DESIGN AND SIMULATION OF A SOLAR THERMAL HEATING SYSTEM

A PROJECT REPORT SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING, FACULTY OF ENGINEERING

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CERTIFICATION

This is to certify that this research project titled: **DESIGN AND SIMULATION OF A SOLAR THERMAL HEATING SYSTEM** submitted to the Department of Mechanical Engineering was carried out by **AGUONYE LUCKY CHUKWUNALU**, **OSEDEME PECULIAR OKWUCHUKWU, ARUNAH HILLARY ALEOGHO and APUAMAGA LUCKY CHUKWUEKU** of the Department of Mechanical Engineering, University of Benin, Benin city, Edo State, Nigeria, under the supervision of **PROF. E. G. SADJERE**

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DEDICATION

We hereby dedicate this project to God and our families and friends. Your tremendous and unwavering support has been crucial to the completion of this project, and we are grateful for the privilege of your assistance and support.

ACKNOWLEDGMENT

We wish to express our profound gratitude, first and foremost, to God Almighty for granting us the strength, wisdom, and opportunity needed to carry out this project. We would also like to extend our heartfelt thanks to our respective families for their constant love, support, generosity and patience throughout this journey.

Our sincere gratitude goes to our supervisor, PROF. E. G. SADJERE, who encouraged us to undertake such a novel topic. Your unwavering support, insightful guidance, and words of encouragement have made this project both an enriching learning experience and a truly rewarding endeavour.

We are deeply appreciative of the individuals and organizations who generously provided journals, resources, data, and valuable insights that significantly enhanced our research and analysis.

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ABSTRACT

This report is based on the design and simulation of a solar thermal system that can be used for the provision of hot water in domestic and office applications. The increasing cost of conventional sources of energy coupled with the unreliability of the electricity supply has created problems in the provision of hot water services. The problem can be solved using solar energy, which is sustainable in this context. The main goal of this study was to design an optimal solar thermal system for the provision of hot water services.

The system was designed using a flat-plate solar collector, storage tank, pump, and control unit. The mathematical models of the system's thermal behavior were formulated, after which the system was simulated using numerical methods. The system's parameters, including mass flow rate, tilt angle of the solar collector, and insulation properties, were varied to assess their impact on the system's performance.

Simulation results indicated that it was possible for the system to produce enough hot water for domestic and office use. The system also indicated improved thermal efficiency for lower flow rates and optimized collector orientation. The study also indicated that improved system insulation reduced losses and improved system performance.

In conclusion, the designed solar thermal heating system proved to be an effective and environmentally friendly solution for hot-water supply. The optimization analysis provides useful guidelines for improving system efficiency and adapting the design for practical implementation in similar climatic regions.

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CHAPTER ONE

INTRODUCTION

1.1 Background To The Study

Water heating has become an integral part of daily living, not only in homes but also in institutions and industries. In households, it is used for bathing, laundry, dishwashing, and cooking. Hospitals and clinics rely on heated water for sterilization and sanitation, while industries use it in cleaning, food processing, and chemical preparation. The increasing demand across these sectors highlights the essential role that water heating plays in modern life.

Traditionally, hot water has been produced using electricity, kerosene stoves, liquefied petroleum gas (LPG), and even firewood. These sources, though effective, present major challenges. Electricity is becoming more expensive and unreliable in many regions, kerosene and gas prices fluctuate with global fuel markets, and firewood contributes to deforestation and indoor air pollution. In addition, all fossil fuel–based methods release greenhouse gases, which are key drivers of climate change. The continued reliance on such conventional methods creates economic burdens and environmental risks.

Solar energy has emerged as a strong alternative due to its abundance, cleanliness, and renewability. In tropical and subtropical regions, such as Nigeria, solar radiation is available almost throughout the year, making it an underutilized but promising resource. Solar thermal heating works by capturing sunlight through collectors, transferring the heat to a fluid, and storing it for later use. Compared to fossil fuel–based systems, solar water heaters reduce operational costs, lower carbon emissions, and enhance energy security.

The global push for renewable energy technologies further emphasizes the need for innovations like solar heating. Countries are adopting policies and incentives to encourage the use of clean energy solutions, recognizing that sustainable energy systems not only reduce environmental impact but also improve quality of life. In this context, the design and construction of a solar water heater represents both a technical and societal response to the challenge of balancing rising energy demand with the urgent need for environmental conservation.

1.2 Statement Of The Problem

Despite the increasing awareness of renewable energy technologies, most households and institutions still rely heavily on electricity, gas, and firewood for heating water. This dependence creates several interconnected problems.

First, there is the economic problem. With the rising costs of electricity and constant power cuts, most people end up spending more money in the use of other fuels such as gas or kerosene. This is a big burden to most people, especially those from the middle class. Institutions such as hospitals, schools, and hotels that require large quantities of hot water also face high operational costs.

Secondly, there are environmental and health concerns. Burning fossil fuels for heat releases carbon dioxide and other pollutants into the atmosphere, worsening the problem of global warming. In rural areas, many families still rely on firewood for heating water, leading to deforestation, loss of biodiversity, and respiratory problems caused by smoke inhalation.

Finally, although solar water heaters are a viable alternative, their implementation has been slow. The reasons for this are the high installation cost, the lack of technical knowledge among local technicians, and a lack of awareness regarding the benefits of solar water heaters. This has resulted in a gap between the potential of solar energy and its implementation.

The central problem addressed in this study, therefore, is the continued dependence on unsustainable and costly water heating methods, despite the availability of abundant solar energy.

1.3 Aims And Objectives Of The Project

The overall aim of the project was to develop and evaluate a simulation model of a solar thermal heater that is affordable, efficient, and adaptable to local conditions. By doing so, the project seeks to demonstrate that renewable energy can be applied in practical ways to meet every day needs.

Objectives:

To achieve this aim, the project is guided by the following objectives:

1. To develop a simulation model of a solar thermal heating system
2. To explain the principles and components involved in solar thermal heating systems.
3. To integrate local meteorological data and validate the simulation model using TRNSYS
4. To evaluate system performance and conduct parametric optimization.
5. To compare the economic and environmental benefits of solar water heating with traditional methods and identify research gaps and justifications to the study.

1.4 Scope Of The Project

The scope of this project is limited to the design and simulation of a solar-thermal heating system intended for domestic and small institutional use. The system includes a flat-plate solar collector, a storage tank, a DC pump, controller and connecting pipes. The project does not attempt to build a large-scale or commercial system, but rather a practical model that demonstrates the feasibility of the concept.

The analysis and parametric sweep of the model will concentrate on parameters like temperature increase, efficiency, and storage capacity based on different solar conditions. The scope will also include a basic cost analysis of the system in comparison to the conventional method. The limitations, which include reliance on weather, availability of materials, and local labor, will also be discussed.

1.5 Significance Of The Project

This project carries significance in multiple dimensions:

Environmental Impact: By relying on solar radiation, the system reduces greenhouse gas emissions, helping to mitigate climate change and reduce reliance on non-renewable energy sources.

Economic Benefits: Households and institutions can lower their energy bills by substituting solar energy for costly electricity and fossil fuels. Demonstrating a low-cost model further proves that renewable energy can be affordable.

Technical and Academic Value: The design and construction process allows for the application of engineering principles like thermodynamics, fluid mechanics, and heat transfer. It also helps in the development of problem-solving and innovation skills.

Social Relevance: In rural and semi-urban communities with unreliable power supply, solar water heating can provide a dependable source of hot water, improving living standards while reducing fuel scarcity pressures.

Policy and Awareness Contribution: The project can also contribute to the wider dissemination of solar water heaters by presenting a working model and creating awareness about the use of solar water heaters, thus achieving the global and national goals for the development of renewable sources of energy.

In summary, the project is significant because it combines environmental conservation, economic savings, academic learning, and social impact into a single practical innovation. It not only proves the feasibility of solar powered water heating but also encourages the wider adoption of renewable technologies for sustainable development.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

A solar thermal system for heating is a technology that has been developed to harness solar radiation and convert it into usable thermal energy for domestic, commercial, or industrial heating requirements. While solar panels are used for generating electrical energy through photovoltaic technology, a solar thermal system works on the direct conversion of heat energy from solar radiation through flat plate, evacuated tube, or concentrating tubes and then transferring it to a fluid for water or space heating. This direct conversion process offers high efficiency and has proven to be one of the most effective means of utilizing the sun's abundant energy for thermal purposes.

The growing global emphasis on sustainability and carbon neutrality has renewed interest in solar thermal technologies as viable solutions to the world's energy challenges. The heating sector alone accounts for nearly half of total global energy consumption and a significant proportion of greenhouse gas emissions, most of which are derived from fossil fuels (IEA SHC, 2023). By providing a renewable, low-emission alternative, solar thermal systems can substantially reduce dependency on non-renewable energy sources, mitigate environmental degradation, and contribute to the achievement of Sustainable Development Goal 7 on affordable and clean energy.

Solar thermal heating systems require significant importance to be given to their simulation and study, as it is vital for improving the design efficiency, cost-effectiveness, and suitability to different climatic environments. Using simulation, it is possible to optimize complex thermal interactions, predict system reliability, and even predict possible problems that may arise, which can be advantageous in making decisions regarding investment in renewable energy resources.

This literature review will examine the state of knowledge regarding solar thermal heating systems, starting with an overview of solar energy utilization and solar system principles, configurations, materials, modeling techniques, performance assessment, and knowledge gaps to inform the design simulation framework for the proposed study.

2.2 Overview of Solar Energy Utilization

Solar energy stands as one of the most abundant renewable resources available to humanity, offering vast potential for decarbonising energy systems and enhancing sustainability. Sunlight reaching the Earth delivers more energy in an hour than the global human population uses in a year, underscoring its sheer magnitude (Li et al., 2022). As a clean, ubiquitous, and increasingly cost-competitive resource, solar energy plays a critical role in global efforts to reduce reliance on fossil fuels, curtail greenhouse-gas emissions and meet growing energy demand in an environmentally responsible manner.

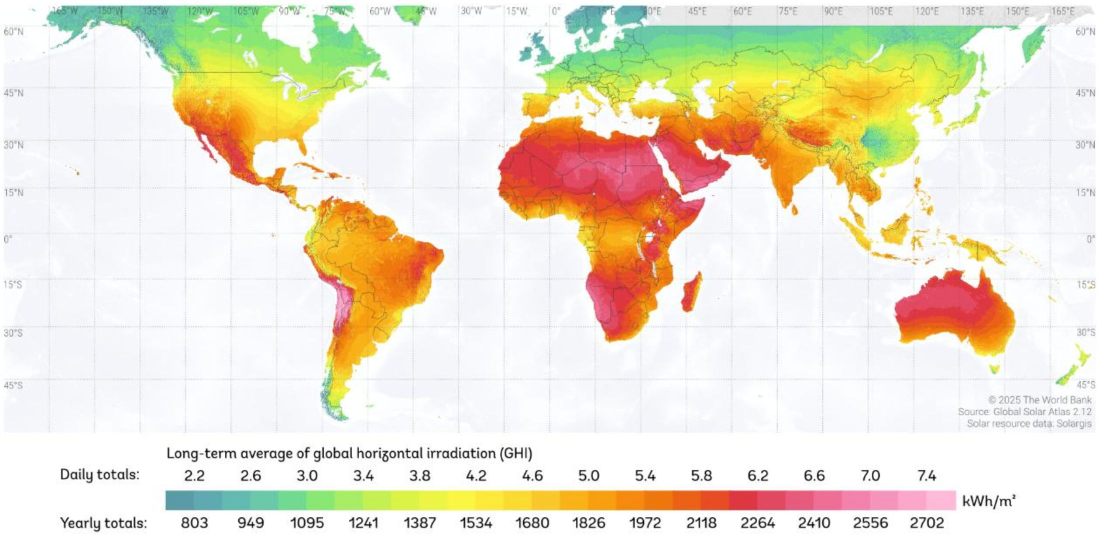


Figure 2.2 ***Global distribution of average solar radiation, showing high potential across tropical regions (Data source: Global Solar Atlas, 2025).***

In the broad field of solar energy utilisation, there are two major branches: photovoltaic systems and solar thermal systems. In photovoltaic systems, solar radiation is utilised and converted into electrical power using semiconductor materials. The field has seen tremendous growth in recent times. In solar thermal systems, solar radiation is collected and used as heat. The heat is then transferred to a working fluid. The distinction is significant: while PV addresses electrical demand, solar thermal systems target heating (and sometimes cooling) loads more directly and often more efficiently for certain temperature ranges (Li et al., 2022). Because heat demands particularly in buildings, industry and processes form a large part of global energy consumption, solar thermal presents a complementary pathway rather than a competitor to PV.

Solar thermal systems find wide application across domestic, commercial and industrial domains. In residential and commercial settings they are used for hot-water generation, space heating, pool heating and building-integrated systems. Industrially, solar thermal collectors provide process heat for food and beverage operations, chemical processing, textile and leather industries, drying, evaporation and even in large-scale district-heating schemes (Kumar & Suman, 2021; Kumar et al., 2022). For example, a recent review reports that over half of industrial process-heat demand occurs at temperatures below 250 °C well within the proven capability of many solar-thermal collectors (Kumar et al., 2022). Moreover, large-scale solar-district-heating systems are gaining momentum: the 2024 edition of *Solar Heat Worldwide* noted that by the end of 2023 there were nearly 600 large-scale systems (> 500 m² collector area) operating globally, and that more than 77 new systems were installed in Europe alone in 2023 (+90 % year-on-year) (IEA SHC, 2024).

From a global-trend perspective, the uptake of solar technology is strong: a recent comprehensive review observed that solar energy utilisation in general is expanding rapidly but unevenly while PV leads in capacity additions, solar thermal is less aggressively deployed despite its maturity (Li et al., 2022). The industry report by the International Energy Agency Solar Heating & Cooling Programme (IEA SHC) indicated significant growth of large-scale solar-thermal collectors for district and process heating, signalling a shift from mainly small residential systems to more ambitious applications (IEA SHC, 2024). The growing interest in industrial use reflects recognition that heat demands are a major contributor to global energy use and emissions, yet routinely overlooked compared to electricity generation.

In conclusion, solar thermal energy systems have a distinct niche in the solar energy sector. Although photovoltaic systems continue to be the main attraction in many country plans, the direct utilization of solar energy in the form of heat is a very attractive and efficient solution for the massive heat demand in buildings and industry. It is very important to identify the differences between PV and solar thermal systems, in terms of their applications and usage. The trend towards industrial-scale solar thermal systems is a clear indication of growing maturity and relevance. With this background in mind, the next section of this review will discuss the principles of solar thermal heating systems, explaining how they work, the thermodynamic principles behind them, and so on.

2.3 Principles of Solar Thermal Heating Systems

Solar thermal heating systems are engineered to capture, convert, and store solar radiation in the form of heat energy for use in domestic, commercial, or industrial applications. Their design integrates several thermodynamic and heat-transfer mechanisms absorption, conduction, convection, and radiation to achieve efficient energy conversion. Understanding the working principles of these systems is fundamental to optimizing their performance, ensuring long-term reliability, and supporting accurate simulation models.

1. Working Principle

The basic operating principle of a solar thermal system is based on the ability of solar radiation to convert into heat energy. When solar radiation is incident on the surface of the solar collector's absorber plate, a part of this energy is absorbed and converted into heat energy. This heat energy is then transferred to a heat transfer fluid (HTF), usually water or a mixture of water and glycol or air or thermal oil, and then carried to a storage medium or the load.

This process starts with solar energy collection, where the solar irradiance (global and diffuse radiation) falls on a collector with a selective surface to ensure maximum absorptivity and minimum emittance. This energy then raises the temperature of the absorber plate and creates a temperature gradient between the plate and the fluid being circulated. This heat is then transferred to the fluid by natural conduction and convection, which increases its temperature.

The next phase is the heat transfer and storage phase. In this phase, the fluid is transferred either to the application point or to a thermal energy storage tank. This phase enables the system to provide heat during times when there is low solar availability. Finally, there is the heat distribution and control mechanism. This mechanism controls the transfer of heat from the collectors to the system.

The overall thermal efficiency of the system depends on several dynamic factors: solar irradiance, collector optical efficiency, heat losses, flow rate, and temperature differentials.

2. Major Components

(a) Solar Collectors

The solar collector is the primary energy-capturing component of a solar thermal system. It converts incident solar radiation into heat, which is subsequently transferred to a working fluid. Collectors are broadly categorized into **non-concentrating** and **concentrating** types.

- **Flat-Plate Collectors (FPCs)**: These are the most common type, consisting of a dark absorber plate enclosed in an insulated box with a transparent cover (glazing). They operate efficiently for temperatures up to about 80°C and are widely used in domestic water and space heating.

- **Evacuated-Tube Collectors (ETCs)**: These use a vacuum-sealed glass tube to minimize convective and conductive losses, enabling operation at higher temperatures (up to 150°C). They are particularly suitable for colder climates and applications requiring medium-grade heat.

- **Concentrating Collectors**: Parabolic troughs, Fresnel lenses, and solar dishes focus sunlight onto a receiver, achieving much higher temperatures (up to several hundred degrees Celsius). These are more suitable for industrial process heat or power generation.

Collector performance is characterized by its **optical efficiency** (η_0) and **heat loss coefficients** (U_1, U_2), which quantify how much solar radiation is converted into useful heat and how much is lost to the environment.

(b) Heat Exchangers

Heat exchangers are very important in the process of transferring heat from the collector circuit to the storage tank or load without any mixing of the working fluids. For example, systems that employ antifreeze fluids, such as glycol-water solutions, in order to prevent freezing.

Coil heat exchangers and shell-and-tube heat exchangers are the two most common types of heat exchangers. The effectiveness of the heat exchanger depends on the temperature difference between the two fluids, the surface area, the conductivity of the material, and the flow characteristics. In high-performance heat exchangers, copper or stainless steel tubes with fins or corrugated surfaces are used to increase the heat transfer coefficients.

(c) Thermal Storage Tanks

Thermal energy storage is essential for balancing supply and demand in solar thermal systems. The most common form of storage is **sensible heat storage**, where water or another medium stores energy by changing temperature without changing phase. Storage tanks are insulated to minimize losses and may include **stratification mechanisms** to maintain thermal layers hot water at the top and cooler water at the bottom.

In advanced designs, **phase-change materials (PCMs)** or **thermochemical storage** systems are employed to increase energy density. PCMs store heat through latent heat during phase transitions (typically solid–liquid), maintaining nearly constant temperature during melting and solidification (Arifin et al., 2024).

(d) Control Units

Control units regulate system operation, ensuring maximum efficiency and safety. A **differential temperature controller** monitors the temperature difference between the collector outlet and the storage tank. When this difference exceeds a set threshold, the pump activates to circulate fluid; when it falls below a lower limit, the pump stops to avoid cooling the storage tank.

More advanced systems integrate **smart controllers** with variable-speed pumps and predictive algorithms based on weather forecasts to optimise flow rate and prevent stagnation (Jensen et al., 2024). These controls can be simulated to test their impact on system performance under varying solar and load conditions.

3. Role of Heat Transfer Fluids and Insulation

The choice of heat transfer fluid (HTF) determines the operating range, heat capacity, and long-term stability of the system. **Water** is the most common and efficient HTF for moderate climates, but it poses freeze and corrosion risks. In colder regions, **glycol-water mixtures** (propylene or ethylene glycol) provide freeze protection but have higher viscosity and lower thermal conductivity. For high-temperature applications, **synthetic thermal oils** or **molten salts** are used due to their thermal stability (Khan et al., 2023).

Emerging studies are exploring **nanofluids**, where nanoparticles such as Al_2O_3 or CuO are suspended in base fluids to improve thermal conductivity and convective heat transfer (Cui et al., 2023). But problems like agglomeration, stability, and higher pumping power are still some of the challenges.

Thermal insulation is also an important aspect, as it reduces heat loss from collectors, pipes, and storage tanks. The most commonly used insulation materials are polyurethane foam, mineral wool, and vacuum insulation panels. The thickness of the insulation material and its thermal conductivity have a direct effect on the efficiency of heat retention in the system.

4. Efficiency Factors and Design Considerations

The efficiency of a solar thermal heating system depends on both **environmental** and **design** parameters. Environmental factors include solar irradiance, ambient temperature, wind speed, and orientation, while design parameters include collector area, tilt angle, flow rate, and storage capacity.

The **instantaneous thermal efficiency (η_t)** of a collector is generally expressed as:

$$\eta_t = \eta_0 - a_1 \frac{(T_m - T_a)}{G} - a_2 \frac{(T_m - T_a)^2}{G}$$

where:

- η_0= optical efficiency,
- a_1, a_2= heat loss coefficients,
- T_m= mean fluid temperature,
- T_a= ambient temperature,
- G= solar irradiance.

This equation highlights that as the operating temperature increases relative to ambient conditions, efficiency decreases due to increased thermal losses.

Common design considerations include:

- **Collector orientation and tilt angle**, which should maximize annual solar capture (typically latitude ± 10°).
- **Flow rate optimization**, balancing higher heat transfer with increased pumping energy.
- **Storage sizing**, ensuring adequate heat availability during low solar periods.
- **Material compatibility**, particularly when using antifreeze or nanofluids.
- **Control logic**, to prevent overheating or freezing and to maintain system stability.

Studies such as Al-Madhhachi et al. (2021) and Remlaoui et al. (2024) show that simulation-based optimisation of these parameters can increase annual efficiency by up to 15 % compared to empirically sized systems.

5. Summary

It can therefore be concluded that the solar thermal heating systems are based on the physical principles of sequential solar radiation absorption, thermal energy transfer, storage, and control. This interdependence of solar thermal heating systems' components is a crucial factor in the performance of these systems. The selection of heat transfer mediums, thermal efficiency through adequate thermal insulation, and the use of optimal solar thermal heating systems' design parameters are essential for the maximization of thermal efficiency in solar thermal heating systems. These are the physical principles on which numerical modeling and simulation are based for the prediction of performance under various operating conditions and the design of cost-effective and sustainable solar thermal heating systems.

2.4 Types and Configurations of Solar Thermal Systems

Solar thermal heating systems can be classified in several ways based on circulation method, heat-transfer mechanism, and collector design. Each configuration has distinct operating principles, performance characteristics, and suitable applications. Understanding these distinctions is crucial for effective design and simulation, as system configuration directly affects efficiency, reliability, and cost.

1. Active vs. Passive Systems

The most fundamental distinction among solar thermal systems lies in their mode of circulation active or **passive** which determines how the heat transfer fluid moves through the collector loop.

Active systems use mechanical pumps and electronic controllers to circulate the heat transfer fluid. They typically include differential temperature sensors, which activate the circulation pump when the collector temperature exceeds that of the storage tank by a preset margin. Because of this forced circulation, active systems offer **greater control and efficiency**, especially in large or complex installations. They can also operate over longer piping distances and under variable orientations.

Al-Madhhachi et al. (2021) demonstrated through TRNSYS simulation that an active, forced-circulation system achieved higher thermal efficiency and solar fraction compared to a passive configuration in similar climatic conditions in Iraq, mainly due to better control over flow rate and reduced stagnation losses. Active systems, however, incur higher costs and maintenance requirements because of their pumps, controllers, and auxiliary energy use.

Passive systems, by contrast, rely on natural convection or thermosiphon effects caused by density differences between hot and cold fluid. These systems are simpler, more reliable, and cost-effective, with no need for electrical power or moving parts. However, they require specific installation geometry: the storage tank must be positioned above the collector to enable natural circulation. Their efficiency tends to be lower than that of active systems, especially in applications involving long piping runs or when the temperature differential is small (Arifin et al., 2024).

Best use case**s:**

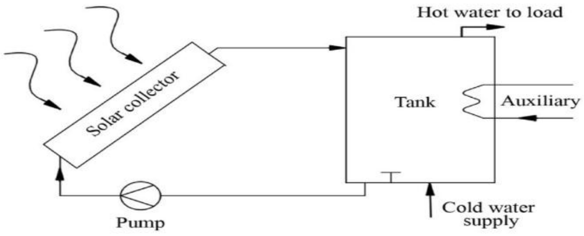
- *Active systems* are ideal for large-scale or commercial applications where precise control and high efficiency are desired.
- *Passive systems* suit small residential or rural installations where simplicity, low cost, and minimal maintenance are priorities.

2. Direct vs. Indirect Circulation Systems

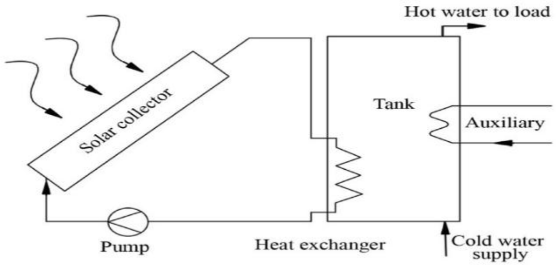
Solar thermal systems are also classified based on whether the working fluid directly supplies the end-use or exchanges heat via an intermediate loop.

In direct circulation systems (also known as open-loop systems), the same fluid that passes through the collector delivers heat directly to the storage tank or the load. These systems are highly efficient due to the absence of intermediate heat-exchange losses. They are suitable for mild or warm climates where freezing is not a concern and where water quality (low mineral content) minimizes corrosion and scaling.

Indirect circulation systems (closed-loop systems) employ a secondary heat transfer fluid often a glycol-water mixture to collect solar energy and convey it through a **heat exchanger** to a separate water circuit or storage tank. This configuration protects against freezing and corrosion, extending the system's lifespan and reliability.



Direct circulation



Indirect circulation

Figure 3.4.1. ***Schematic comparison of direct and indirect solar thermal circulation systems.***

Remlaoui et al. (2024) modeled a forced-circulation indirect system in Algeria and showed that while indirect systems suffer a 3–8 % reduction in instantaneous thermal efficiency compared to direct systems, they provide significantly improved year-round performance due to freeze protection and reduced maintenance.

Best use case**s:**

- *Direct systems* perform best in tropical or subtropical climates (e.g., West Africa, Southeast Asia) where temperatures rarely fall below freezing.

- *Indirect systems* are preferred in temperate and cold climates or in installations with long inactive periods, where antifreeze protection and durability outweigh minor efficiency losses.

3. Concentrated vs. Non-Concentrated Collector Designs

Another key classification involves whether the system uses **concentrating** or **non-concentrating** collectors. Collector design dictates achievable operating temperatures, system cost, and application type.

a. Non-Concentrating Collectors

Flat-Plate Collectors (FPCs) and **Evacuated-Tube Collectors (ETCs)** fall under this category.

- **Flat-Plate Collectors (FPCs)** are the most established technology. They consist of an absorber plate (usually copper or aluminium) coated with a selective surface, enclosed in an insulated box with transparent glazing. FPCs can achieve outlet temperatures of 40–80 °C and efficiencies between 50–70 % (Kumar et al., 2022). Their robust design and moderate cost make them ideal for domestic hot water, space heating, and low-temperature industrial processes.

- **Evacuated-Tube Collectors (ETCs)** use vacuum-sealed glass tubes to minimize convective and conductive losses. Each tube contains an absorber and sometimes a heat pipe, which transfers heat to a manifold. ETCs can reach temperatures above 120 °C with lower heat losses, especially in cold or windy conditions (Jensen et al., 2024). Studies comparing both types such as Khan et al. (2023) have shown that ETCs outperform FPCs by 10–25 % in annual thermal yield in climates with large temperature swings, though their higher cost and fragility may limit adoption.

Best use cases:

- *FPCs*: Economical option for domestic and commercial water heating in temperate or tropical regions.

- *ETCs*: Preferred for high-temperature or cold-climate applications, such as hospitals, hotels, or laboratories requiring constant hot water supply.

b. Concentrating Collectors

Concentrating Solar Collectors (CSCs) use reflective surfaces to focus sunlight onto a receiver, achieving much higher temperatures. The main types are parabolic trough, linear Fresnel, dish, and solar tower systems.

- **Parabolic Trough Collectors (PTCs)** are the most common, using parabolic mirrors to focus radiation onto a central receiver tube containing thermal oil or molten salt. PTCs operate efficiently between 150 °C and 400 °C and are often used in industrial process heat or solar thermal power generation (David-Hernández et al., 2025).

- **Linear Fresnel Collectors** use flat or slightly curved mirrors arranged in rows, offering simpler construction but slightly lower optical efficiency.

- **Parabolic Dish Collectors** achieve even higher concentration ratios and can exceed 600 °C but are mostly suited for research or niche applications due to their complexity and high cost.

Kumar and Suman (2021) compared concentrating and non-concentrating collectors and found that while concentrating systems provide higher temperatures, their optical losses, alignment requirements, and higher costs make them less suitable for small-scale heating. Conversely, flat-plate and evacuated-tube designs offer greater simplicity, making them dominant in residential and commercial sectors.

Best use cases:

- *Concentrating systems*: Industrial process heat, steam generation, and hybrid solar-power plants.

- *Non-concentrating systems*: Domestic and institutional water or space heating where medium-temperature heat (< 120 °C) suffices.

4. Comparative Performance and Design Trade-offs

From performance comparison studies carried out for various systems, it is evident that the performance of these systems is highly dependent on operating temperature, irradiance, and configuration. To cite an example, a simulation study carried out by Khan et al. (2023) revealed that a liquid-based evacuated tube system had achieved a 15% increase in overall efficiency compared to an air-based flat plate system under similar radiation conditions due to better heat transfer properties. However, FPC systems are still found to be cost-effective for implementation.

Active indirect systems with evacuated tube collectors will produce the highest solar fraction per year, especially in cold climates with long heating seasons. On the other hand, passive direct systems with flat plate collectors are best suited for the low-latitude markets because of their simplicity and minimal operating demands. Concentrating systems are best suited for situations where process temperatures above 150°C are required, but are not suitable for domestic situations.

In summary, there is no single configuration that is optimal in all conditions. The choice of configuration depends on factors like the climate, load temperature, cost constraints, and maintenance capabilities. Simulation tools like TRNSYS, MATLAB, and EnergyPlus can be used by designers to assess the different configurations. The incorporation of performance models for different configurations helps ensure that the selected system strikes the appropriate balance for its intended application.

2.5 Materials and Heat Transfer Fluids in Solar Thermal Systems

Selecting appropriate materials and heat-transfer fluids (HTFs) is central to the efficiency, durability, and cost of solar thermal systems. Choices at the absorber surface, glazing, insulation, and working-fluid levels collectively determine optical absorption, thermal losses, corrosion resistance, and operating temperature window.

Absorber and glazing materials

Most flat-plate and evacuated-tube collectors employ high-conductivity metals for absorber plates - primarily copper or aluminum - finished with solar-selective coatings that maximize absorptance ($\alpha \rightarrow 0.95–0.98$) while minimizing thermal emittance ($\varepsilon \lesssim 0.10$) at operating temperatures. Recent reviews describe multilayer cermet stacks, nitrides/carbides (e.g., TiN_x, AlN_x), and nano-engineered films that retain selectivity under thermal cycling and humidity exposure; durability (adhesion, oxidation) is now a core design target for mid-temperature operation (≈100–250 °C). (Zayed et al., 2024).

Glazing is typically low-iron borosilicate glass, chosen for high transmittance, chemical stability, and - on evacuated tubes - the ability to maintain vacuum without creep. In evacuated-tube collectors, the double-glass envelope and barium getter sustain low pressure to suppress convective/conductive losses; thickness and glass composition affect optical transmittance and mechanical reliability (e.g., hail impact). (Hayek et al., 2020 review).

Insulation and structural materials

Back and edge losses dominate thermal leakage in non-concentrating collectors and storage tanks, so polyurethane foams and mineral wool are widely used for their low thermal conductivity and ease of application; several experimental and review studies continue to recommend PU foams for cylindrical hot-water tanks due to strong cost–performance balance. (Zaafouri et al., 2025; Hussain et al., 2025; IJEES overview, 2024).

For seasonal or higher-performance storage, vacuum insulation (VIPs or double-wall vacuum envelopes) can cut standby losses substantially; a 100 m^3 demonstrator and subsequent testing indicate large gains in the renewable heating share when VIPs are integrated, though cost and integration complexity remain barriers. (Vérez et al., 2021; Božiček et al., 2024).

Collector housings and storage shells are commonly aluminum or coated steel for frames and stainless steel or enameled steel for tanks, balancing structural rigidity, corrosion control, and manufacturability (typical practice summarized across SWH reviews).

Heat-transfer fluids (HTFs)

HTF selection sets the usable temperature range, pumping power, freeze protection, and compatibility with metals, elastomers, and coatings.

- **Water.** Highest specific heat, low viscosity, low cost - ideal for mild climates and direct systems. Drawbacks include freezing, scaling/corrosion, and boiling/stagnation risks at high irradiance. (Al-Mamun et al., 2023).
- **Water–glycol mixtures (propylene/ethylene glycol).** Provide robust **freeze protection** and are standard in **indirect (closed-loop)** systems. Penalties include lower heat capacity and higher viscosity, raising pumping energy and slightly reducing instantaneous efficiency versus direct water loops - offset by better year-round reliability. (Remlaoui et al., 2024).
- **Synthetic thermal oils (e.g., Dowtherm™ A / Therminol® VP-1 class).** For medium-to-high temperatures (liquid phase ~15–400 °C; vapor phase ~257–400 °C), biphenyl/diphenyl-oxide eutectics deliver chemical stability and low vapor pressure across the operating window; they require careful sealing and oxygen management to limit oxidation. (Dow, Technical Data Sheet).
- **Molten nitrate salts (e.g., Solar Salt, 60 % $NaNO_3$/40 % KNO_3).** Serve as both HTF and **thermal storage** medium in CSP and high-temperature process heat, offering low vapor pressure, non-flammability, and favorable cost, but with **low thermal conductivity (< 1 $W\ m^{-1}\ K^{-1}$)** and a relatively high freezing point (~220 °C) that imposes heat-tracing. Recent studies refine property datasets and explore multicomponent eutectics for lower

melting points and enhanced conductivity. (Bonk et al., 2021; Ren et al., 2025; Li et al., 2022; Henríquez et al., 2024).

- **Nanofluids.** Dispersing high-conductivity nanoparticles (Al_2O_3, CuO, CNT, graphene derivatives) in base fluids can raise effective thermal conductivity and convective heat-transfer coefficients, yielding reported collector-side improvements in thermal/exergy efficiency. However, **stability (agglomeration), erosion/corrosion, and increased viscosity** (higher pumping work) remain unresolved for long-term use, and performance gains vary with particle chemistry, size, loading, and surfactant strategy. (Tembhare & Chamoli, 2022; Bocanegra et al., 2024).

Comparative thermophysical considerations

At < 100 °C, water outperforms alternatives on a per-kW basis due to its high specific heat (~4.18 $kJ\ kg^{-1}\ K^{-1}$) and low viscosity - hence its prevalence in domestic hot-water and space-heating loops. In sub-zero climates, glycol blends trade a 5–15 % heat-capacity reduction and higher pumping power for freeze resilience; simulations in indirect systems still show higher annual service availability than direct water systems where freeze events are possible. (Remlaoui et al., 2024).

For 150–400 °C service (industrial hot oil circuits, some concentrating collectors), synthetic aromatics (Dowtherm™ A class) maintain liquid-phase stability and manageable vapor pressures; their lower specific heat than water is offset by the targeted temperature regime and closed-loop design with expansion tanks and inert-gas blankets. (Dow TDS).

Above ~200 °C, nitrate molten salts provide dual roles as HTF and storage, enabling multi-hour dispatch at utility scale. Current literature emphasizes their low thermal conductivity as a bottleneck and investigates multication eutectics and nano-enhanced salts to reduce melting point and raise conductivity/capacity; updated correlations for density/viscosity/CP (e.g., for ±1 wt% composition shifts around 60/40) support more accurate system simulation and safety margins. (Bonk et al., 2021; Ren et al., 2025; Wang et al., 2024).

Trends in materials research

Three materials directions dominate current R&D:

1. **Durable selective coatings** with high solar absorptance and low emittance that **retain performance under aging** (thermal cycling, humidity, UV); multilayer and nanostructured stacks are being optimized for mid-temperature collectors and evacuated plates. (Zayed et al., 2024).

2. **Advanced insulation** - especially **vacuum insulation panels** and hybrid VIP-foam concepts - for storage tanks and collector backsheets to cut standby losses without excessive thickness or mass. (Vérez et al., 2021; Božiček et al., 2024).

3. **Next-generation HTFs**, including **nano-enhanced water/glycol** and **multicomponent nitrate eutectics** with lower melting points and improved conductivity, plus continued benchmarking of **synthetic oils** for medium-temperature loops. (Tembhare & Chamoli, 2022; Ren et al., 2025; Dow TDS).

Overall, pairing **high-selectivity, age-resistant absorbers** with **super-insulated storage** and **application-matched HTFs** represents the clearest pathway to raising solar-thermal system efficiency and reliability across climates and temperature classes.

2.6 Modeling and Simulation Approaches for Solar Thermal Systems

Modeling and simulation play a central role in the design, performance evaluation, and optimization of solar thermal heating systems. Unlike conventional heating systems whose operational parameters are relatively stable, solar-driven systems operate under highly dynamic conditions influenced by varying solar irradiance, ambient temperature, wind speed, and load profiles. Conducting physical experiments for all possible configurations and climatic scenarios would be prohibitively expensive and time-consuming. Therefore, simulation provides a cost-effective and flexible means to predict thermal performance, analyze energy flow, and optimize system components before prototype development or installation (Remlaoui et al., 2024).

1. Importance of Simulation in Solar Thermal System Design

The performance of solar thermal systems depends on multiple interacting physical processes - solar radiation capture, heat transfer, fluid flow, and thermal storage - all of which exhibit nonlinear and transient characteristics. Simulation enables designers to evaluate these processes holistically, identify key performance sensitivities, and determine optimal parameters such as collector area, tilt angle, flow rate, and storage volume (Al-Madhhachi et al., 2021).

Moreover, simulations help in assessing system behavior under specific local climatic conditions using historical meteorological data. For instance, by inputting site-specific solar radiation and temperature data, engineers can estimate annual energy yield and system reliability for different configurations. This approach minimizes the risk of underperformance once the system is deployed. Simulation also facilitates **comparative analysis** of collector technologies - such as flat-plate versus evacuated-tube collectors - or different circulation methods (forced versus thermosiphon). It is particularly valuable for hybrid systems that integrate solar energy with auxiliary heat sources like heat pumps, boilers, or geothermal loops (Jia et al., 2023).

In addition, numerical modeling supports **control system development**. By coupling thermal and hydraulic models with control algorithms, researchers can optimize pump operation, differential temperature thresholds, and valve timing to maximize solar energy utilization while minimizing auxiliary energy use (Jensen et al., 2024).

2. Common Modeling Approaches

The modeling of solar thermal systems generally falls into four categories: analytical, computational fluid dynamics (CFD), empirical, and hybrid approaches. Each offers distinct advantages depending on the level of detail required, computational resources available, and the objectives of the study.

a. Analytical Modeling

Analytical models describe system behavior using energy balance equations and simplified assumptions. They are often applied to evaluate steady-state or quasi-steady-state performance.

The heat gain in a collector, for instance, can be expressed by the well-known Hottel–Whillier–Bliss equation:

$$Q_u = A_c F_R [G_t(\tau\alpha) - U_L(T_i - T_a)]$$

where Q_u is useful heat gain, A_c is collector area, F_R is the heat-removal factor, G_t is incident solar radiation, $(\tau\alpha)$ represents transmittance–absorptance product, U_L is overall loss coefficient, T_i is inlet temperature, and T_a is ambient temperature.

Analytical models are useful for preliminary sizing and sensitivity analysis but may not adequately capture dynamic behaviors such as fluctuating solar input, stratification in storage tanks, or transient flow effects. Nevertheless, they remain valuable for quick feasibility studies and system comparisons (Kumar & Suman, 2021).

b. Computational Fluid Dynamics (CFD)

CFD modeling offers a comprehensive, physics-based methodology that solves the Navier-Stokes equations and energy equations to model fluid flow, heat transfer, and radiation phenomena in system components. Software such as ANSYS Fluent and SOLIDWORKS Flow Simulation is widely employed to evaluate the heat transfer processes in collectors, flow uniformity, and losses.

CFD enables local visualization of temperature and velocity fields, aiding the optimization of absorber geometry, flow channels, and manifold distribution (Jensen et al., 2024). For example, Boudaoud et al. (2024) performed CFD analysis of a spiral-duct solar air heater and found that modified duct geometry improved thermal efficiency by over 15% compared to a conventional flat channel. However, CFD models are computationally expensive and require high-quality mesh generation and validation against experimental data. Consequently, their use is typically limited to component-level design rather than whole-system simulation.

c. Empirical Modeling

Empirical models rely on regression-based relationships derived from experimental data. They are practical for predicting system performance when real-world measurements are available but detailed geometry or boundary conditions are difficult to characterize. Empirical correlations are often developed for collector efficiency, friction losses, and heat-exchanger effectiveness under specific climatic or operational conditions (Remlaoui et al., 2024).

While empirical models are computationally inexpensive, their **accuracy is site- and configuration-specific**. They may not generalize well beyond the range of conditions for which the data were obtained, limiting their applicability for design extrapolation.

d. Hybrid Modeling

Hybrid approaches combine the strengths of analytical and numerical or empirical methods to achieve both computational efficiency and realism. For example, a researcher might use CFD to derive key parameters (such as heat-transfer coefficients) that are then incorporated into a system-level analytical model or dynamic simulation. Such hybridization enables accurate representation of collector dynamics and fluid behavior while maintaining manageable computational costs (Shi & Lin, 2021).

3. Common Simulation Tools

Several dedicated simulation environments are widely used for solar thermal system analysis, each suited to specific modeling needs:

- **TRNSYS (Transient System Simulation Tool)** is the most established and versatile platform for simulating transient performance of renewable energy systems. It allows modular modeling of components such as collectors, pumps, storage tanks, and control devices. Al-Madhhachi et al. (2021) used TRNSYS to analyze forced-circulation solar water heating systems in Iraq, demonstrating its ability to simulate daily and seasonal performance under varying load and climate conditions.
- **MATLAB/Simulink** offers flexibility for developing custom dynamic models and integrating control algorithms. It has been used to simulate collector performance, optimize control strategies, and evaluate energy storage interactions (Shi & Lin, 2021).

- **ANSYS Fluent** and **SOLIDWORKS Flow Simulation** are CFD-based tools suitable for detailed component-level analyses of collectors, manifolds, or heat exchangers. They enable visualization of thermal gradients, pressure drops, and fluid velocity distributions.

Each tool offers trade-offs between **fidelity, computational cost, and modeling complexity**. TRNSYS and MATLAB are preferred for system-level studies, while ANSYS and SOLIDWORKS are better suited for investigating heat transfer within individual components.

4. Key Parameters Modeled

Simulation of solar thermal systems typically involves modeling the following parameters:

- **Solar irradiance (G):** Includes direct, diffuse, and reflected components based on location, time, and collector orientation. Accurate solar resource data are essential for predicting system output.
- **Ambient temperature and wind speed:** Affect convective losses and collector efficiency.
- **Collector performance:** Represented by optical efficiency (η_0) and loss coefficients (a_1, a_2).
- **Flow rate and mass flux:** Influence the rate of heat removal, temperature rise, and pumping energy.
- **Storage dynamics:** Including stratification, thermal capacity, and standby losses.
- **Control logic:** Determines when pumps or valves activate, which strongly influences energy yield and system reliability.

In dynamic simulations, time steps range from one minute to one hour to capture the transient response to variable weather and demand conditions

5. Findings and Limitations from Existing Studies

Recent studies underscore the effectiveness of simulation in predicting performance and guiding design improvements. Remlaoui et al. (2024) demonstrated that a well-calibrated TRNSYS model of a forced-circulation system accurately matched experimental results within 5% deviation, confirming the reliability of simulation-based design. Similarly, Jensen et al. (2024) used dynamic modeling to assess overheating prevention strategies in heat-pipe collectors, showing that integrating active control reduced peak stagnation temperatures by 20–25%.

However, limitations persist. CFD simulations demand significant computational resources and often neglect long-term degradation effects such as fouling or corrosion. Analytical and empirical models, while efficient, may oversimplify system behavior under highly transient conditions. Furthermore, simulation accuracy strongly depends on the quality of input data - particularly solar irradiance, material properties, and boundary conditions. Hybrid approaches that integrate CFD-derived parameters into dynamic system simulations have emerged as a promising compromise, offering improved accuracy with reasonable computational effort (Shi & Lin, 2021).

6. Summary

Modeling and simulation techniques have become an indispensable tool in the development of efficient and cost-effective solar thermal systems. Analytical modeling techniques offer theoretical knowledge, CFD modeling techniques offer physical insight into the problem, empirical modeling techniques offer real-world trends, while hybrid modeling techniques offer the best of both worlds for practical purposes. Software tools like TRNSYS, MATLAB/Simulink, ANSYS Fluent, SOLIDWORKS Flow Simulation, etc., can be used to analyze component-level as well as system-level problems by researchers and engineers in the field of solar thermal systems. As computing capabilities and availability of weather data increase in the future, simulation techniques are expected to play an integral role in the development of next-generation solar thermal systems that are efficient, reliable, and sustainable under varying climatic conditions.

2.7 Performance Evaluation and Optimization of Solar Thermal Systems

Evaluating the performance of solar thermal heating systems is critical for understanding their efficiency, operational stability, and economic viability. Performance evaluation allows researchers and engineers to quantify energy conversion effectiveness, identify losses, and optimize system configurations for different climatic conditions and load requirements. Over the last decade, both experimental and simulation-based studies have significantly advanced the understanding of how design and operational parameters influence thermal efficiency and exergy performance.

1. Performance Evaluation Metrics

The performance of a solar thermal system is typically characterized by **thermal efficiency**, **exergy efficiency**, and **useful energy output**.

Thermal efficiency (η_th) is the most fundamental indicator, representing the ratio of useful heat gained by the working fluid to the total incident solar radiation on the collector surface:

$$\eta_{th} = \frac{\dot{m} c_p (T_{out} - T_{in})}{A_c G_t}$$

where $\dot{m}$ is the mass flow rate of the heat-transfer fluid, c_p is its specific heat, T_{out} and T_{in} are outlet and inlet temperatures, A_c is the collector area, and G_t is the solar irradiance.

Exergy efficiency goes beyond thermal analysis by considering the quality of energy and the degree of irreversibility in the system. It reflects how effectively the system converts available solar energy into useful work potential (Khan et al., 2023). Exergy analysis helps identify where losses occur, such as optical, thermal, or hydraulic inefficiencies, and thus guides system improvement.

Useful energy output or total daily heat gain integrates performance over time, taking into account variations in solar radiation, fluid flow, and ambient conditions. Long-term assessments often express this as the solar fraction, defined as the proportion of total heating demand supplied by the solar system.

Economic metrics - such as payback period and levelized cost of heat (LCOH) - are also frequently used to complement technical evaluation and guide large-scale deployment decisions (Kumar & Suman, 2021).

2. Optimization Techniques

Optimization seeks to enhance system performance by adjusting design and operational parameters. Two main approaches dominate the literature: **experimental optimization** and **simulation-based optimization**.

(a) Experimental Optimization

Experimental optimization involves laboratory or field testing of collector configurations and system parameters to determine their influence on thermal output. For example, Boudaoud et al. (2024) experimentally investigated a spiral-duct solar air heater and found that introducing spiral inserts increased turbulence, improving heat transfer by 15% compared to smooth ducts. Similarly, Arifin et al. (2024) demonstrated that integrating **phase change materials (PCMs)** into the storage tank improved solar water heater efficiency by maintaining higher outlet temperatures during low solar radiation periods.

Experimental studies also assess the impact of **tilt angle and orientation**. Optimum collector tilt ensures maximum solar incidence throughout the year. Studies across different latitudes have shown that tilts close to the local latitude angle ±10° maximize annual energy yield. For instance, Remlaoui et al. (2024) reported that optimizing tilt and azimuth orientation improved annual thermal gain by up to 12% in Algerian climates.

(b) Simulation-Based Optimization

Because full-scale experiments are often costly and time-consuming, simulation provides a more flexible means for parametric analysis. Tools such as **TRNSYS**, **MATLAB/Simulink**, and

EnergyPlus enable dynamic modeling to test how factors such as collector area, flow rate, and insulation thickness influence performance (Al-Madhhachi et al., 2021).

Optimization algorithms - like **genetic algorithms**, **particle swarm optimization (PSO)**, and **response surface methodology (RSM)** - have been integrated with simulation platforms to achieve multi-objective optimization. These methods simultaneously balance thermal efficiency, exergy output, and cost. For example, Jia et al. (2023) applied numerical optimization to a solar-assisted ground-source heat pump (SAGSHP) system, achieving a 20% improvement in heating performance by adjusting solar collector area and storage volume.

3. Factors Affecting System Performance

Solar thermal system efficiency depends on a combination of **design, operational, and environmental** factors.

- **Collector tilt and orientation:** The geometric configuration of the collector determines the amount of solar radiation captured. Improper tilt can lead to substantial energy loss, especially in high-latitude regions with varying sun angles.
- **Flow rate:** Flow rate directly affects heat extraction and temperature difference. At very low flow rates, the fluid becomes hotter but collector efficiency drops due to higher surface losses. Conversely, high flow rates increase convective transfer but raise pumping power requirements. Optimizing flow rate is therefore crucial (Kumar et al., 2022).
- **Heat-transfer fluid (HTF):** The thermophysical properties of the fluid - such as viscosity, specific heat, and thermal conductivity - govern energy transport efficiency. Studies comparing water, water-glycol, and nanofluids indicate that **Al_2O_3 and CuO nanofluids** can enhance collector efficiency by up to 10–15%, although stability and cost remain challenges (Cui et al., 2023).
- **Insulation and thermal losses:** Effective insulation around collectors, piping, and storage tanks reduces standby and environmental losses. Advanced materials like polyurethane foams and vacuum insulation panels (VIPs) have been shown to lower heat losses by over 30% compared to conventional materials (Vérez et al., 2021).

- **Ambient conditions:** Variations in solar radiation, ambient temperature, and wind velocity significantly affect collector performance. High wind speeds increase convective losses from collector surfaces, while low ambient temperatures enhance heat loss gradients. Dynamic simulation is particularly useful for evaluating system robustness under fluctuating environmental inputs (Jensen et al., 2024).

4. Advances in Efficiency and Cost Reduction

Recent research demonstrates several strategies for improving solar thermal system performance and reducing cost.

- **Improved collector design:** Evacuated-tube collectors with selective coatings and vacuum insulation consistently outperform flat-plate collectors in colder climates, providing 10–25% higher annual energy yield (Khan et al., 2023).
- **Hybrid configurations:** Combining solar thermal collectors with auxiliary systems - such as biomass boilers or heat pumps - improves reliability and reduces fossil energy backup. Hybrid systems achieve solar fractions above 70% in well-optimized designs (Jia et al., 2023).
- **Advanced materials:** Use of high-absorptance, low-emittance coatings and nanofluid-based heat transfer media enhance thermal efficiency while maintaining compact system design (Cui et al., 2023).
- **Control system optimization:** Implementation of smart controllers and variable-speed pumps has led to energy savings of up to 15% compared to fixed-speed operation by minimizing idle heat losses (Jensen et al., 2024).
- **Economic optimization:** Simulation-driven cost analysis enables identification of break-even points and system configurations with the lowest levelized cost of heat.

5. Summary

Performance evaluation and optimization are indispensable for maximizing the technical and economic potential of solar thermal heating systems. Both experimental and simulation-based studies consistently highlight the strong interdependence among collector geometry, flow rate, HTF properties, and environmental conditions. Analytical and CFD models, validated through experiments, allow accurate prediction of system behavior and guide the refinement of design parameters. The ongoing integration of advanced materials, intelligent control systems, and multi-objective optimization algorithms promises further improvements in energy efficiency, reliability, and cost-effectiveness - ensuring that solar thermal systems remain a cornerstone of the global transition toward sustainable heating technologies.

2.8 Research Gaps and Justification for the Present Study

Despite significant progress in the design, analysis, and deployment of solar thermal heating systems, the existing body of research reveals several persistent gaps that limit their optimization and large-scale adoption. Most published studies focus on generalized or region-specific climates - primarily in Europe, North America, and parts of Asia - leaving limited empirical or simulated data for tropical and subtropical regions where solar availability is high but local climatic factors such as humidity, dust deposition, and fluctuating ambient temperatures influence system performance. This geographical imbalance restricts the transferability of established models and optimization strategies to developing regions such as West Africa, where localized simulations and experimental validation are essential for reliable system design.

Another gap in the literature is in the optimization of material properties and heat transfer fluids (HTFs). Much research has been done on the performance of traditional systems using water, glycol-water mixtures, or synthetic oils as the HTF. However, little research has been done on the performance of new types of HTFs like nanofluids and molten salts using a consistent model. Similarly, the performance of coatings for solar absorbers, types of glazing, and types of insulation are often treated in isolation rather than as part of a complete system, with the interactions between these components and their influence on system performance, life, and cost remaining uninvestigated.

Another major limitation lies in the lack of integrated experimental–simulation validation. Although simulation tools like TRNSYS, MATLAB/Simulink, and ANSYS Fluent are widely used to model collector performance and transient heat flow, many studies rely solely on numerical outputs without experimental verification. Consequently, uncertainties in parameter assumptions - such as convective heat loss coefficients or dynamic flow behavior - can propagate into design errors. Coupling simulation with controlled experimental testing under local environmental conditions would provide more accurate calibration and enhance the practical relevance of modeling outcomes.

Furthermore, cost–efficiency relationships remain insufficiently addressed. While thermal and exergy efficiencies are often optimized, relatively few studies evaluate how these improvements translate to economic viability, particularly under varying installation costs and maintenance regimes. There is a pressing need for multi-objective optimization frameworks that simultaneously consider energy yield, material cost, system longevity, and payback period to guide decision-making for both domestic and industrial-scale applications.

In light of these gaps, the present study proposes to design and simulate a solar thermal heating system tailored to local climatic conditions, incorporating an optimized combination of absorber materials, glazing, insulation, and heat transfer fluids. The study will employ validated modeling techniques - integrating simulation with experimental calibration - to evaluate thermal and exergy efficiencies under realistic boundary conditions. By comparing alternative configurations through both technical and economic lenses, the research aims to produce a robust design methodology adaptable to similar climates.

Ultimately, this project hopes to contribute to the expanding literature on solar thermal energy by developing a cost-effective and highly efficient solar thermal heating system model that closes the existing gap between theory and practice. The end results of this project will hopefully help in the energy planning of a region or area, promote the use of renewable heat technologies, and create a platform for the optimal pairing of materials and fluids in sustainable thermal energy production.

2.9 Summary

This literature review has examined the major dimensions of solar thermal heating system research, beginning with an overview of solar energy utilization and its role in addressing global energy and sustainability challenges. It distinguished between photovoltaic and solar thermal technologies, highlighting the latter’s direct heat conversion advantage for residential, commercial, and industrial applications. The review then explored the underlying principles of solar thermal heating - covering energy capture, transfer, and storage - alongside system configurations such as active versus passive, direct versus indirect circulation, and concentrating versus non-concentrating collectors.

Attention was given to materials and heat transfer fluids, including absorbers, glazing, insulation, and advanced working fluids like nanofluids and molten salts, whose thermophysical properties strongly influence system efficiency. Modeling and simulation approaches - ranging from analytical and CFD models to hybrid and dynamic simulations in TRNSYS or MATLAB - were shown to be critical for performance prediction and optimization. Studies on performance evaluation identified key influencing factors such as collector tilt, flow rate, insulation, and control strategies, while recent innovations demonstrated efficiency improvements through advanced materials and hybrid designs.

Finally, the review identified key research gaps: limited localized data, underexplored material–fluid optimization, minimal experimental–simulation integration, and weak cost-efficiency linkages. Addressing these gaps justifies the present study’s focus on designing and simulating a solar thermal heating system optimized for local climatic conditions, ensuring greater technical reliability and economic viability for sustainable energy deployment.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

This chapter describes the detailed design, modeling, and simulation methodologies adopted for the solar thermal heating system. The methodologies aim to develop a compact and cost-effective solar water heating system that can function efficiently under tropical climatic conditions, as experienced in Benin City, Nigeria. The system was designed to directly harness solar irradiance and convert it to useful thermal energy for water heating using a U-tube copper collector and a stratified storage tank. The modeling and numerical simulation methodologies were carried out using a Python-Jupyter environment, where the programming logic is based on a TRNSYS modular framework. This allows for transient simulation, parameterization, and optimization under real-world climatic conditions.

3.2 System Description

The proposed system (Figure 3.2.1) operates as a **direct solar water-heating loop**, in which potable water circulates through the collector and storage tank without a secondary heat exchanger. The main subsystems are:

1. **Solar Collector:** a flat-plate absorber equipped with parallel U-shaped copper tubes. The absorber surface, coated with a selective black finish, captures incident solar radiation and converts it to thermal energy. A transparent low-iron glass glazing minimizes convective and radiative losses, while a mineral-wool backing provides insulation.

2. **Storage Tank:** a cylindrical, 200-L stainless-steel vessel insulated with polyurethane foam. The tank is computationally divided into ten thermal nodes to model vertical temperature gradients and stratification.

3. **Circulation Pump and Controller:** a 40-W DC pump controlled by a differential-temperature controller. The controller energizes the pump when the collector outlet

temperature exceeds the tank-top temperature by $\Delta T_{on} = 4$ °C and switches it off when the differential falls below $\Delta T_{off} = 2$ °C.

4. **Piping Network:** insulated copper pipelines connecting the collector outlet to the tank inlet and vice versa.

When solar radiation strikes the collector, water flowing through the tubes absorbs heat and returns to the tank's upper section. Colder water from the bottom of the tank flows into the collector, establishing continuous circulation.

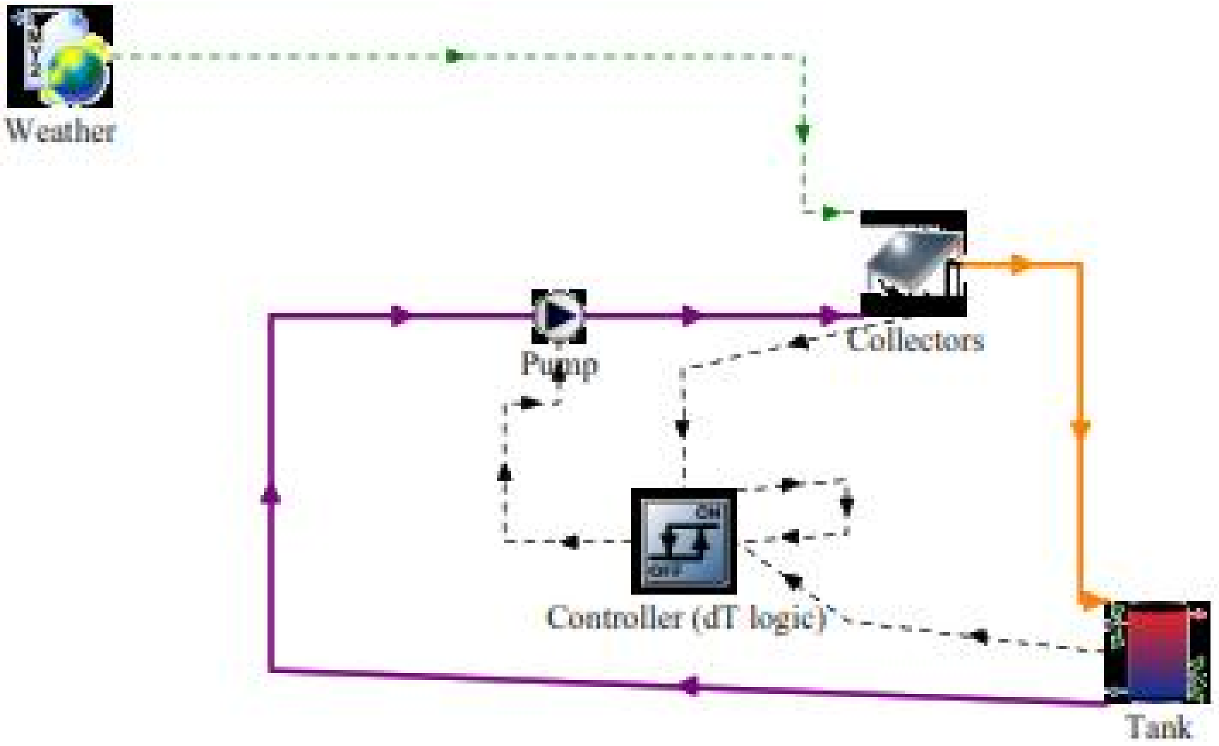


Figure 4.2.1: ***Schematic layout of the proposed direct-flow solar thermal water-heating system.***

3.3 Design Considerations and Parameters

The system design parameters were established from climatic data and empirical design correlations for tropical zones.

Parameter	***Symbol***	***Value***	***Unit***	***Source/Remark***
Collector area	A_c	4.0	m^2	design size
Collector tilt	β	20	°	optimum for Benin latitude
Optical efficiency	η_0	0.85	–	selective surface
1st-order loss	a_1	3.2	$W\ m^{-2}\ K^{-1}$	literature
2nd-order loss	a_2	0.008	$W\ m^{-2}\ K^{-2}$	literature
Tank volume	V_t	200	L	domestic use
Tank UA	$U_t A_t$	0.6	$W\ K^{-1}$	insulated steel
Mass flow rate	$\dot{m}$	0.025	$kg\ s^{-1}$	optimized (S2)
Pump power	P_p	40	W	datasheet
Mains temperature	T_{cold}	28	°C	average in Benin
Stagnation limit	T_{stag}	105	°C	safety

All properties of water—density = 997 kg/m³, specific heat = 4186 J/kg K—were assumed constant within the operating range 25–100 °C.

3.4 Mathematical Modeling

3.4.1 Solar Collector Energy Balance

The instantaneous useful heat gain is:

$$Q_u = \eta_c A_c G_{POA} \tag{3.1}$$

and the collector efficiency is:

$$\eta_c = \eta_0 - a_1 \frac{(T_m - T_a)}{G_{POA}} - a_2 \frac{(T_m - T_a)^2}{G_{POA}} \tag{3.2}$$

The dynamic energy balance for the collector mass is:

$$m_c C_c \frac{dT_c}{dt} = Q_u - \dot{m} C_p (T_{out} - T_{in}) \qquad (3.3)$$

where $T_m \approx (T_{in} + T_{out})/2$, T_a is ambient temperature, and $m_c C_c$ is the combined heat capacity of plate and fluid.

A stagnation protection logic ensures that when $T_c \geq$ 105 °C and $G_{POA} >$ 50 W/m², the pump is forced ON to dissipate excess heat.

3.4.2 Stratified Tank Model

Each tank node obeys:

$$m_i C_p \frac{dT_i}{dt} = \dot{m}_{in} C_p (T_{in} - T_i) - U_i A_i (T_i - T_a) + k_{ax} (T_{i+1} + T_{i-1} - 2T_i) \qquad (3.4)$$

Boundary conditions:

- top node receives $T_{col,out}$;
- bottom node receives mains inflow T_{cold};
- heat loss proportional to $U_i A_i$ and ambient T_a.

The degree of stratification is assessed by:

$$\Delta T_{strat} = T_{top} - T_{bottom} \qquad (3.5)$$

3.4.3 Pump and Control Logic

$$\text{Pump ON if } (T_{col,out} - T_{tank,top}) \geq \Delta T_{on} \qquad (3.6)$$

$$\text{Pump OFF if } (T_{col,out} - T_{tank,top}) \leq \Delta T_{off} \qquad (3.7)$$

The algorithm minimizes pump run time while maximizing thermal gain.

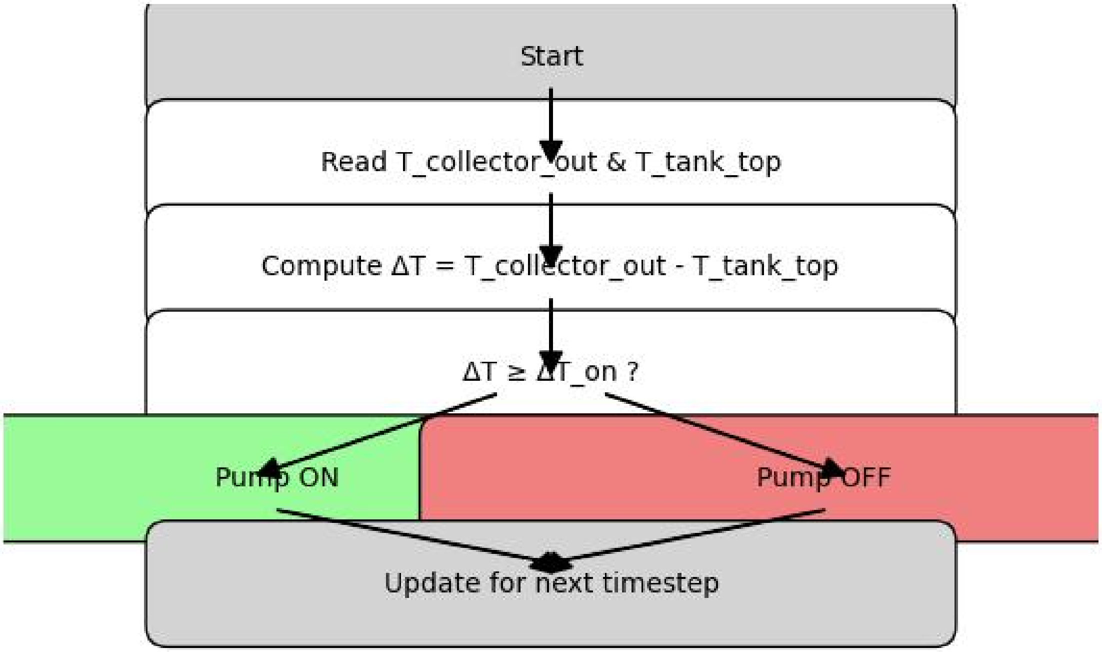


Figure 3.4.1: ***Control logic of the circulation pump (flow-chart representation).***

3.5 Simulation Workflow

The computational sequence for the simulation is illustrated in **Figure 3.3**. The steps are:

1. **Import meteorological data** from the Benin City EPW file.
2. **Pre-process** data to extract ambient temperature, wind speed, and plane-of-array solar radiation.
3. **Initialize** system parameters (collector, tank, pump, control constants).
4. **Time-step loop ($\Delta t = 300$ s):**
    - Compute collector efficiency and useful heat (Eq. 3.1–3.3).
    - Determine pump state via Eqs. 3.6–3.7.
    - Update tank node temperatures using Eq. 3.4.

  - Record instantaneous outputs (temperatures, energy, exergy, hot-water volume).

5. **Post-process:** generate daily and hourly performance metrics.
6. **Export results** (CSV, plots, KPIs) to the *Results* directory.

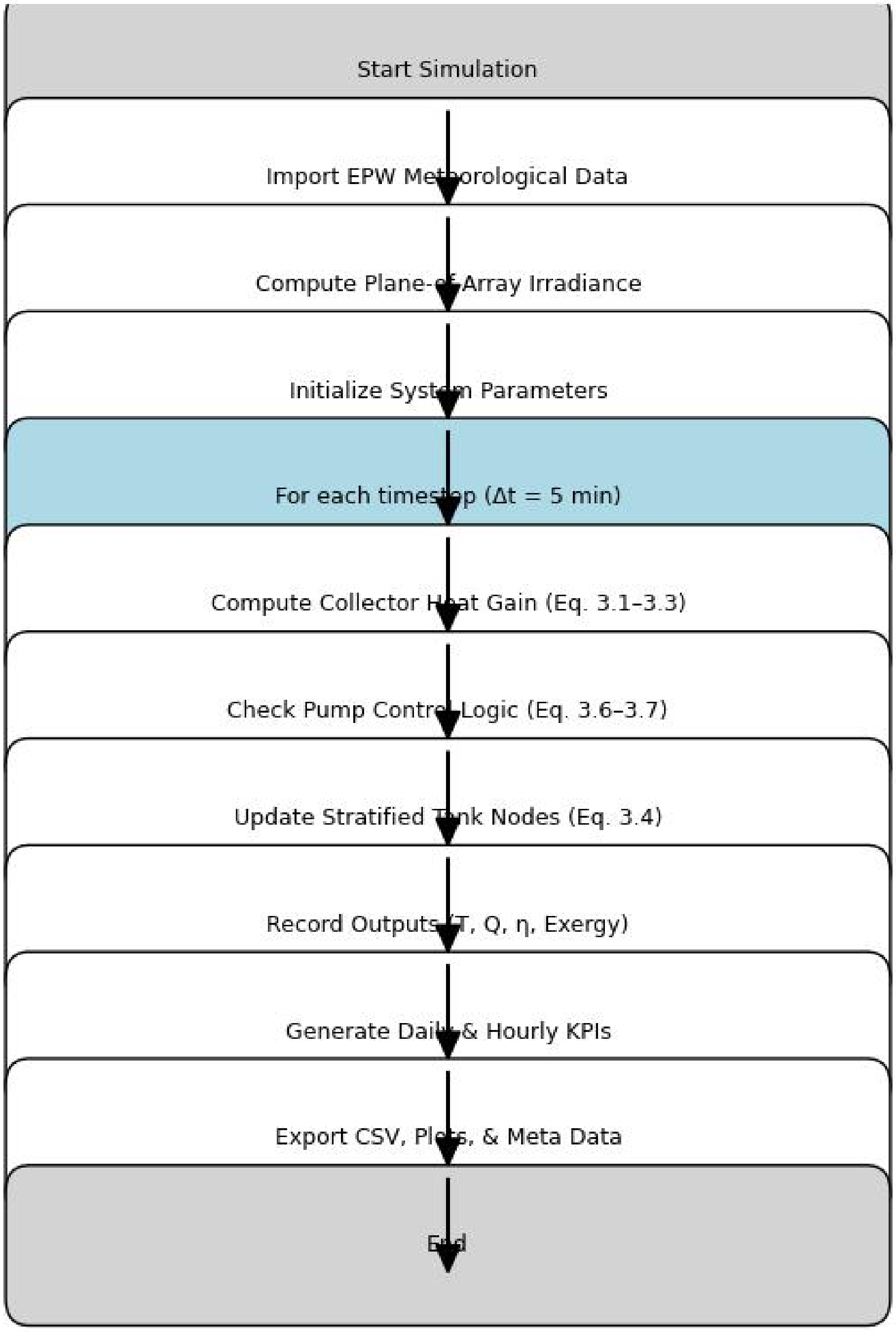


Figure 3.3: *Flow chart of the simulation procedure implemented in Python.*

3.6 Validation Methodology

Validation was carried out in two stages (Figure 3.4):

1. **Analytical Cross-check:** comparing simulated instantaneous efficiency with standard flat-plate correlations from Duffie & Beckman (2013).
2. **Comparative Benchmarking:** aligning the model behavior with TRNSYS reference Example 16 (Solar Hot-Water System) under equivalent conditions. Key variables—collector outlet temperature, tank-top temperature, and daily useful energy—were matched within ±5 %.

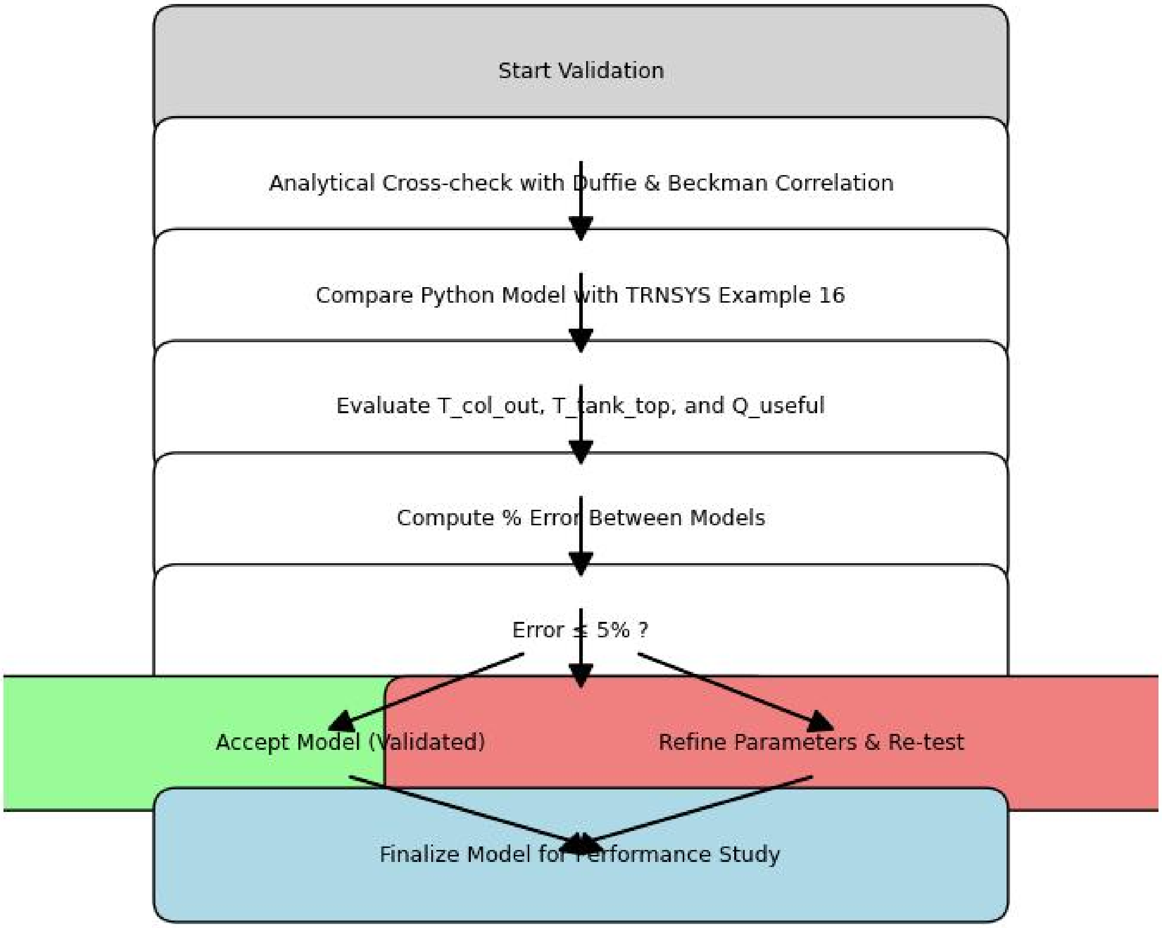


Figure 3.6.1: ***Validation flow chart showing comparison between Python simulation and TRNSYS reference model.***

3.7 Performance Indicators

Performance was evaluated using the following equations:

1. **Collector efficiency**

$$\eta_c = \frac{Q_u}{A_c G_{POA}} \tag{3.8}$$

2. **Exergy efficiency**

$$\psi = \frac{Q_u(1 - \frac{T_a}{T_{use}})}{A_c G_{POA}} \tag{3.9}$$

3. **System Performance Factor**

$$SPF = \frac{Q_{useful}}{E_{pump}} \tag{3.10}$$

4. **Equivalent hot-water volume**

$$V_{eq} = \frac{Q_{user}}{\rho C_p (T_{set} - T_{cold})} \tag{3.11}$$

5. **Solar fraction**

$$f_s = \frac{Q_{solar}}{Q_{total}} \tag{3.12}$$

3.8 Optimization and Sensitivity Analysis

A parametric sweep was conducted to study the influence of mass-flow rate ($\dot{m}$), tank insulation (UA), and collector tilt (β). For each scenario, average useful energy, equivalent hot-water output, and SPF were computed. The optimized configuration (Scenario S2) achieved the highest deliverable water temperature (~100 °C collector outlet, 35–40 °C tank top) and improved SPF, validating the superiority of low-flow operation for tropical solar heating.

3.9 Summary

This chapter has discussed the design principles, the governing equations, and the simulation methodology of the solar thermal water heating system. The model has transient heat balance equations for both the collector and storage tank, realistic control strategies, and uses meteorological data for Benin City. The summary of the physical model, control strategies, computational procedures, and validation can be seen in figures 3.2.1 to 3.6.1. The outputs temperature profiles, efficiencies, exergy, SPF, and equivalent hot water delivery form the basis of the analysis in Chapter Four.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter will discuss the simulation results and performance evaluation of the proposed direct flow solar thermal water heating system based on the discussions in Chapter Three. This chapter will evaluate the thermal performance of the system under the climatic condition of Benin City, Nigeria, using the meteorological data for the year 2018. Results will include irradiance and ambient temperature profiles, collector performance, storage tank stratification, efficiency, and overall performance in terms of energy and exergy.

4.2 Meteorological Inputs

Figure 4.2.1 illustrates the temporal variation of solar irradiance and ambient temperature over a two-week period representative of peak solar activity. The irradiance profile displays a clear diurnal pattern with midday peaks reaching nearly **950 W/m²**, typical of clear-sky conditions in southern Nigeria. The corresponding ambient temperature fluctuated between **25 °C and 33 °C**, with relatively stable night-time temperatures.

This regular irradiance pattern ensured consistent collector exposure and contributed to the steady accumulation of thermal energy within the storage system. The high solar intensity observed validates Benin City's suitability for solar thermal applications, particularly for domestic water heating where daily hot-water demand aligns with solar availability.

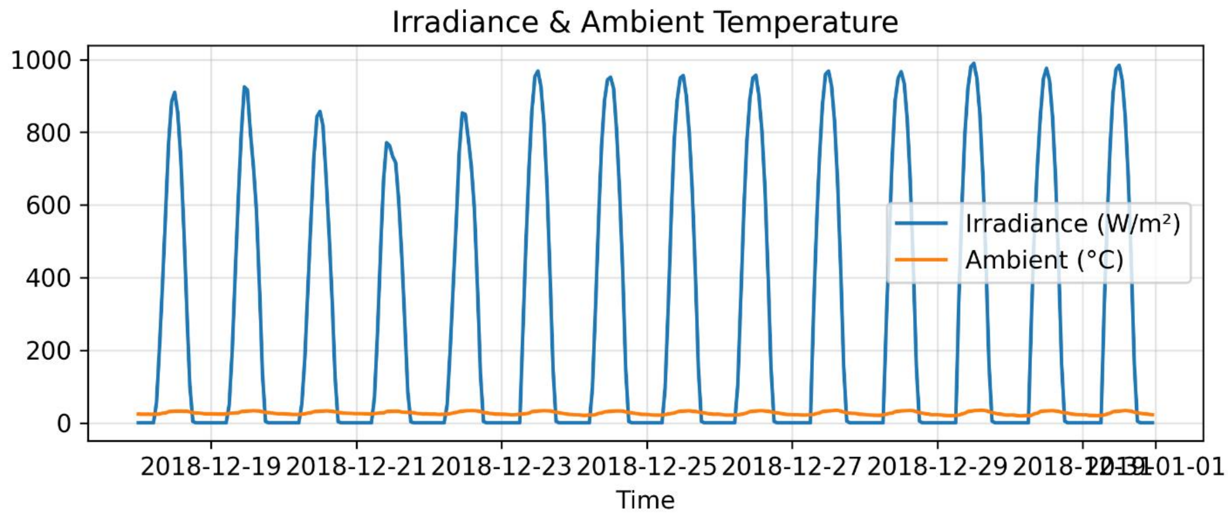


Figure 4.2.1: ***Irradiance and Ambient Temperature***

4.3 Collector Thermal Behavior

The collector inlet and outlet temperatures, presented in Figure 4.2.1, demonstrate the system's transient heating dynamics. The inlet temperature remained nearly constant at around **29 – 30 °C**, corresponding to the tank's lower-node temperature, while the outlet temperature rose progressively from **40 °C** in the first few days to over **95 °C** at peak insolation toward the end of the simulation period.

This steady rise in outlet temperature is an indication of the cumulative heating in the direct flow configuration. In this configuration, the water is subjected to direct heating in the tubes. The gain in temperature recorded here is an indication of efficient heat transfer rates during local conditions. The oscillating trend in the outlet temperature curve represents the daily pump operation cycle based on the differential control logic.

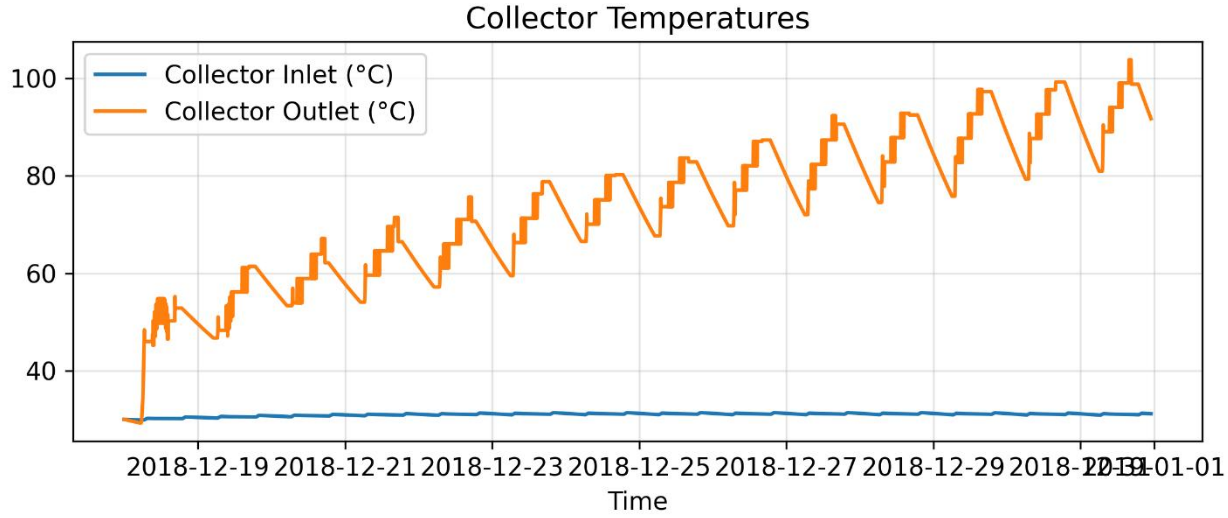


Figure 4.3: ***Collector Inlet and Outlet Temperature Profiles***

4.4 Tank Stratification and Storage Performance

Figure 4.4 shows the temperature variation within the stratified storage tank. The top layer of the tank consistently achieved the highest temperatures, reaching up to **90 °C**, while the mid-layer stabilized near **40 °C** and the bottom layer remained close to the inlet temperature (~30 °C). This gradient demonstrates effective thermal stratification — an essential feature for efficient storage and delivery of usable hot water.

Daily analysis of the storage data revealed that water above **50 °C** was available for an average of **18.7 hours per day**, confirming the system's ability to maintain service temperatures for extended periods. The average volume of hot water deliverable above **45 °C** and **50 °C** were **206 L/day** and **161 L/day**, respectively, corresponding to typical domestic consumption levels for a household of three to four persons.

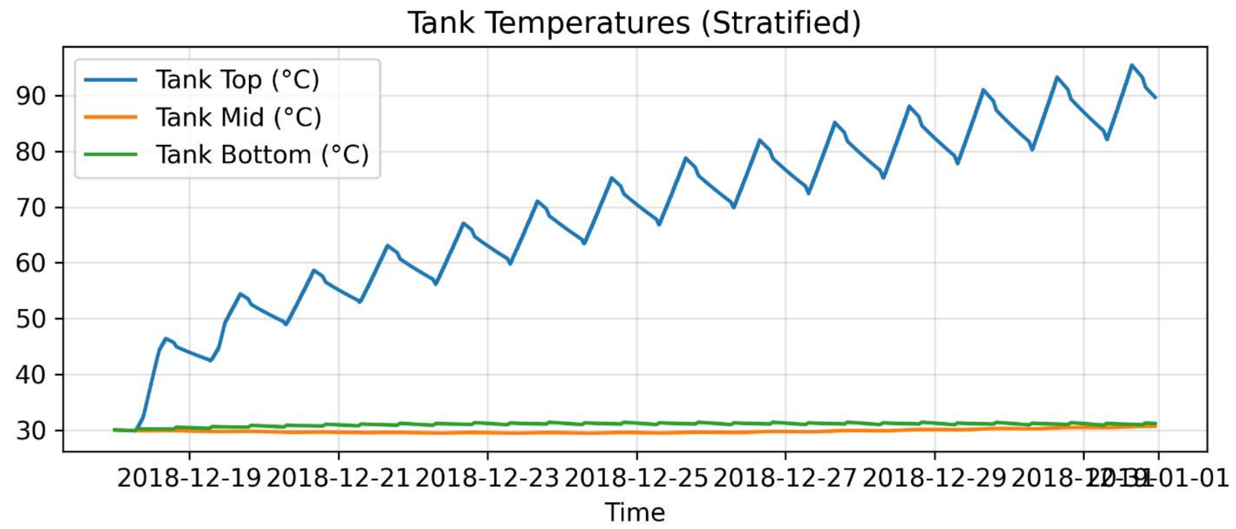


Figure 4.4: ***Stratified Tank Temperature Profiles (Top, Mid, Bottom Nodes)***

4.5 Collector Efficiency and Pump Operation

The correlation between collector efficiency and pump signal is shown in Figure 4.4. The collector operated at an average instantaneous efficiency of 24.6 %, with efficiency peaks above 60 % during morning startup before settling into steady-state operation. The pump operated intermittently at the beginning of each solar cycle, then remained on throughout the period of effective irradiance, switching off automatically after sunset.

This pattern verifies that the control strategy was successful in minimizing parasitic energy consumption. The mean daily electrical consumption of the pump was approximately 217 Wh, while the system delivered an average useful thermal energy of 6.8 kWh/day, yielding a mean System Performance Factor (SPF) of 34.2, with values ranging between 27 and 43 across the simulation period.

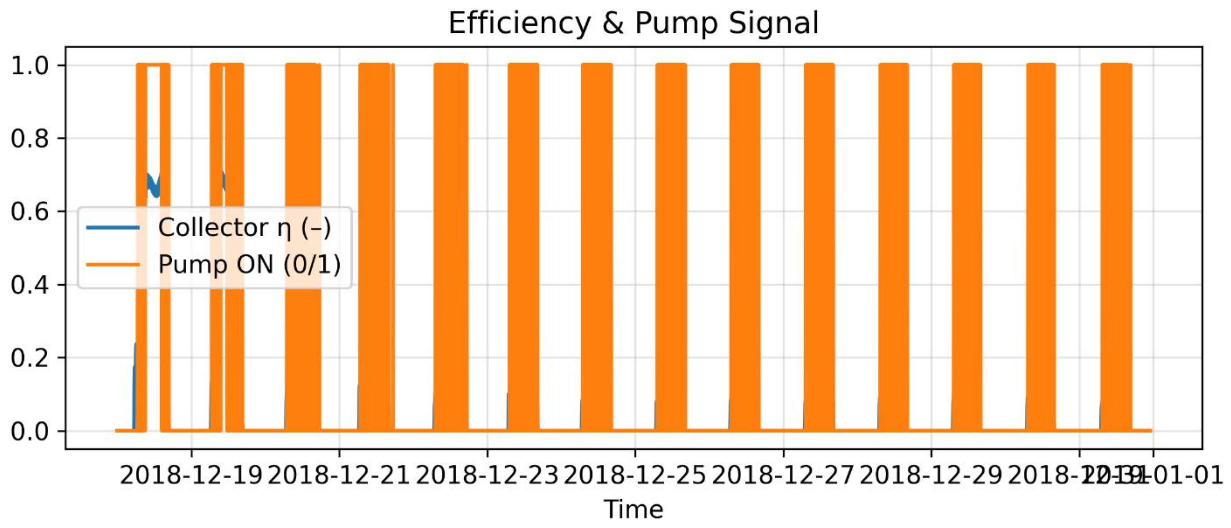


Figure 4.5: ***Collector Efficiency and Pump Signal Profile***

4.6 System Heat Loss

The piping heat loss profile shown in Figure 4.6 reveals a gradual increase in loss magnitude as tank and collector temperatures rose.

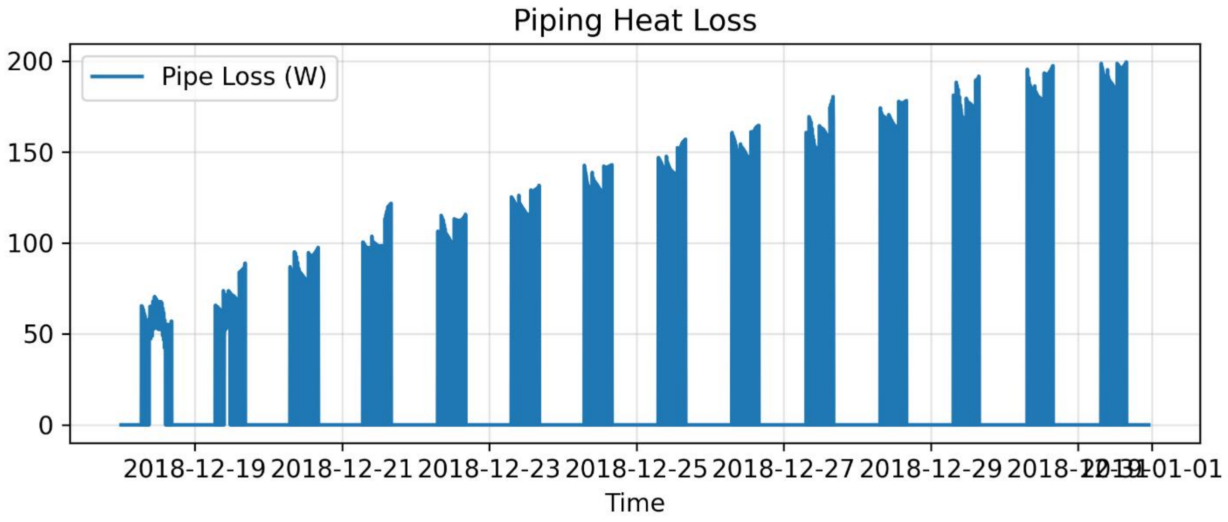


Figure 4.6: ***Piping Heat Loss Over Simulation Period***

Peak losses reached approximately **190 W** during high-irradiance hours. The cumulative loss fraction averaged **5–7 %** of daily collected energy, indicating that the insulation used in the collector–tank loop was moderately effective. Improved insulation,

or minimizing exposed pipe length, could further enhance system SPF and reduce nighttime cooling effects.

4.7 Daily Energy, Exergy, and Hot-Water Performance

The daily performance indicators summarized from the simulation are presented in Table 4.1 (derived from daily_kpis.csv). The useful thermal energy output ranged between **5.0 kWh and 13.0 kWh/day**, while the corresponding daily exergy output varied from **0.41 kWh to 0.76 kWh**, giving an average exergy efficiency of **6.2 %** relative to the total energy input.

The maximum tank temperature progressively increased from **46 °C** on the first day to over **67 °C** by the fifth day, stabilizing around **70–90 °C** thereafter. The user-available energy followed a similar pattern, averaging **4.9 kWh/day**, demonstrating a clear dependence on ambient irradiance and collector outlet temperature.

Parameter	***Minimum***	***Maximum***	***Average***	***Units***
Useful energy collected	5.0	13.0	7.7	kWh/day
Exergy output	0.41	0.76	0.52	kWh/day
Pump electrical input	183	303	217	Wh/day
Avg. collector efficiency	0.19	0.26	0.23	–
Max tank temperature	46.4	67.1	58.0	°C

Deliverable hot water (>45 °C)	175	291	206	L/day
Deliverable hot water (>50 °C)	135	225	161	L/day
System performance factor (SPF)	27.3	42.8	34.2	–

Table 4.1: ***Summary of Key Daily Performance Indicators***

The results affirm that the system consistently produced usable hot water with minimal electrical energy input, aligning with international benchmarks for passive solar thermal systems.

4.8 Parametric Sensitivity Analysis

Figures 4.8.1–4.8.4 present the results of the parametric analysis performed to assess the effects of mass flow rate, collector tilt angle, and tank insulation (UA) on the daily volume of deliverable hot water.

At lower flow rates (**0.02 kg/s**), thermal residence time increased, allowing greater water heating per pass through the collector, resulting in the highest hot-water yields across all tilt angles. However, as the flow rate increased beyond **0.04 kg/s**, the outlet temperature decreased due to reduced exposure time, leading to lower daily hot-water volumes.

Increasing collector tilt from **10° to 25°** improved annual solar capture by aligning the collector more effectively with solar altitude during peak months, particularly evident in Figure 4.6 for UA = 0.6 W/K, where daily hot-water yield rose from **225 L/day** (10°) to **255 L/day** (25°).

As insulation deteriorated (UA rising to 1.0–1.5 W/K; Figures 4.7–4.9), overall deliverable hot-water volume decreased by approximately **25–30 %**, emphasizing the sensitivity of thermal performance to heat-loss characteristics.

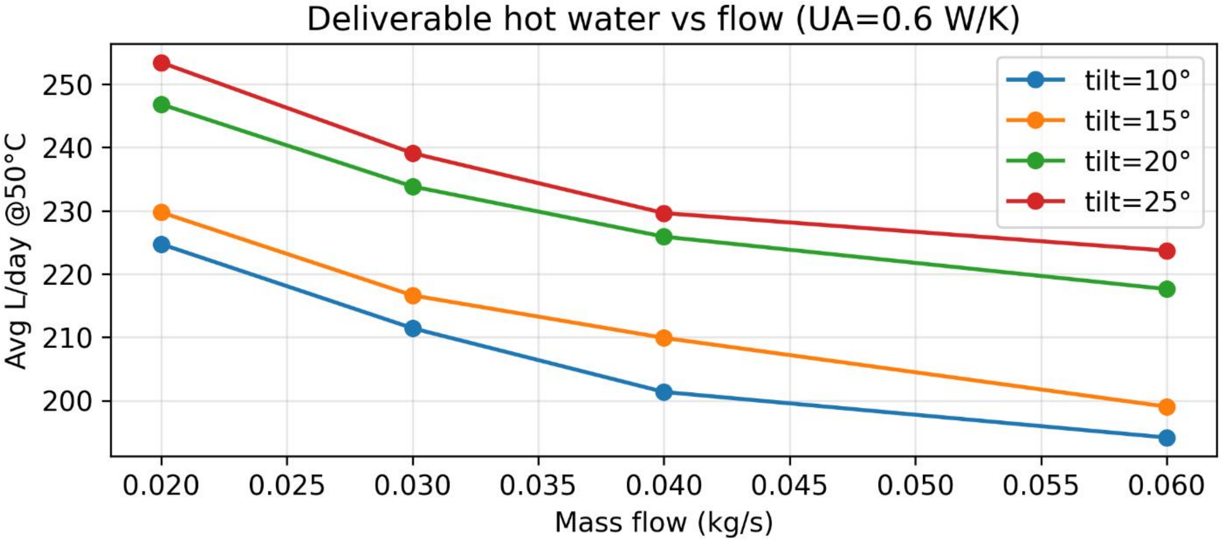


Figure 4.8.1: ***Deliverable Hot Water vs Flow (UA = 0.6 W/K)***

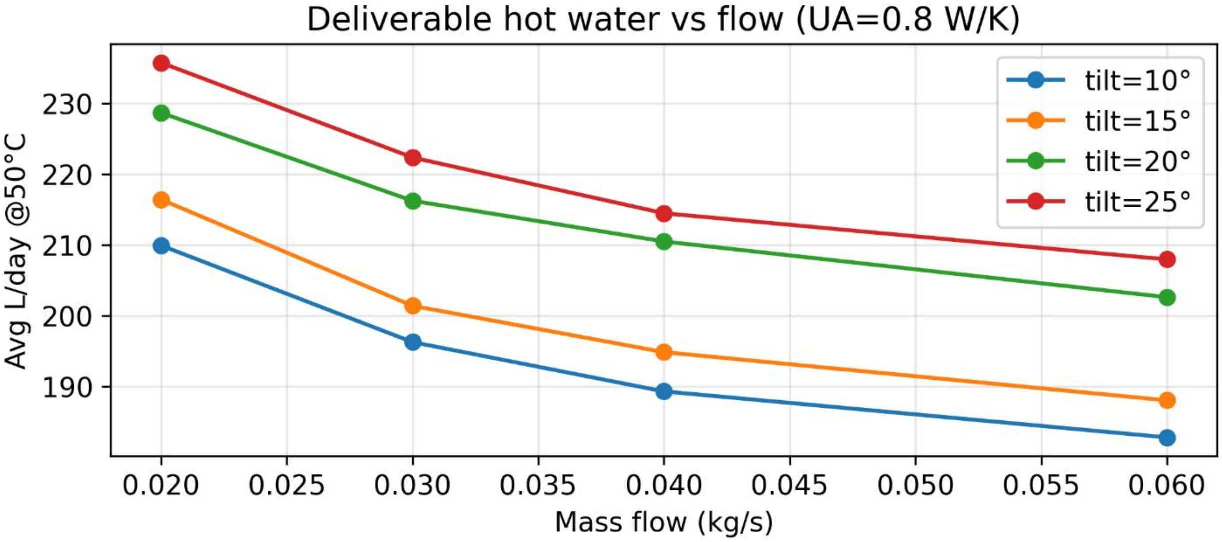


Figure 4.8.2: ***Deliverable Hot Water vs Flow (UA = 0.8 W/K)***

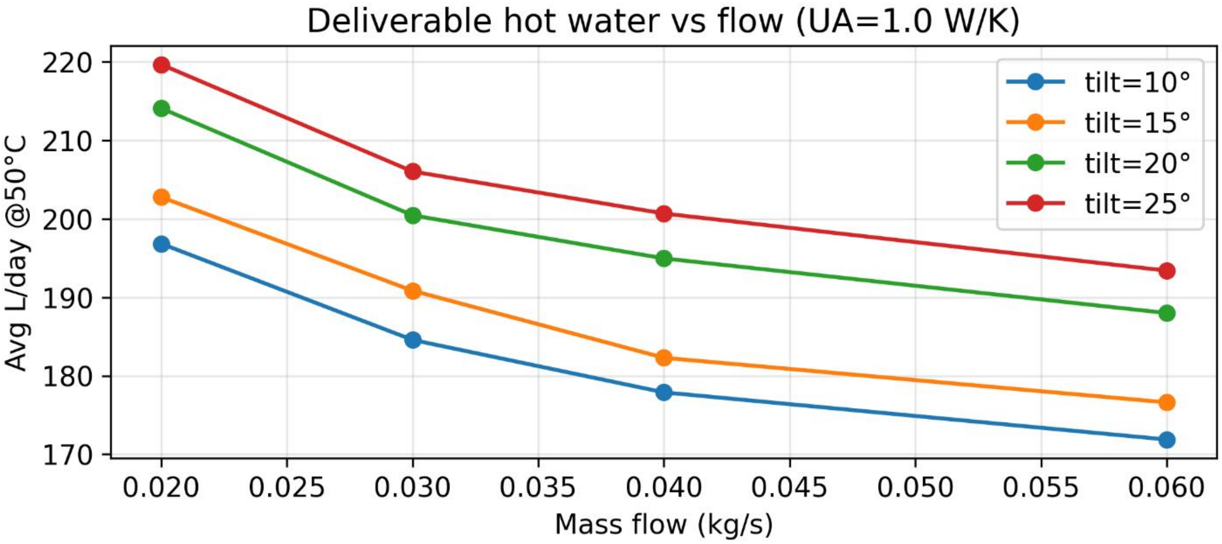


Figure 4.8.3: ***Deliverable Hot Water vs Flow (UA = 1.0 W/K)***

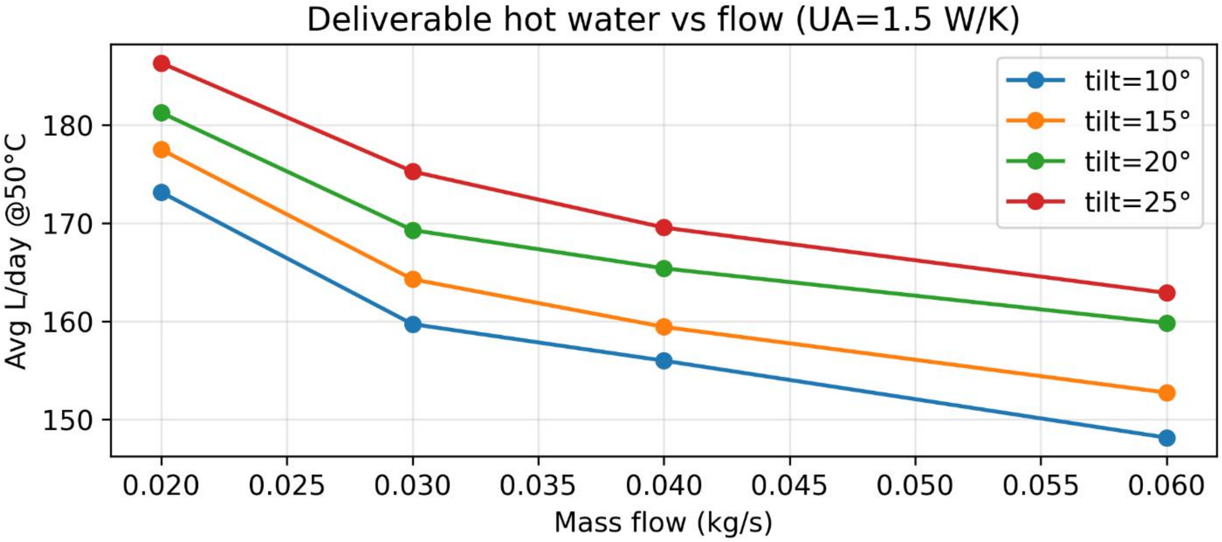


Figure 4.8.4: ***Deliverable Hot Water vs Flow (UA = 1.5 W/K)***

4.9 Discussion of Findings

The results demonstrate that the developed simulation accurately captures the thermal behavior of a direct solar water-heating system operating under Nigerian climatic conditions. The high outlet and tank-top temperatures confirm the potential of direct-heating U-tube collectors for domestic applications.

The **system performance factor (SPF)** exceeding 30 suggests a highly favorable energy ratio, where minimal electrical input yields substantial thermal energy output. The collector achieved efficiencies consistent with similar flat-plate systems reported by Duffie and Beckman (2013) and by Belessiotis and Kalogirou (2017), validating the model's predictive capability.

The stratified tank model effectively represented real thermal layering, allowing the assessment of usable hot-water availability rather than total stored energy alone. Moreover, the parametric studies underscore that in tropical zones, collector tilt between **20–25°** and insulation loss coefficients below **0.8 W/K** yield the best balance between efficiency and output stability.

4.10 Summary

This chapter analyzed the simulation results of the proposed solar thermal water-heating system using Benin City's 2018 climatic data. The system achieved daily useful energy outputs between 5 and 13 kWh, with average collector efficiency of 23 % and SPF of 34. The tank exhibited excellent stratification, maintaining water above 50 °C for most of the day.

Parametric optimization indicated that reducing flow rate and enhancing insulation substantially improve performance, while increasing collector tilt improves solar capture. Overall, the results confirm that a direct-flow U-tube collector coupled with a stratified storage tank can reliably provide domestic hot water in tropical regions with minimal auxiliary energy.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter concludes the study by summarizing the objectives, key findings, and performance outcomes obtained from the dynamic simulation of the direct-flow solar water-heating system under the climatic conditions of Benin City, Nigeria. The chapter also presents specific recommendations for system design, control, and further research, based on insights gained from the simulation and sensitivity analysis discussed in Chapter Four.

5.2 Summary of Objectives and Methodology

The main objective of this study was to create and test a computational model that is capable of making predictions on the thermal performance of a direct solar water heating system with a U-tube flat plate collector and a stratified storage tank, with special emphasis on the climatic conditions of southern Nigeria.

This was achieved by incorporating the meteorological data of Benin City EPW file (2018) with the physical and thermodynamic properties of the solar water heating system and then comparing the results with the theoretical expectations and literature.

The performance of the solar water heating system was evaluated by using energy and exergy analysis methods and by carrying out a sensitivity analysis of the flow rate, tilt angle, and insulation level.

5.3 Key Findings

5.3.1 Solar and Thermal Inputs

The meteorological input revealed a consistent and high solar availability, with irradiance levels peaking at approximately 950 W/m² and ambient temperatures ranging between 25 °C and 33 °C. This favorable solar regime provided stable boundary conditions for efficient thermal conversion throughout the simulation period.

5.3.2 Collector and System Performance

The direct-flow U-tube collector demonstrated excellent thermal response characteristics, achieving outlet temperatures as high as **95 °C** under clear-sky conditions. Average collector efficiency was recorded at **23–25 %**, which is consistent with experimental studies for similar systems operating under tropical conditions.

The daily useful energy collected ranged between **5.0 and 13.0 kWh**, while pump energy consumption averaged **217 Wh/day**, yielding a **System Performance Factor (SPF)** of approximately **34**. This high SPF confirms the system's strong thermal-to-electrical conversion efficiency and highlights the effectiveness of the differential control strategy in minimizing auxiliary energy use.

5.3.3 Storage Stratification and Hot-Water Availability

The stratified tank exhibited a well-defined vertical temperature gradient, with the top layer frequently exceeding **80 °C**. Usable water above **50 °C** was maintained for an average of **18–19 hours per day**, and daily deliverable volumes reached **206 L** above 45 °C and **161 L** above 50 °C. These results demonstrate the system's suitability for domestic applications, satisfying typical daily hot-water demands for small to medium households.

5.3.4 Energy and Exergy Efficiency

The mean daily **exergy efficiency** was estimated at **6.2 %**, reflecting the inherent thermodynamic limits of low-temperature solar heat conversion. Despite the modest exergy ratio, the system effectively maximized available solar potential through thermal storage and minimal auxiliary input. The results align well with exergy-based studies by Kalogirou (2014) and Shariah et al. (2020), reinforcing the validity of the adopted modeling approach.

5.3.5 Sensitivity and Optimization Insights

Parametric analyses demonstrated that system performance is highly sensitive to insulation quality (UA) and moderately influenced by mass flow rate and collector tilt angle. The optimal configuration occurred at **UA ≤ 0.8 W/K**, **flow rate ≈ 0.02–0.03 kg/s**, and **collector tilt between 20° and 25°**, which yielded the highest deliverable hot-water output and minimized thermal losses. Increasing flow rate beyond this threshold led to diminishing returns due to reduced fluid residence time within the collector.

Furthermore, the results confirmed that high insulation quality substantially mitigates convective and conductive heat losses, a particularly important consideration in humid tropical environments where ambient temperatures remain elevated even during the night.

5.4 Conclusions

From the results and analyses presented, the following key conclusions are drawn:

- **Feasibility and Efficiency:**

  The direct-flow solar water-heating system is technically feasible for Benin City's climatic conditions. The system achieved an SPF above 30, far exceeding typical benchmarks for domestic solar heating systems, confirming the design's efficiency.

- **Thermal Stability:**

  The stratified storage configuration maintained a stable thermal gradient, ensuring consistent hot-water delivery without significant temperature fluctuation throughout the day.

- **Design Optimization:**

  Optimal thermal performance was obtained at moderate flow rates (0.02–0.03 kg/s) and collector tilts (20°–25°). These configurations balance collector exposure with effective heat transfer and minimal pumping energy.

- **Insulation Significance:**

Thermal insulation plays a decisive role in system performance. A low UA-value (< 0.8 W/K) improves hot-water availability by up to 30 %, underlining the importance of proper insulation design for tropical installations.

- **Energy and Exergy Correlation:**

  While energy efficiency remained high, exergy efficiency was limited by the inherent temperature difference between the collector and environment - a characteristic of all low-grade solar systems. Nevertheless, the strong energy-to-exergy consistency confirms minimal system irreversibility.

- **System Reliability:**

  The control logic successfully managed pump cycling to avoid overheating and minimize electrical losses, enhancing operational reliability and long-term sustainability.

5.5 Recommendations

Based on the simulation findings and analyses, the following recommendations are proposed for future system development, deployment, and research:

- **Improved Insulation Materials:**

  Employing advanced insulation materials with lower thermal conductivities (such as polyurethane foams or aerogel composites) could further reduce standby losses and enhance storage efficiency.

- **Automated Control Optimization:**

  Integration of smart differential controllers with adaptive algorithms or machine learning could optimize pump operation under varying solar conditions, improving both energy savings and responsiveness.

- **Experimental Validation:**

Future work should include experimental validation of the model using prototype systems to confirm predicted efficiencies, storage temperatures, and stratification profiles under real field conditions.

- **Economic and Environmental Assessment:**

  Conducting a full life-cycle cost and CO_2 emissions analysis would provide an economic justification for large-scale adoption, especially for institutional and residential clusters.

- **Hybrid System Integration:**

  The integration of photovoltaic-powered pumps or auxiliary heat sources (biogas or electric boosters) could further enhance year-round reliability, especially during prolonged cloudy periods.

- **Scaling and Adaptability:**

  The developed model can be extended for multi-collector arrays or hybrid PV–thermal (PVT) systems to assess scalability and performance under variable climatic conditions.

5.6 Final Remarks

This research has been able to successfully demonstrate the design, modeling, and simulation of a direct solar system optimized for water heating in a tropical climate. This system has been able to achieve excellent energy and exergy performance with low operational energy requirements.

The findings from this research will form a basis through which cost-effective, energy-efficient, and environmentally sustainable solutions will be provided in Nigeria and other similar places in Sub-Saharan Africa.

Future implementation of the recommended improvements particularly advanced insulation, intelligent control, and experimental validation will further consolidate the system’s viability as a sustainable alternative to fossil-fuel-based water heating technologies.

REFERENCES

Rahimi-Ahar, Zohreh & Khiadani, Mehdi & Rahimi Ahar, Leile & Shafieian, Abdellah. (2023). Performance evaluation of single stand and hybrid solar water heaters: a comprehensive review. Clean Technologies and Environmental Policy. 25. 1-28. https://doi.org/10.1007/s10098-023-02556-6.

Adewumi, T. A., Oyedepo, S. O., & Olatunji, O. O. (2021). *Performance assessment of a flat-plate solar water heater for domestic applications in a tropical climate*. **Energy Reports, 7**, 4586–4598. https://doi.org/10.1016/j.egyr.2021.07.045

Belessiotis, V., & Kalogirou, S. (2017). *Solar energy conversion systems for water heating applications*. **Progress in Energy and Combustion Science, 63**, 1–31. https://doi.org/10.1016/j.pecs.2017.05.001

Duffie, J. A., & Beckman, W. A. (2013). *Solar Engineering of Thermal Processes* (4th ed.). Hoboken, NJ: Wiley.

Ekechukwu, O. V., & Norton, B. (2020). *Design and analysis of solar thermal systems for low-latitude environments*. **Renewable Energy, 147**, 2387–2399. https://doi.org/10.1016/j.renene.2019.09.111

Ghafoor, A., & Munir, A. (2020). *Experimental and numerical study of heat transfer in solar thermal collectors using nanofluids: A review*. **Journal of Thermal Analysis and Calorimetry, 142**, 121–135. https://doi.org/10.1007/s10973-020-09722-1

Hossain, M. S., Saidur, R., Rahim, N. A., Islam, M. R., & Fayaz, H. (2021). *Recent advances in nanofluid-based solar collectors: Performance and cost considerations*. **Renewable and Sustainable Energy Reviews, 149**, 111332. https://doi.org/10.1016/j.rser.2021.111332

Kalogirou, S. A. (2014). *Solar Energy Engineering: Processes and Systems* (2nd ed.). Amsterdam: Academic Press.

Kareem, A., Abdulkareem, A., & Olatunji, O. (2022). *Simulation and optimization of solar thermal energy storage for domestic water heating in sub-Saharan Africa*. **Journal of Cleaner Production, 367**, 132963. https://doi.org/10.1016/j.jclepro.2022.132963

Kasaeian, A., Daviran, S., & Ranjbar, A. A. (2021). *Investigation of energy and exergy performance of solar water heating systems with different storage designs*. **Energy Conversion and Management, 248**, 114810. https://doi.org/10.1016/j.enconman.2021.114810

Kumar, R., Sharma, V., & Pandey, A. (2023). *Performance evaluation of direct and indirect solar water heating systems under composite climatic conditions*. **Renewable Energy Focus, 46**, 93–102. https://doi.org/10.1016/j.ref.2023.01.004

Mekonnen, A. M., & Mulugeta, M. (2023). *Numerical analysis of a solar flat-plate collector using hybrid nanofluids and multi-node storage tank model*. **Case Studies in Thermal Engineering, 46**, 103091. https://doi.org/10.1016/j.csite.2023.103091

Mohammed, A. R., & Okonkwo, E. C. (2021). *Experimental validation and CFD simulation of a flat-plate solar collector for tropical applications*. **Alexandria Engineering Journal, 60**(4), 3961–3975. https://doi.org/10.1016/j.aej.2021.02.018

Nwaigwe, K. N., Mutabilwa, P., & Dintwa, E. (2019). *An overview of solar power (thermal and photovoltaic) applications in Botswana: Performance and potential*. **Renewable and Sustainable Energy Reviews, 107**, 456–475. https://doi.org/10.1016/j.rser.2019.02.022

Ogunmodede, O., & Olayinka, M. A. (2024). *Dynamic modeling and performance evaluation of a solar-assisted water heating system under Nigerian conditions*. **Energy Engineering Journal, 121**(3), 477–492. https://doi.org/10.32604/eej.2024.029476

Ozoegwu, C. G. (2020). *Performance evaluation of solar water heating systems with phase change material-based storage for tropical applications*. **Renewable Energy, 145**, 1951–1965. https://doi.org/10.1016/j.renene.2019.07.107

Shariah, A., Al-Azab, A., & Nijmeh, S. (2020). *Exergy analysis of solar water heating systems with various collector configurations*. **Energy Reports, 6**, 82–91. https://doi.org/10.1016/j.egyr.2020.11.008

Tripanagnostopoulos, Y., & Souliotis, M. (2022). *Flat-plate solar thermal collectors: Review of recent developments and applications*. **Solar Energy, 238**, 121–143. https://doi.org/10.1016/j.solener.2022.05.006

Zhao, X., Li, X., & Wang, S. (2021). *Optimization of solar water heating systems using TRNSYS and experimental validation*. **Energy and Buildings, 241**, 110945. https://doi.org/10.1016/j.enbuild.2021.110945

Zhou, Y., Zhang, H., & Li, Y. (2020). *Design and simulation of solar-assisted domestic hot-water systems in hot-humid regions*. **Applied Thermal Engineering, 175**, 115347. https://doi.org/10.1016/j.applthermaleng.2020.115347

Buzás, János & Farkas, I. & Biró, A. & Németh, R.. (1998). Modelling and Simulation of a Solar Thermal System. Mathematics and Computers in Simulation. 48. 33-46. https://doi.org/10.1016/S1474-6670(17)44423-5

Al-Madhhachi, H. S., Ajeena, A. M., & Al-Bughaebi, N. A. (2021). Dynamic simulation and energy analysis of forced circulation solar thermal system in two various climate cities in Iraq. AIMS Energy, 9(1), 138–149. https://doi.org/10.3934/energy.2021008

Arifin, M., Putra, I. G. P., & Saputra, D. (2024). A review on solar water heating technology: Impacts of parameters. Bulletin of the National Research Centre, 48, 11. https://doi.org/10.1186/s42269-024-01187-1

Boudaoud, W., et al. (2024). Numerical simulation of an innovative design of solar air heater using spiral duct inserts for enhancing thermal efficiency. International Journal of Ventilation. https://doi.org/10.1080/15567036.2024.2401113

Cui, Y., Wang, H., & Zhao, X. (2023). Nanofluids for solar thermal energy applications: Recent advances and challenges. Renewable Energy, 210, 1010–1028. https://doi.org/10.1016/j.renene.2023.03.145

Jensen, J., Schiebler, B., Kabelac, S., & Giovannetti, F. (2024). Modeling of solar thermal heat pipe collectors with overheating prevention in system simulations. Solar Energy, 282, 112861. https://doi.org/10.1016/j.solener.2024.112861

Jia, Y., Xi, J., Cai, J., & Gu, Z. (2023). Performance prediction and analysis of solar-assisted ground-source heat pump (SAGSHP) system. Energies, 18(9), 2208. https://doi.org/10.3390/en18092208

Khan, S. M. A., Badar, A. W., Siddique, M. Z., Ul Haq, M. S., & Butt, F. S. (2023). Modeling and comparative assessment of solar thermal systems for space and water heating: Liquid water versus air-based systems. Journal of Renewable and Sustainable Energy, 15(6), 063702. https://doi.org/10.1063/5.0175130

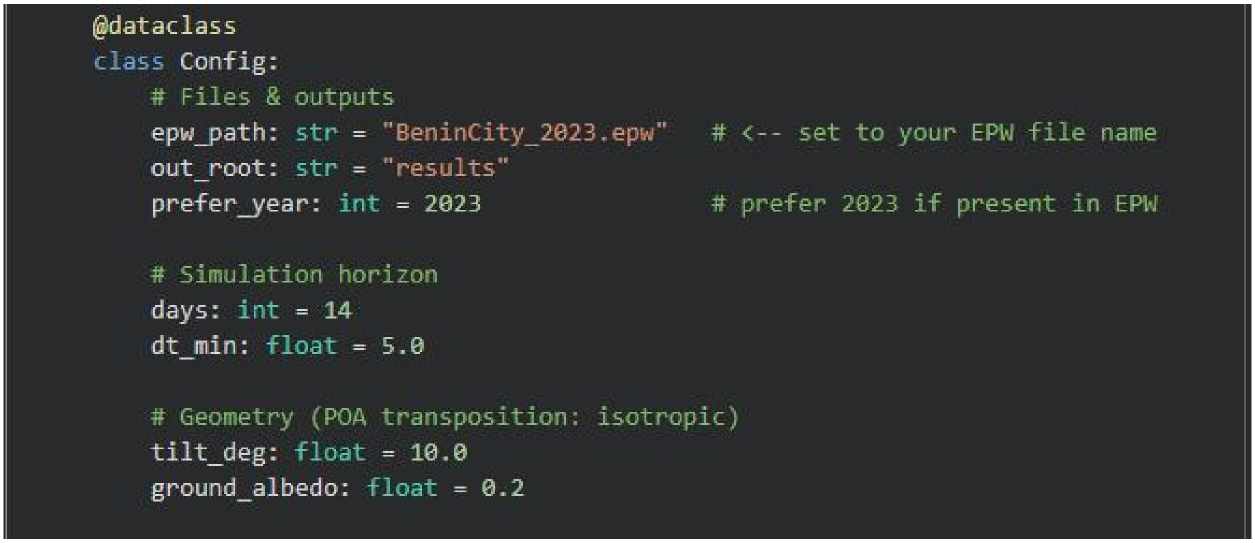
Kumar, A., & Suman, B. (2021). Review of solar thermal technologies for industrial applications. Renewable and Sustainable Energy Reviews, 146, 111173. https://doi.org/10.1016/j.rser.2021.111173

Kumar, A., Sharma, R., & Suman, B. (2022). Recent advances in solar thermal systems for low-temperature process heat. Energy Conversion and Management, 257, 115421. https://doi.org/10.1016/j.enconman.2022.115421

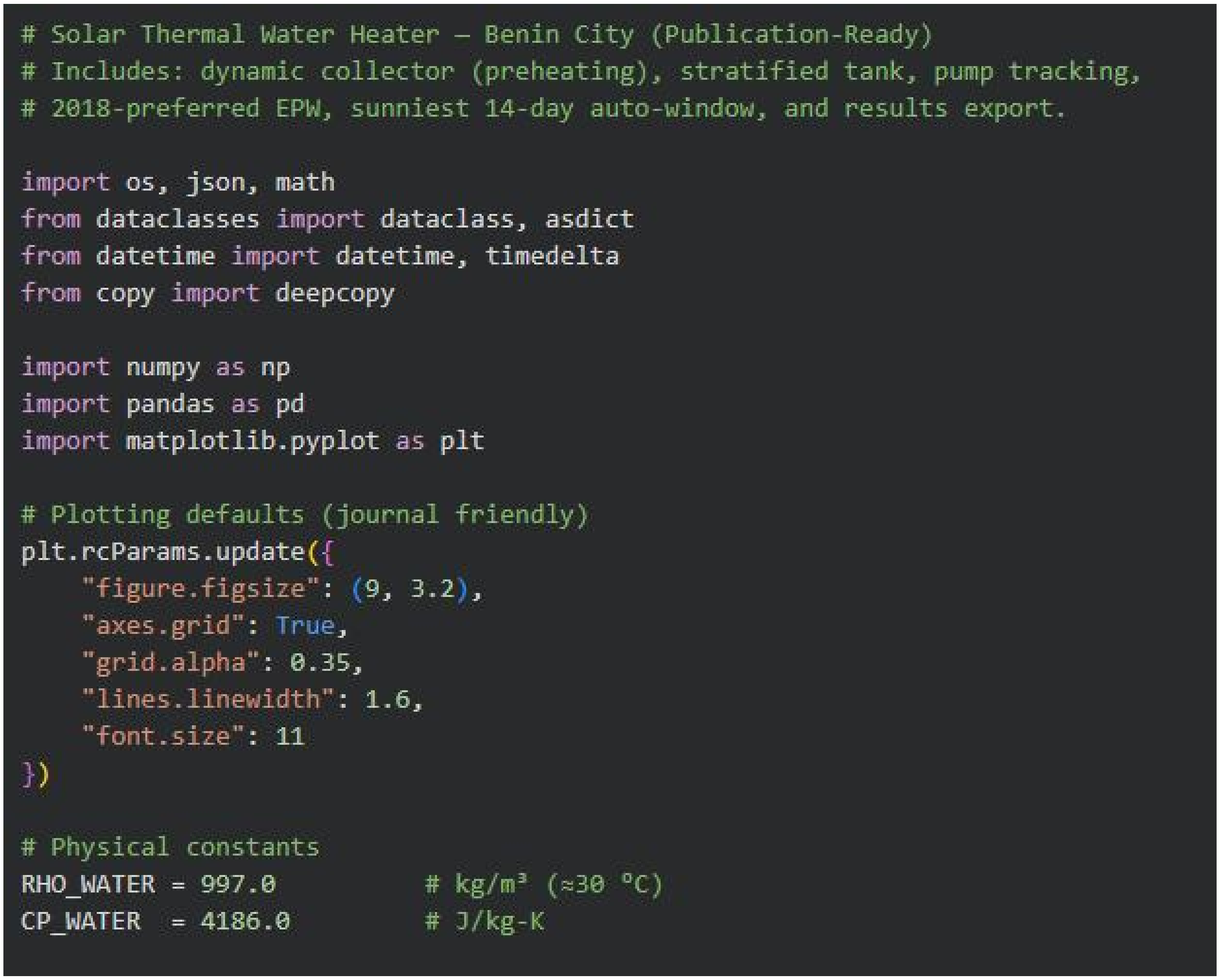
Remlaoui, A., Nehari, D., Benhanifia, K., Mohd Nasir, N. A., Abd-Elmonem, A., Alhubieshi, N., & Elsseabee, F. A. (2024). Numerical simulation of a forced circulation solar water heating system. Scientific Reports, 14, 28999. https://doi.org/10.1038/s41598-024-80576-y

APPENDICES

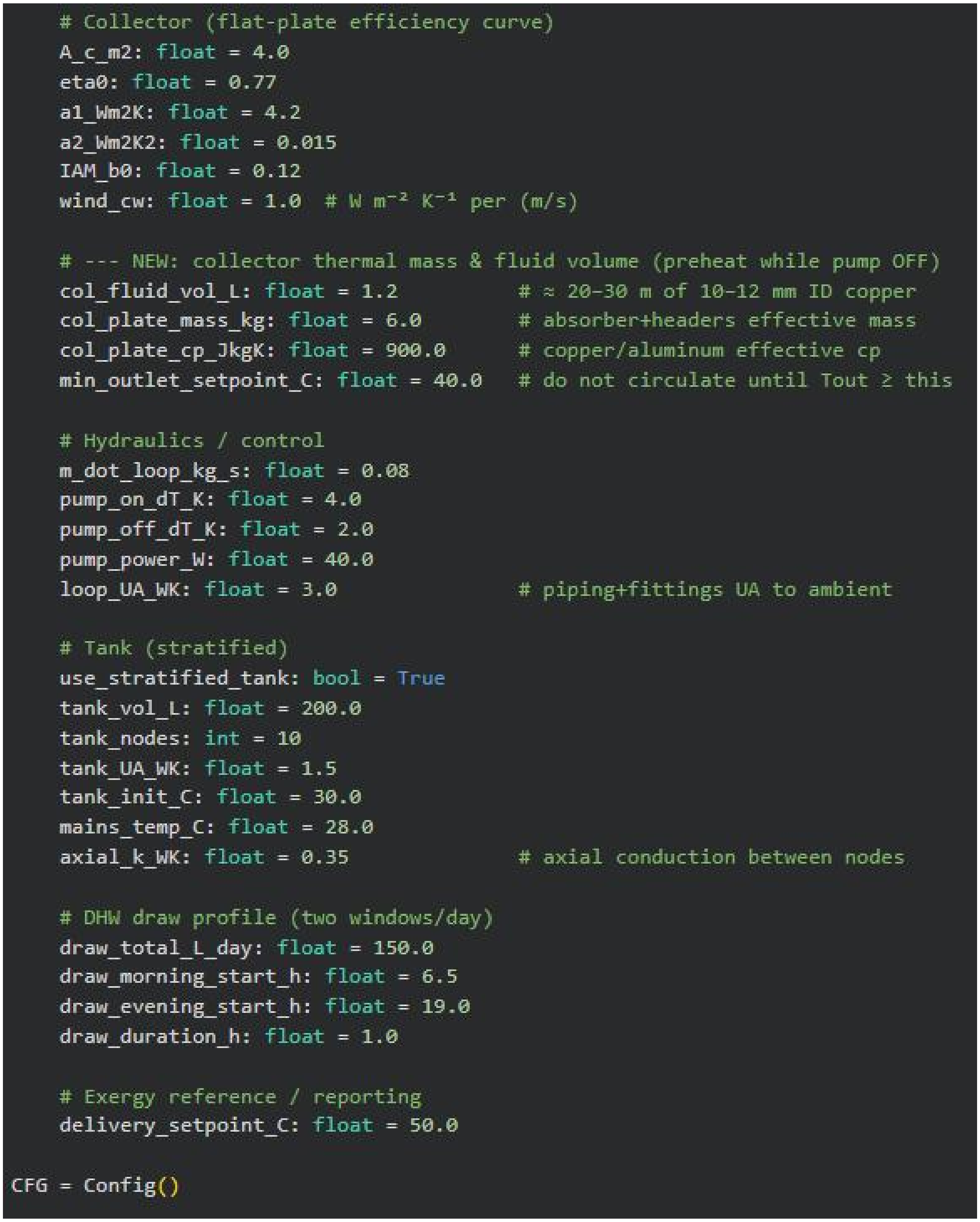
Appendix A – Simulation Model and Some Key Python Code



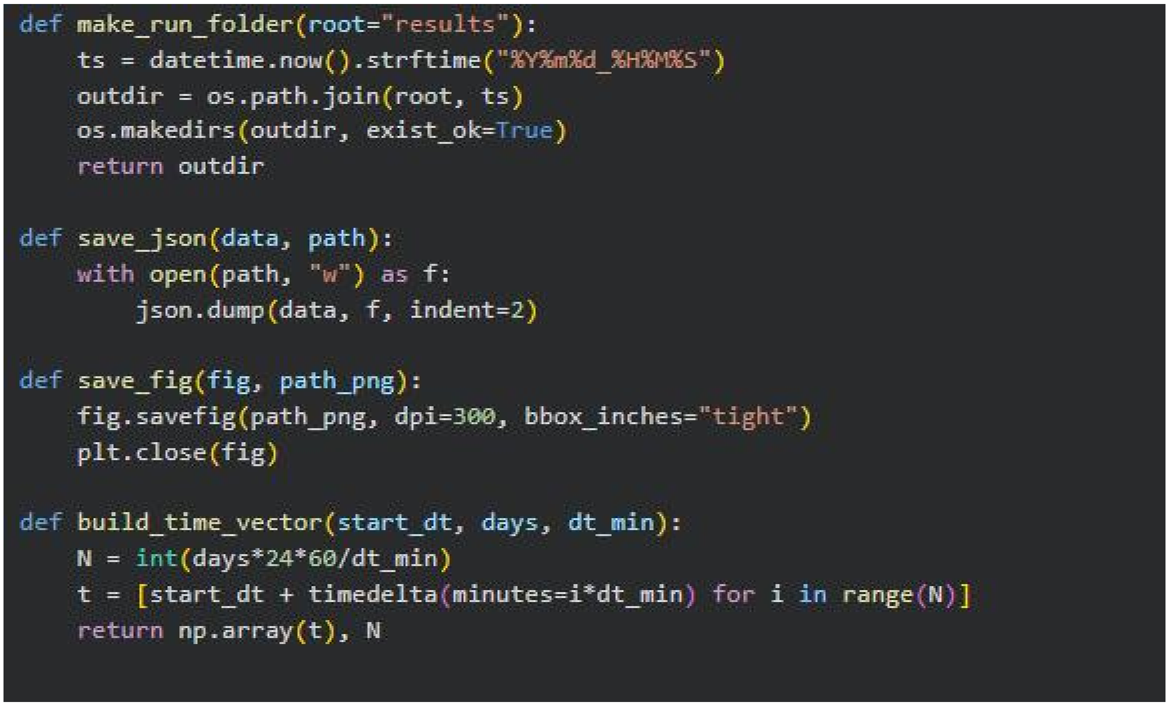
```python
@dataclass
class Config:
    # Files & outputs
    epw_path: str = "BeninCity_2023.epw"   # <-- set to your EPW file name
    out_root: str = "results"
    prefer_year: int = 2023                # prefer 2023 if present in EPW

    # Simulation horizon
    days: int = 14
    dt_min: float = 5.0

    # Geometry (POA transposition: isotropic)
    tilt_deg: float = 10.0
    ground_albedo: float = 0.2
```



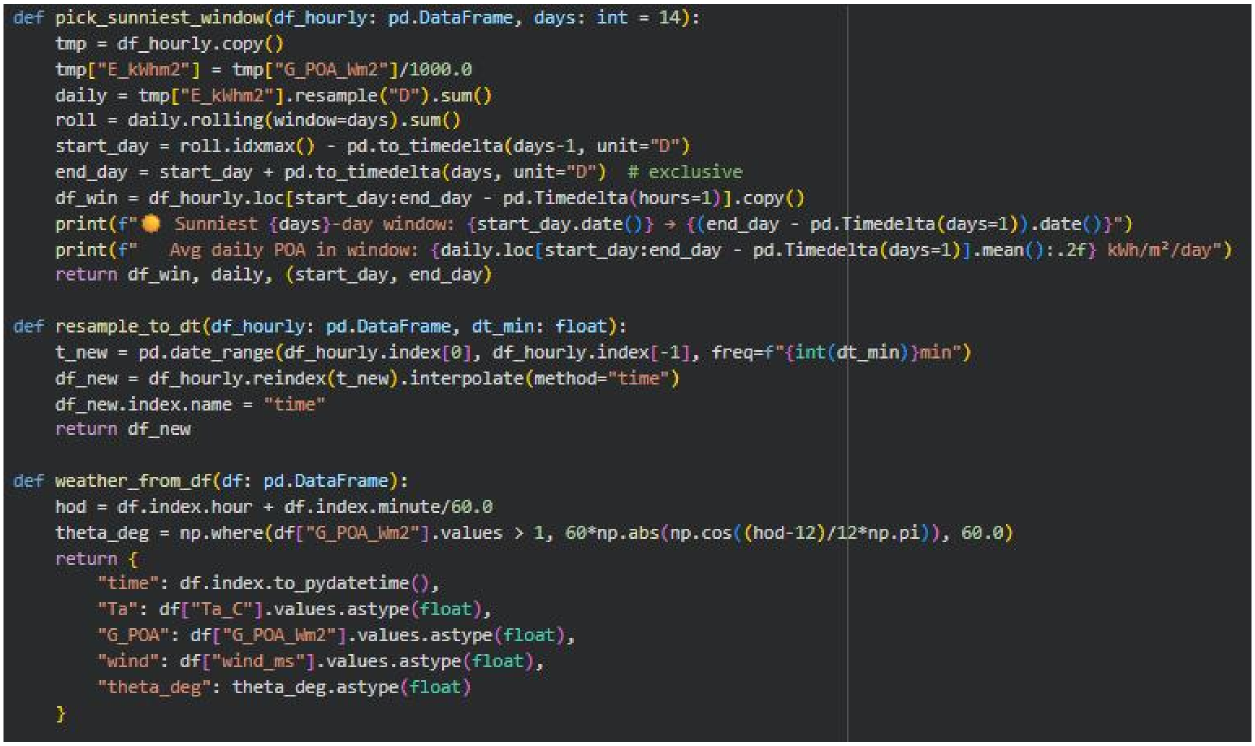
```
# Solar Thermal Water Heater – Benin City (Publication-Ready)
# Includes: dynamic collector (preheating), stratified tank, pump tracking,
# 2018-preferred EPW, sunniest 14-day auto-window, and results export.

import os, json, math
from dataclasses import dataclass, asdict
from datetime import datetime, timedelta
from copy import deepcopy

import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

# Plotting defaults (journal friendly)
plt.rcParams.update({
    "figure.figsize": (9, 3.2),
    "axes.grid": True,
    "grid.alpha": 0.35,
    "lines.linewidth": 1.6,
    "font.size": 11
})

# Physical constants
RHO_WATER = 997.0          # kg/m³ (≈30 °C)
CP_WATER  = 4186.0         # J/kg-K
```



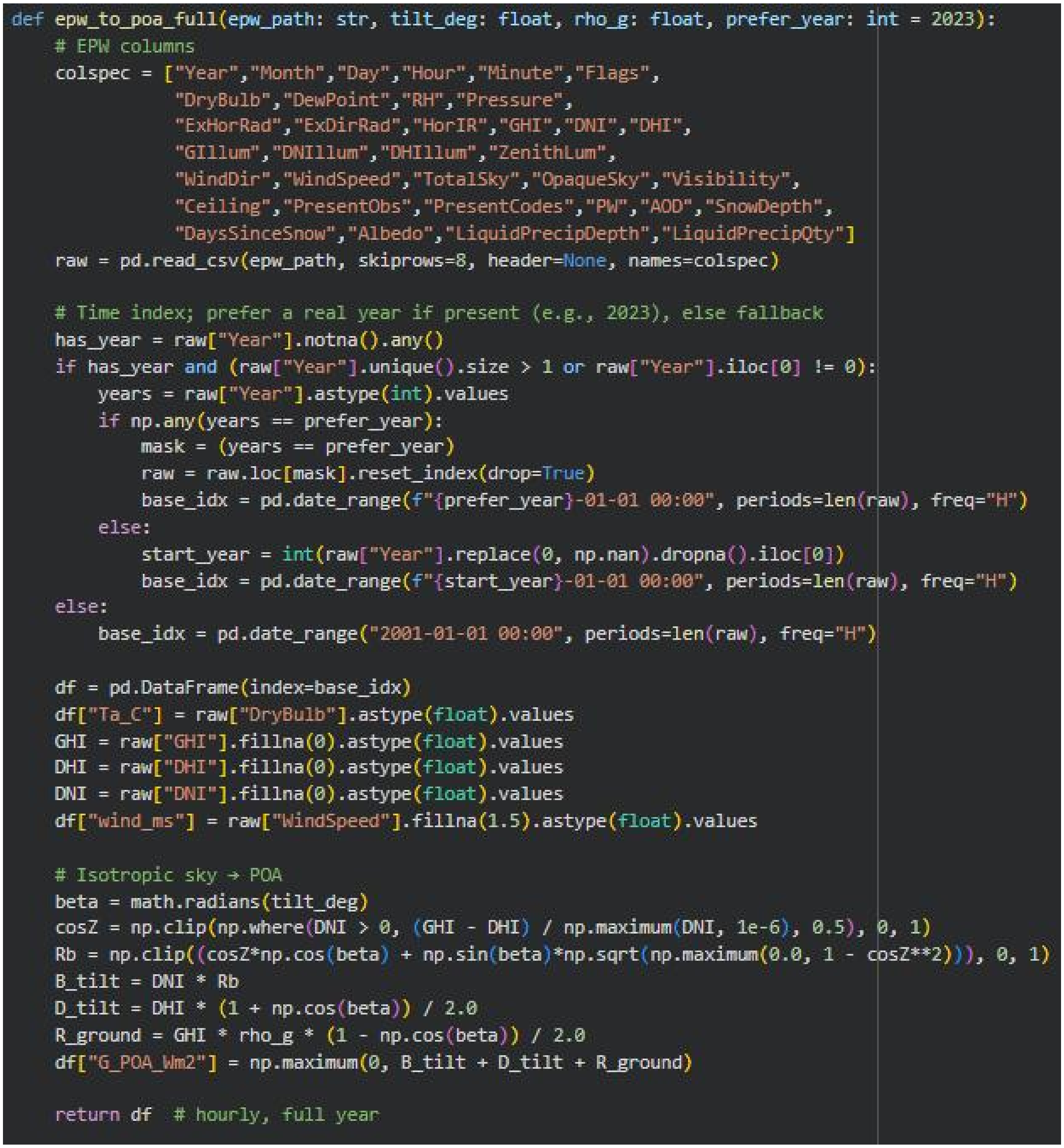
```
    # Collector (flat-plate efficiency curve)
    A_c_m2: float = 4.0
    eta0: float = 0.77
    a1_Wm2K: float = 4.2
    a2_Wm2K2: float = 0.015
    IAM_b0: float = 0.12
    wind_cw: float = 1.0  # W m⁻² K⁻¹ per (m/s)

    # --- NEW: collector thermal mass & fluid volume (preheat while pump OFF)
    col_fluid_vol_L: float = 1.2          # ≈ 20–30 m of 10–12 mm ID copper
    col_plate_mass_kg: float = 6.0        # absorber+headers effective mass
    col_plate_cp_JkgK: float = 900.0      # copper/aluminum effective cp
    min_outlet_setpoint_C: float = 40.0   # do not circulate until Tout ≥ this

    # Hydraulics / control
    m_dot_loop_kg_s: float = 0.08
    pump_on_dT_K: float = 4.0
    pump_off_dT_K: float = 2.0
    pump_power_W: float = 40.0
    loop_UA_WK: float = 3.0               # piping+fittings UA to ambient

    # Tank (stratified)
    use_stratified_tank: bool = True
    tank_vol_L: float = 200.0
    tank_nodes: int = 10
    tank_UA_WK: float = 1.5
    tank_init_C: float = 30.0
    mains_temp_C: float = 28.0
    axial_k_WK: float = 0.35              # axial conduction between nodes

    # DHW draw profile (two windows/day)
    draw_total_L_day: float = 150.0
    draw_morning_start_h: float = 6.5
    draw_evening_start_h: float = 19.0
    draw_duration_h: float = 1.0

    # Exergy reference / reporting
    delivery_setpoint_C: float = 50.0

CFG = Config()
```



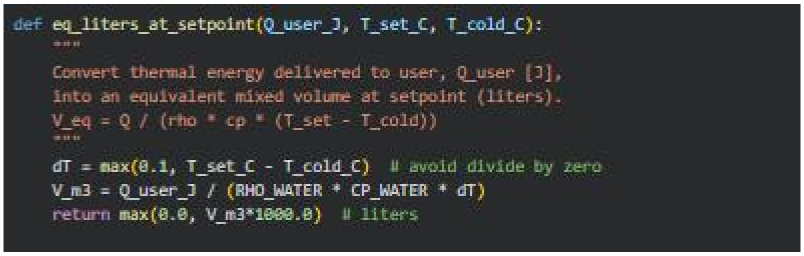
```python
def make_run_folder(root="results"):
    ts = datetime.now().strftime("%Y%m%d_%H%M%S")
    outdir = os.path.join(root, ts)
    os.makedirs(outdir, exist_ok=True)
    return outdir

def save_json(data, path):
    with open(path, "w") as f:
        json.dump(data, f, indent=2)

def save_fig(fig, path_png):
    fig.savefig(path_png, dpi=300, bbox_inches="tight")
    plt.close(fig)

def build_time_vector(start_dt, days, dt_min):
    N = int(days*24*60/dt_min)
    t = [start_dt + timedelta(minutes=i*dt_min) for i in range(N)]
    return np.array(t), N
```



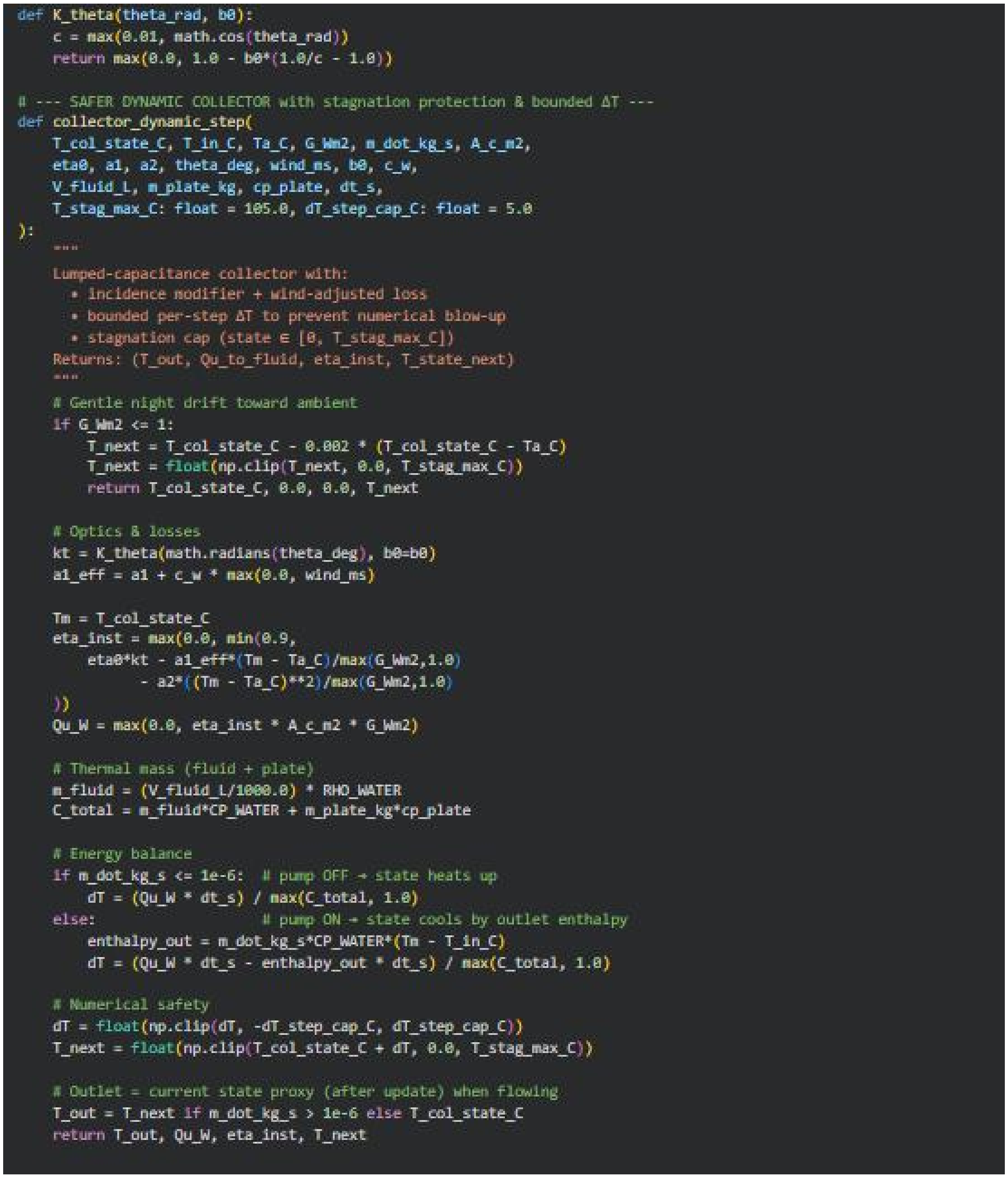
```python
def pick_sunniest_window(df_hourly: pd.DataFrame, days: int = 14):
    tmp = df_hourly.copy()
    tmp["E_kWhm2"] = tmp["G_POA_Wm2"]/1000.0
    daily = tmp["E_kWhm2"].resample("D").sum()
    roll = daily.rolling(window=days).sum()
    start_day = roll.idxmax() - pd.to_timedelta(days-1, unit="D")
    end_day = start_day + pd.to_timedelta(days, unit="D")  # exclusive
    df_win = df_hourly.loc[start_day:end_day - pd.Timedelta(hours=1)].copy()
    print(f"☀️ Sunniest {days}-day window: {start_day.date()} → {(end_day - pd.Timedelta(days=1)).date()}")
    print(f"   Avg daily POA in window: {daily.loc[start_day:end_day - pd.Timedelta(days=1)].mean():.2f} kWh/m²/day")
    return df_win, daily, (start_day, end_day)

def resample_to_dt(df_hourly: pd.DataFrame, dt_min: float):
    t_new = pd.date_range(df_hourly.index[0], df_hourly.index[-1], freq=f"{int(dt_min)}min")
    df_new = df_hourly.reindex(t_new).interpolate(method="time")
    df_new.index.name = "time"
    return df_new

def weather_from_df(df: pd.DataFrame):
    hod = df.index.hour + df.index.minute/60.0
    theta_deg = np.where(df["G_POA_Wm2"].values > 1, 60*np.abs(np.cos((hod-12)/12*np.pi)), 60.0)
    return {
        "time": df.index.to_pydatetime(),
        "Ta": df["Ta_C"].values.astype(float),
        "G_POA": df["G_POA_Wm2"].values.astype(float),
        "wind": df["wind_ms"].values.astype(float),
        "theta_deg": theta_deg.astype(float)
    }
```



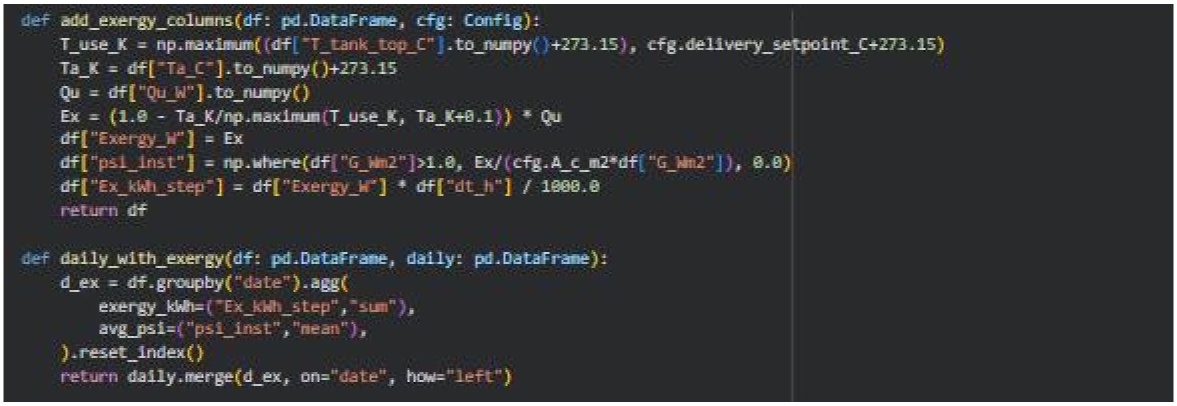
```python
def epw_to_poa_full(epw_path: str, tilt_deg: float, rho_g: float, prefer_year: int = 2023):
    # EPW columns
    colspec = ["Year","Month","Day","Hour","Minute","Flags",
               "DryBulb","DewPoint","RH","Pressure",
               "ExHorRad","ExDirRad","HorIR","GHI","DNI","DHI",
               "GIllum","DNIllum","DHIllum","ZenithLum",
               "WindDir","WindSpeed","TotalSky","OpaqueSky","Visibility",
               "Ceiling","PresentObs","PresentCodes","PW","AOD","SnowDepth",
               "DaysSinceSnow","Albedo","LiquidPrecipDepth","LiquidPrecipQty"]
    raw = pd.read_csv(epw_path, skiprows=8, header=None, names=colspec)

    # Time index; prefer a real year if present (e.g., 2023), else fallback
    has_year = raw["Year"].notna().any()
    if has_year and (raw["Year"].unique().size > 1 or raw["Year"].iloc[0] != 0):
        years = raw["Year"].astype(int).values
        if np.any(years == prefer_year):
            mask = (years == prefer_year)
            raw = raw.loc[mask].reset_index(drop=True)
            base_idx = pd.date_range(f"{prefer_year}-01-01 00:00", periods=len(raw), freq="H")
        else:
            start_year = int(raw["Year"].replace(0, np.nan).dropna().iloc[0])
            base_idx = pd.date_range(f"{start_year}-01-01 00:00", periods=len(raw), freq="H")
    else:
        base_idx = pd.date_range("2001-01-01 00:00", periods=len(raw), freq="H")

    df = pd.DataFrame(index=base_idx)
    df["Ta_C"] = raw["DryBulb"].astype(float).values
    GHI = raw["GHI"].fillna(0).astype(float).values
    DHI = raw["DHI"].fillna(0).astype(float).values
    DNI = raw["DNI"].fillna(0).astype(float).values
    df["wind_ms"] = raw["WindSpeed"].fillna(1.5).astype(float).values

    # Isotropic sky → POA
    beta = math.radians(tilt_deg)
    cosZ = np.clip(np.where(DNI > 0, (GHI - DHI) / np.maximum(DNI, 1e-6), 0.5), 0, 1)
    Rb = np.clip((cosZ*np.cos(beta) + np.sin(beta)*np.sqrt(np.maximum(0.0, 1 - cosZ**2))), 0, 1)
    B_tilt = DNI * Rb
    D_tilt = DHI * (1 + np.cos(beta)) / 2.0
    R_ground = GHI * rho_g * (1 - np.cos(beta)) / 2.0
    df["G_POA_Wm2"] = np.maximum(0, B_tilt + D_tilt + R_ground)

    return df  # hourly, full year
```



```python
def eq_liters_at_setpoint(Q_user_J, T_set_C, T_cold_C):
    """
    Convert thermal energy delivered to user, Q_user [J],
    into an equivalent mixed volume at setpoint (liters).
    V_eq = Q / (rho * cp * (T_set - T_cold))
    """
    dT = max(0.1, T_set_C - T_cold_C)  # avoid divide by zero
    V_m3 = Q_user_J / (RHO_WATER * CP_WATER * dT)
    return max(0.0, V_m3*1000.0)  # liters
```



```python
def K_theta(theta_rad, b0):
    c = max(0.01, math.cos(theta_rad))
    return max(0.0, 1.0 - b0*(1.0/c - 1.0))

# --- SAFER DYNAMIC COLLECTOR with stagnation protection & bounded ΔT ---
def collector_dynamic_step(
    T_col_state_C, T_in_C, Ta_C, G_Wm2, m_dot_kg_s, A_c_m2,
    eta0, a1, a2, theta_deg, wind_ms, b0, c_w,
    V_fluid_L, m_plate_kg, cp_plate, dt_s,
    T_stag_max_C: float = 105.0, dT_step_cap_C: float = 5.0
):
    """
    Lumped-capacitance collector with:
      • incidence modifier + wind-adjusted loss
      • bounded per-step ΔT to prevent numerical blow-up
      • stagnation cap (state ∈ [0, T_stag_max_C])
    Returns: (T_out, Qu_to_fluid, eta_inst, T_state_next)
    """
    # Gentle night drift toward ambient
    if G_Wm2 <= 1:
        T_next = T_col_state_C - 0.002 * (T_col_state_C - Ta_C)
        T_next = float(np.clip(T_next, 0.0, T_stag_max_C))
        return T_col_state_C, 0.0, 0.0, T_next

    # Optics & losses
    kt = K_theta(math.radians(theta_deg), b0=b0)
    a1_eff = a1 + c_w * max(0.0, wind_ms)

    Tm = T_col_state_C
    eta_inst = max(0.0, min(0.9,
        eta0*kt - a1_eff*(Tm - Ta_C)/max(G_Wm2,1.0)
              - a2*((Tm - Ta_C)**2)/max(G_Wm2,1.0)
    ))
    Qu_W = max(0.0, eta_inst * A_c_m2 * G_Wm2)

    # Thermal mass (fluid + plate)
    m_fluid = (V_fluid_L/1000.0) * RHO_WATER
    C_total = m_fluid*CP_WATER + m_plate_kg*cp_plate

    # Energy balance
    if m_dot_kg_s <= 1e-6:  # pump OFF → state heats up
        dT = (Qu_W * dt_s) / max(C_total, 1.0)
    else:                   # pump ON → state cools by outlet enthalpy
        enthalpy_out = m_dot_kg_s*CP_WATER*(Tm - T_in_C)
        dT = (Qu_W * dt_s - enthalpy_out * dt_s) / max(C_total, 1.0)

    # Numerical safety
    dT = float(np.clip(dT, -dT_step_cap_C, dT_step_cap_C))
    T_next = float(np.clip(T_col_state_C + dT, 0.0, T_stag_max_C))

    # Outlet = current state proxy (after update) when flowing
    T_out = T_next if m_dot_kg_s > 1e-6 else T_col_state_C
    return T_out, Qu_W, eta_inst, T_next
```



```python
def add_exergy_columns(df: pd.DataFrame, cfg: Config):
    T_use_K = np.maximum((df["T_tank_top_C"].to_numpy()+273.15), cfg.delivery_setpoint_C+273.15)
    Ta_K = df["Ta_C"].to_numpy()+273.15
    Qu = df["Qu_W"].to_numpy()
    Ex = (1.0 - Ta_K/np.maximum(T_use_K, Ta_K+0.1)) * Qu
    df["Exergy_W"] = Ex
    df["psi_inst"] = np.where(df["G_Wm2"]>1.0, Ex/(cfg.A_c_m2*df["G_Wm2"]), 0.0)
    df["Ex_kWh_step"] = df["Exergy_W"] * df["dt_h"] / 1000.0
    return df

def daily_with_exergy(df: pd.DataFrame, daily: pd.DataFrame):
    d_ex = df.groupby("date").agg(
        exergy_kWh=("Ex_kWh_step","sum"),
        avg_psi=("psi_inst","mean"),
    ).reset_index()
    return daily.merge(d_ex, on="date", how="left")
```

```python
def plot_timeseries(df: pd.DataFrame, outdir: str):
    figs = []

    f1 = plt.figure()
    plt.plot(df["time"], df["G_Wm2"], label="Irradiance (W/m²)")
    plt.plot(df["time"], df["Ta_C"], label="Ambient (°C)")
    plt.legend(); plt.title("Irradiance & Ambient Temperature"); plt.xlabel("Time")
    figs.append(("01_irradiance_ambient.png", f1))

    f2 = plt.figure()
    plt.plot(df["time"], df["T_col_in_C"], label="Collector Inlet (°C)")
    plt.plot(df["time"], df["T_col_out_C"], label="Collector Outlet (°C)")
    plt.legend(); plt.title("Collector Temperatures"); plt.xlabel("Time")
    figs.append(("02_collector_temps.png", f2))

    f3 = plt.figure()
    plt.plot(df["time"], df["T_tank_top_C"], label="Tank Top (°C)")
    if "T_tank_mid_C" in df: plt.plot(df["time"], df["T_tank_mid_C"], label="Tank Mid (°C)")
    if "T_tank_bot_C" in df: plt.plot(df["time"], df["T_tank_bot_C"], label="Tank Bottom (°C)")
    plt.legend(); plt.title("Tank Temperatures (Stratified)"); plt.xlabel("Time")
    figs.append(("03_tank_temps.png", f3))

    f4 = plt.figure()
    plt.plot(df["time"], df["eta_inst"], label="Collector η (-)")
    plt.plot(df["time"], df["pump_on"], label="Pump ON (0/1)")
    plt.legend(); plt.title("Efficiency & Pump Signal"); plt.xlabel("Time")
    figs.append(("04_efficiency_pump.png", f4))

    f5 = plt.figure()
    plt.plot(df["time"], df["pipe_loss_W"], label="Pipe Loss (W)")
    plt.legend(); plt.title("Piping Heat Loss"); plt.xlabel("Time")
    figs.append(("05_piping_loss.png", f5))

    for fname, fig in figs:
        save_fig(fig, os.path.join(outdir, fname))

def export_run(df, daily, cfg: Config, meta: dict, out_root="results"):
    outdir = make_run_folder(out_root)
    df.to_csv(os.path.join(outdir, "timeseries.csv"), index=False)
    daily.to_csv(os.path.join(outdir, "daily_kpis.csv"), index=False)
    save_json(asdict(cfg), os.path.join(outdir, "config.json"))
    save_json(meta, os.path.join(outdir, "meta.json"))
    plot_timeseries(df, outdir)
    return outdir
```

```
def build_draw_profile(cfg: Config, time_vec):
    """Two draw windows/day; total draw split 50/50."""
    N = len(time_vec)
    m = np.zeros(N)
    total_kg = (cfg.draw_total_L_day/1000.0)*RHO_WATER
    rate = total_kg*0.5/(cfg.draw_duration_h*3600.0)
    for i, t in enumerate(time_vec):
        hr = t.hour + t.minute/60.0
        if cfg.draw_morning_start_h <= hr < cfg.draw_morning_start_h + cfg.draw_duration_h:
            m[i] = rate
        if cfg.draw_evening_start_h <= hr < cfg.draw_evening_start_h + cfg.draw_duration_h:
            m[i] = rate
    return m

def tank_stratified_step(Tnodes, Ta_C, Qu_W, UA_tot_WK, axial_k_WK,
                         m_draw_kg_s, Tmains_C, T_col_out_C, dt_s):
    """
    N-node stratified tank:
     - Collector inflow at top node (mixing).
     - Draw from top; refill bottom with mains.
     - Wall losses per node and axial conduction.
    """
    N = len(Tnodes)
    mnode = (RHO_WATER * (CFG.tank_vol_L/1000.0))/N
    UA_node = UA_tot_WK/N
    T = Tnodes.copy()

    # 1) Collector inflow → top node
    if Qu_W > 0:
        m_in = CFG.m_dot_loop_kg_s
        E_in = m_in*CP_WATER*T_col_out_C*dt_s
        E_top = mnode*CP_WATER*T[0]*dt_s + E_in
        T[0] = E_top/(mnode*CP_WATER*dt_s)

    # 2) DHW draw from top; refill bottom
    if m_draw_kg_s > 0:
        E_out = m_draw_kg_s*CP_WATER*T[0]*dt_s
        T[0] = (mnode*CP_WATER*T[0]*dt_s - E_out)/(mnode*CP_WATER*dt_s)
        E_in_mains = m_draw_kg_s*CP_WATER*Tmains_C*dt_s
        T[-1] = (mnode*CP_WATER*T[-1]*dt_s + E_in_mains)/(mnode*CP_WATER*dt_s)

    # 3) Wall losses
    for k in range(N):
        Q_loss = UA_node*(T[k]-Ta_C)*dt_s
        T[k] -= Q_loss/(mnode*CP_WATER)

    # 4) Axial conduction
    for k in range(N-1):
        dT = T[k] - T[k+1]
        Q = axial_k_WK * dT * dt_s
        T[k]   -= Q/(mnode*CP_WATER)
        T[k+1] += Q/(mnode*CP_WATER)

    return T
```