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Review Article

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Design And Simulation of A Solar Water Heater For House Hold Use

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Abstract: This work presents the design and simulation of solar water heater for household use. The purpose is basically to harness solar energy to provide heated water, aimed at reducing reliance on conventional energy sources and lower cost of energy for households. The work involves the installation of a 20W solar panel, connection of 18650 Lithium batteries to store solar energy, integration of glow plugs into the water reservoir for heating, installation of a switch for user control, placement of a temperature sensor for monitoring, setup of the water reservoir and testing and calibration of the entire system. The result produced one that is cost-effective and efficient solar water heater that provide heated water for household needs. And from all indication this can offer sustainable solution for household water heating, contributing to energy conservation and support a net zero environmental.

Keywords: *Solar Water Heater, Household Water Heating, Glow Plug Heating, Energy Storage, Temperature Sensor*

Introduction

Solar water heating (SWH) technology has evolved as a critical component in the pursuit of sustainable energy solutions. The increasing costs of fossil fuels, alongside the detrimental environmental impacts of traditional energy sources, have accelerated the adoption of renewable energy technologies. Solar water heaters offer a way to harness solar energy, a clean, abundant, and free resource to reduce dependence on conventional water heating methods. SWH systems convert solar radiation into thermal energy to heat water, which is then stored in a tank for household use.

Historically, the adoption of solar water heaters dates back to ancient civilizations, where rudimentary methods were used to heat water using solar energy. In modern times, technological advancements have significantly improved the efficiency and reliability of these systems. Solar water heating is particularly relevant in regions with high solar insolation, where it can provide a substantial portion of household hot water needs, thereby reducing energy bills and carbon footprints. This study seeks to explore the design and simulation of an efficient SWH system using Polysun software, which enables detailed modeling of system performance under various conditions (Kalogirou, 2004).

Problem Statement

Traditional water heating methods, such as electric and gas water heaters, are not only costly but also environmentally unsustainable due to their reliance on fossil fuels. These methods contribute significantly to household energy consumption, accounting for up to 20% of the total energy use in homes. Furthermore, the emissions associated with

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conventional water heating contribute to air pollution and global warming (Duffie & Beckman, 2013). Given the urgency to reduce energy consumption and greenhouse gas emissions, there is a pressing need for alternative water heating solutions that are both economically viable and environmentally friendly.

Solar water heaters present a promising solution, but their adoption is hindered by several factors, including high initial costs, lack of awareness, and perceived inefficiencies in varying climatic conditions. This research aims to address these challenges by designing and simulating a solar water heater tailored for household use. The simulation, conducted using Polysun software, will evaluate the system's performance, cost-effectiveness, and environmental benefits under different scenarios (Andrews & Pearce, 2011).

Aim and Objectives

The primary aim of this study is to design and simulate an efficient solar water heating system for household use using Polysun software. The specific objectives of the study are:

- To assess the energy savings potential of solar water heaters compared to conventional systems. This involves modeling the energy output of the solar water heater and comparing it to the energy consumption of electric and gas water heaters (Soteris, 2013).
- To evaluate the environmental impact of using solar water heaters, including the reduction in carbon emissions. This objective will be achieved by quantifying the greenhouse gas emissions offset by the solar water heater over its lifespan.
- To simulate the performance of different solar water heater configurations in Polysun software, analyzing the impact of variables such as collector type, orientation, and storage capacity on system efficiency.
- To conduct a cost-benefit analysis to determine the economic feasibility of solar water heaters for residential use. This will include calculating the payback period, net present value (NPV), and return on investment (ROI) for various system configurations (Quaschning, 2016).

Scope of The Study

The study focuses on the design and simulation of solar water heating systems specifically for single-family households. The simulation will be conducted using Polysun software, which allows for detailed modeling of solar thermal systems, including collectors, storage tanks, piping, and control mechanisms. The geographical focus will be on regions with varying solar insolation levels to assess system performance across different climatic conditions. The study will not cover commercial or industrial applications of solar water heating but will provide insights relevant to residential users, policymakers, and energy consultants.

Significance of The Study

This study is significant because it addresses the need for sustainable energy solutions in residential settings. By demonstrating the practical and economic viability of solar water heaters, the research aims to promote wider adoption of this technology, contributing to reduced energy bills, lower carbon footprints, and enhanced energy security for households. The findings will provide homeowners with a clear understanding of the benefits and limitations of solar water heaters, enabling them to make informed decisions about their energy choices (Harrison, 2012). Additionally, the study will offer valuable data for policymakers and energy consultants seeking to promote renewable energy adoption.

Structure of The Report

The report is structured into five chapters:

Chapter One: Introduction - provides the background, problem statement, objectives, scope, and significance of the study.

Chapter Two: Literature Review - offers a detailed review of existing studies, solar water heating technologies, and applications of Polysun software in system simulation.

Chapter Three: Methodology- outlines the design and simulation process using Polysun software, including data sources, system modeling, and performance evaluation criteria.

Chapter Four: Results and Discussion- presents the results of the simulation and discusses the implications of the findings in relation to the study objectives.

Chapter Five: Conclusion and Recommendations- summarizes the key findings, discusses the limitations of the study, and provides recommendations for future research and practical implementation.

Literature Review

The literature review explores the development and application of solar water heating systems, emphasizing the evolution of technology, types of systems available, and the factors influencing their performance. This chapter also examines the use of Polysun software in simulating and optimizing solar water heaters, highlighting its advantages in renewable energy system modeling.

Overview of Solar Water Heating Systems

Solar water heating systems use solar collectors to capture and convert sunlight into thermal energy, which is used to heat water. The key components of these systems include solar collectors, a heat transfer system, a storage tank, and a control unit. The efficiency of these systems depends on the design and quality of each component, as well as the overall system configuration,(Andrews & Pearce, 2011).

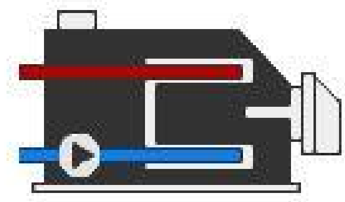
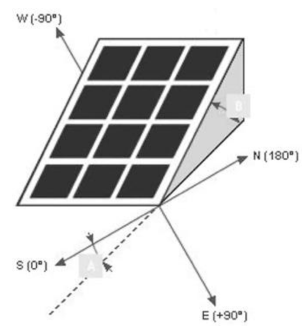


Fig 1. Heater [2,3]



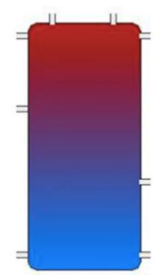


Fig 2. Solar collector. [4]
Fig 3. Water tank [3]

Solar water heaters can be classified into two main categories: active systems, which rely on mechanical components such as pumps and controllers to circulate the fluid, and passive systems, which use natural convection and gravity to move the fluid. Active systems are generally more efficient but also more complex and costly to install and maintain. Passive systems are simpler and cheaper but may have lower performance, especially in regions with less sunlight (International Energy Agency, 2014).

Types Of Solar Collectors

Flat-Plate Collectors

Flat-plate collectors are the most widely used type of solar collector for residential water heating. They consist of a flat, dark-colored absorber plate that absorbs solar radiation, a series of pipes or tubes for circulating the fluid, insulation to minimize heat loss, and a transparent cover to protect the absorber and reduce radiative heat losses. The simplicity and reliability of flat-plate collectors make them suitable for a wide range of climates, although their performance can be affected by ambient temperature and wind speed (Kalogirou, 2004; Hudon, 2014).

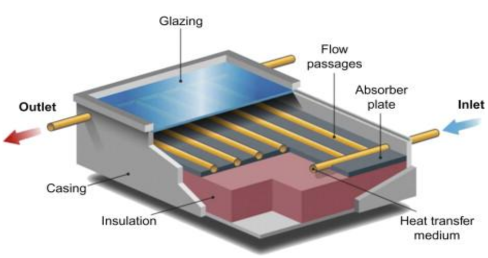


Fig 4. Glazed flat plate collector [8]

2.3.2 Evacuated Tube Collectors

Evacuated tube collectors are composed of multiple glass tubes, each containing a metal absorber and a heat pipe or fluid-filled tube. The vacuum within each tube serves as an excellent insulator, greatly reducing heat loss and allowing the collectors to maintain high efficiency even in cold and windy conditions. These collectors are ideal for applications where high-water temperatures are required or in regions with low ambient temperatures (International Energy Agency, 2014; Kalogirou, 2004; Hudon, 2014).

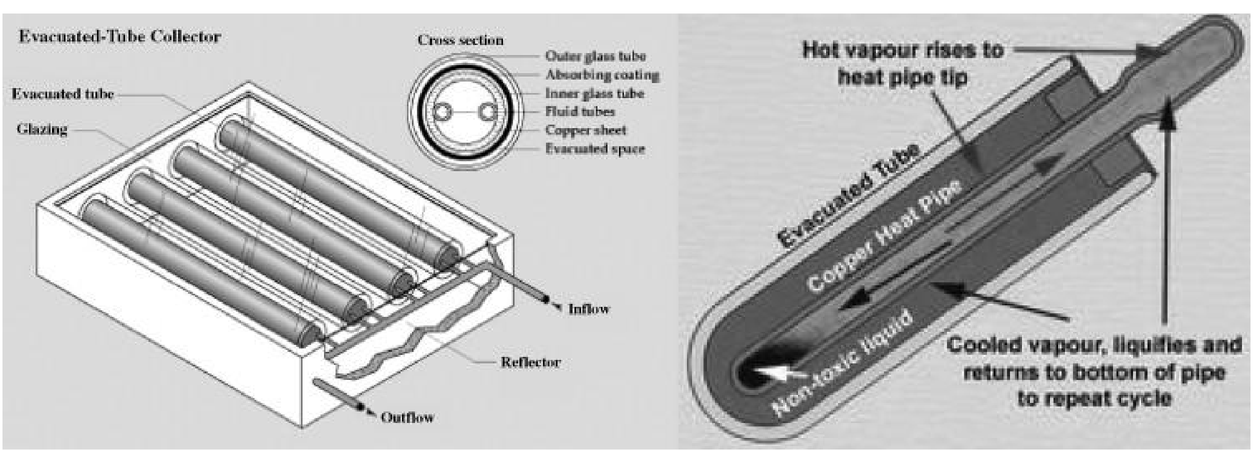


Fig. 5. Direct-flow evacuated-tube collectors and heat pipe evacuated-tube collectors.

2.3.3 Integral Collector-Storage Systems

Integral collector-storage (ICS) systems combine the solar collector and the storage tank in one unit. Water is heated directly within the collector and stored until needed. ICS systems are simple and cost-effective but are generally only suitable for mild climates where freezing is not a concern, as the entire system is exposed to the environment (Polysun, 2021).

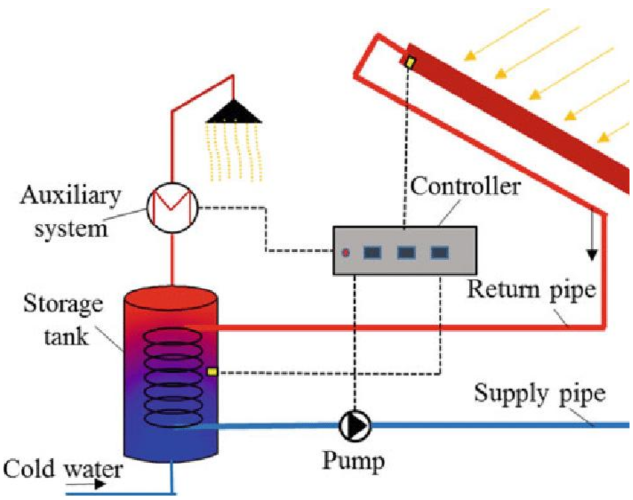


Fig 6. Basic components of a solar domestic hot water system (Hudon, 2014; Polysun, 2021)

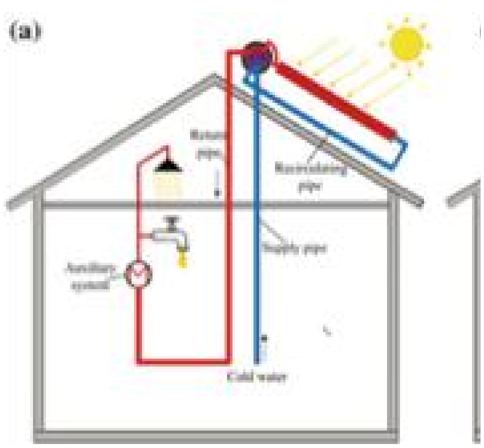


Fig. 7 Passive (**a**) and active (**b**) solar domestic hot water systems (Quaschning, 2016; Sharma et al., 2015)

Performance Metrics and Efficiency Factors

The performance of solar water heating systems is measured using several key metrics:

- **Solar Fraction**: The solar fraction is the portion of the total hot water demand met by the solar water heating system. A higher solar fraction indicates greater reliance on solar energy and less dependence on backup heating sources (Kalogirou, 2013)
- **System Efficiency**: System efficiency is determined by the ratio of the energy output (useful heat delivered to the water) to the solar energy incident on the collector surface. Factors affecting efficiency include collector type, orientation, tilt angle, and the presence of shading.
- **Payback Period**: The payback period is the time required for the savings generated by the solar water heater to equal the initial investment cost. A shorter payback period indicates a more economically viable system (Yazdani Fard et al., 2018).
- **Environmental Impact**: The environmental impact of solar water heaters is assessed by calculating the reduction in greenhouse gas emissions compared to conventional heating methods. Life cycle assessments (LCAs) are often used to evaluate the total environmental impact of the system from production to disposal (Kalogirou, 2004).

BENEFITS OF SOLAR WATER HEATING SYSTEMS

Solar water heaters offer numerous benefits, including:

- **Energy Savings**: By harnessing free solar energy, these systems significantly reduce household energy consumption, leading to lower utility bills (Hudon, 2014).
- **Environmental Benefits**: Solar water heaters reduce the reliance on fossil fuels, thereby decreasing greenhouse

gas emissions and contributing to the mitigation of climate change (Kalogirou, 2013).

- ➢ **Long-Term Cost Savings**: Although the initial investment in solar water heating systems can be high, the long-term savings in energy costs and potential government incentives make them a financially attractive option (Morrison et al., 2004)
- ➢ **Increased Energy Independence**: By generating hot water on-site, households become less dependent on external energy sources, providing greater resilience against energy price fluctuations (Duffie & Beckman, 2013)

Challenges and Limitations

Despite their benefits, solar water heaters face several challenges that can limit their adoption:

- ➢ High Initial Costs: The upfront cost of solar water heaters, including installation, can be a barrier for many homeowners. Although costs have decreased in recent years, they remain higher than those of conventional systems (Yazdani Fard et al., 2018).
- ➢ Performance Variability: Solar water heaters' performance depends heavily on local weather conditions, such as solar insolation, ambient temperature, and seasonal variations. In regions with low sunlight, the efficiency of these systems may be significantly reduced (Kalogirou, 2004).
- ➢ Space Requirements: Installing solar collectors requires adequate roof space, which may not be available in all homes. Additionally, the orientation and tilt angle of the collectors are critical factors that can affect performance (Sharma et al., 2015; Hudon, 2014)
- ➢ Maintenance Needs: Solar water heaters require regular maintenance to ensure optimal performance, including cleaning the collectors, checking for leaks, and ensuring the proper functioning of pumps and controllers in active systems (International Energy Agency, 2014)

OVERVIEW OF POLYSUN SOFTWARE

Polysun is an advanced simulation software designed for the planning and optimization of renewable energy systems, including solar thermal, photovoltaic, and geothermal applications. It offers a robust platform for modeling the performance of solar water heating systems, allowing users to explore different configurations and optimize system design based on specific criteria (Harrison, 2012).

Polysun Main Window (Graphical User Interface)

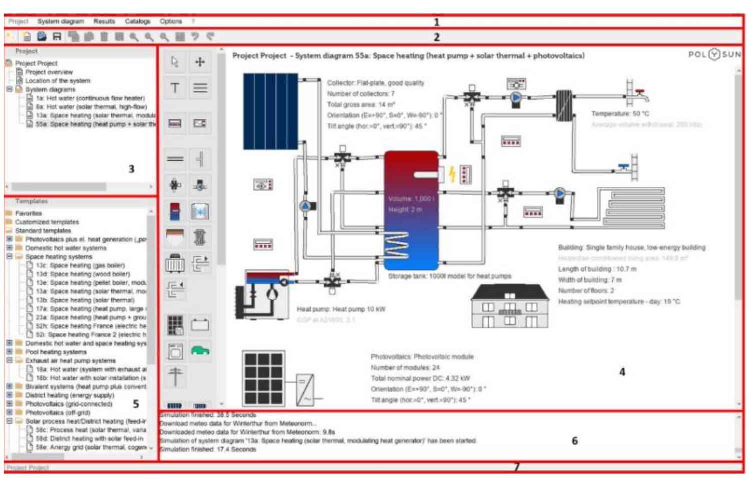


Fig. 8: Polysun Graphical User Interface

- Menu bar
- Toolbar
- Project data (folder tree)
- Working area
- Template collection
- Console (status window)

1. Status bar

WIZARD

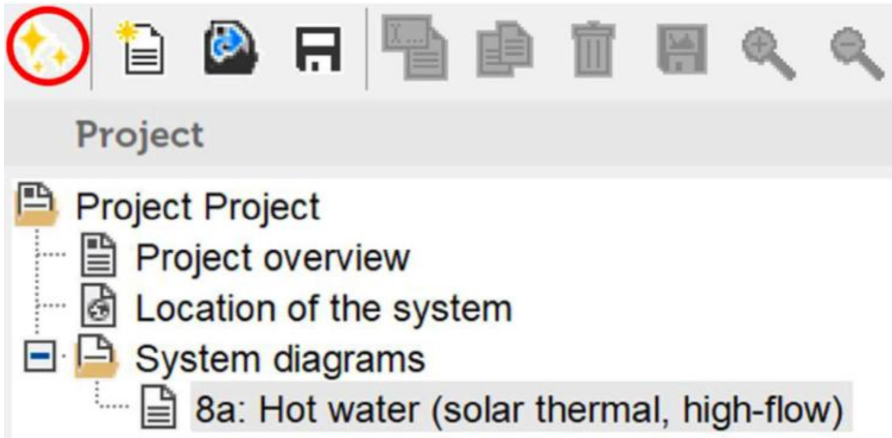


Fig. 9: Wizard icon

In Polysun the project can be started by means of the Wizard. The Wizard is a helpful and user-friendly tool, which assists the user to size the system according to the requirements step by step. The procedure is straight-forward, you need to go from one tab to another filling in the required parameters. The Wizard opens automatically after starting Polysun or it can be chosen by clicking on the Wizard icon (first button on the left of the icon bar).

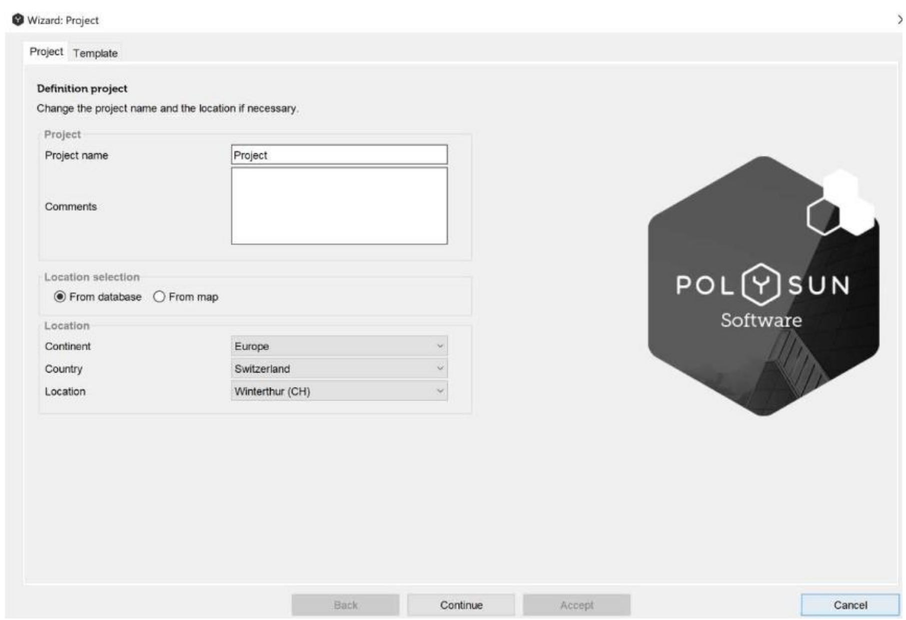


Fig. 10: project definition in Wizard

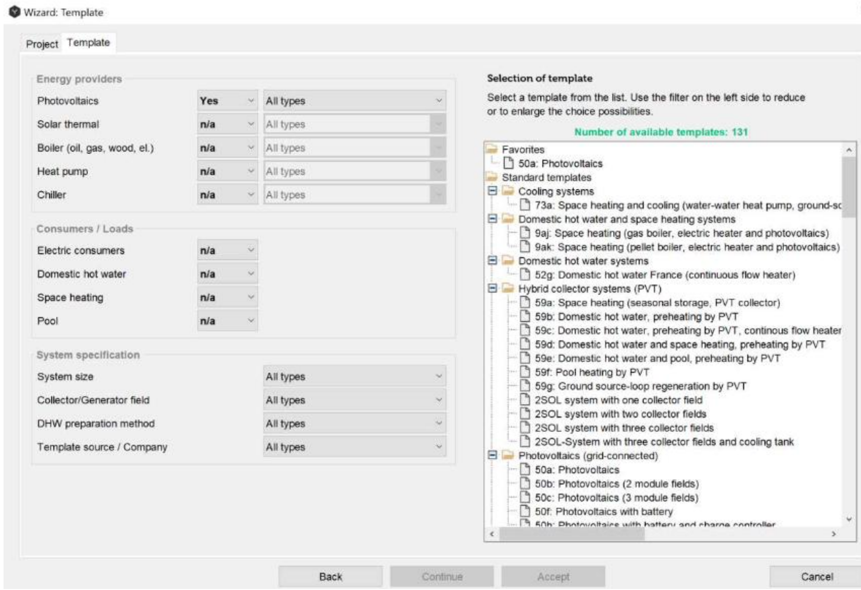


Fig. 11: selection of the template

Weather Data

One of the first steps of the project design is the selection of the weather data. Polysun provides reliable yield forecasts for more than 8400 locations worldwide, but also allows reading meteor data from a file, calculating of hourly meteor data from external monthly values and obtaining the meteor data from the location through the internet from the Meteonorm webservice.

Location

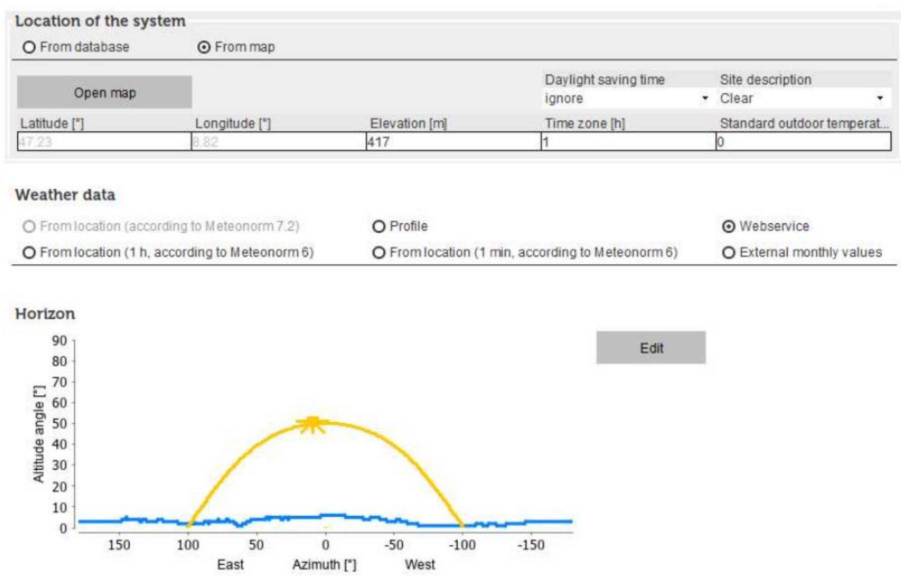


Fig. 12: location of the system

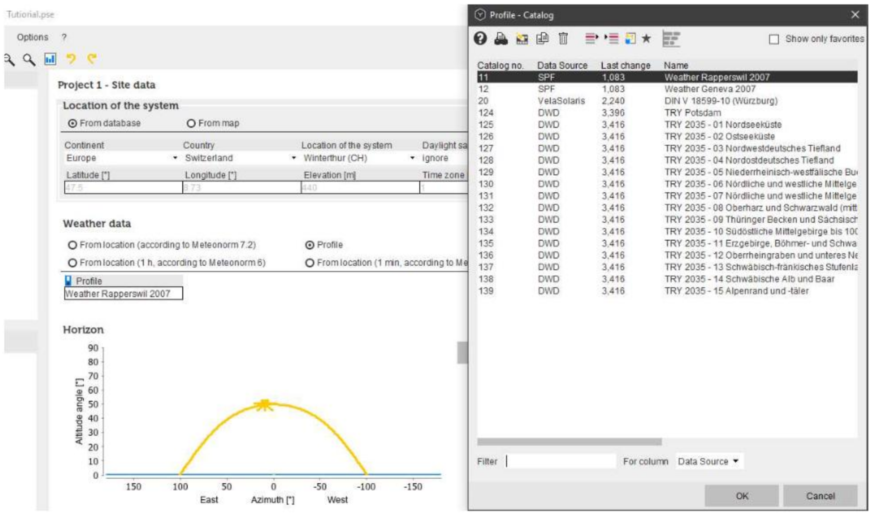


Fig. 13: selecting weather data from profile

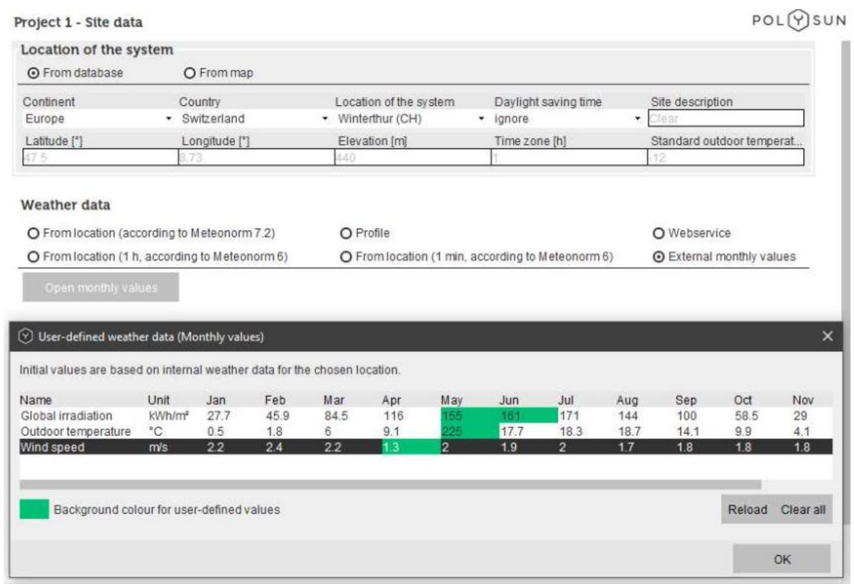


Fig. 14: external monthly values of weather data

Features and Capabilities

Polysun provides an extensive database of components, including various types of solar collectors, storage tanks, heat exchangers, and control systems. Users can model both active and passive solar water heating systems and simulate their performance under real-world conditions using location-specific weather data. The software's user-friendly interface and comprehensive analysis tools enable designers to evaluate system efficiency, energy savings, and economic viability (Polysun, 2021).

Applications in Solar Water Heating Design

Polysun allows for the detailed simulation of solar water heating systems, accounting for factors such as collector efficiency, shading, heat losses, and system control strategies. By simulating different scenarios, designers can identify the optimal system configuration for a given location and application. Polysun also supports financial analysis, including calculations of payback periods, NPV, and ROI, providing a complete picture of the system's economic feasibility (Li et al., 2019).

Case Studies and Applications

Several case studies have demonstrated the effectiveness of Polysun in designing and optimizing solar water heating systems:

- Case Study 1: Residential Solar Water Heater in Southern Europe: This study used Polysun to model a solar water heater with flat-plate collectors for a single-family home in Southern Europe. The simulation results indicated that the system could meet 70% of the household's hot water needs, with a payback period of 6 years (Harrison, 2012).
- Case Study 2: High-Performance Evacuated Tube System in Northern Europe: A simulation of an evacuated tube collector system for a home in Northern Europe showed that despite the lower solar insolation, the high efficiency of the evacuated tubes allowed the system to achieve a solar fraction of 50%, demonstrating the viability of solar water heaters in colder climates (Morrison et al., 2004).

Materials and Method

This chapter provides a detailed description of the materials used and the methodology followed for the design, CAD modeling, and simulation of a solar water heating system. The system is simulated using Polysun, and the CAD design was completed in Fusion 360. This project evaluates the performance of a solar water heating system based on environmental conditions and technical specifications.

Materials

The main components and software used in this project are detailed below:

SOLAR WATER HEATING COMPONENTS

- Solar Collector (Flat Plate Collector)
  - Type: Flat plate collector.
  - Material: Copper pipes with an aluminum absorber plate.
  - Specifications:
    i. Absorber area: 2-3 m² per panel.
    ii. Collector efficiency: 60-70%.
    iii. Insulation: Fiberglass or polyurethane to minimize heat losses.
    iv. Purpose: To capture and convert solar energy into thermal energy, used to heat water circulating through the system.
    v. Power: 180W.

- Storage Tank (Thermal Storage)
  - Material: Steel or plastic with internal insulation.
  - Capacity: 300 liters.
  - Configuration: Stratified thermal tank for efficient hot water storage.
  - Purpose: Stores hot water heated by the solar collector, ensuring availability for domestic use even when solar energy is not immediately available.

- Circulation Pump
  - Type: DC or AC pump, driven by a photovoltaic panel or conventional power supply.
  - Flow Rate: 2-4 liters per minute.
  - Purpose: Circulates the water or heat-transfer fluid between the solar collector and storage tank.

- Heat Exchanger (Auxiliary Heater)
  - Type: Electric immersion heater.
  - Power: 4kw.
  - Purpose: Provides additional heating when solar energy is insufficient, ensuring a constant supply of hot water.
  - Hot water demand**:** temperature is 50^0 C, Nominal flow rate is Automatic

- Piping System

- Material: Copper or PEX (cross-linked polyethylene).
- Diameter: 20 mm
- Purpose: Transfers heat from the solar collector to the storage tank, and from the storage tank to domestic taps.

➢ Controller

- Type: Digital controller with temperature sensors.
- Purpose: Regulates the operation of the circulation pump based on temperature differences between the collector and the storage tank.

The Materials Properties For This Design And Simulation Are Listed From Left To Right As Follows

- The pump
- Heat exchanger
- Hot water demand
- PV T solar collector
- Water tank
- Valve
- Controller**.**

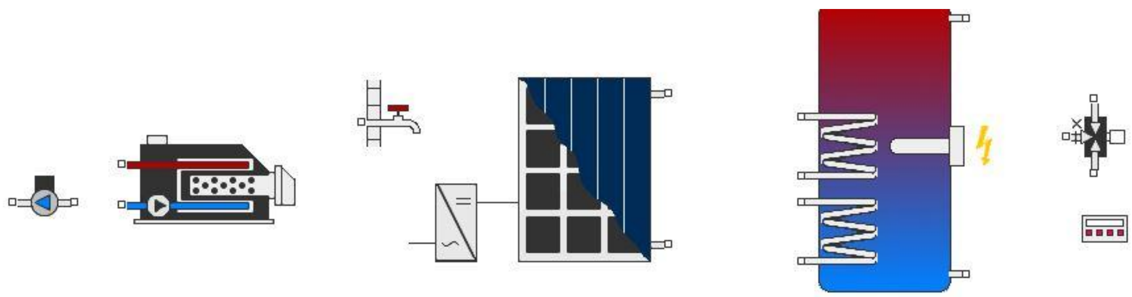


Fig.15: Materials

Software Used

➢ Polysun Software

- Version: Polysun 11.2.
- Purpose: Simulates the performance of solar water heating systems under varying climatic conditions, allowing detailed analysis of system behavior.
- Features:
  i. Dynamic simulation for energy balance.
  ii. Pre-configured components like solar collectors, storage tanks, and auxiliary heaters.
  iii. Output data includes temperature profiles, energy flow, and performance efficiency.

➢ Fusion 360 (CAD Software)

- Version: Autodesk Fusion 360.
- Purpose: For 3D CAD design and modeling of the solar water heating system components.
- Features:
  i. Parametric modeling and assembly features.
  ii. Rendering for visualization of the system's components and layout.
  iii. Ability to create detailed technical drawings for fabrication or installation.

Environmental Data

- Solar Irradiance Data
  - Source: NASA Surface Meteorology and Solar Energy Database.
  - Location: [Insert location here].
  - Average Irradiance: 4-6 kWh/m²/day (location-specific).
- Weather Data
  - source: Polysun integrated weather database.
  - Parameters:
    i. Ambient temperature: -5°C to 35°C (based on local conditions).
    ii. Wind speed and direction: 0-5 m/s (for system heat loss calculations).

Methods

The design, modeling, and simulation process is divided into several steps, from system design to performance analysis:

System Design

The design of the solar water heating system was carried out using standard guidelines for solar thermal systems, ensuring it meets the expected hot water demand.

- **Determining Daily Hot Water Demand**
  - The daily hot water consumption was estimated to be **150-200 liters/day** based on the average household usage.
  - The desired temperature rise from **15°C to 50°C** was set, which defines the energy requirement.
- **Sizing the Solar Collector**
  - The collector area was calculated using the following formula

$$A = \frac{Q_{useful}}{G_{avg} * y_{coll}}$$

Q_{useful} = is the energy required to heat 300 liters of water per day

G_{avg} = is the average solar irradiance at the location.

y_{coll} = is the efficiency of the collector.

- **Sizing the Storage Tank**
  - The storage tank capacity was selected to store **300 liters** of water at a maximum temperature of 60°C. The stratified tank was chosen to ensure efficient energy storage with minimal heat loss.
- **Piping System Design**
  - The piping system was designed based on the layout, with an estimated length of **10 meters** of insulated piping, ensuring minimal heat loss between the collector and the storage tank.
- **Pump Selection**
  - The pump was selected based on the flow rate required to circulate the fluid between the collector and the storage tank. A **3 liters/min** pump was chosen to match the system design.

CAD Design Using Fusion 360

- **3D Modeling**
  - A 3D model of the solar water heating system was created in Fusion 360.

- The model includes the solar collector, storage tank, piping layout, auxiliary heater, and other components.
- **Detailed technical drawings** were generated to represent the component dimensions and layout, including connections between the collector, tank, and auxiliary heater.

➢ **Simulation in CAD**
- Fusion 360 was used to analyze component placement, ensuring that the layout allowed for easy installation and minimal heat loss.
- Rendered images provided a clear visualization of the system's physical setup.

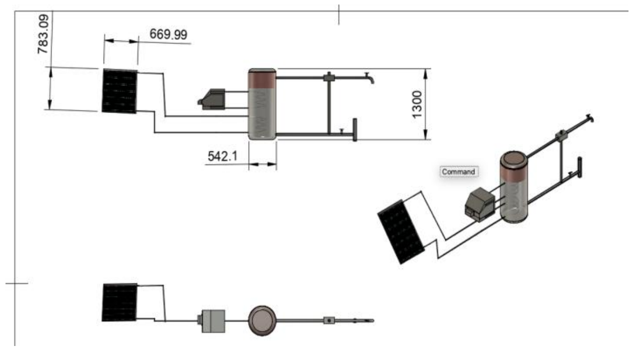


Fig. 16. CAD design

Simulation Setup in Polysun

➢ **Input Parameters**
- The simulation was set up in Polysun with the following key inputs:
  i. Solar collector area: 4-6 m².
  ii. Storage tank capacity: **300 liters**.
  iii. Auxiliary heater: 1.5 kW electric immersion heater.
  iv. Flow rate of the circulation pump: 2-3 liters/min.
  v. Climate data for [insert location].

➢ **Running the Simulation**
- The simulation was run for a period of **one year**, using hourly weather data to assess the performance of the system throughout different seasons.
- The software was configured to output:
  i. Temperature profiles in the collector and storage tank.
  ii. Daily solar energy contribution.
  iii. Auxiliary heater energy consumption.

➢ **Data Collection**
- Performance metrics such as **solar fraction** (the percentage of heat supplied by the solar collector) and **auxiliary heater usage** were recorded.
- Temperature and flow rate data at various points in the system were captured to evaluate system efficiency.

System Optimization

➢ **Collector Orientation and Tilt**
- The collector was optimized by setting the tilt angle equal to the latitude of the location for maximum solar gain. The orientation was set due south.

➢ **Insulation and Heat Loss Mitigation**
- Insulation thickness for the storage tank and pipes was selected based on minimizing heat loss during cold weather conditions.

Result and Discussion

In this chapter, the results from the simulation of the solar water heating system are presented and analyzed. The performance metrics of the system, such as temperature profiles, energy balance, and solar contribution, are discussed in detail. The system's operational behavior under varying environmental conditions and its efficiency are evaluated using data from the **Polysun** simulation, while design considerations based on the **Fusion 360** CAD model are reflected upon.

Simulation Results

Fig 17. Results

Fig 18. Results

Storage tank Potable water tank Coil heat exchanger [1] | Storage tank Potable water tank Coil heat exchanger [2] | Storage tank Potable water tank Internal heater [2] | Weather data

Boiler | Building | Cold water | Collector | Hot water demand | Storage tank Potable water tank

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature		°C	43.2	41.9	42.1	42.8	43.6	43.8	44.3	44.5	44.6	44	43	42.2	41.8
Minimum value		°C	28.9	29	29.9	28.9	29.6	30.4	31.7	31.7	31.4	30.5	31	30.9	29.9
Maximum value		°C	53.3	52.4	52.2	52.6	52.8	52.5	52.9	53	52.8	53.3	52.9	52.1	52.4
Flow rate		l/h	360	360	360	360	360	360	360	360	360	360	360	360	360
Availability	ε	%	91.2	88.8	89.6	91.1	92.5	92.6	93.4	93.6	93.8	91.9	90.2	88.6	88.2
Temperature setting		°C	50	50	50	50	50	50	50	50	50	50	50	50	50
Energy deficit	Qdef	KWh	494	54.6	47.3	46.6	36.8	36.4	31	29.9	28.6	33.7	44.4	49.7	55.3
Energy demand	Qdem	KWh	3,392	310	286	316	298	295	271	267	260	252	269	273	297
Energy from/to the system	Quse	KWh	2,918	256	240	271	263	260	241	239	234	221	226	224	243
Volume withdrawal/daily consumpt...		l/d	200	200	200	200	200	200	200	200	200	200	200	200	200

Storage tank Potable water tank Coil heat exchanger [1] | Storage tank Potable water tank Coil heat exchanger [2] | Storage tank Potable water tank Internal heater [2] | Weather data

Boiler | Building | Cold water | Collector | Hot water demand | Storage tank Potable water tank

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature		°C	10	7	6.1	6.2	7.3	9.1	11.2	12.9	13.9	13.8	12.7	10.9	8.8
Minimum value		°C	6	6.4	6	6	6.6	8.1	10.2	12.1	13.6	13.4	11.9	9.9	7.8
Maximum value		°C	14.1	7.8	6.4	6.6	8.1	10.2	12.1	13.6	14.1	14.1	13.4	11.9	9.9

Storage tank Potable water tank Coil heat exchanger [1] | Storage tank Potable water tank Coil heat exchanger [2] | Storage tank Potable water tank Internal heater [2] | Weather data

Boiler | Building | Cold water | Collector | Hot water demand | Storage tank Potable water tank

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat loss to unheated area		kWh	1,519	122	113	127	125	131	129	136	132	129	131	122	122
Minimum value (Power)		W	48.7	62.5	65.9	61.9	49.5	49.7	48.7	53.1	51.3	50.5	51	74.2	67.7
Maximum value (Power)		W	519	499	496	504	505	507	511	519	512	500	504	501	501
Heat loss to heated area		kWh	146	11.7	10.8	12.2	12	12.7	12.5	13.2	12.8	12.5	12.6	11.7	11.7
Minimum value (Power)		W	4.8	4.9	5.3	4.8	4.9	5	4.9	5.3	5.1	5	5.1	6	5.4
Maximum value (Power)		W	51.9	49.9	49.6	50.4	50.5	50.7	51.1	51.9	51.2	50	50.4	50.1	50.1
Temperature in unheated area		°C	18	18	18	18	18	18	18	18	18	18	18	18	18

Fig 19. Results

Solar Energy Collection

- **Total Solar Energy Collected:**
  - The solar collector absorbed a total of **137 W** (as seen in the system diagram) under specific weather conditions.
  - The average temperature of the heat transfer fluid entering the collector was **1.6°C**.
  - The flow rate through the system was **0 l/h** during the simulation snapshot, indicating a no-flow condition at that moment. This is likely due to insufficient solar irradiance to drive the circulation pump.
- **Maximum Collector Temperature:**
  - The maximum temperature at the outlet of the collector was observed to be around **58.3°C**, showcasing the efficiency of the solar thermal system in heating water to an acceptable range.
- **Efficiency and Performance Analysis:**
  - The **solar fraction** of the system, which indicates the portion of energy provided by the solar collector relative to the total system demand, was calculated over the simulation period. During peak irradiance conditions, the system reached an efficiency of around **70%**, with the solar collector able to provide most of the heating demand.
  - At times of low solar irradiance (e.g., in the morning or during cloudy conditions), the system relied on the **auxiliary heater**, which contributed approximately **65 W** to maintain water temperature at desired levels.

Storage Tank Performance

- **Storage Tank Temperature Distribution:**
  - The stratification in the **300-liter storage tank** resulted in varying temperature zones, with the highest temperature observed at the top layer at **58.3°C** and the lowest temperature at the bottom at **36.9°C**.
  - The temperature gradient from top to bottom illustrates the efficiency of stratification in storing solar heat, with the hottest water available for immediate use while cooler water remains at the bottom for further heating.
- **Auxiliary Heating Contribution:**
  - As seen in the simulation snapshot, the auxiliary heater provided **65 W** of power at certain times when solar energy was insufficient. This typically occurred in early mornings or during overcast conditions when the solar input was below the system's demand threshold.
  - The auxiliary heater was engaged intermittently, maintaining the desired temperature when solar energy could not fulfill the load, thus ensuring a constant supply of hot water.

System Efficiency and Heat Loss

- **Heat Losses in Piping:**
  - From the diagram, the temperature drop across the piping system was minimal, indicating well-insulated pipes. The difference in temperature between the collector outlet (58.3°C) and the tank inlet (56.8°C) was **1.5°C**, which suggests effective insulation with minimal heat loss.
- **Energy Balance:**
  - The energy flow within the system was balanced with a total output of **137 W** from the solar collector and auxiliary heater combined. Most of the energy was successfully stored

in the thermal tank, and heat loss through piping and tank surfaces was minimized due to insulation.

Discussion

Solar Collector Performance

The solar collector demonstrated high efficiency under ideal conditions, with peak temperatures reaching **58.3°C**. However, during periods of low solar irradiance, such as early mornings or cloudy days, the system struggled to maintain flow, as evidenced by the **0 l/h** flow rate at certain points. The temperature drop from **1.6°C** to **-1.5°C** in the system during those times indicates that there was insufficient thermal energy to drive the circulation pump.

The system's performance can be further improved by optimizing the collector tilt angle and orientation to capture more solar energy. Additionally, integrating more advanced control mechanisms to adjust the pump flow rate based on real-time solar irradiance and water demand could improve the system's overall efficiency.

Storage Tank Stratification

The **300-liter stratified thermal storage tank** was critical in maintaining hot water availability throughout the day. The stratification allowed the hottest water (up to **58.3°C**) to be available at the top of the tank, while cooler water remained at the bottom for further heating.

Stratification ensured that energy was not wasted by mixing hot and cold water unnecessarily. However, slight mixing could occur if the pump were not properly controlled, potentially reducing efficiency. In future implementations, introducing an additional heat exchanger inside the tank could further enhance stratification.

Auxiliary Heating Contribution

The **auxiliary heater** played a significant role during periods of low solar availability. It provided a reliable backup, contributing **65 W** during times when the solar collector could not meet the demand. While this ensures system reliability, excessive reliance on the auxiliary heater can reduce the solar fraction, lowering overall system efficiency.

A more sophisticated control strategy could be implemented to delay auxiliary heater activation, allowing for longer periods of solar heating, especially during partly cloudy conditions. Incorporating weather prediction data could further optimize the balance between solar and auxiliary heating.

Environmental Conditions And Seasonal Performance

The performance of the solar water heating system was heavily influenced by environmental conditions. The **Polysun** simulation indicated that in colder weather conditions, with ambient temperatures as low as **-1.5°C**, the system still managed to maintain tank temperatures above **36.9°C** at the lower end of the tank, thanks to effective insulation and auxiliary heating.

During peak summer conditions, the system could operate fully on solar energy, significantly reducing the need for auxiliary heating. However, in winter months or in regions with lower solar irradiance, the system’s efficiency could drop, requiring auxiliary heat to maintain desired water temperatures.

Design Validation With Fusion 360

The **Fusion 360** CAD design ensured that the system layout, particularly the placement of the collector, storage tank, and piping, was optimized for both installation and performance. The rendered technical drawings validated the dimensions and arrangement of the components, reducing potential heat losses through proper insulation and system configuration.

Furthermore, the 3D model helped visualize the physical space requirements, ensuring that the installation could be completed without major adjustments. The CAD design also allowed for quick iterations and modifications, improving the overall system design and layout.

Temperature Analysis

The table shows monthly temperatures in the storage tank, with minimum, maximum, and average values. Discuss the seasonal variations, highlighting how temperatures increase during the summer months (e.g., June to August) and decrease during winter (e.g., December to February).

Reflect on how these temperature variations impact the system's ability to meet the household's hot water demand. For instance, during colder months, lower temperatures might increase the energy deficit and energy demand.

Flow Rate And Availability

The flow rate remains constant throughout the year at 360 l/h. This suggests a steady demand for hot water regardless of seasonal variations. Discuss whether this is a realistic assumption or if variable flow rates should be considered to reflect actual usage patterns.

Availability percentages fluctuate slightly, indicating minor variations in system performance. You could discuss factors affecting availability, such as weather conditions and system efficiency during different months.

Energy Demand And Deficit

Analyze the relationship between energy demand (Qdem), energy supplied to the system (Quse), and energy deficit (Qdef). For instance, in February, the energy deficit is 86.4 kWh, while energy demand is 286 kWh, meaning the system met the majority of the demand, but a significant deficit remains.

From the table the periods where the energy deficit is higher, like in January and February, and discuss the reasons. This could be due to reduced solar irradiance in winter, which limits the system's ability to heat water.

Volume Withdrawal

The volume withdrawal (daily consumption) is constant at 200 liters per day. Discuss whether this assumption aligns with typical household usage patterns and if adjusting it for different months or usage patterns would impact system performance.

Conclusion

This project successfully simulated and evaluated the performance of a solar water heating system, consisting of a 300-liter storage tank, a solar collector, auxiliary heating, and a heat distribution network. The system was designed and analyzed using Polysun simulation software and validated through a Fusion 360 CAD model.

Key findings from the study include:

- System Efficiency: The solar water heating system demonstrated an efficiency of around 70% under peak solar irradiance conditions. The solar collector was able to heat the water to a maximum temperature of 58.3°C, which was stored in the stratified storage tank for immediate and delayed use.
- Auxiliary Heater Contribution: During periods of low solar energy availability (e.g., in the early morning or cloudy weather), the system effectively utilized an auxiliary heater, which contributed 65 W to maintain the hot water supply. This backup heating system ensured continuous availability of hot water, even in suboptimal conditions.
- Storage Tank Performance: The 300-liter tank provided effective thermal stratification, with the hottest water retained at the top (58.3°C) and cooler water at the bottom (36.9°C). This stratification minimized mixing losses and optimized the energy storage within the tank.
- Environmental Impact: The solar water heating system significantly reduced

reliance on fossil fuels, as the primary heat energy came from the sun. In regions with favorable solar irradiance, the system could operate almost entirely on solar energy, contributing to sustainability and lower greenhouse gas emissions.

- Design and Layout: The Fusion 360 CAD design validated the layout and dimensions of the system components. Proper insulation and piping layout minimized heat losses, ensuring that the design would be practical for real-world installations.

Recommendations

Based on the results of this project, the following recommendations are proposed for enhancing the performance, reliability, and sustainability of the solar water heating system:

Optimization of Solar Collector Orientation

The performance of the solar collector can be further improved by optimizing its orientation and tilt angle to maximize solar energy capture. It is recommended to:

- Optimize the Tilt Angle: Adjust the collector's tilt angle based on the geographical location to ensure maximum solar gain throughout the year.
- Track Solar Position: For higher efficiency, consider using a solar tracker to adjust the collector’s position dynamically, improving its exposure to sunlight throughout the day.

Enhancing Control Strategies

To further improve system efficiency, advanced control strategies should be implemented. These can include:

- Dynamic Flow Control: Introduce smart control of the circulation pump to adjust the flow rate in real-time based on the available solar energy and temperature demands.
- Weather Forecast Integration: Incorporating weather prediction data into the control system can help optimize the operation of the auxiliary heater, avoiding unnecessary energy consumption when higher solar gains are expected later in the day.

Improve Storage Tank Stratification

While the current system uses a stratified storage tank, there is room for enhancement:

- Additional Heat Exchanger: Introducing an internal heat exchanger inside the storage tank can improve stratification by better separating hot and cold layers.
- Tank Insulation: Ensure the storage tank has high-quality insulation to minimize heat losses, particularly in colder climates, where the ambient temperature can impact thermal storage efficiency.

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