Fabrication & Performance Analysis of Cost Effective Low Energy Consumption Solar Water Heater with Energy Storage

A Thesis
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MAY,2026

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A thesis report submitted to the department of mechanical engineering for the partial fulfillment of the degree of Bachelor of Science in Mechanical Engineering.

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Declaration

It is declared hereby that this thesis paper titled "Fabrication & Performance Analysis of Cost Effective Low Energy Consumption Solar Water Heater with Energy Storage" or any part of it has not been submitted to anywhere else for the award any degree.

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Certification

This is to certify that this project entitled "**Fabrication & Performance Analysis of Cost Effective Low Energy Consumption Solar Water Heater with Energy Storage**" is done by the following students under my direct supervision. This project work has been carried out by them in the laboratories of the Department of Mechanical Engineering under the Faculty of Engineering, Sonargaon University (SU) in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering.

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Acknowledgement

At first, we would like to express our gratitude to Almighty Allah for giving us the strength and opportunity to complete our dissertation within the scheduled time successfully. The presentation of the project paper represents the collaborative efforts and generous support of a number of individuals. The Department of Mechanical Engineering (ME), Sonargaon University provided important subject expertise and information technology services to carry out the project work successfully. We feel proud to express our deep sense of gratitude to our reverend teacher, guide and supervisor, for his day to day supervision, dexterous management, adept analysis, keen interest, optimistic counseling, and unremitting backup. We are very much indebted to Ibrahim Khalil Apurba, Lecturer, Department of Mechanical Engineering, Sonargaon University, for including a dissertation as a course in B.Sc. in engineering to strengthen eligibility of students. We would also like to thank those persons of Department of Mechanical, Sonargaon University, for their encouragement and help in our project work.

Abstract

Driven by escalating global energy demands and the critical depletion of fossil fuels, the shift toward hybrid renewable energy solutions has become essential for sustainable rural electrification. This project details the design, fabrication, and performance evaluation of a decentralized hybrid system incorporating a 40W photovoltaic panel and a 12V/9Ah lead-acid battery for storage. Utilizing a 40W solar panel and an ESP32-based IoT monitoring framework, the system achieved an average electrical output of 24.98W (15.52V, 1.61A). Beyond power generation, the configuration utilizes incident solar energy to heat water via a copper tube assembly, reaching thermal efficiencies between 16% and 76%. Results demonstrate stable battery charging performance (11.9V to 12.7V) and enhanced system reliability through real-time data logging on the ThingSpeak platform. The inclusion of a dedicated charge controller ensured operational safety, making this hybrid configuration a highly efficient and versatile solution for rural electrification and renewable energy research. Findings suggest that this integrated approach significantly enhances energy reliability and operational consistency over single-source systems, offering a scalable and cost-effective framework for remote power applications and academic inquiry.

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Chapter 1

Introduction

1.1. Introduction

The world is increasing interested in reducing global warming because of the belief that it may be a real threat and we must find ways to reduce carbon emissions to protect the environment. As a result, there is a heightened interest in renewable energy production that can reduce the future demand for coal and natural gas fired power plants. Renewable power production technologies such as wind farms, photovoltaics, geothermal, hydroelectric, and biomass systems are all receiving a lot of attention. Another, less costly alternative, is solar thermal water heating systems. The term “solar power” can be used to denote either solar thermal systems or photovoltaic systems. Photovoltaic systems generate electricity by using the interaction of sunlight with a semi-conducting material, which frees electrons in the material to create an electric current. In contrast, solar thermal systems use the heat generated by sunlight to heat air or water.

The growing demand for sustainable and eco-friendly energy solutions has led to significant advancements in solar technologies. One such application is the solar water heater, which uses renewable solar energy to provide heated water without depending on conventional power sources. This project, "A Comprehensive Model of Solar Water Heater," aims to demonstrate an efficient and practical system that can be used in residential and small-scale industrial settings. The system is designed using a solar panel to capture solar energy, a 12V battery for energy storage, and an inverter circuit to regulate the electrical output. A burner coil submerged in a water tank acts as the heating element, converting the stored electrical energy into heat to warm the water. This integration showcases a clean and sustainable approach to water heating, promoting the use of renewable energy and reducing dependence on fossil fuels. The model not only highlights the principles of energy conversion and storage but also encourages the adoption of green technologies for everyday needs.

1.2. Study Background

With increasing global concerns over energy consumption and environmental degradation, the search for alternative energy sources has become a priority. Solar energy stands out as one of the most abundant, clean, and renewable resources available. Solar water heating systems have emerged as a practical application of solar technology, helping to reduce dependency on non-renewable energy sources and lowering carbon emissions. Traditional water heating methods rely heavily on electricity or fossil fuels, both of which are costly and contribute to environmental pollution. By utilizing solar panels to convert sunlight into electrical energy, storing it in a 12V battery, and using an inverter circuit to regulate the output for heating a burner coil placed inside a water tank, this project aims to create a highly efficient and sustainable system. This study explores the integration of simple, readily available components to create an affordable and reliable solar water heating model. It provides insights into how solar energy can be effectively harnessed, stored, and utilized to meet basic domestic needs while contributing to a greener future.

Energy is fundamental to human development, but conventional energy sources like coal, oil, and natural gas are limited and harmful to the environment. Growing concerns about climate change, rising fuel costs, and resource depletion have intensified the need for sustainable alternatives. Solar energy, due to its abundance, renewability, and zero carbon footprint, has become a leading solution for clean energy systems. Among the various applications of solar energy, solar water heating represents one of the simplest and most effective methods for utilizing solar power at the domestic level. Traditional solar water heaters directly use thermal energy from sunlight. However, to enhance versatility and allow operation even during low sunlight periods, an electrically assisted model becomes beneficial. This project focuses on creating an electrically powered solar water heating system. A solar panel captures solar radiation and converts it into electrical energy, which is stored in a 12V battery. To ensure compatibility with the heating element, an inverter circuit adjusts the voltage and current. The burner coil, submerged in a water tank, uses this electrical energy to heat the water efficiently. This model bridges two important areas of renewable energy: solar photovoltaic technology (energy conversion and storage) and thermal energy utilization (water heating). It not only provides a functional solution for hot water needs but also encourages the practical implementation of renewable energy systems in everyday life. The study aims to inspire further innovation in clean energy applications, making sustainable living more accessible and affordable.

1.3. Statement of Problems

Access to reliable and affordable hot water is essential for domestic, industrial, and commercial activities. However, conventional water heating systems primarily rely on electricity or fossil fuels, leading to high energy costs, environmental pollution, and increased carbon emissions. In regions with limited electricity access or frequent power outages, obtaining hot water becomes even more challenging. Despite the availability of solar energy, many existing solar water heating systems are expensive, complex, or dependent solely on direct sunlight, making them less effective during cloudy weather or nighttime. There is a critical need for a simple, cost-effective, and energy-efficient solar water heating model that can store solar energy and provide hot water consistently, even in varying environmental conditions. This project addresses the problem by developing a comprehensive model of a solar-powered water heater that combines solar energy collection, battery storage, and electrical heating. By integrating a solar panel, 12V battery, inverter circuit, burner coil, and water tank, the model aims to deliver a practical, eco-friendly solution that reduces dependence on traditional energy sources and promotes sustainable living.

1.4. Objectives

The main objective of this project is to design and develop a comprehensive solar- powered water heating system that is efficient, cost-effective, and environmentally friendly. The specific objectives are:

- To harness solar energy using a solar panel and convert it into electrical energy for storage in a 12V battery for continuous availability, even during non-sunny periods.
- To design an inverter circuit that regulates and supplies the required power to the heating element using a burner coil powered by the stored solar energy.
- To do analysis for rural electrification.

1.5. Significance of the Project

The project "A Comprehensive Model of Solar Water Heater" holds significant importance in the current global push toward sustainable and renewable energy solutions. By effectively utilizing solar energy for water heating, the project contributes to reducing the reliance on non-renewable energy sources such as electricity generated from fossil fuels. This helps in lowering carbon emissions, combating climate change, and promoting environmental conservation. The model demonstrates a practical and affordable solution for households, especially in remote or rural areas where access to conventional electricity may be limited or unreliable. It ensures that hot water can be made available using free and abundant solar energy, even during periods of low sunlight, by integrating a battery storage system. Moreover, the project encourages innovation and awareness among students, engineers, and the general public about the possibilities of clean energy technologies. It serves as a learning platform for understanding the working of solar panels, energy storage, inverter circuits, and electric heating mechanisms. Ultimately, this project aligns with global goals for renewable energy adoption, energy efficiency, and sustainable living, offering a small yet impactful step toward a greener and more self-reliant future.

1.6. Scope of the project

This project focuses on the design, development, and demonstration of a solar-powered water heating system using simple and cost-effective components. The scope includes:

- **Solar Energy Collection:** Using a solar panel to capture sunlight and convert it into electrical energy suitable for water heating applications.
- **Energy Storage:** Storing the generated energy in a 12V battery to ensure continuous water heating availability, even during cloudy days or nighttime.
- **Power Management:** Designing and implementing an inverter circuit to regulate and supply the appropriate voltage and current to the heating element.
- **Water Heating System:** Utilizing a burner coil placed in a water tank to efficiently heat water using the stored solar energy.
- **Demonstration Model:** Developing a functional prototype that showcases the integration and working of the complete system in a practical and understandable way.

- **Environmental Impact:** Promoting the use of renewable energy sources to reduce environmental pollution and encourage sustainable practices.
- **Affordability and Accessibility:** Creating a low-cost model that can be adapted for small households, rural areas, and regions with unreliable power supply.

The project is primarily a small-scale model aimed at educational, demonstrational, and research purposes, but the concepts can be scaled up for larger domestic or community-based solar water heating systems.

Chapter 2

Literature Review

2.1. Literature Review

The need for sustainable and energy-efficient technologies has led to extensive research and development in the field of solar water heating systems. Over the years, different designs and models have been proposed and implemented to utilize solar energy effectively for heating water, reducing reliance on conventional energy sources, and lowering environmental impact.

Traditional solar water heaters typically rely on flat plate collectors or evacuated tube collectors to absorb solar radiation and transfer heat directly to water. These systems are efficient but often expensive and depend heavily on continuous sunlight, making them less effective during cloudy days or nighttime [1]

Recent research has explored combining solar photovoltaic (PV) panels with electrical heating elements, allowing the conversion of sunlight into electricity, which is then used to heat water via resistive coils. This method provides more flexibility since electrical energy can be stored in batteries, ensuring hot water availability even when sunlight is not present [3].

Studies have shown that integrating battery storage with solar water heating systems greatly enhances their usability and efficiency. Batteries allow the system to operate independently of real-time solar availability and offer backup energy storage for continuous performance [5].

Research also emphasizes the development of low-cost and easily replicable models, especially for rural and remote areas. Using basic components like 12V batteries, small inverters, and simple heating coils can significantly reduce the overall cost while maintaining reasonable efficiency [7].

An important aspect discussed in the literature is the role of inverter circuits in adjusting the output voltage and current to match the requirements of heating elements. Proper voltage regulation ensures efficient use of stored solar energy and prevents damage to the system components. Despite advances, most existing systems are either too costly or complex for low-income and rural populations. Therefore, a need persists for a simple, affordable, and reliable solar water heating model that combines PV technology, energy storage, and basic heating mechanisms. [8]

This project addresses these gaps by developing a comprehensive model that integrates a solar panel, battery storage, inverter circuit, and a burner coil for heating water in a water tank. The model provides a sustainable, scalable, and affordable solution for water heating needs, especially in areas where traditional systems are impractical. [9]

2.2. Overview of This Project

This project, titled "A Comprehensive Model of Solar Water Heater," focuses on creating an efficient and sustainable system to heat water using renewable solar energy. The main objective is to design a model that captures solar energy, stores it, and uses it to heat water in a simple, cost-effective manner suitable for residential or small-scale applications. The system consists of a solar panel that converts sunlight into electrical energy. This energy is stored in a 12V battery, ensuring a continuous power supply even when sunlight is unavailable. An inverter circuit is used to regulate and adjust the voltage and current from the battery to match the requirements of the heating element. The burner coil, placed inside a water tank, uses the regulated electrical energy to heat the water effectively. This model demonstrates a practical integration of solar power, energy storage, and heating technology. It provides a reliable solution to the problem of energy-dependent water heating systems, particularly in areas with frequent electricity shortages or a need for sustainable living practices. The project highlights the importance of renewable energy use, efficient energy management, and innovative design in addressing everyday energy needs. Overall, the system offers an eco-friendly alternative to conventional water heating methods, promotes clean energy adoption, and serves as a foundation for further research and real-world applications.

2.3. Types of Solar Thermal Heater

Solar water heaters use the sun to heat either water or a heat-transfer fluid in the collector. Heated water is then held in the storage tank ready for use, with a conventional system providing additional heating as necessary. Solar water heating systems can be either active or passive, but the most common are active systems.

Active circulation systems require electric power to activate pumps and/or controls and passive circulation systems rely on natural convection rather than electric power to circulate the water. In addition to active versus passive, the systems are also classified as either direct or indirect heating. A direct heating, or open loop system, heats potable water directly in the collector and circulates it through the end use storage tank. An indirect heating, or closed loop system, heats a fluid such as propylene glycol in the collector and transfers this heat to potable water via a heat exchanger.

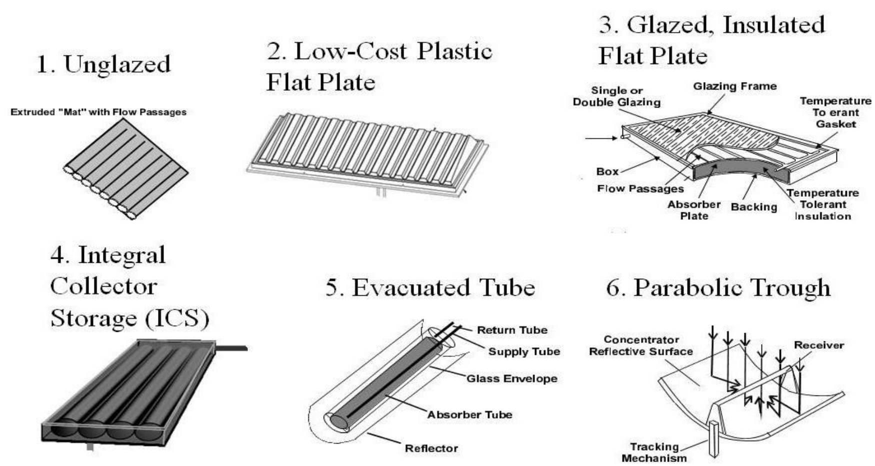

Figure-2.1: Different types of circulation system [2]

2.3.1. Active solar water heaters

Active solar water heaters rely on electric pumps, and controllers to circulate water, or other heat-transfer fluids through the collectors. There are the two types of active solar water-heating systems: Direct-circulation systems and indirect-circulation systems. Direct-circulation systems use pumps to circulate pressurized potable water directly through the collectors. These systems are appropriate in areas that do not freeze for long periods and do not have hard or acidic water. These systems are not approved by the Solar Rating & Certification Corporation (SRCC) if they use recirculation freeze protection (circulating warm tank water during freeze conditions) because of the additional electrical power required for the protection to be effective.

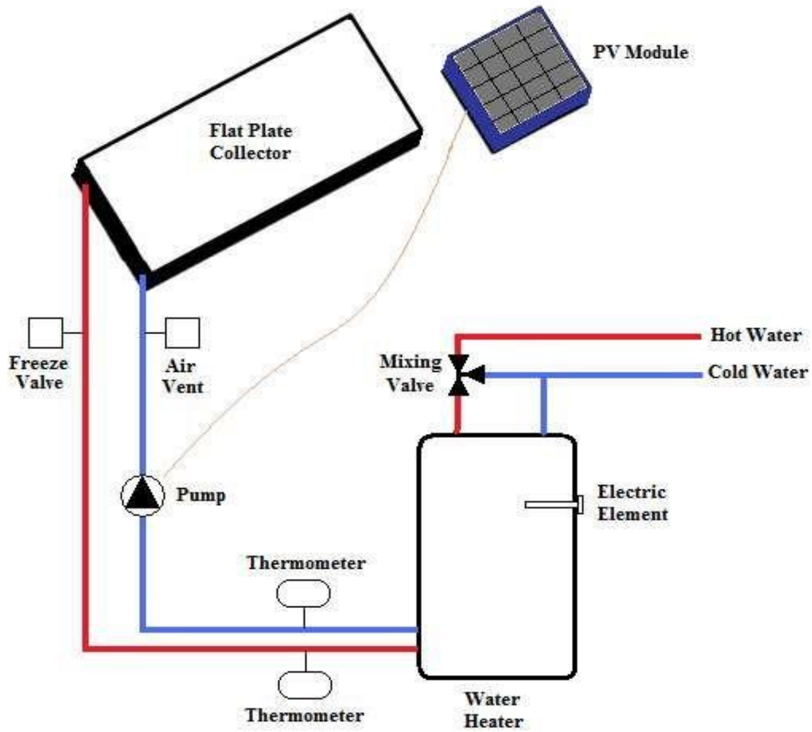

Figure-2.2: Active direct-circulation system [2]

Figure 2.1 shown below is an active direct-circulation system. It has a photovoltaic cell to power the pump and is a single tank system.

Active systems may be considered either zero carbon or low carbon systems depending on how the solar water heating system is pumped and controlled. Low carbon systems principally use electricity to circulate the fluid through the collector. The use of electricity typically reduces the carbon savings of a system by 10% to 20%. Conventional low carbon system designs use a utility powered circulation pump whenever the hot water tank is positioned below the solar panels.

Newer zero carbon solar water heating systems' pumps are powered by photovoltaic cells. These typically use a 5-20W PV panel which faces in the same direction as the main solar heating panel and a small, low power diaphragm pump or centrifugal pump to circulate the water.

2.3.2. Passive Solar Water Heater

Passive solar water heaters rely on gravity and the tendency for water to naturally circulate as it is heated. Because they contain no electrical components, passive systems are generally more reliable, easier to maintain, and possibly have a longer work life than active systems. However, at night the remaining water can freeze and damage the panels, and the storage tank is exposed to the outdoor temperatures that will cause excessive heat losses on cold days. Passive systems are less costly and more efficient than active systems. Some systems can work for up to 25 years with minimum maintenance. The two most popular types of passive systems are integral-collector storage systems and thermal syphon systems.

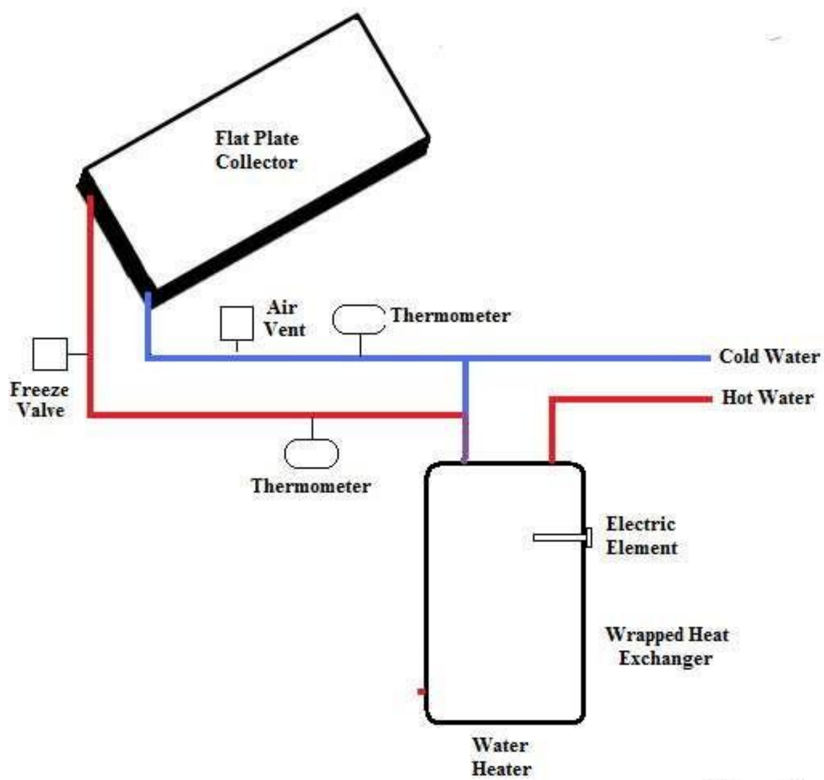

Figure-2.3: Passive Direct Circulation System [2]

Integral-collector storage systems consist of one or more storage tanks placed in an insulated box with a glazed side facing the sun. These solar collectors are suited for areas where temperatures rarely go below freezing. They are also effective in households with significant daytime and evening hot-water needs; but they do not works well in households with predominantly morning draws because they lose most of the collected energy overnight. These systems are called batch systems because the tank acts as both storage and solar collector. Batch heaters are basically thin rectilinear tanks with glass in front of it generally in or on house wall or roof. They are seldom pressurized and usually depend on gravity flow to deliver their water.

They are simple, efficient and less costly than intense plate and tube collectors but only suitable in moderate climates with good sunshine. [3]

2.3.3. Flat-Plate Circulation System

Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate. These collectors heat liquid or air at temperatures less than 180°F.

In a flat-plate collector, fluid is circulated through the tubing to remove the heat from the absorber and to transport it to an insulated water tank, sometimes directly or otherwise to a heat exchanger or to some other device for using the heated fluid. Some fabricants have a completely flooded absorber consisting of two sheets of metal stamped to produce a circulation zone.

Because the heat exchange area is greater, they may be marginally more efficient than traditional absorbers.

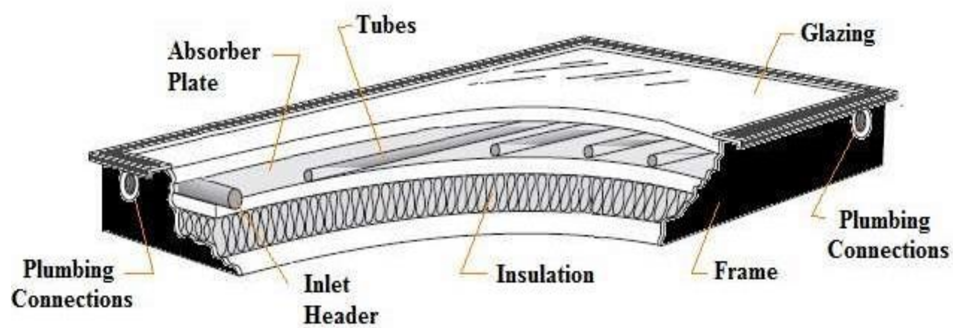

Figure-2.4: Flat Plate Collector [4]

As an alternative to metal collectors, new polymer flat plate collectors are now being produced. These may be wholly polymer, or they may be metal plates behind which are freeze-tolerant water channels made of silicone rubber instead of metal. Polymers, being flexible and therefore freeze-tolerant, are able to contain plain water instead of antifreeze, so that in some cases they are able to plumb directly into existing water tanks instead of needing the tank to be replaced with one using heat exchangers. By dispensing with a heat exchanger in these flat plate panel, temperatures need not be quite so high for the circulation system to be switched on, so such direct circulation panels, whether polymer or otherwise, can be somewhat more efficient, particularly at low light levels. Figure 6 shows a typical flat plate collector design.

2.3.4. Evacuated-tube Circulation System

Evacuated-tube collectors can achieve extremely high temperatures (170°F to 350°F), making them more appropriate for cooling applications and commercial and industrial application. However, evacuated-tube collectors are more expensive than flat-plate collectors, with unit area costs about twice that of flat-plate collectors. Figure 7 shows a typical evacuated-tube collector

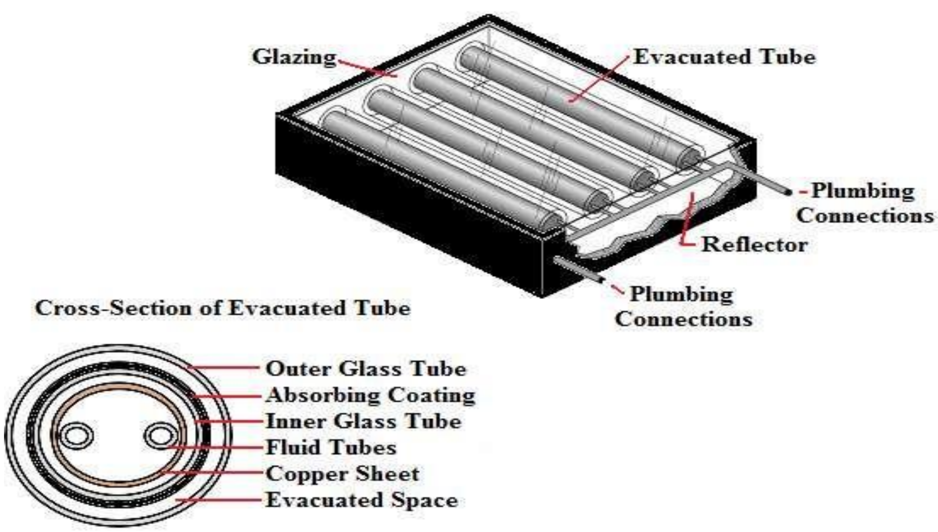

Figure-2.5: Evacuated-Tube Collector [5]

Evacuated tube collectors heat to higher temperatures, with some models providing considerably more solar yield per square foot than flat panels. However, they are more expensive and fragile than flat panels. Evacuated heat tubes perform better than flat plate collectors in cold climates because they only rely on the light they receive and not the outside temperature. The high stagnation temperatures can cause antifreeze to break down, so careful consideration must be used if selecting this type of system in temperate climates. Tubes come in different levels of quality so the different kinds have to be examined as well. High quality units can efficiently absorb diffuse solar radiation present in cloudy conditions and are unaffected by wind. They also have the same performance in similar light conditions summer and winter.

For a given absorber area, evacuated tubes can maintain their efficiency over a wide range of ambient temperatures and heating requirements. In extremely hot climates, flat-plate collectors will generally be a more cost-effective solution than evacuated tubes. They are well suited to extremely cold ambient temperatures and work well in situations of consistently low-light. [5]

2.4. Solar Water Heating Technology

Solar water heating (SWH) is one of the most practical and widely adopted applications of solar energy. It harnesses the sun's energy to heat water for residential, commercial, and industrial use, thereby reducing reliance on conventional energy sources such as electricity or fossil fuels. Over the years, various technologies have been developed to improve the efficiency, affordability, and applicability of solar water heaters in different climatic and geographic conditions.

1. **Classification of Solar Water Heating Systems**

   Solar water heating technologies can broadly be classified based on:

   - Collector Type
   - Circulation Method
   - Application Scale

Each classification impacts system design, efficiency, and suitability for specific uses.

2. Based on Collector Type

a. Flat Plate Collectors (FPCs)

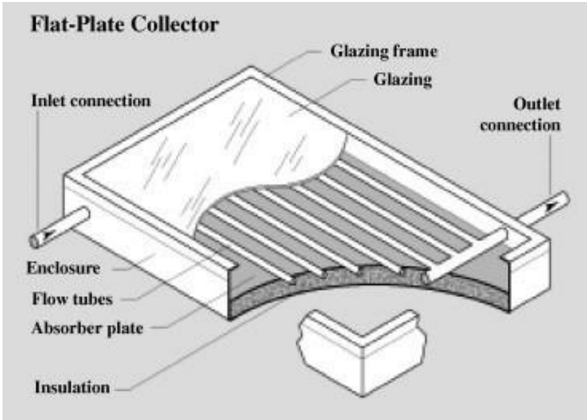

Figure-2.6: Flat Plate collector [8]

Flat Plate Collectors are the most commonly used type of collector for domestic hot water applications. They consist of an absorber plate, transparent cover(s), insulation, and a casing. Water or heat transfer fluid flows through pipes attached to the absorber plate, which is heated by solar radiation. FPCs are simple in design, durable, and suitable for temperatures up to 80°C.

b. Evacuated Tube Collectors (ETCs)

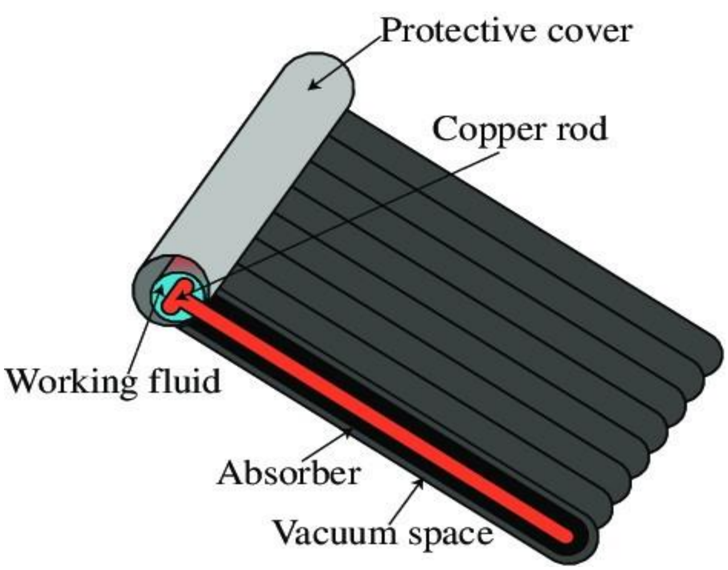

Figure-2.7: Evacuated Tube [10]

ETCs use a series of glass tubes, each containing an absorber and heat pipe enclosed in a vacuum. The vacuum acts as an excellent insulator, reducing heat loss and allowing operation in colder climates and at higher temperatures (up to 150°C). ETCs are generally more efficient but costlier than FPCs.

c. Integral Collector-Storage Systems (ICS)

Figure-2.8: Integral Collector Storage System [10]

These systems combine the collector and storage tank in one unit. Water is heated directly in the tank during the day and used as needed. ICS systems are simple and ideal for mild climates but are prone to heat loss during cold nights.

3. Based on Circulation Method

a. Thermosiphon Systems

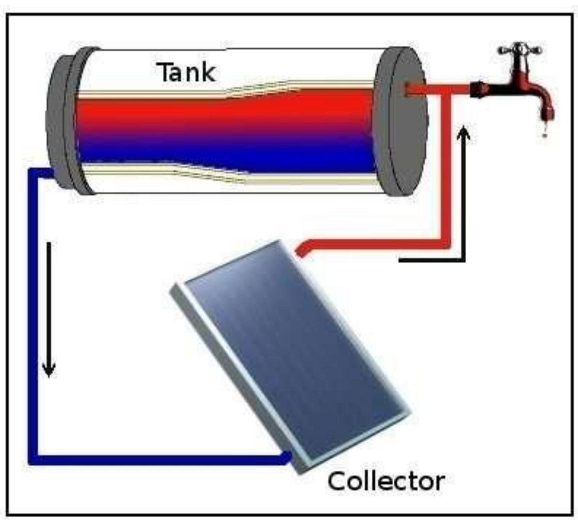

Figure-2.9: Thermosiphon System [10]

These systems rely on natural convection. As water heats up in the collector, it becomes less dense and rises into the storage tank placed above the collector. Cooler water from the tank flows down to replace it, creating a continuous flow. Thermosiphon systems are passive, requiring no pumps or controllers.

b. Forced Circulation (Active) Systems

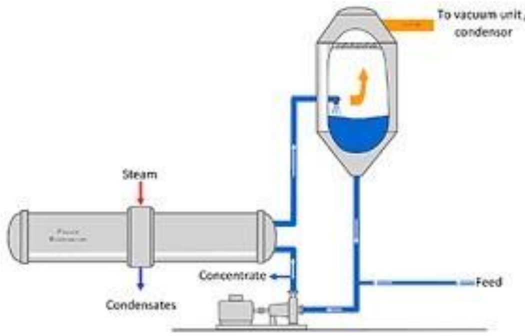

Figure-2.10: Forced Circulation System [10]

These systems use pumps to circulate water or heat transfer fluid through the collectors and into a storage tank. They offer better control and efficiency, especially in large or complex installations, but require electricity and system monitoring.

2.5. Comparative Studies of Collector Types

Solar thermal collectors are the backbone of solar water heating systems, and their efficiency, cost, and suitability vary based on design and application. The main types of solar collectors include:

- Flat Plate Collectors (FPCs)
- Evacuated Tube Collectors (ETCs)
- Concentrating Collectors (e.g., Parabolic Trough Collectors)

A comparative study of these types helps in identifying the most appropriate technology for a given application, climate, and economic condition.

2.5.1 Flat Plate Collectors (FPCs)

- **Design**: Consist of an absorber plate with tubes, covered with one or two transparent layers and insulated at the back.
- **Working Principle**: Absorbs solar radiation and transfers heat to the water passing through the tubes.
- **Efficiency**: Moderate thermal efficiency (30–60%) depending on insulation, materials, and conditions.
- **Advantages**:
  - Simple and robust construction
  - Low maintenance
  - Suitable for moderate climates
- **Disadvantages**:
  - Heat loss due to convection and radiation
  - Performance drops in colder climates

2.5.2 Evacuated Tube Collectors (ETCs)

- **Design**: Consist of multiple glass tubes with vacuum insulation between inner and outer layers.
- **Working Principle**: Minimizes heat loss by vacuum insulation; often uses a heat pipe or direct-flow design.
- **Efficiency**: Higher than FPCs (up to 70–80%), especially in cold or cloudy conditions.
- **Advantages**:
  - High thermal efficiency
  - Performs well in low ambient temperatures
- **Disadvantages**:
  - More expensive
  - Fragile and complex structure
  - Requires careful handling and maintenance

2.5.3 Concentrating Collectors

- **Design**: Use mirrors or lenses to focus sunlight onto a small area (e.g., receiver or tube).

- **Working Principle**: Suitable for high-temperature applications; works efficiently in direct sunlight.
- **Efficiency**: Very high thermal efficiency (up to 80–90%) under optimal conditions.
- **Advantages**:
  - Suitable for industrial-scale heating
  - High-temperature output
- **Disadvantages**:
  - Requires tracking system
  - Ineffective in diffuse or cloudy sunlight
  - High cost and complexity

2.5.4 Comparative Table

Feature	Flat Plate Collector (FPC)	Evacuated Tube Collector (ETC)	Concentrating Collector
Efficiency	30–60%	60–80%	70–90%
Cost	Low	Medium to High	High
Maintenance	Low	Medium	High
Suitable Climate	Moderate	Cold to Moderate	Sunny, clear skies
Temperature Range	Up to ~80°C	Up to ~120°C	>150°C
Complexity	Low	Medium	High
Application Type	Domestic	Domestic/Commercial	Industrial

While flat plate collectors are the most widely used in domestic applications due to their simplicity and affordability, evacuated tube collectors offer better performance in colder climates. Concentrating collectors, though efficient, are more suitable for industrial applications where high temperatures are required. The choice of collector type should consider not only thermal efficiency but also economic feasibility, maintenance needs, and local climatic conditions. [6]

2.6. Flat Plate Collectors: History and Evolution

Flat Plate Collectors (FPCs) are among the oldest and most established technologies in solar thermal energy conversion. Their evolution reflects the broader development of solar energy utilization, beginning from rudimentary concepts to highly engineered systems capable of serving domestic, commercial, and industrial needs.

1. Early Developments

The concept of harnessing solar energy to heat water dates back thousands of years. Ancient civilizations such as the Greeks and Romans designed bathhouses and architecture that maximized sunlight for passive heating. However, the first documented flat plate collector as a dedicated device emerged in the late 19th century.

- **1891**: Clarence Kemp, a Baltimore inventor, patented the first commercially available solar water heater called the **"Climax"**. It used a black-painted water tank placed inside a wooden box covered with glass to trap solar heat. This was the foundational principle of the flat plate collector.
- **Early 1900s**: Solar water heaters became relatively popular in sunny regions such as California and Florida, where hundreds of systems were installed.

2. Mid-20th Century Innovation

The real momentum in flat plate collector development began in the mid-20th century, driven by scientific interest, rising energy demand, and technological advancement.

- **1950s–1970s**: Engineers and researchers refined collector design for better thermal efficiency. Key developments included:
    - The use of selective coatings on absorber plates to increase solar absorption and reduce infrared emission.
    - Improved glazing materials such as tempered low-iron glass for better transmittance and durability.
    - Fiberglass insulation to minimize heat losses from the back and sides.
    - Integration of copper or aluminum absorber tubes to enhance thermal conductivity.

- During the 1973 oil crisis, interest in solar energy surged, leading to large-scale adoption and government-supported research in countries like the USA, Israel, and Germany.

3. Modern Advancements

From the 1980s to the present, flat plate collectors have undergone significant refinement to meet modern efficiency standards, durability expectations, and environmental considerations.

- **Enhanced Absorber Coatings**: Modern FPCs often use selective surface coatings such as black chrome or titanium oxide, which have high solar absorptivity and low emissivity.
- **Advanced Glazing**: Anti-reflective and low-iron glass help minimize radiation loss while increasing solar transmission.
- **High-efficiency Designs**: Innovations include serpentine tube layouts, fin-tube designs, and improved fluid dynamics to increase heat transfer.
- **Integration with Smart Systems**: Modern FPCs are often part of automated solar water heating systems with smart sensors, controllers, and backup integration, improving user convenience and energy savings.
- **Modular and Aesthetic Designs**: New collector designs now consider aesthetic appeal and ease of installation, making them more suitable for residential rooftops and building-integrated solar systems.

4. Global Adoption and Standards

Today, flat plate collectors are widely adopted in over 80 countries and are included in national and international standards. Countries like China, Iran and Germany have heavily invested in solar thermal technologies for both domestic and industrial use.

Organizations such as the International Energy Agency (IEA) and Solar Heating and Cooling Program (IEA SHC) promote research, policy, and data sharing for continual development.

5. Comparison with Newer Technologies

While flat plate collectors remain dominant in solar water heating, they face competition from evacuated tube collectors (ETCs) in colder climates or applications requiring higher temperatures. However, due to their simplicity, robustness, and cost- effectiveness, FPCs continue to be the preferred choice in moderate climate zones.

2.7. Gaps in Existing System

Despite extensive studies on flat plate solar collectors, several gaps remain that limit the optimization and broader application of these systems:

1. **Inconsistent Performance Data Across Climatic Regions**
   Most performance studies are conducted under specific geographic and climatic conditions, making it difficult to generalize findings. There's a lack of standardized data collection across different latitudes and altitudes.
2. **Insufficient Integration with Modern Control Systems**
   Many studies do not explore how smart sensors and IoT technologies could enhance efficiency, real-time monitoring, and fault detection in flat plate collector systems.
3. **Limited Long-Term Durability Studies**
   While initial performance is well-documented, fewer studies examine long- term degradation of materials such as absorber coatings, insulation, and glass covers under real-world conditions.
4. **Economic Viability in Low-Income Regions**
   Research often overlooks the economic feasibility and local manufacturing potential of flat plate collectors in low- and middle-income countries, where such systems could have the most social impact.
5. **Comparative Studies with Advanced Collector Types**
   There is a shortage of direct, empirical comparisons between flat plate collectors and newer technologies like evacuated tube and compound parabolic collectors under the same environmental conditions.
6. **Underexplored Hybrid Systems**
   Research on integrating flat plate collectors with auxiliary heating systems

(e.g., heat pumps or biomass) remains limited, even though such hybrid systems could ensure more reliable performance during cloudy or cold conditions.

7. **Modeling and Simulation Limitations**

   Existing thermal models often simplify environmental variables or do not consider transient behavior effectively. This limits their accuracy in predicting real-time performance.

8. **User Behavior and Maintenance Patterns**

   Studies rarely consider how user behavior, maintenance frequency, and incorrect installation affect long-term performance, which is crucial for practical deployment. [7]

Chapter 3

Methodology

3.1. System Methodology

The development of the Comprehensive Model of Solar Water Heater follows a systematic approach to ensure the design is efficient, functional, and sustainable. The steps involved in the methodology are as follows:

1. **Component Selection:**
   - Select a solar panel with sufficient output to charge a 12V battery efficiently.
   - Choose a battery capable of storing enough energy to operate the burner coil for extended periods.
   - Design or select an inverter circuit suitable for regulating the output voltage and current for the heating coil.
   - Choose a burner coil with appropriate resistance and power rating for efficient water heating.
   - Use a water tank made of heat-resistant material to safely hold water during heating.
2. **System Design:**
   - Design the electrical connections between the solar panel, battery, inverter, and burner coil.
   - Create a setup ensuring proper energy flow and safety measures, such as fuses and switches where necessary.
3. **Circuit Construction:**
   - Assemble the solar panel to the battery using a charge controller (optional but recommended for better battery life).
   - Build the inverter circuit to regulate the battery output as per the burner coil's requirements.
   - Connect the burner coil through the inverter output and install it securely inside the water tank.
4. **Integration and Assembly:**
   - Integrate all components into a compact system.

- Ensure the burner coil is properly submerged inside the water tank and that electrical connections are insulated and safe.

5. **Testing and Evaluation:**
   - Test the system by exposing the solar panel to sunlight and observing the charging process.
   - Monitor battery performance and inverter output to ensure they meet the burner coil's operational needs.
   - Evaluate the time required to heat a given quantity of water and system efficiency under different sunlight conditions.
6. **Analysis and Improvements:**
   - Record performance data, such as charging time, heating time, and energy consumption.
   - Identify any inefficiencies or energy losses and suggest improvements, such as better insulation, higher efficiency solar panels, or improved circuit design.

3.2. Materials

The experimental setup for the Comprehensive Model of Solar Water Heater is designed to demonstrate the functionality and efficiency of the system in real-world conditions. The setup consists of the following components and arrangements:

3.2.1 Solar Panel:

Figure-3.1: Image of Solar Panel

- **Specifications:** A 12V photovoltaic (PV) solar panel with sufficient wattage to generate electrical power for the system.
- **Positioning:** The solar panel is placed in an open area with direct exposure to sunlight. The panel is positioned at an optimal angle to maximize energy absorption throughout the day.

3.2.2 Battery (12V):

Figure-3.2: Image of 12V Battery

- **Specifications:** A 12V lead-acid or lithium-ion battery with a suitable capacity (e.g., 7Ah or higher) to store the energy generated by the solar panel.
- **Connection:** The solar panel is connected to the battery using a charge controller (if necessary) to manage the charging process and prevent overcharging.
- **Placement:** The battery is housed in a safe, insulated location to prevent damage from heat or environmental factors.

3.2.3 Solar Charge Controller:

Figure-3.3: Solar Charge Controller

- Basics: A solar charge controller is a device that regulates the power coming from a solar panel to a battery. It protects the battery from overcharging, deep discharging, and unstable voltage.
- **Working Principle:** Solar panel → Charge controller → Battery → Load (lights, inverter, etc.).
- **Functionality:** It controls charging voltage and current, prevents battery overcharge, stops reverse current from battery to panel at night, protects battery life and efficiency etc.

3.2.4 Burner Coil (Heating Element):

Figure-3.4: Image of Burner Coil

- **Specifications:** A 12V electric heating coil made of heat-resistant material such as chrome wire or a similar high-resistance wire.
- **Placement:** The coil is submerged inside the water tank, where it acts as the heating element. The coil's size and wattage are selected to ensure efficient heating of the water.

3.2.5 ESP-32 Microcontroller

The ESP32 is a powerful and low-cost microcontroller developed by Espressif Systems for embedded systems and Internet of Things (IoT) applications. It is widely used in modern electronic and renewable energy projects because of its built-in WiFi and Bluetooth communication features, high processing speed, and low power consumption.

In this project, the ESP32 acts as the main control and monitoring unit of the hybrid renewable energy system. It collects real-time data from voltage and current sensors connected to the solar panel. The analog sensor signals are processed by the ESP32 to calculate voltage, current, and generated power. The processed data is then displayed on the LCD module and uploaded to the ThingSpeak IoT platform through WiFi communication.

Figure 3.5: ESP-32 Microcontroller

The ESP32 microcontroller contains a dual-core processor operating at up to 240 MHz, which provides fast and efficient data processing capability. It also includes multiple GPIO pins, analog-to-digital converter (ADC) channels, PWM outputs, serial communication interfaces, and low-power operating modes. These features make it suitable for sensor interfacing, automation, and remote monitoring systems.

One of the major advantages of the ESP32 is its integrated wireless communication capability, which eliminates the need for external WiFi modules. This reduces circuit complexity and system cost. The ESP32 supports programming through the Arduino IDE using Embedded C/C++ language, making it easy for students and researchers to develop IoT-based applications.

Due to its compact size, high performance, reliability, and low power consumption, the ESP32 is an ideal microcontroller for renewable energy monitoring and smart rural electrification systems.

3.2.6 Voltage Sensor

A voltage sensor is a crucial component in this solar power management system, used to measure the electrical potential difference of both the solar panel and the battery. In this project, a DC Voltage Sensor Module is employed due to its simplicity, affordability, and compatibility with the Arduino UNO. The module works on the principle of a voltage divider, which scales down higher voltages (up to 25V) into a safe range (0–5V) suitable for the Arduino's analog input pins.

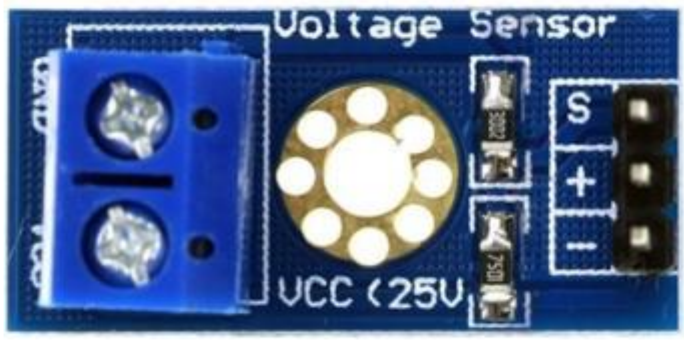

Figure 3.6: Voltage Sensor

The voltage sensor module typically consists of precision resistors that divide the input voltage proportionally. The reduced voltage is then fed into the Arduino's analog-to-digital converter (ADC), which converts the analog signal into a digital value. Using a predefined calibration factor, the Arduino calculates the actual voltage of the solar panel and battery. This allows accurate monitoring of system conditions in real time.

In this system, two voltage sensors are used—one for the solar panel and another for the battery. Monitoring the solar voltage helps determine whether sufficient sunlight is available for power generation, while battery voltage measurement is essential for assessing the charge level and preventing overcharging or deep discharge. These readings are continuously displayed on the LCD for user awareness.

The voltage sensor plays a key role in decision-making within the system. Based on voltage levels, the Arduino controls relay switching between solar power, battery. This ensures efficient energy utilization and system protection. Overall, the voltage sensor enhances system performance, reliability, and safety by providing accurate voltage monitoring and enabling intelligent power management.

3.2.7 LCD (16x2) With I2C

The 16x2 LCD display with I2C module is a commonly used output device in embedded systems and Arduino-based projects for displaying real-time data in a simple and readable format. It can show 16 characters per line across 2 lines, making it suitable for displaying sensor readings, system status, and user messages in compact form.

The I2C LCD Display (16x2) is an enhanced version of the standard 16x2 LCD module, integrated with an I2C communication interface. This interface significantly reduces the number of required microcontroller pins from 6–8 pins to just 2 pins (SDA and SCL). As a result, it simplifies wiring complexity and allows easier integration with microcontrollers such as Arduino UNO, ESP32, and Raspberry Pi.

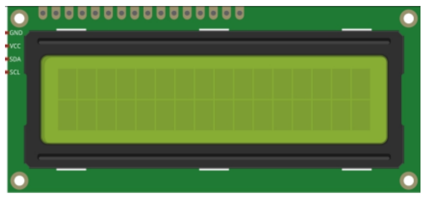

Figure 3.7: LCD (16x2) With I2C

This LCD typically operates at 5V and uses the HD44780 driver chipset, which is widely supported in embedded programming libraries. The I2C module is usually built using a PCF8574 I/O expander, enabling serial communication between the microcontroller and display. The default I2C address can be modified in some modules, allowing multiple I2C devices to be used on the same bus.

In practical applications, the 16x2 I2C LCD is used to display sensor data such as temperature, humidity, gas levels, and system alerts in IoT-based monitoring systems. It improves user interaction by providing real-time feedback without requiring a computer or mobile interface.

Another advantage of this module is its adjustable contrast and backlight control, which enhances visibility under different lighting conditions. Additionally, it supports custom character creation, allowing users to design symbols for specific project requirements.

Overall, the 16x2 LCD with I2C interface is a reliable, efficient, and user-friendly display solution that simplifies hardware design while improving readability and system performance in embedded electronics projects.

3.2.8 Buck Converter

A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage (while drawing less average current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) typically containing at least two semiconductors (a diode and a transistor, although modern buck converters frequently replace the diode with a second transistor used for synchronous rectification) and at least one energy storage element, a capacitor, inductor, or the two in combination.

To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter). It is called a buck converter because the voltage across the inductor "bucks" or opposes the supply voltage.

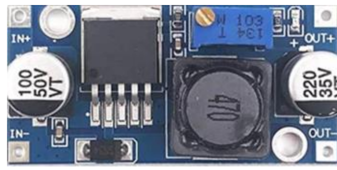

Figure 3.8: DC -DC Buck Converter

DC-DC Buck Converter Step Down Module LM2596 Power Supply is a step- down(buck) switching regulator, capable of driving a 3-A load with excellent line and load regulation. These devices are available in fixed output voltages of 3.3 V, 5 V, 12 V, and an adjustable output version. The LM2596 series operates at a switching frequency of 150kHz, thus allowing smaller sized filter components than what would be required with lower frequency switching regulators.
Specifications of DC-DC Buck Converter Step Down Module LM2596 Power Supply:

- Conversion efficiency: 92%(highest)
- Switching frequency: 150KHz
- Output ripple: 30mA9maximum)
- Load Regulation: ± 0.5%
- Voltage Regulation: ± 0.5%
- Dynamic Response speed: 5% 200uS
- Input voltage:4.75-35V
- Output voltage:1.25-26V(Adjustable)
- Output current: Rated current is 2A, maximum 3A (Additional heat sink is required)
- Conversion Efficiency: Up to 92% (output voltage higher, the higher the efficiency)
- Switching Frequency: 150KHz
- Rectifier: Non-Synchronous Rectification
- Module Properties: Non-isolated step-down module (buck)
- Short Circuit Protection: Current limiting, since the recovery
- Operating Temperature: Industrial grade (-40 to +85) (output power 10W or less)

3.2.9 Water Temperature Monitoring

A temperature sensor or thermometer is used to monitor the water temperature inside the tank.

This data helps to evaluate the heating efficiency of the system.

3.3 Testing Conditions

- **Sunlight Exposure:** The system is tested during various times of the day to observe its performance under different sunlight conditions (e.g., morning, noon, and evening).
- **Water Volume:** A set amount of water (e.g., 5 liters) is used in the tank to ensure consistent results across trials.

3.4 Material Requirements & Cost Analysis

Table 3.1: Materials List & Cost Analysis

No	Product Name	Specification	Qty.	Unit Price	Total Price
01.	Microcontroller	ESP-32	1	600	600
02.	Battery	12V	1	2000	2000
03.	Voltage Sensor	ZMPT101B	2	220	440
04.	Current Sensor	ACS712	2	230	460
05.	LCD (16x2) With I2C		1	500	500
06.	Buck Converter	LM2596	1	120	240
07.	Others				1500
Total =					5740/=

Chapter 4
System Design and Architecture

4.1 Circuit Diagram

The circuit diagram of the hybrid renewable energy system represents the electrical connections among the solar panel, wind turbine, battery, charge controller, sensors, ESP32 microcontroller, LCD display, and buck converter. The circuit is designed to ensure proper power generation, energy storage, monitoring, and safe system operation.

In this project, the solar panel and wind turbine are connected to the solar charge controller. The charge controller regulates the charging process and safely transfers electrical energy to the 12V battery. It also protects the battery from overcharging, deep discharge, and reverse current flow. The battery acts as the main energy storage unit and supplies backup power to the system.

Voltage sensors and current sensors are connected to both the solar and wind energy sources to measure electrical parameters such as voltage and current. The output signals from these sensors are connected to the analog input pins of the ESP32 microcontroller. The ESP32 processes the sensor data and calculates the generated power from both renewable energy sources.

A buck converter is connected between the battery and the ESP32 to step down the battery voltage to a stable operating voltage suitable for the microcontroller and other electronic components. A 16×2 LCD with I2C module is connected to the ESP32 through SDA and SCL communication pins for displaying real-time system information.

The ESP32 also communicates with the ThingSpeak server using WiFi for remote monitoring and performance analysis. The complete circuit diagram ensures proper integration of all components for efficient operation of the hybrid renewable energy system.

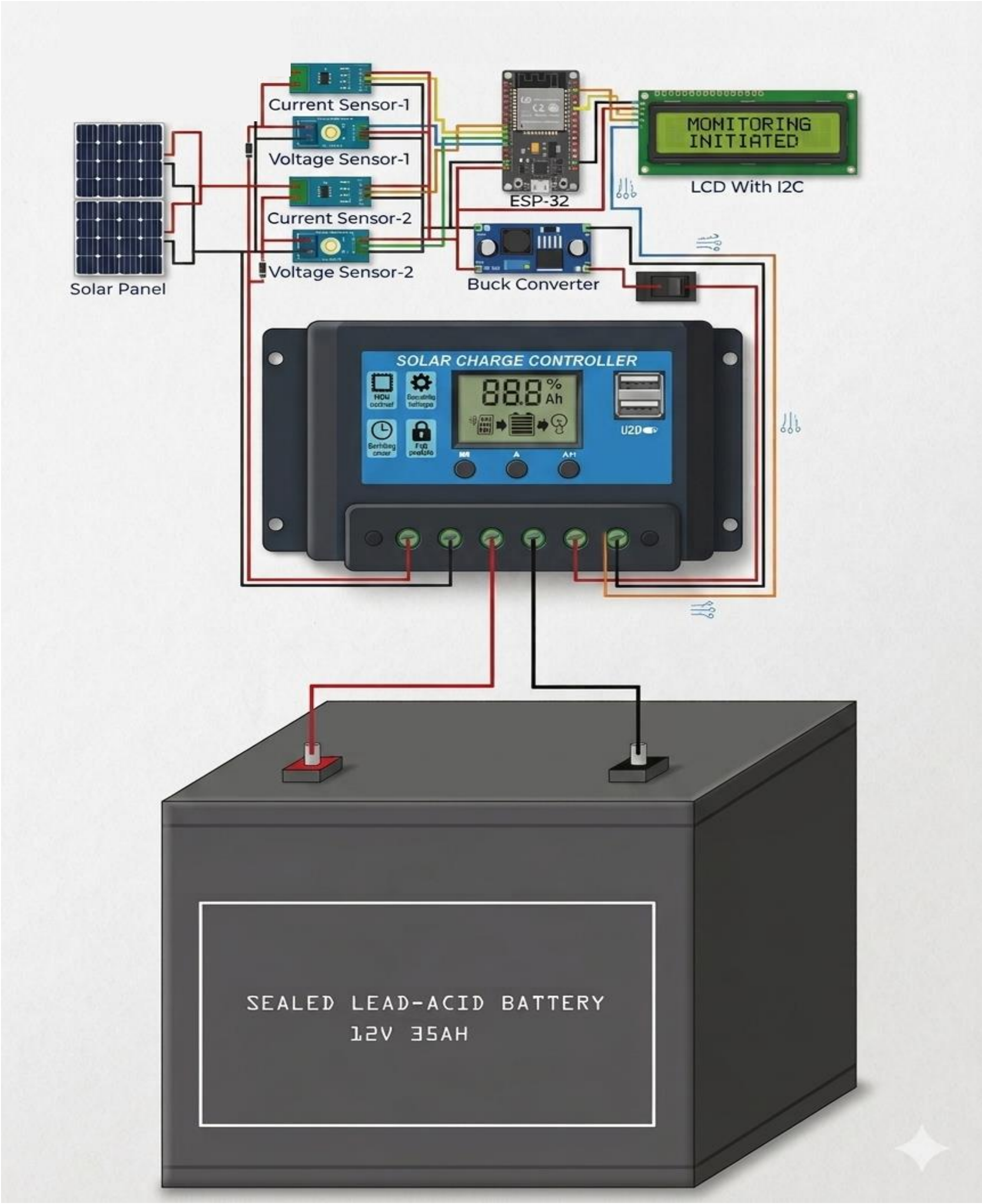

Figure 4.1: Circuit Diagram

4.2 Block Diagram

The block diagram of the hybrid renewable energy system provides a simplified representation of the overall system structure and functional relationships among different components. It helps to understand the flow of energy and information within the system.

In this project, the main energy sources are the solar panel. The solar panel converts sunlight

into electrical energy. This renewable energy source is connected to the solar charge controller. The charge controller regulates the charging process and safely stores the generated energy in the 12V battery. It also protects the battery from overcharging and deep discharge.
The battery acts as the energy storage unit of the system. The stored electrical energy can be used when solar energy generation becomes low. A buck converter is connected to the battery to provide a stable and regulated voltage supply for the ESP32 microcontroller and other electronic components.

Voltage sensors and current sensors are connected to the solar energy systems to measure voltage and current values. These sensors send analog signals to the ESP32 microcontroller. The ESP32 processes the collected data and calculates generated power and other electrical parameters.

A 16×2 LCD with I2C module is connected to the ESP32 for displaying real-time voltage, current, and power information. The ESP32 also uploads monitoring data to the ThingSpeak through WiFi communication for remote monitoring and performance analysis.

The block diagram clearly illustrates the energy generation, storage, monitoring, and IoT communication process of the hybrid renewable energy system.

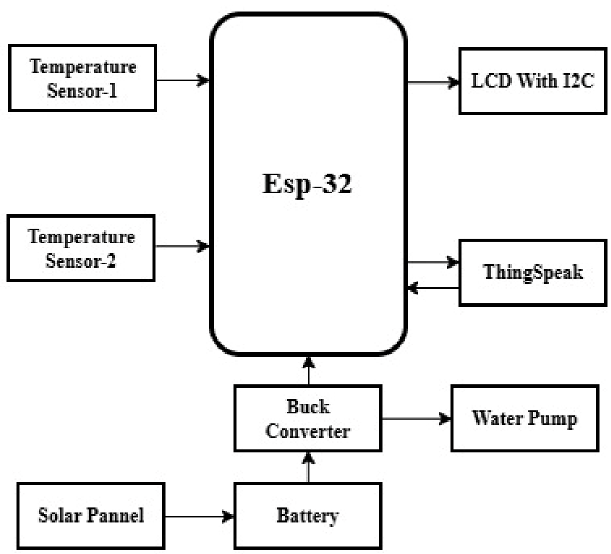

Figure 4.2: Block Diagram

4.3 Complete Project Prototype Image:

Figure 4.3: Complete Project Prototype Image

4.4 Working Principle

The working principle of the solar energy system is based on the generation, storage, monitoring, and utilization of electrical energy from solar sources. The system is designed to provide continuous and reliable electrical power for rural electrification.

The solar panel converts sunlight into direct current (DC) electrical energy through the photovoltaic effect. This renewable energy sources are connected to the solar charge controller, which regulates the charging process and safely transfers electrical energy to the 12V battery.

The charge controller protects the battery from overcharging, deep discharge, and reverse current flow.The stored energy can supply power during nighttime or low renewable energy generation periods.

Voltage sensors and current sensors continuously measure the electrical parameters of solar systems. These sensor outputs are connected to the ESP32 microcontroller. The ESP32 reads the analog sensor data, calculates voltage, current, and generated power, and processes the information in real time.

A buck converter is used to provide a stable operating voltage to the ESP32 and other electronic components. The calculated system parameters are displayed on the 16×2 LCD with I2C module for local monitoring. Simultaneously, the ESP32 uploads the data to the ThingSpeak through WiFi communication for remote monitoring and performance analysis.

Thus, the hybrid system ensures efficient energy generation, storage, monitoring, and uninterrupted power supply for rural electrification.

Chapter 5

Data Collection & Result Analysis

5.1 Data Analysis

Table 5.1: Data analysis(Solar Energy Storage)

Interval	Solar Voltage (V)	Solar Current (A)	Solar Power (W)
10.00 am	17.0	1.21	20.65
10.30 am	16.73	1.46	24.48
11.00 am	16.97	2.74	46.48
11.30 am	17.0	2.66	45.17
12.00 am	16.71	2.34	39.17
12.30 am	16.91	2.32	39.22
01.00 pm	17.0	2.18	37.13
01.30 pm	16.79	1.46	24.44
02.00 pm	14.0	0.73	10.17
03.00 pm	13.66	0.82	11.2
04.00 pm	11.52	0.47	5.43
05.00 pm	12.06	0.96	11.6

Here is the Calculation,

1.Solar:

$Avg\ Solar\ Voltage\ (Vs)$

$$= \frac{17.0 + 16.73 + 16.97 + 17.0 + 16.71 + 16.91 + 17 + 16.79 + 14.0 + 13.66 + 11.52 + 12.06}{12}$$

$$\therefore Vs = 15.52W$$

Avg Solar Current (Is)

$$= \frac{1.21 + 1.46 + 2.74 + 2.66 + 2.34 + 2.32 + 2.18 + 1.46 + 0.73 + 0.82 + 0.47 + 0.96}{12}$$

$$\therefore \text{Is} = 1.61\text{A}$$

$$\text{Solar Power Ps} = \text{Vs} \times \text{Is} = 15.52 \times 1.61$$

$$\therefore \text{Ps} = 24.98\text{W}$$

Therefore, the average solar panel output generated from the collected experimental data was approximately 24.98 W.

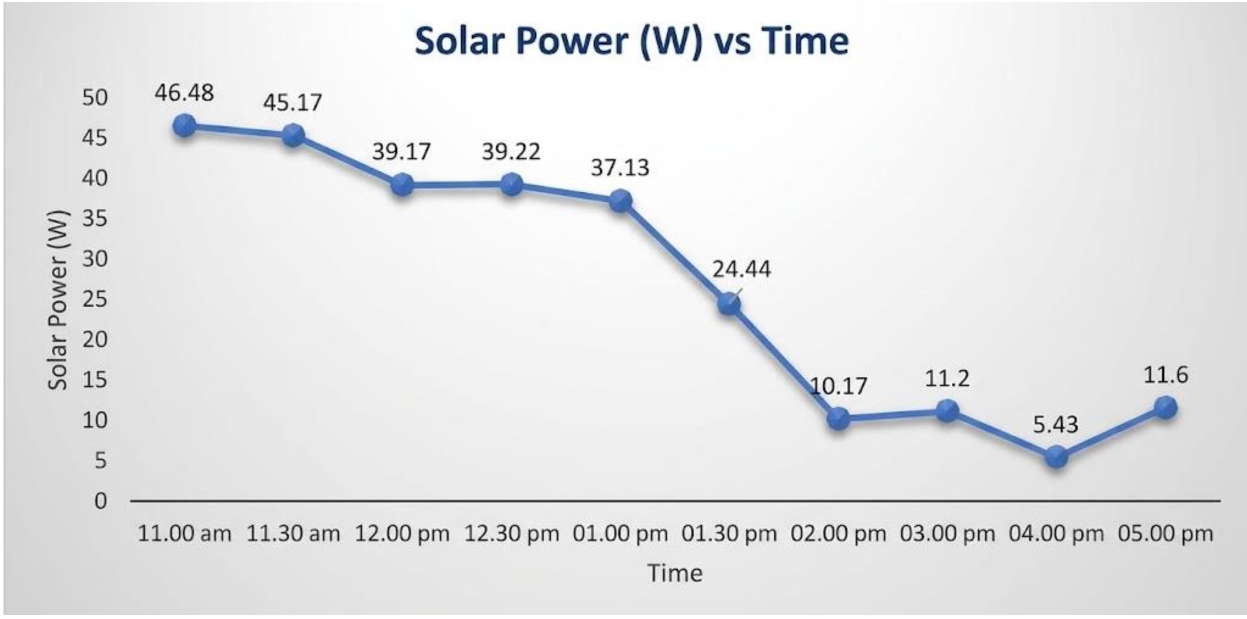

Figure 5.1: Solar Power Vs Time Graph

2. Battery Capacity and Backup Analysis:

Battery Specification = 12V, 9Ah

Formula:

$\text{Battery Energy} = \text{Voltage} \times \text{Ampere} - \text{hour}$

$\text{Battery Energy} = 12 \times 9$

$\text{Battery Energy} = 108\ \text{Wh}$

$\text{Applied Load} = 20\text{W}$

$$\text{Backup Time} = \frac{\text{Battery Energy}}{\text{Load}}$$

$$= \frac{108}{20}$$

$$\therefore \text{Backup Time} = 5.4\ \text{hours}$$

Therefore, the battery can provide backup power for approximately 5.4 hours.

3. Efficiency Analysis:

$$\text{Solar Efficiency} = \left(\frac{\text{Actual Output}}{\text{Rated Output}}\right) \times 100$$

$$\text{Solar Efficiency} = \left(\frac{24.98}{40}\right) \times 100$$

$$\text{Solar Efficiency} = 62.45\%$$

4. Daily Energy Production:

Assumptions:

$$\text{Solar operation time} = 8 \text{ hours/day}$$

$$\text{Daily Solar Energy} = 24.98 \times 8 = 199.84 \text{ Wh/day}$$

Therefore, the solar system can produce approximately 199.84 Wh of electrical energy per day.

5. Water Heat Treatement Process:

Table 5.2: Data analysis(Water Heat Treatement)

SL	Time	Time Duration	Tin (°C)	T_{out} (°C)	T_{def} = Tout – Tin (°C)	Useful Heat Gain (W)	Incident Solar Energy (W/m^2)	Thermal Efficiency (%)
1	10 AM – 11 AM	5 Mins	31.4	36.4	5.0	418.6	800	52.325
			31.9	37.2	5.3	443.716		55.4645
2	11 AM – 12 PM		32.2	38.4	6.2	519.064		64.883
			32.6	39.0	6.4	535.808		66.976
3	12 PM – 1 PM		32.9	40.0	7.1	594.412		74.3015
			33.2	40.5	7.3	611.156		76.3945
4	1 PM – 2 PM		33.4	40.7	7.3	611.156		76.3945
			33.1	40.2	7.1	594.412		74.3015
5	2 PM – 3 PM		32.8	39.1	6.3	527.436		65.9295
			32.4	38.3	5.9	493.948		61.7435
6	3 PM – 4 PM		31.8	36.8	5.0	418.6		52.325
			31.2	35.7	4.5	376.74		47.0925

7	4 PM – 5 PM		30.4	34.0	3.6	301.392		37.674
			29.8	33.0	3.2	267.904		33.488
8	5 PM – 6 PM		28.9	31.0	2.1	175.812		21.9765
			28.2	29.8	1.6	133.952		16.744

Given,

- Collector Area A_c = 1.0 m^2
- Mass Flow Rate m = 0.02 kg/s
- Time.t= 5 minutes=300 seconds
- Specific Heat of Water C_p = 4186 J/kg
- Incident Solar Energy, G_t=800W/m^2

Step 1: Calculate Useful Heat Gain

$$Qu = m \cdot cp \cdot (Tout - Tin)$$

Step 2: Calculate Incident Solar Energy

$$Q_{solar} = A_c \cdot G_t$$

Step 3: Calculate Thermal Efficiency

$$\eta = \frac{Qu}{Q_{solar}} *100\%$$

5.2 Result and Analysis

The implemented Solar Energy System was experimentally analyzed under different operating conditions using a 100W solar panel and a 12V, 9Ah battery storage system. During testing, the solar panel generated an average voltage of 15.52V, current of 1.61A, and output power of approximately 24.98W. The battery charging performance was also analyzed, where the battery voltage increased from 11.9V to 12.7V during charging operation, indicating stable energy storage capability. Also, Solar incident energy is used not only for storing that energy as current, but also it is used to increase the temperature of water flowing through the pipe on the top side of solar panel.The thermal efficiency of it ranges from approximately 16% to 76% based upon incident solar energy on different time of the day. Compared to single-source solar energy storage systems, the proposed hybrid working configuration improves system reliability and ensured continuous energy usability during low sunlight conditions. The ESP32-based monitoring system successfully displayed voltage, current, and power data on the LCD and uploaded real-time information to the ThingSpeak IoT platform for remote monitoring and analysis. The charge controller effectively protected the battery from overcharging and deep discharge, improving operational safety and battery life. From the overall experimental results, the system demonstrated stable output performance, efficient energy management, and reliable operation for small-scale rural electrification and educational renewable energy applications.

5.3 Advantage

- The system provides continuous power supply using both solar and battery backup.
- It reduces dependency on the national electricity grid.
- Solar energy is renewable and environmentally friendly.
- The system helps in reducing electricity bills significantly.
- It automatically manages charging through the solar charge controller.
- Battery life is improved due to proper charging control.
- It works efficiently in remote and rural areas without grid access.
- Low maintenance cost makes it economically beneficial.
- Solar heat is used to heat water.

5.4 Applications

- It can be used in home lighting systems.
- Suitable for rural electrification projects.
- Useful in street lighting systems.
- Can be implemented in smart agriculture systems.
- Applicable in remote monitoring stations.

5.5 Limitations

- Initial installation cost is relatively high.
- Energy generation depends on weather conditions.
- Solar panel efficiency reduces during cloudy days.
- Battery storage capacity is limited.
- Requires proper placement for maximum sunlight exposure.

5.6 Discussion

The implemented Hybrid Renewable Energy System demonstrated stable and reliable performance under different operating conditions by integrating solar energy, wind energy, and battery storage. During the experimental analysis, the solar panel generated an average output power of approximately 24.98W, while the vertical axis wind turbine (VAWT) produced an average output power of approximately 2.53W under available wind conditions. The combined hybrid system therefore achieved an average total output power of about 27.51W, ensuring continuous energy generation for low-power DC applications.

The experimental results showed that solar energy contributed the major portion of the total generated power due to higher solar irradiance during daytime operation. In contrast, the wind turbine provided supplementary backup power during fluctuating sunlight conditions, improving overall system reliability. Compared to a single-source solar system, the hybrid configuration provided more stable output performance and reduced dependency on environmental variations.

The 12V, 9Ah battery demonstrated stable charging and discharging characteristics throughout the testing period. The battery voltage gradually increased from approximately 11.9V to 12.7V during charging operation, indicating efficient energy storage capability. The solar charge controller successfully prevented overcharging and deep discharge, which improved battery protection and operational safety.

The ESP32-based IoT monitoring system effectively displayed real-time voltage, current, and power data on the LCD and uploaded system parameters to the ThingSpeak cloud platform for remote monitoring and analysis. This real-time monitoring capability simplified system supervision and improved performance observation.

Although the wind turbine generated comparatively lower power due to low and inconsistent wind speed conditions, the overall hybrid system demonstrated satisfactory performance for small-scale renewable energy applications. The integration of multiple renewable energy sources improved energy continuity, system flexibility, and operational efficiency. Therefore, the proposed system can be considered a low-cost, environmentally friendly, and sustainable solution for rural electrification, educational research, and small-scale backup power applications.

Chapter 6
Conclusion and Recommendations

6.1 Conclusion

The Solar Energy System designed and implemented in this project successfully demonstrates an efficient and reliable method of combining solar energy with battery storage. The main objective of reducing dependency on conventional grid electricity has been effectively achieved through proper integration of renewable energy technology. The system ensures continuous power supply by utilizing solar energy during the daytime and switching to battery backup during low or no sunlight conditions. The use of a solar charge controller enhances system performance by protecting the battery from overcharging and deep discharge, thereby increasing its lifespan. The real-time monitoring system using sensors and LCD display provides accurate information about voltage, current, and battery status, which improves system control and safety. The overall design is simple, cost-effective, and suitable for small-scale applications. In addition to this, this energy can be used to heat water. It means double output with single input.

From the experimental results, it is clear that the system performs efficiently under different environmental conditions. Although there are limitations such as dependency on weather and limited storage capacity, these can be improved in future developments by using advanced batteries and higher efficiency solar panels.

In conclusion, this hybrid energy system is a sustainable and practical solution for rural electrification, home applications, and educational purposes. It contributes to energy conservation and supports the use of clean renewable energy for a better future.

6.2 Future Scopes

- Smart IoT-based monitoring can be added for remote control.
- Advanced lithium-ion batteries can replace lead-acid batteries.
- AI-based energy management can optimize power usage.
- Wireless energy monitoring using mobile apps can be implemented.

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