also represents a turning point in the field of solar system optimization and can lead to increased efficiency. Survey in this area is still in its early stages and is still under development.

A review of Antecedent Research concludes that there is a continuing need for more research and studies in the field of solar heating systems.

3 Methodology.

In this part of the survey, a design methodology will be developed for a solar system that integrates PCMs and artificial intelligence, according to a climate system that is compatible with the case study within the Jordanian capital, Amman, for the extended period of autumn and winter. The methodology for the analysis consists of the following steps.

3.1 Climatic data for the case study

It is necessary to monitor the climatic data related to two aspects:

- The duration of solar radiation, which is the time period between sunrise and sunset at the beginning of autumn and the end of winter within the geographical area of the capital, Amman.

Given the long period of time extending from the autumnal solstice to the spring solstice, which is 180 days, this period was divided into time groups that includes ten consecutive days from the beginning of the autumnal solstice to the beginning of the spring solstice. The following equations 1 to 3 show how to calculate the average values.
Mathematical representation of the average sunrise and sunset values are given by:

$$T_{av(10days)} = \frac{1}{n}\sum_{i=1}^{n} T_i,\ n = 10 \qquad (1)$$

$$D_{av(Daylight)} = \frac{1}{n}\sum_{i=1}^{n}(Ss_i - Sr_i),\ n = 10 \qquad (2)$$

$$N_{av(Daylight)} = \frac{1}{n}\sum_{i=1}^{n}(24 - (Ss_i - Sr_i)),\ n = 10 \qquad (3)$$

where,
$T_{av(10days)}$: Average time for each 10-day period.
n: Number of days in the interval (10 days).
T_i: The specific time (Sunrise or Sunset) for each day i within the interval.
$D_{av(Daylight)}$: Average Daylight Duration.
$N_{av(Daylight)}$: Average Night Duration.
Ss_i: Sunset time today i.
Sr_i: Sunrise time today i.

- Temperatures, which are the daily maximum and minimum temperatures during the same period within the geographical area of Amman. Equations (4) and (5) demonstrate the mechanism for calculating average temperature values.

Mathematical representation of the average temperature values are given by:

$$TeD_{av(10\ days)} = \frac{1}{2n}\sum_{i=1}^{n}(TeD_{max,i} + TeD_{av,i}),\ n = 10 \qquad (4)$$

$$TeN_{av(10\ days)} = \frac{1}{2n}\sum_{i=1}^{n}(TeN_{min,i} + TeN_{av,i}),\ n = 10 \qquad (5)$$

where,
$TeD_{av(10\ days)}$: Average daytime temperature for each 10-day period.
$TeN_{av(10\ days)}$: Average nighttime temperature for each 10-day period.
$TeD_{max,i}$: Maximum value of daytime temperature for each i.
$TeD_{av,i}$: Average daytime temperature for each for each i.
$TeN_{min,i}$: Minimum value of nighttime temperature for each i
$TeN_{av,i}$: Average nighttime temperature for each for each i.

3.2 Collector Heat Loss:

$$\mu = \mu_0 - a_1\frac{T_m - T_a}{G}\, a_2\frac{(T_m - T_a)^2}{G}, \qquad (6)$$

where,
μ: Collector Efficiency.
μ_0: Optical Efficiency.

T_m: Heating Fluid Temperature
T_a: Ambient Temperature.
a_1: First-order Heat Loss Coefficient.
a_2: Second-order Heat Loss Coefficient.
G: Solar Radiation Watt/m^2.

3.3 Tank Energy Balance

$$Q_{LS} = U.A(T_{tank} - T_{min}).TeN_{av,i}, \quad (7)$$

where,
Q_{LS}: Amount of energy lost.
U: Heat Transfer Coefficient.
A: Surface Area.
T_{tank}: Tank Temperature.
T_{min}: Minimum Temperature.
$N_{av(Daylight)}$: Average Night Duration.

3.4 Stratification Index

$$SI = \sqrt{\frac{\int_0^H \left(T(Z) - T_{tank(av)}\right)^2 dz,}{H}} \quad (8)$$

where,
SI: Stratification Index, where this indicates how successfully the tank separates hot and cold water.
H: Total Height of the Tank.
$T(Z)$: Vertical Height of the Tank (y-axis coordinates).
$T_{tank(av)}$: Average Tank Temperature.
dz: Temperature measurement point (y-axis point).

3.5 Newton's Law of Cooling

$$\frac{dT}{dt} = -k\left(T(t) - T_{night}\right), \quad (9)$$

where,
$\frac{dT}{dt}$: Rate of Change in Temperature.
$T(t)$: Instantaneous Water Temperature.
T_{night}: Ambient Temperature of the Tank at Night
k: Cooling Constant.

3.6 Heating Tank

Due to the thermal conditions, variations, and types of materials that the tank may be exposed to, the following materials were chosen to make up the tank:

- Stainless Steel 316L: High resistance to corrosion and pressure, ideal for PCM temperatures [37, 38, 39].

- Cross-linked Polyethylene (PEX): It withstands high temperatures and has less heat loss [40, 41].
- Vacuum Insulation Panels (VIP): Placed around tanks for insulation [42, 43, 44].
- Paraffin-based RT series: Organic paraffin wax within a variable series (RT55, RT42, and RT32): To operate within varying temperature conditions [34, 35, 36, 45, 46, 47]. Table 1 represents its characteristics.

TABLE 1. Properties of Phase-Change Materials

Unit (Full Name)	Tank 3: Bottom (RT32)	Tank 2: Middle (RT42)	Tank 1: Top (RT55)	Thermal Property
Degrees Celsius	31	42	55	Melting Point
Kilojoules per Kilogram	160	174	210	Latent Heat Capacity
Kilojoules per Kilogram Kelvin	1.8	2.0	2.0	Specific Heat (Solid)
Kilojoules per Kilogram Kelvin	2.4	2.0	2.0	Specific Heat (Liquid)
Watts per Meter Kelvin	0.2	0.2	0.2	Thermal Conductivity
Kilograms per Cubic Meter	820	880	880	Density (Solid Phase)
Kilograms per Cubic Meter	750	760	770	Density (Liquid Phase)
Percentage	11	12.5	12.5	Volume Expansion

3.7 Fuzzy Logic

The system design and simulation are based on the inherent uncertainty of temperature variations throughout the day. This uncertainty serves as a key input for developing a mathematical model using fuzzy logic, which describes the operational mechanism of the control unit managing the PCMs tanks. The fuzzy logic framework relies on variable characterization and rule-based control to determine the activation and operation of each tank.

The mathematical rules for determining control options will be based on the temperature difference between the reference temperature and the temperature measured in the main tank, and fuzzy logic will allow the controller to broaden its ability to determine the appropriate decision regarding supporting the main tank with heat and then selecting the appropriate material tank.

4. Results. Through digital simulation using the previously mentioned equations, the following outcomes were obtained:

Table 2 represents the data extracted through the analysis of astronomical data for sunrise and sunset times.

TABLE 2. Solar Path Data for Amman (Intervals from Sep 22- Mar 20)

Time Interval (10-Day Blocks)	Average Sunrise $T_{av(10days)}$	Average Sunset $T_{av(10days)}$	Average Daylight Duration	Average Night Duration
Sep 22 – Oct 01	06:25 AM	06:27 PM	12h 02m	11h 58m
Oct 02 – Oct 11	06:33 AM	06:14 PM	11h 41m	12h 19m
Oct 12 – Oct 21	06:40 AM	06:02 PM	11h 22m	12h 38m
Oct 22 – Oct 31	06:48 AM	05:52 PM	11h 04m	12h 56m
Nov 01 – Nov 10	06:57 AM	05:42 PM	10h 45m	13h 15m
Nov 11 – Nov 20	07:07 AM	05:35 PM	10h 28m	13h 32m
Nov 21 – Nov 30	07:16 AM	05:31 PM	10h 15m	13h 45m
Dec 01 – Dec 10	07:23 AM	05:31 PM	10h 08m	13h 52m
Dec 11 – Dec 20	07:30 AM	05:34 PM	10h 04m	13h 56m
Dec 21 – Dec 30	07:35 AM	05:39 PM	**10h 04m**	**13h 56m**
Dec 31 – Jan 09	07:38 AM	05:47 PM	10h 09m	13h 51m
Jan 10 – Jan 19	07:38 AM	05:56 PM	10h 18m	13h 42m
Jan 20 – Jan 29	07:35 AM	06:05 PM	10h 30m	13h 30m
Jan 30 – Feb 08	07:29 AM	06:15 PM	10h 46m	13h 14m
Feb 09 – Feb 18	07:20 AM	06:24 PM	11h 04m	12h 56m
Feb 19 – Feb 28	07:10 AM	06:32 PM	11h 22m	12h 38m
Mar 01 – Mar 10	06:58 AM	06:40 PM	11h 42m	12h 18m
Mar 11 – Mar 20	06:46 AM	06:48 PM	12h 02m	11h 58m

Table 3 represents the data extracted through the analysis of climate data:

TABLE 3. Temperature Path Data for Amman (Intervals from Sep 22- Mar 20)

Time Interval	Avg. Night Temp ($\boldsymbol{TeN_{av(10\ days)}}$)	Avg. Day Temp ($\boldsymbol{TeN_{av(10\ days)}}$)	Impact on Solar System
Sep 22 – Oct 01	18.5°C	27.5°C	**High solar gain / Minimal night loss**
Oct 02 – Oct 11	17.0°C	25.0°C	**Stable performance**
Oct 12 – Oct 21	15.5°C	22.5°C	**Increasing insulation demand**
Oct 22 – Oct 31	13.5°C	20.0°C	**Significant night cooling starts**
Nov 01 – Nov 10	11.0°C	17.5°C	**Lower collector efficiency**
Nov 11 – Nov 20	09.5°C	15.5°C	**High thermal gradient in tank**
Nov 21 – Nov 30	08.0°C	13.5°C	**Peak heating demand period**
Dec 01 – Dec 10	07.5°C	12.0°C	**Need for high-performance collectors**
Dec 11 – Dec 20	06.5°C	11.5°C	**Maximum storage stress**
Dec 21 – Dec 30	05.5°C	10.5°C	**Lowest Yearly Performance**
Dec 31 – Jan 09	05.0°C	10.5°C	**Risk of pipe freezing**
Jan 10 – Jan 19	05.0°C	11.0°C	**Deep winter / Minimal ambient gain**
Jan 20 – Jan 29	06.0°C	11.5°C	**Recovery phase begins**
Jan 30 – Feb 08	06.5°C	12.5°C	**Gradual efficiency increase**
Feb 09 – Feb 18	07.5°C	14.0°C	**Better stratification stability**
Feb 19 – Feb 28	08.0°C	15.0°C	**Spring transition**
Mar 01 – Mar 10	09.5°C	17.5°C	**Improved solar fraction**
Mar 11 – Mar 20	11.0°C	19.5°C	**Ideal equinox conditions**

It is essential to develop an appropriate system design that aligns with the aforementioned climatic data and the type of PCMs, in addition to simulating the system within the artificial intelligence control logic.

The system relies on a main control unit that monitors the temperature sensitivity of the water in the main tank and the surrounding environment. Based on reading this data, the control unit determines the water flow path from the main tank, directing the water along intelligent path options according to the appropriate temperature, thus ensuring high system efficiency.

The path selection mechanism includes the following:

Scenario 1: For short-term hot water usage, the water flows through a winding path system within the three tanks to ensure rapid heat transfer.

Scenario 2: In low-radiance environments, the water flows from the main tank to the RT42 tank because conditions do not allow for a significant increase in temperature.

Scenario 3: For moderate hot water flow, higher temperatures can be achieved by utilizing paths within the tank containing the RT42 tank.

Scenario 4: At night, the system is completely sealed to prevent heat transfer to the outside.

Figure 5 provides a visual representation of the system.

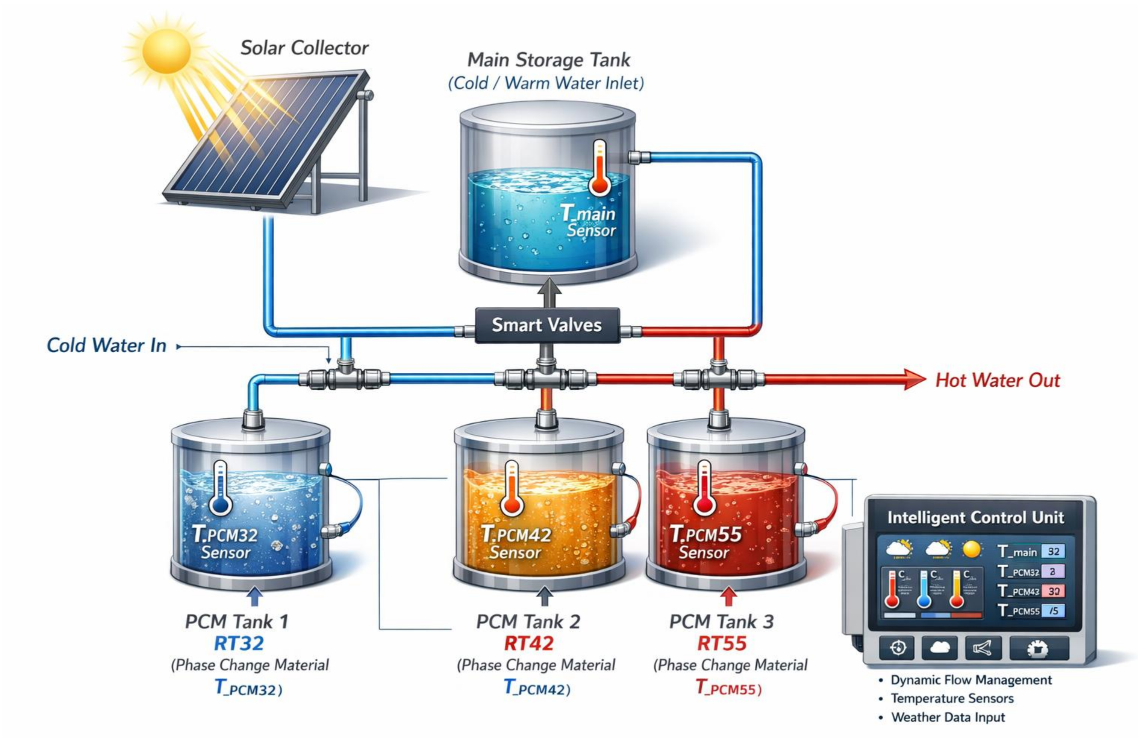

FIGURE 5. Initial Overview of the Smart Heating System

Table 4 represents a comparison of the efficiency of the system within the traditional scope and the smart system, where the table shows the difference in system efficiency.

TABLE 4. System Efficiency and Performance Comparison

Criteria	Single Standard System	Smart PCM Integrated System	Technical Reasoning
Collector Thermal Efficiency	45% – 55%	70% – 85%	Use of Nanofluids and Vacuum Insulation Panels (VIP).
Annual Solar Fraction	55%	82%	Higher capacity to meet heating demand during winter months.
Nightly Temperature Drop	12°C – 18°C	3°C – 5°C	Latent heat release from PCMs compensates for heat loss.
Heat Loss Coefficient	High	Ultra-Low	Smart control prevents reverse circulation during night hours.
System Reliability	Moderate	High (Autonomous)	Smart sensing adjusts to weather changes (Amman intervals).

Table 4 represents the digital simulation of system efficiency at 6 key time points. The table shows higher efficiency and stability of the smart system compared to the non-smart system.

TABLE 5. Efficiency Analysis at the 6 Key Time Points

Date Event	Standard System Efficiency	Smart System Efficiency	Efficiency Gain (%)
Sep 22 (Equinox)	52%	88%	+36%
Nov 05 (Mid-Autumn)	48%	82%	+34%
Dec 21 (Solstice)	38%	74%	+36%
Jan 20 (Peak Cold)	35%	72%	+37%
Feb 15 (Late Winter)	45%	79%	+34%
Mar 20 (Equinox)	55%	86%	+31%

From the previous table, the efficiency ranges between 88% and 72% in the smart system, while in the individual (ordinary) system it ranges between 55% and 35%, where the stability in the smart system is evident, while the high variability in efficiency is evident in the ordinary system. The following curves in Figure 6 represent a comparison between the smart heating system and the traditional (normal) system. The differences between the two systems are evident from the levels of the difference in favor of the smart system in terms of efficiency and stability. It is clear that there is a variation in temperatures and a fixed solar radiation path or constant temperatures cannot be relied upon due to rapid changes in weather conditions within the short time range and the uncertainty of what the weather will be like. This requires that the control system include fuzzy logic in determining the path of phase-change materials according to that change.

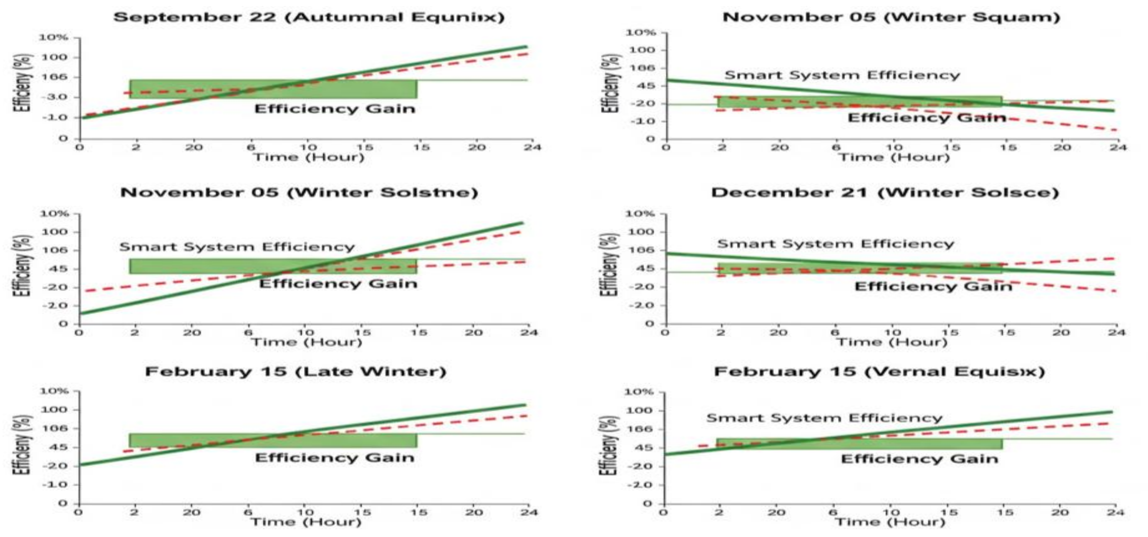

FIGURE 6. Comparison in Terms of Efficiency and Stability

Observations and conclusions from the curves in Figure 6:

Solid Green Line: Indicates the smart solar system. This line represents the system's superior performance, demonstrating consistent efficiency over time.

Dashed Red Line: Indicates the conventional solar system. This line represents the performance of a typical single-storage tank, clearly showing its low efficiency due to heat loss.

Shaded Area: Represents the efficiency gap and the extent of improvement achieved by the smart system compared to the conventional system. The larger this area, the more successful the smart system will be in handling cold climatic conditions.

Figure 7 represents the need to change the selection of appropriate phase-change materials according to the change in time, and this supports the feasibility of using an intelligent system that determines the appropriate path for water according to a digital reading of history based on a time archive of stability within those time ranges.

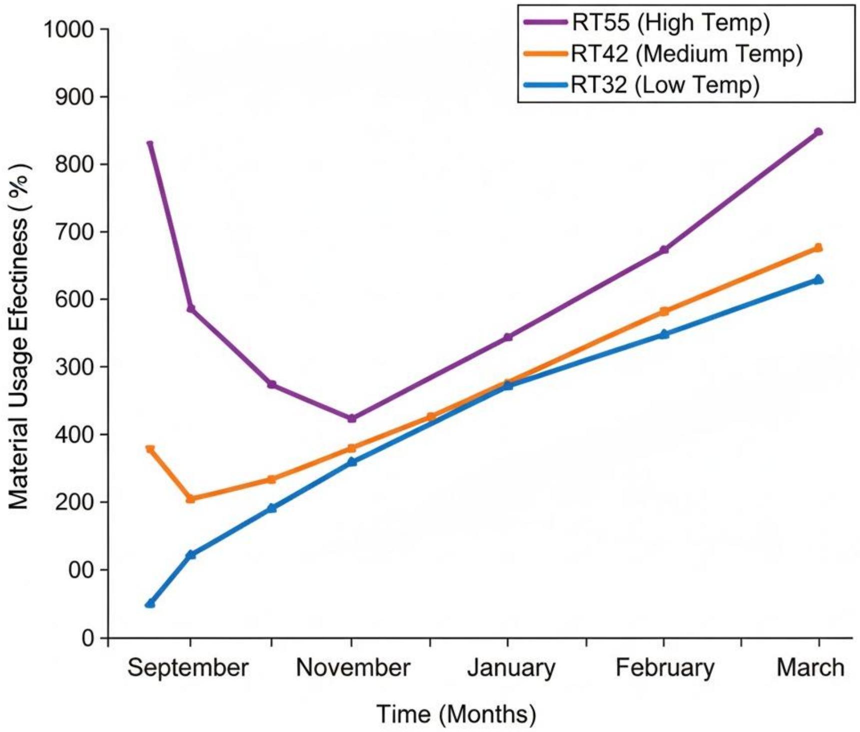

FIGURE 7. Level of Difference Between Phase Change Materials

The following curves in Figure 8 represent the need to change the selection of suitable PCMs according to the change in temperature. This supports the feasibility of using an intelligent system that determines the appropriate path for water according to a digital reading of the ambient temperature of the system, based on a time archive of this data or through an instantaneous reading. It is also evident that the efficiency of the phase-change material RT32 is within low temperatures, while RT42 is appropriate for medium temperatures, and RT55 is distinguished within high temperatures.

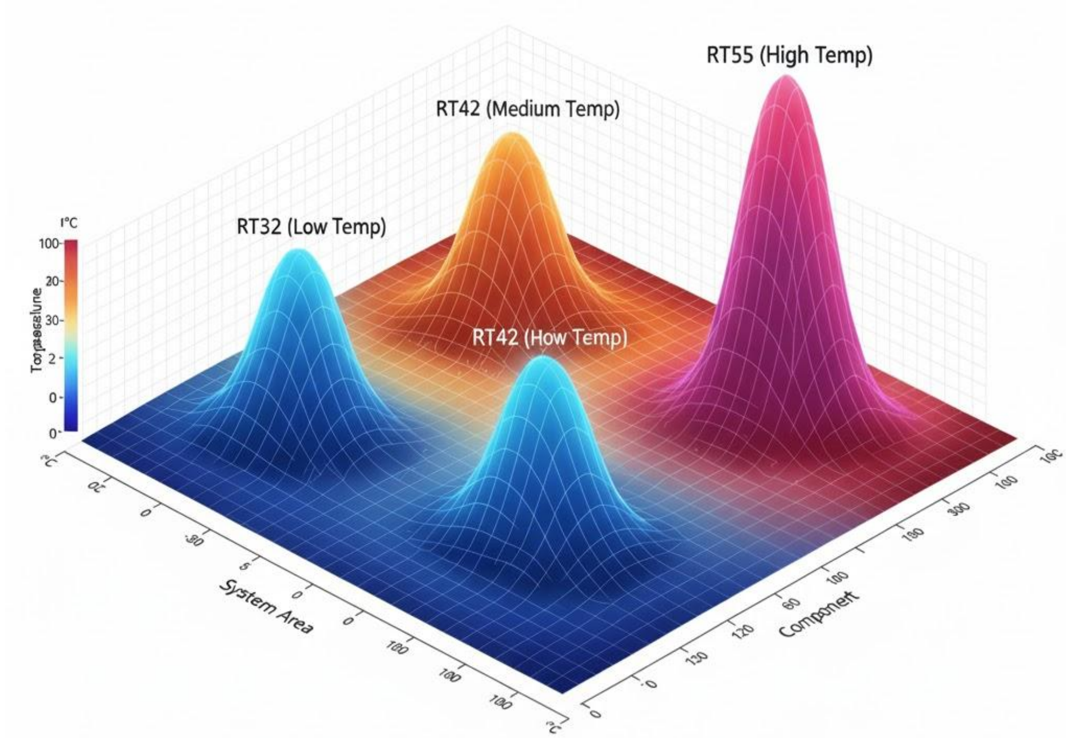

FIGURE 8. Thermal Variation of PCMs According to Temperature

It is clear that there is a variation in temperatures, and it is not possible to rely on a fixed solar radiation path or fixed temperatures due to the rapid changes in weather conditions within the short time range, and the uncertainty about what the weather will be like. This requires that the control system include fuzzy logic in determining the path of phase-change materials according to those variables. Therefore, time ranges were determined for those variables to contribute to determining of the control system to determine the appropriate phase-change material according to changing instantaneous readings.

Based on the above, the heat distribution of the system as a whole can be given according to Figure 9:

FIGURE 9. Simulation of Thermal Expansion in the System

The operation of the control unit in this model is based on fuzzy logic to control the three tanks containing the phase-change materials supporting the main tank. The fuzzy control unit evaluates the temperature difference between the reference value and the tank temperature, and thus determines the appropriate material. The control unit activates tanks RT32, RT42, or RT55 in accordance with the heat requirement. The following is a sequence of steps for the control unit to operate:

- Reference Temperature: $T_{Ref} = 40^{o}C$, where T_{Ref} represents the reference temperature for the main tank in a solar heating system.
- Stand Temperature: T_s , where T_s represents the measured temperature of the water inside the main solar storage tank.
- The fuzzy control unit is based on a comparison between T_{Ref} and T_s:

If $T_{Ref} \geq T_s \rightarrow$ No need to activate thermal support.

If $T_{Ref} \leq T_s \rightarrow$ Activating the thermal support system.

- Depending on the difference between between T_{Ref} and T_s, the PCMs reservoirs are activated as follows:

1. Slight temperature difference → Activate RT32 for moderate thermal support.
2. Moderate temperature difference → Activate RT42 for moderate thermal support.
3. Severe temperature difference → Activate RT55 for strong thermal support.

- Converting temperature variations into fuzzy linguistic variables to enable the control system to identify the appropriate material.
- The above cases result in an activation signal for the tank valve to be activated, in addition to the degree of valve opening.
- The presence of a continuous system for monitoring tank temperatures and continuous comparisons to ensure the continuity of the control cycle.

Conclusion

In this research study, a vision was formulated for the integration of artificial intelligence and phase-change materials to improve the efficiency of solar water heaters. The digital simulation was demonstrated through calculations that included a case study of the Jordanian capital, Amman, through the climatic system within the time range extending from the autumnal equinox to the spring equinox. The simulation demonstrated the control of three tanks containing three types of phase-change materials, namely RT32, RT42, and RT55, connected to a main water supply tank supported by a solar heating system and an intelligent control system based on fuzzy logic, based on temperature sensing and valve control according to data that ensures higher efficiency of the heating process. The study focuses on the need to expand the integration between the solar water heater industry and artificial intelligence, and the positive impact this has on the efficiency of solar heating systems.

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