NEXT-GEN EASY BIKE WITH EFFICIENT SOLAR AND IOT-BASED NAVIGATION SYSTEM

An Undergraduate CAPSTONE Project
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Spring Semester 2024-2025
May 2025

Faculty of Engineering
American International University - Bangladesh

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A CAPSTONE Project submitted to the Faculty of Engineering, American International University - Bangladesh (AIUB) to partially fulfil the Bachelor of Science degree requirements in their respective programs.

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DECLARATION

This is to certify that this project is our original work. No part of this work has been submitted elsewhere, partially or entirely, for the award of any other degree or diploma. Any material reproduced in this project has been appropriately acknowledged.

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APPROVAL

The CAPSTONE Project titled "**Next-Gen Easy Bike with Efficient Solar and IoT Based Navigation System**" has been submitted to the following respected members of the Board of Examiners of the Faculty of Engineering on **May 22, 2025** by the following students in partial fulfillment of the requirements for the degree of Bachelor of Science in the respective programs mentioned below and has been accepted as satisfactory.

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ABSTRACT

This capstone project presents the design, development, and evaluation of the "Next-Gen Easy Bike with Efficient Solar and IoT-Based Navigation System," which aims to revolutionize urban transportation in Bangladesh through sustainable technology integration. Addressing challenges such as dependency on unreliable grid electricity, limited charging infrastructure, and environmental concerns, the project is equipped with a Solar Panel, a Maximum Power Point Tracking (MPPT) charger, and an IoT-enabled innovative navigation system.

The innovative system maximizes solar energy capture using MPPT algorithms and a DC-DC boost converter, supported by a hybrid charging approach that integrates grid electricity to ensure reliability under variable weather conditions. IoT capabilities enable real-time location tracking and ensure the safety of the easy bike. Extensive simulation and hardware implementation validate the design's technical feasibility, demonstrating significant improvements in energy autonomy, operational cost reduction, and environmental impact compared to conventional grid-dependent Easy Bikes. Economic analyses reveal a favorable cost-benefit profile with a short payback period, making the solution accessible to low-income users and scalable for broader deployment.

The project multidisciplinary framework combines mechanical, electrical, and socio-economic factors essential for adoption in developing regions. In conclusion, this approach provides an effective, eco-friendly, and affordable solution that supports sustainability goals worldwide and creates a strong base for future growth in renewable energy and smart transportation.

Chapter 1

INTRODUCTION

1.1. Overture

The growth of transportation has significantly influenced modern society, with swift progress in energy-efficient and sustainable solutions propelling the industry ahead. Electric three-wheeler autorickshaws, called Easy Bikes, have become a prevalent means of transportation in developing countries, especially Bangladesh. Despite their extensive utilization, these vehicles have substantial obstacles, such as inadequate charging infrastructure, reliance on grid electricity, and restricted operational range. Integrating solar energy with IoT-based navigation systems offers a novel and sustainable resolution to these issues, guaranteeing increased energy efficiency, superior navigation, and fewer environmental effects. This article examines the potential of Next-Gen Easy Bikes, with efficient solar charging and IoT-based navigation systems, to transform urban mobility, especially in developing nations. The transportation sector is a major contributor to global carbon emissions, requiring a shift to more sustainable options. Conventional fuel-powered autorickshaws contribute to air pollution and present economic difficulties due to escalating fuel prices. Although electric Easy Bikes have become popular as an alternative, their need for grid electricity, frequently produced from fossil fuels, restricts their sustainability. The lack of a well-organized charging infrastructure in numerous areas induces range anxiety for drivers, resulting in operational inefficiencies. Integrating solar power into the charging system of Easy Bikes can markedly improve their energy efficiency and sustainability. Solar energy has emerged as an up-and-coming renewable energy source, providing a clean, abundant, and economical solution for electric vehicle charging. Equipping Easy Bikes with photovoltaic (PV) panels and Maximum Power Point Tracking (MPPT) charge controllers enables the vehicles to utilize solar energy for charging while in transit, diminishing reliance on grid electricity. Research on solar charging stations in Bangladesh underscores the viability of employing photovoltaic-based charging networks to sustain electric car fleets, guaranteeing continuous service while reducing operational expenses. Integrating solar energy into Easy Bike operations necessitates an effective energy management system to enhance power utilization. MPPT-based charge controllers optimize the power transfer from solar panels to the battery, improving charging efficiency. Moreover, hybrid systems that combine battery storage with grid backup enhance reliability, enabling vehicles to charge even under low sunshine conditions. In addition to the energy economy, the incorporation of Internet of Things (IoT) technology in Easy Bikes provides significant advantages in navigation, fleet administration, and real-time monitoring. IoT-based systems facilitate GPS tracking and intelligent navigation, ensuring optimized route planning to diminish energy consumption and travel duration, predictive maintenance utilizing sensor data to foresee potential issues prior to breakdowns, thereby reducing downtime and maintenance expenses, and dynamic charging station allocation to aid drivers in identifying nearby solar charging stations to minimize delays and enhance battery utilization. By utilizing IoT, operators can adopt data-driven decision-making strategies, enhancing the overall efficiency of Easy Bike fleets. Moreover, the use of AI-driven traffic management systems can facilitate the analysis of congestion patterns and provide alternate routes, so assuring more efficient transit experiences for passengers. Solar-powered, IoT-integrated Easy Bikes are economically and environmentally beneficial. Reduced dependence on grid electricity and fossil fuels lowers drivers' operational costs, increasing profitability. Over time, energy savings offset the upfront cost of solar charging infrastructure, making it economically viable. Solar-powered Easy Bikes reduce greenhouse gas emissions, promoting worldwide environmental goals. These automobiles reduce urban air pollution and promote sustainable transportation by eliminating exhaust emissions and non-renewable energy use. Solar and IoT-integrated Easy Bikes have great potential, but they must overcome some obstacles to succeed. This includes technological obstacles like the development of lightweight, efficient photovoltaic panels and high-capacity batteries for long-term operations, policy and regulatory support that encourage government incentives and subsidies for sustainable transportation solutions, and public awareness and acceptance. These issues require a multi-stakeholder strategy involving lawmakers, technological developers, and transportation authorities. Public-private partnerships can establish smart charging infrastructure, while energy storage and IoT research can advance innovation. The next generation of Easy Bikes will have solar charging and IoT-enabled navigation, revolutionizing sustainable urban mobility. These vehicles use renewable energy and innovative technologies to replace conventional transportation, reducing environmental impact and enhancing efficiency. Future advances in battery technology, AI-based route optimization, and smart grid integration will boost system efficiency and scalability. Research and strategic investments may allow solar and IoT-powered Easy Bikes to transform urban transportation worldwide, creating a cleaner, smarter, and more efficient ecosystem. This article analyzes the technological, economic, and environmental aspects of deploying Next-Gen Easy Bikes to predict the future of sustainable transportation in developing countries.

1.2. Engineering Problem Statement

In Bangladesh, the widespread adoption of electric three-wheeler autorickshaws, also known as Easy Bikes, Rahman et al. highlighted that the widespread use of electric three-wheeler autorickshaws, commonly known as Easy Bikes, in Bangladesh has significantly reduced carbon emissions and dependence on fossil fuels.[5] Hossain and Islam pointed out that the current charging infrastructure for these vehicles primarily relies on grid electricity, which leads to increased pressure on the national power system, higher operational costs, and continued dependence on non-renewable sources.[6] Chowdhury et al. emphasized inefficiencies in conventional charging practices, such as extended waiting times and the absence of intelligent routing support, which hamper operational efficiency.[7]

To address the identified issues, the project proposes a solar-powered charging system integrated with an IoT-based smart navigation framework. Karmaker et al. emphasized the need for Maximum Power Point Tracking (MPPT) controllers, which help optimize solar energy usage and battery storage efficiency, even under variable environmental conditions.[9]

Ahmed et al. demonstrated that IoT integration in navigation systems allows:

- Real-time route optimization
- Dynamic charging station allocation
- Battery status monitoring

These features collectively enhance fleet management and reduce operational downtime. [9]

Furthermore, Lee et al. advocated for the development of advanced Battery Management Systems (BMS) to enhance battery lifespan and energy efficiency.[8] Wang et al. showed that IoT-based fleet and battery data collection supports predictive maintenance and smarter energy usage.[8,10] Lastly, Zhou et al. emphasized the need for scalable, adaptable infrastructure to keep pace with future developments in electric vehicle technologies and smart transport systems.[9]

These studies collectively support the project's goal to overcome current limitations, thereby contributing to the establishment of affordable, sustainable, and environmentally friendly urban transportation systems in developing regions like Bangladesh.

1.3. Related Research Works

The development of Next-Gen Easy Bikes with Efficient Solar and IoT-Based Navigation Systems is underpinned by comprehensive research on solar energy applications, MPPT charge controllers, and IoT-driven vehicle management. A vital component of solar-powered vehicles is the Maximum Power Point Tracking (MPPT) charge controller, which guarantees optimal energy extraction from solar panels. MPPT technology stabilizes power generation under variable solar circumstances by continuously optimizing the operating point of the solar panels.[1] Numerous methods, such as Perturb and Observe (P&O) and Incremental Conductance (IC), have been extensively researched and confirmed through simulations, showcasing their efficacy in improving energy efficiency. Integrating MPPT controllers with electric bikes can reduce energy waste and enhance battery performance, resulting in extended travel ranges and decreased operational expenses. [1,3]

Studies demonstrate that solar photovoltaic (PV) panels integrated with battery storage offer a dependable and economical charging solution. Solar-powered charging stations demonstrably lower operational expenses relative to grid-based charging, rendering them an economically feasible choice for widespread implementation.[2] Furthermore, hybrid solar-grid systems guarantee uninterrupted power supply, averting service interruptions even during periods of low irradiance.

IoT-enabled vehicle management allows real-time battery monitoring, predictive maintenance, and AI-driven route optimization. Intelligent sensors can monitor battery health, charge cycles, and energy usage trends for proactive maintenance and energy optimization. Vehicle-to-Grid (V2G) communication lets easy bikes and charging stations communicate seamlessly, tailoring charging schedules to grid demand.[3] Solar energy, better energy management, and IoT-enabled smart navigation could make easy bikes environmentally and economically sustainable in metropolitan areas. Future research should examine how IoT might simplify these vehicle navigation systems and how AI-driven optimization can improve energy efficiency and user experience. [3,5]

1.3.1. Earlier Research

The successful integration of solar energy into electric vehicle charging systems is contingent upon the optimization of power extraction from photovoltaic (PV) panels, which are susceptible to fluctuations in environmental conditions, including temperature and irradiance. MPPT charge controllers are essential in this respect, as they continuously monitor the optimal operating point of the solar panels to optimize energy harvest. Although more sophisticated methods, such as fuzzy logic-based methods and incremental conductance, have been proposed to enhance responsiveness and stability, the Perturb and Observe (P&O) algorithm remains one of the most extensively implemented due to its consistent performance and simplicity [2]. Recent research has also underscored the significance of hybrid energy storage solutions, which integrate supercapacitors with lead-acid or lithium-ion batteries to balance the requirements for power density and energy density. This hybridization has the potential to enhance the overall efficacy of the system and the battery's longevity by mitigating the effects of transient loads and rapid charge-discharge cycles [3].

Additionally, the utilization of tools such as MATLAB/Simulink for system-level modeling and simulation has become essential for the assessment of the performance of solar MPPT systems in a variety of real-world scenarios. The design of robust controllers that can mitigate the effects of partial shading, temperature variation, and component non-linearities, which are prevalent obstacles in solar-powered EV applications, is facilitated by these simulations [4].

Parallel to this, MPPT charge controllers are gradually incorporating hardware innovations, such as high-frequency DC-DC converters and enhanced semiconductor devices such as Silicon Carbide (SiC) MOSFETs, to enhance thermal management and reduce switching losses. The compactness and efficiency of solar charging units that are purpose-built for light electric vehicles, such as Easy Bikes, are substantially enhanced by these advancements [5].

1.3.2. Recent Research

Pursuing energy-efficient and environmentally sustainable transportation has become increasingly prominent in modern urban development. In developing countries such as Bangladesh, Easy Bikes have emerged as a popular mode of transport due to their affordability and practicality. However, their widespread adoption faces several limitations, including insufficient charging infrastructure, high dependence on grid electricity, and limited operational range. Recent studies suggest that integrating solar energy systems and Iot-based navigation technologies can significantly enhance these vehicles' energy efficiency, range, and environmental impact, thereby offering a sustainable solution to urban mobility challenges.

El-Samahy and El-Saadany (2005) emphasized that distributed generation (DG) systems have a measurable impact on power quality, particularly in deregulated environments, highlighting the importance of intelligent energy management in urban transport electrification initiatives [5]. Karmaker et al. (2018) assessed the feasibility of hybrid renewable energy-based electric vehicle charging stations in Bangladesh. Their findings demonstrated that photovoltaic (PV) systems integrated with Maximum Power Point Tracking (MPPT) charge controllers can effectively maximize solar energy utilization while reducing reliance on conventional grid electricity. Deploying lead-acid battery storage in these systems ensures consistent energy availability, particularly in regions with intermittent sunlight [6].

Further advancements in the field have focused on developing adaptive and artificial intelligence-driven MPPT algorithms capable of responding dynamically to fluctuating solar irradiance, thereby optimizing energy conversion. These technologies are instrumental in improving solar-powered electric vehicles' overall efficiency and resilience. Contemporary research has also explored the potential of Iot-enabled systems for vehicle tracking, battery health monitoring, and predictive maintenance. These technologies significantly enhance fleet performance and reduce downtime, thus improving operational reliability [6].

In addition, studies by Bowes and Grewal (2001) on inverter technologies introduced novel adaptive hysteresis band modulation strategies, which enhance inverter efficiency and contribute to energy optimization in electric drive systems [7]. Innovations in vehicle design have also played a critical role, with lightweight materials and aerodynamic structures contributing to reduced energy consumption and extended vehicle range. Moreover, integrating regenerative braking systems facilitates kinetic energy recovery during deceleration, further improving battery longevity and system efficiency.

Recent experimental implementations have explored battery swapping stations as a faster and more efficient alternative to conventional charging methods, offering reduced vehicle downtime and improved service continuity. Enhanced IoT infrastructure now enables real-time monitoring of vehicle parameters, providing predictive maintenance alerts to prevent failures. Furthermore, the growing integration of Vehicle-to-Grid (V2G) systems enables Easy Bikes to return surplus energy to the grid, contributing to the stability of local energy systems and promoting circular energy use.

These advancements collectively present a comprehensive and scalable framework for developing Next-Generation Easy Bikes, combining solar charging technologies, intelligent control systems, advanced battery management, and IoT-based navigation. These innovations are poised to redefine urban mobility in developing regions by offering a sustainable, efficient, and intelligent transportation solution.

1.4. Critical Engineering Specialist Knowledge

The "design of an electric vehicle" project requires a thorough awareness of many disciplines to reach the goals. We are talking about all-terrain capability and modular usefulness. This is the necessary engineering knowledge for this project:

1.4.1. Mechanical Engineering

Next-generation vehicles' design and structural integrity rely on sophisticated mechanical engineering principles. Optimization of factors such as lightweight frame materials, aerodynamics, and vibration resistance is essential for ensuring durability and efficiency. Incorporating solar panels and battery storage necessitates exact mechanical engineering solutions to equilibrate weight and stability while preserving vehicle performance.

1.4.2. Renewable Energy and Sustainability

The shift to solar-powered vehicles corresponds with international sustainability objectives. Understanding photovoltaic (PV) technologies, energy storage systems, and hybrid charging methodologies is crucial for optimizing efficiency. Engineers must prioritize optimizing solar energy capture, battery lifespan, and energy conversion efficiency to establish a sustainable transportation paradigm.

1.4.3. Environmental Policy Knowledge

Compliance with environmental norms and regulations is essential for effectively deploying solar-powered vehicles. Policies concerning renewable energy subsidies, emissions requirements, and sustainable urban development must be considered. Adherence to governmental laws and environmental rules will promote project approval and broad acceptance.

1.4.4. Software Engineering

Performance analysis and simulations:

- Simulating a boost converter and general performance under various running situations requires MATLAB/Simulink.
- Modern MPPT (maximum power point tracking) algorithms improve the use of solar energy.

IoT and data analysis:

- Creating a web-based or mobile interface to track energy use, battery condition, and vehicle performance.
- Using real-time data analytics, predictive maintenance techniques are implemented to increase lifetime and lower downtime.

1.4.5. Project Management and Systems Engineering

Collaboration Across Disciplines:

- A project manager must effectively coordinate multiple engineering disciplines, including mechanical, electrical, software, and energy specialists, to ensure the seamless integration of all components.
- Effective communication across teams ensures smooth progress toward project objectives.

Distribution of Resources:

- Efficient strategic planning for material acquisition, budgetary management, and manpower allocation is crucial for project execution in a timely manner.
- Assessing project success through key performance indicators (KPIs) ensures efficiency and cost-effectiveness.

1.4.6. Field Testing and Validation

- Prototypes must undergo stringent field testing to verify solar efficiency and IoT system stability.
- Performance testing in various environmental situations guarantees adaptation and robustness.
- Field testing data must be assessed to implement essential design improvements, enhancing overall system efficiency and performance.

1.5. Stakeholders

The successful implementation of next-generation easy bikes with solar and IoT-based navigation systems requires active participation from various stakeholders. Support, financing, and decision-making depend critically on stakeholders. Their opinions can point out hazards, prospects, and different approaches. Involving stakeholders throughout the project life helps us raise their happiness, establish confidence, and guarantees that the project fits their needs and expectations. The success of any endeavor is contingent upon the involvement of stakeholders. The following is a list of our stakeholders:

1.5.1. Project Owner

The sponsor is the individual or organization responsible for leading the project by establishing overarching objectives, securing funding, and providing strategic guidance. Their importance is essential in demonstrating that the sponsor is accountable for the project's foundation and the successful attainment of its objectives. Through its leadership and advice, the sponsor enables resource alignment, mitigates risks, and drives initiatives toward achieving targeted outcomes.

1.5.2. Government and Policy Makers

Bangladesh's government is a notable participant in the effort to seek sustainability. This electric vehicle promotes environmental sustainability through the government's "Digital Bangladesh" agenda. Government assistance through grants, low-interest loans, or subsidies can promote the widespread acceptance of such an innovative concept.

1.5.3. Microfinance Institutions and Banks

The effective deployment of next-generation easy bikes equipped with solar and IoT-based navigation systems necessitates the active involvement of multiple stakeholders. Microfinance Institutions and Rural Banks (e.g., Grameen Bank, BRAC) are essential in offering financial assistance and low-interest loans to drivers and enterprises investing in solar-powered vehicles. Access to economic financing guarantees wider implementation and sustainable expansion of the activity.

1.5.4. Local Manufacturers and Workshops

Local manufacturers and workshops participate by designing and building efficient and cost-effective vehicles, integrating improvements in solar power and IoT technologies. Their participation is essential for sustaining affordability and accessibility while promoting local economic development.

1.5.5. Rural Development Organizations

Rural Development Organizations promote the utilization of vehicles in isolated areas, thus narrowing the urban-rural gap where conventional transportation alternatives are limited. These organizations facilitate pilot activities, awareness campaigns, and community engagement.

1.5.6. Environmental Organizations in Bangladesh

Environmental organizations in Bangladesh promote sustainable transportation legislation and urge the widespread adoption of solar-powered easy bikes to mitigate carbon emissions. Their function in policy advocacy and ecological impact evaluations is essential for guaranteeing regulatory compliance and enduring advantages.

1.5.7. Non-Governmental Organizations (NGOs)

Ultimately, Non-Governmental Organizations (NGOs) enhance efforts by executing awareness campaigns, capacity-building initiatives, and technical training for operators and mechanics. Non-governmental organizations interact with policymakers and stakeholders to improve the regulatory environment and facilitate fair access to sustainable transportation alternatives. The collaboration among these parties guarantees that solar-powered vehicles emerge as a feasible, efficient, and sustainable transportation option in Bangladesh.

1.6. Objectives

This project focuses on developing easy bikes integrated with solar power and IoT-based navigation to enhance urban transportation efficiency. By leveraging renewable energy and innovative technology, the project aims to provide a sustainable, cost-effective, intelligent mobility solution for modern cities.

1.6.1. Primary Objectives

The main goals of the project center on the basic features and capabilities of the easy bike, meant for adequate transportation:

1. Establish an Effective Solar Energy Integration System—Utilize high-efficiency photovoltaic panels and maximum power point tracking charge controllers to optimize energy acquisition for next-generation easy bikes.
2. Improve IoT-Enabled Navigation and Intelligent Energy Management — Employ GPS, cloud analytics, and predictive maintenance for real-time monitoring and optimization.
3. Enhance Power Electronics and Control Systems — Integrate DC-DC boost converters and intelligent charge controllers for improved energy efficiency.

4. Evaluate the Economic and Environmental Effects — Examine cost-effectiveness, decrease in carbon emissions, and sustainability of solar-powered easy bikes.

1.6.2. Secondary Objectives

The project's secondary aim is to complement the main objectives and improve the general influence of easy bikes:

1. Examine Hybrid Charging Methodologies—Formulate solutions that integrate grid-based and solar-based charging to guarantee uninterrupted operation.
2. Develop Advanced AI for Route and Energy Optimization — Employ artificial intelligence to improve battery longevity and maximize ride efficiency.

1.7. Organization of Book Chapters

This book has been organized with the following chapter.

1.7.1. Chapter - 2: Project Management

The project management methodologies presented in this chapter guarantee their successful completion. They include risk management, collaboration, scheduling, resource allocation, and strategic planning.

Specifications and Connectivity:

Planning and Scheduling: This section addresses the preliminary planning phases, including delineating project scope, deadlines, and milestones.

Resource Allocation: Details the distribution of resources (human, financial, and material) throughout several project phases.

Risk Management: Involves identifying, evaluating, and alleviating potential risks.

Team Coordination: Emphasizes the significance of explicit communication and coordination among team members, correlating with individual roles addressed thereafter.

1.7.2. Chapter - 3: Methodology and Modeling

This chapter delineates the modeling methodologies and research protocols utilized in the design. It also encompasses software development frameworks and mechanical design concepts.

Specifications and Connectivity:

Research Methodologies: Outlines the research techniques employed to collect pertinent data and guide design choices.

Mechanical Design Modeling: Describes the application of CAD in the structure's design.

Software Development: Encompasses the frameworks and programming languages utilized, establishing the foundation for implementation.

1.7.3. Chapter - 4: Implementation of Project

It defines the sensible actions needed to move the project from the planning and design phases to a tangible outcome. It covers software programming, mechanical assembly, and electrical wiring.

Specifications and Connectivity:

Mechanical Assembly: Offers a comprehensive description of physical construction, correlating with the design models.

Software Development and Integration: This section outlines the creation and use of software components, assuring cohesive functionality among all elements.

1.7.4. Chapter - 5: Results Analysis & Critical Design Review

This chapter analyzes the project findings, encompassing performance metrics, testing outcomes, and a critical design evaluation. It evaluates the efficacy of the executed solutions and pinpoints opportunities for enhancement.

Specifications and Connectivity:

Performance Indicators: Evaluates critical performance metrics.

Testing Outcomes: Delivers comprehensive results from multiple assessments.

Critical Design Review: This reflective design evaluation connects to the methods and implementation phases. It examines insights gained and possible enhancements.

1.7.5. Chapter - 6: Conclusion

The concluding chapter encapsulates the project's accomplishments, examines its ramifications, and suggests avenues for subsequent endeavors. It assesses the project's objectives and determines if they were achieved.

Specifications and Connectivity:

Project Summary: Summarizes the primary and secondary objectives and the methods employed during the project.

Implications: Examines the overarching influence of the project and associated domains.

Future Work: Proposes prospective domains for more research and development.

This planned approach guarantees a logical and harmonious development of ideas and material within the book. Every chapter builds on the preceding one, forming a cohesive narrative that encapsulates the project's spirit from inception to conclusion.

Chapter 2

PROJECT MANAGEMENT

2.1 Introduction

This chapter discusses the critical elements of project management that were implemented during the development of the multifunctional electric power cultivator. Resource allocation, risk management, cost optimization, and meticulous implementation planning are all critical components of the project that necessitate a phased approach. In the case analysis section, a thorough S.W.O.T. (Strengths, Weaknesses, Opportunities, Threats) analysis is provided, which can be used to identify both positive and negative internal and external factors that may impact on the project's effectiveness.

This chapter provides a structured roadmap to guarantee cost-effective and timely execution by establishing a clear project timeline and delineating key phases and milestones. A PEST (Political, Economic, Social, Technological) analysis is performed to assess the broader environmental factors that influence the project's scope, such as regulatory constraints, market dynamics, and technological advancements. A comprehensive project life cycle cost analysis is incorporated to evaluate the financial feasibility and identify the cost implications throughout the product's operational lifecycle. The chapter also investigates the engineering team's ethical, sustainable, and innovative obligations during the design and development.

Furthermore, it investigates the fundamental management principles and economic models that direct project surveillance, resource optimization, and the assessment of the economic feasibility of easy bikes. In general, this chapter's objective is to offer a thorough examination of the practical project management strategies that facilitate the development of an economically viable, sustainable, and efficient product.

2.2 S.W.O.T. Analysis

SWOT analysis can be employed to evaluate a project's strengths and weaknesses, as well as its opportunities and threats. The internal analysis uses a functional approach to identify the project's strengths in all areas (finance, management, infrastructure, procurement, production, distribution, marketing, reputational factors, and innovation), as well as its weaknesses (the same) and growth opportunities (the same). Thorough internal research is necessary to identify the source of competitive advantage. It does so by identifying areas that require investment in developing resources that will maintain a team's motivation.

Research on the sector's surroundings, including industry, competition, and broader economy, reveals potential advantages and disadvantages. The competition landscape is determined by examining each competitor's assets and capabilities. Part of the industry's external environment is analyzing competition, new entrants, suppliers, consumers, and product substitution using the Five Forces Model. Environmental, demographic, ethical, and regulatory repercussions are explored in the context of the external environment and political, economic, sociological, and technological factors. Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is used to aid in developing a company's strategy by examining its unique context. Here, the assets and weaknesses are identified through SWOT analysis.

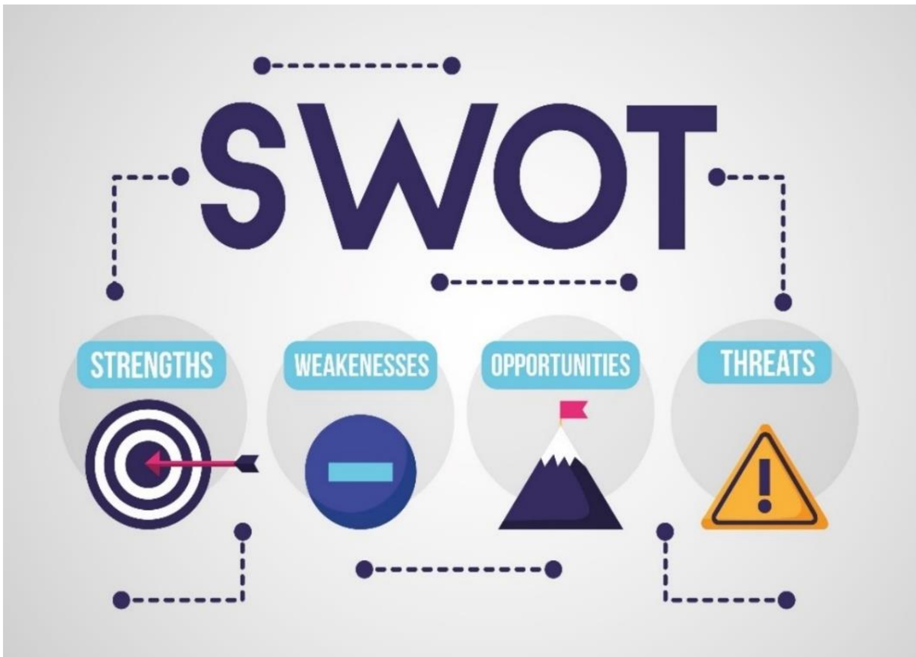

Figure 2.1: S.W.O.T Analysis.

The SWOT analysis assesses internal and external factors affecting project success.

2.2.1. Strengths:

- The incorporation of renewable solar energy diminishes reliance on grid electricity.
- The implementation of MPPT technology guarantees optimal energy efficiency.
- Real-time IoT monitoring enhances user experience and optimizes routes through live data and dynamic adjustments.
- Eco-friendly alternative advocating for sustainable transportation.

2.2.2. Weaknesses:

- Substantial initial financial commitment required for solar and IoT components.
- Technical intricacy in hardware-software amalgamation.

- Inadequate public infrastructure for solar electric vehicle charging.

2.2.3. Opportunities:

- Government assistance through "Digital Bangladesh" initiatives and renewable energy legislation.
- Expansion of markets in urban and peri-urban regions.
- Advancements in artificial intelligence, the Internet of Things, and battery technologies.

2.2.4. Threats:

- Risks associated with the removal of a policy or a subsidy.
- Opposition from conventional transportation industries.
- Challenges in market penetration arise from cost perception or technological adoption constraints.

2.3 Schedule Management

Project activities and tasks are structured using a schedule management framework with temporal factors. Details the necessary actions for the project's timely and budget-compliant conclusion. Establishing a schedule management system is essential for initiating a project, monitoring its advancement, and guaranteeing completion. The Gantt chart illustrates the project's timetable and phases, including all critical dates.

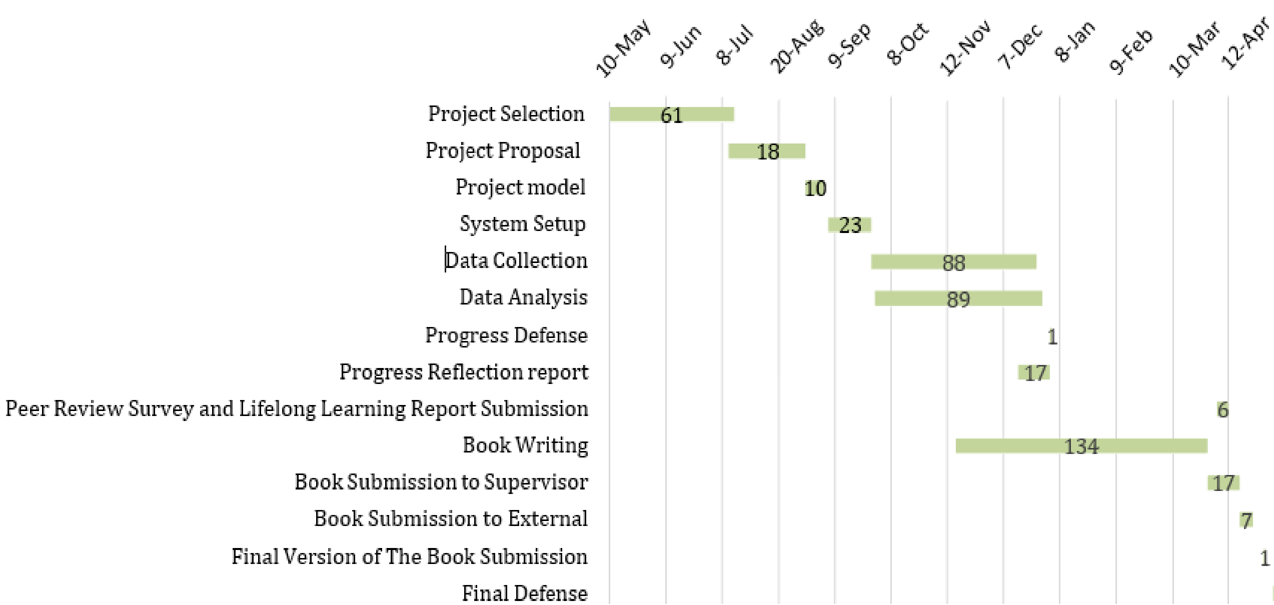

Figure 2.2: Gantt chart

2.4 Cost Analysis

Here, the total cost analysis of object detection and authentication devices is shown. The components' estimated price and buying price are displayed.

Table 2.1: Cost analysis of this project

Equipment List	**Quantity**	**Estimated Cost X (BDT)**	**Total Estimated Cost (BDT)**	**Market Price** X' **(BDT)**	X-X'	$(X\text{-}X')^2$
Solar Panel	1	9000	9000	8800	200	40000
Battery Protection Circuit	1	600	600	620	-20	400
ESP32	1	450	450	420	30	900
GPS Module	1	1600	1600	1580	20	400
Capacitor	5	230	230	220	10	100
Inductor	2	240	240	235	5	25
LCD Display	1	600	600	550	50	2500
MOSFET	2	70	70	130	-60	3600
MOSFET Gate Driver	1	120	120	123	-3	9
Resistor	10	25	25	20	5	25
Multimeter	1	1150	1150	1200	-50	2500
Current Sensor	2	400	400	430	-30	900
Schottky Diode	4	10	10	12	-2	4
Wire	4 sets	500	500	480	20	400
Veroboard	1	90	90	80	10	100
Miscellaneous	-	-	550	600	-50	2500
Total (N=16)						$\sum (X\text{-}X')^2$ =54363

The standard deviation, SD = $\sqrt{\frac{\sum((X-X'))^2}{n-1}} = \sqrt{\frac{54363}{16-1}}$ =60.2013289

2.5. P.E.S.T. Analysis

The PEST analysis is invaluable for assessing a project's current situation, prospects, and strategic course of action. Businesses and other organizations often do market analyses by considering political, economic, social, and technological (PEST) issues. A P.E.S.T. analysis considers different aspects, such as those related to the law and the environment.

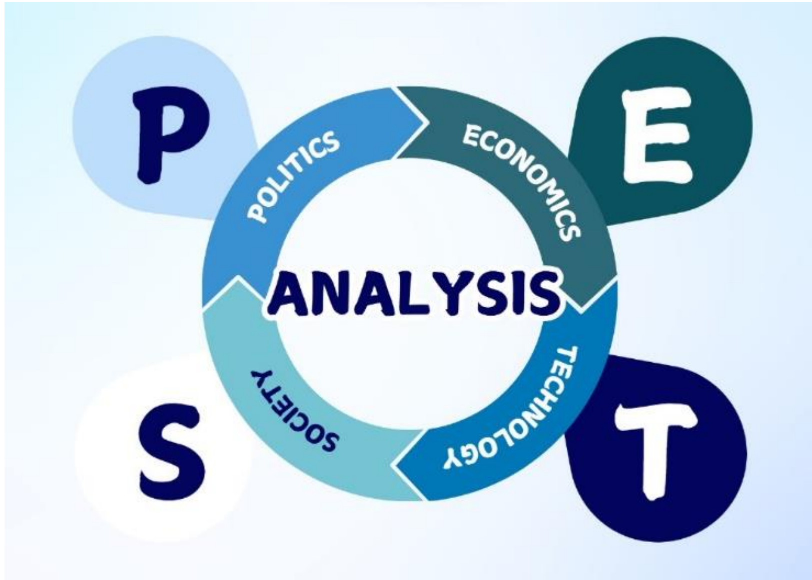

Figure 2.3: P.E.S.T. Analysis.

A PEST analysis frames the macro-environmental context of the project:

2.5.1. Political:

- Government policies promoting electric mobility.
- Import duties on EV components.
- Municipal backing for low-emission zones.

2.5.2. Economics:

- Fluctuating fuel prices create a demand for alternatives.
- Micro-loans and bank schemes for EV adoption.
- Operational savings offset high initial costs.

2.5.3. Social:

- Increasing environmental awareness among youth and urban commuters.
- Employment opportunities for local technicians and drivers.
- Resistance from traditional rickshaw owners.

2.5.4. Technological:

- Rapid advancement in solar cell and battery tech.
- Widespread mobile device access facilitates IoT integration.
- Emerging AI applications for predictive routing and diagnostics.

2.6. Professional Responsibilities

2.6.1. Norms of Engineering Practice

A professional role describes an individual's role in their work, which is their occupation. This principle is fundamental to all professional disciplines — law, health care, psychology, engineering, etc., as it lays out expectations for conduct and responsibility to clients, coworkers, and society.

Cored Pillar of Professional Duties

Ethical Responsibility: Professionals have ethical responsibilities regarding their behavior. This involves keeping information confidential, providing competent services, and avoiding conflicts of interest. Psychologists, for example, must ensure that they offer services that recognize cultural differences and preserve client confidentiality.

Accountability: Professionals are expected to assume responsibility for their actions and decisions. This involves being open about their methods and results, enabling stakeholders to make decisions based on reliable information. Taking accountability means having the maturity and long-range vision to admit to mistakes and take opportunities to learn from them for better practices in the future.

Ongoing Learning: We ask people to be lifelong learners and strive to be competent and professional at their jobs. It also helps professionals stay competitive, render quality services, and adapt to environmental changes.

Respect for Diversity: Professionals should respect the rights and dignity of all individuals and participate in creating an inclusive environment that enables diversity. This extends to respecting cultural differences and ensuring equal treatment for all clients.

Compliance with Legal Standards: Individuals must ensure they act by the laws and regulations that apply to their practice. The Seven Principles of Ethical Legal Practice - The legal profession is governed by ethical guidelines and a code of conduct to protect clients' rights and safeguard the profession's reputation.

Fostering a Collaborative Environment: Encourage interdisciplinary teamwork by including experts from various domains, including robotics, artificial intelligence, human-computer interaction, psychology, and ethics.

Documentation and Intellectual Property: Maintain detailed records of the design, development, and testing processes, including algorithms, source code, design specifications, and user documentation. Ensure that intellectual property rights are protected through appropriate mechanisms (e.g., patents, copyrights, trade secrets), and maintain an open-source approach to advance the field's growth faster.

2.6.2. Being a Dividual Contributor and a Cooperative Team Player

This is a capstone project, so all the group members work as a team. We divided the research work into different parts and assigned them to others.

Table 2.2: Contribution

Name	Contribution
Sayem Bin Helal	Prepared simulation, Design
	Prepared block diagram
	Prepared Chapter 1,3,5 and 6
	Responsible for book formatting
Shakib-ul Haque Chowdhury	Prepared Literature review and collected related research papers
	Arrange a workshop for the project hardware with members 01
	Collected required component information
	Prepared Chapters 2,4, and 5
Md. Saiful Abid Sirajee	Prepared Chapter 6
	Prepare the paper summary.
	Working to prepare the poster.
Md. Kamrul Hasan	Prepared Chapter 3
	Prepared block diagram
	Working on the paper summary

2.7. Management Principles and Economic Models

Management strategies adopted include:

2.7.1. Strategic Resource Allocation: The alignment of project execution with critical milestones and deliverables was significantly influenced by strategic resource allocation. The complexity and impact of each development stage were carefully considered when allocating manpower, time, and financial resources. Early on, most resources were allocated to high-priority areas, including integrating photovoltaic power systems, developing IoT infrastructure, and implementing advanced safety features to mitigate risks, expedite prototyping, and guarantee adherence to technical standards.

This concentrated strategy reduced delays, enhanced productivity, and facilitated a more efficient project completion process.

2.7.2. Lean Project Management: Lean project management principles were rigorously implemented to optimize the development of lifecycles, minimize waste, and improve efficiency. Value-focused design choices, just-in-time resource utilization, and meticulous planning were implemented to reduce material wastage and redundancy. Iterative development cycles were implemented throughout the project, allowing for rapid prototyping and ongoing enhancements informed by real-time performance testing, stakeholder input, and evolving technical requirements. In addition to expediting decision-making and minimizing revisions, this adaptive approach guaranteed that each project phase met or exceeded quality standards without resulting in unnecessarily high costs or delays.

2.7.3. Economic Models Used:

Life Cycle Costing (LCC): The exhaustive Life Cycle Costing analysis was employed to evaluate the total cost of ownership (TCO) of the system throughout its entire lifecycle, which encompassed initial design, prototyping, and deployment, as well as ongoing operation, maintenance, and eventual system retirement or upgrade. Direct and indirect costs, including energy consumption, capital expenditure, spare parts, service intervals, and decommissioning, were accounted for in this model. The energy-efficient components, such as solar-powered modules and intelligent energy management, significantly reduced the operational costs, while the system's modular architecture significantly reduced the long-term maintenance expenses. LCC provided a dependable framework for contrasting long-term savings with upfront investments, facilitating sustainable decision-making and informed financial planning.

Net Present Value (NPV): A Net Present Value analysis was implemented to evaluate the system's financial sustainability over a projected service life of 8–10 years. Cash flows were estimated using reduced fuel consumption, decreased maintenance frequency, and potential revenue from increased system availability and service reliability. To mitigate inflation and investment risk, a conservative discount rate was implemented. The investment would generate considerable net gains over time, as the NPV results were consistently positive across multiple urban transport scenarios. This bolsters the system's appeal as a sustainable and cost-effective solution for public transit stakeholders and fleet operators.

Breakeven Analysis: A comprehensive break-even analysis was conducted to ascertain the time necessary to recoup initial capital expenditures under typical urban operating conditions. In addition to energy cost savings from hybrid or entirely electric operation, the variables included average daily ridership, fare collection, and reduced maintenance overhead. On the assumption of consistent ridership and stable energy prices, the analysis indicated a break-even point of approximately three years. The short payback period further enhances the system's feasibility for adoption by small-scale transport entrepreneurs, private fleet managers, and public-private partnerships pursuing low-risk, high-return infrastructure investments.

2.8. Summary

This chapter details the comprehensive project management structure for developing the Next-Gen Easy Bike. It addresses project management, encompassing cost analysis, schedule management, and SWOT and PEST analyses. It comprises the project life cycle, the duties of various stakeholders, and the management of disparate components. SWOT and PEST analyses are implemented to assess both internal and external variables. Economic forecasts indicate that the market will expand, reducing prices because of the independent management of purchases, deliveries, and workshops. The project adheres to robust engineering management principles, including quality assurance, risk management, team collaboration, key performance indicators, and precise specifications. Sustainability is achieved by utilizing cost-benefit analysis and life cycle costing models to ensure long-term financial viability. The project is highly relevant to sustainable transport solutions with economic feasibility, as it addresses professional responsibilities such as ethics, stakeholder commitment, and innovation, all of which must be considered by the project.

Chapter 3

METHODOLOGY AND MODELING

3.1. Introduction

This chapter outlines the comprehensive methodology adopted for developing the Next-Gen Easy Bike, an intelligent, solar-powered electric bike integrated with Internet of Things (IoT)- based monitoring systems. The design uses an energy-efficient solar charging framework, smart navigation, and battery management systems to improve sustainability, reliability, and operational transparency.

The methodology integrates photovoltaic technology, embedded systems, MPPT control algorithms, power electronics, and real-time data communication. Emphasis is placed on creating a modular and cost-effective system that can function reliably under off-grid and grid-assisted conditions. A detailed working model, supported by a functional block diagram, explains how power flows from solar panels to the battery, how data is collected and transmitted via microcontrollers, and how safety and performance are maintained using protection circuits and user feedback interfaces. Each subsystem—from solar energy capture to data visualization—is modelled and implemented with real-world constraints, including power fluctuations, overvoltage risks, and user accessibility. By incorporating hardware and software-level techniques, the chapter provides a clear view of how the system components interact and function cohesively as an innovative solar-powered transportation platform.

3.2. Block Diagram and Working Principle

3.2.1 Working Principle

3.2.1.1. Photovoltaic (PV) Panels: A mounted solar panel harnesses solar energy, either a 200 Wp module or a 400 Wp module, installed on the roof of the easy bike, depending on the test scenario. This energy is then converted into electrical power through the photovoltaic effect. The solar cells absorb Photons from sunlight, causing electrons to become excited and generating direct current (DC).

3.2.1.2. MPPT Charge Controller: The output from the solar panel is connected to the input of a Maximum Power Point Tracking (MPPT) charge controller, which integrates a DC-DC boost converter in its design. The voltage and current generated by the solar panel are continuously monitored using algorithms such as Perturb & Observe, enabling the controller to operate the panel at its maximum power point. To meet the 60V battery's charging requirements, the lower voltage from the panel is internally stepped up using the boost converter. Energy is stored in an inductor and released through a controlled pathway involving a MOSFET, diode, and capacitor. The MOSFET is rapidly switched ON and OFF using Pulse Width Modulated (PWM) signals generated by the controller, ensuring efficient voltage regulation and stable charging performance.

3.2.1.3. ESP32 microcontroller: The ESP32 microcontroller manages all core system operations. Sensor data such as current, voltage, power, and GPS coordinates is collected, processed, and displayed in real time. Communication with the Neo-8M module is carried out via serial commands. Additionally, real-time data transmission to cloud platforms is handled by the ESP32 over Wi-Fi, allowing smooth and uninterrupted system monitoring. IoT-Based Monitoring System.

3.2.1.4. IoT: The ESP32 microcontroller implements an IoT-based monitoring system. Multiple current and voltage sensors and the Neo-8M GPS module collect real-time data. This data is transmitted via Wi-Fi to a cloud server, where users can access it remotely. This setup allows for continuous solar panel output and vehicle location monitoring, enabling efficient performance tracking and fault detection without needing physical inspection.

3.2.1.5. Overvoltage Protection: To prevent damage due to overcharging, an XH-M604 battery protection module is employed in the system. The module continuously monitors battery voltage and automatically disconnects the charging circuit when a predefined voltage threshold is exceeded. Threshold values are configured via onboard buttons, while real-time voltage readings are shown on the integrated digital display. When the upper voltage limit is reached, the internal relay of the XH-M604 interrupts the charging source, thus protecting the 60V lead-acid battery from degradation and other safety risks associated with overvoltage conditions. This protective mechanism ensures safe battery operation, extending lifespan and system reliability.

3.2.1.6. 60V Battery Pack: Depending on availability, energy is stored in a 60V lead-acid battery, either through the MPPT-regulated solar input or a grid-connected charger. During grid connection, charging is handled via a dedicated charger, while in off-grid conditions, energy is supplied by the solar system through the MPPT controller. The stored energy powers the motor and the system's electronic components. Battery overcharging is prevented through proper voltage monitoring and regulation, maintaining operational safety, and prolonging battery life. This hybrid charging approach enhances overall system reliability and flexibility.

3.2.1.7. Display: Real-time system parameters such as voltage, current, and power are displayed using a 20x4 character LCD module with an I2C interface. Through I2C communication, only two microcontroller pins (SDA and SCL) are required to transmit data, significantly minimizing the usage of GPIO pins. The ESP32 microcontroller continuously refreshes the LCD to present live measurements from the solar panel and the MPPT controller. In particular, the display provides the solar panel's output voltage, current, and power, along with the corresponding output values delivered by the MPPT controller to the battery.

Adopting the I2C interface allows for simplified wiring, efficient data communication, and seamless integration with the ESP32-based embedded control system, ensuring reliable real-time visualization of energy flow.

3.2.2 Block Diagram

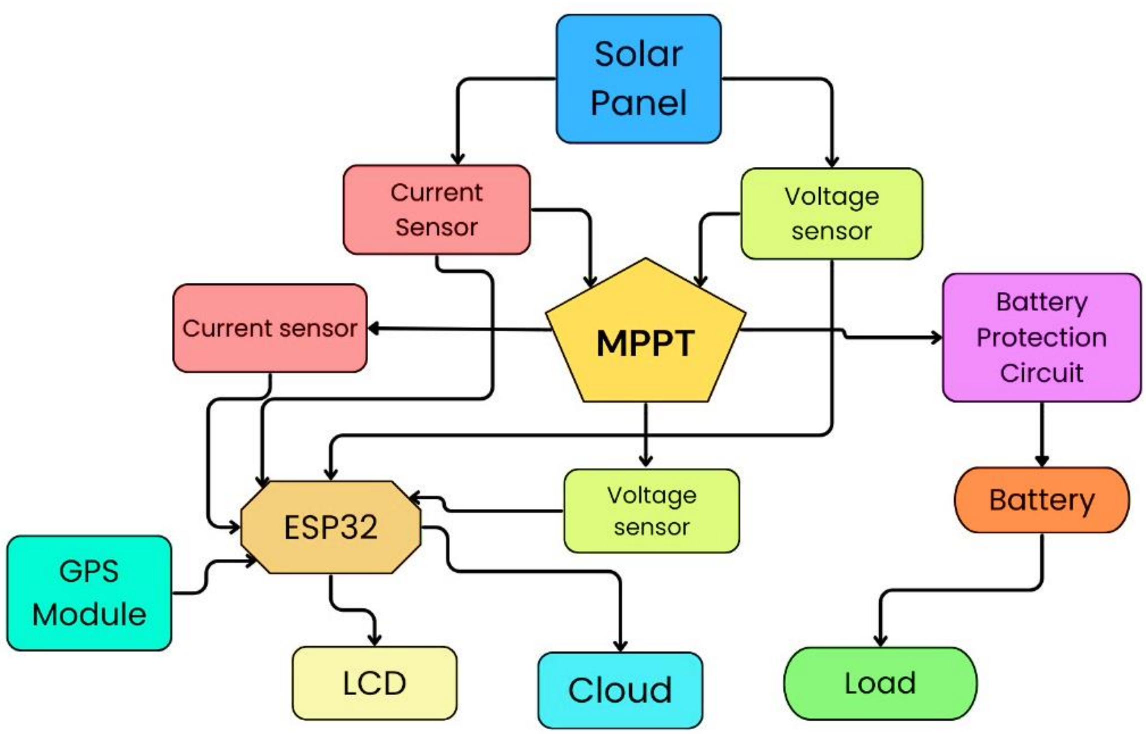

Figure 3.1: Block Diagram

Figure 3.1 illustrates a comprehensive block diagram of an innovative MPPT-based solar charge controller system integrated with IoT features and real-time location tracking. The system's primary component is the MPPT (Maximum Power Point Tracking) controller. It utilizes the Perturb and Observe (P&O) algorithm to extract the optimum power from the solar panel intelligently. The MPPT algorithm continuously monitors the solar panel's output with dedicated current and voltage sensors to adjust operating conditions and ensure dynamic optimal performance.

The MPPT controller regulates the power, and it is subsequently transmitted through a battery protection circuit to guarantee the safe charging and discharging of the connected battery. A voltage sensor installed at the output monitors the battery's condition. The system can operate in hybrid or standalone configurations due to the power routing from the battery to the load. The system utilizes an ESP32 microcontroller to facilitate real-time communication and monitoring. This microcontroller gathers sensor data and transmits it to the cloud platform for remote access and analytics. It also provides power to an LCD, giving users a real-time view of the system's status, current, and voltage.

The NEO-8M GPS module is a unique element of this system, as it allows for monitoring of the photovoltaic unit's geographical location. This is particularly advantageous in remote solar installations, disaster response units, or mobile solar setups, where geolocation data is essential for performance analytics or maintenance.

The system's intelligent incorporation of ESP32, sensors, MPPT control, and GPS monitoring makes it energy-efficient, connected, and intelligent. This enables enhanced performance, user monitoring, and location-aware energy management, rendering it optimal for modern renewable energy systems based on the Internet of Things (IoT).

3.3. Modeling

Figure 3.2: 3D model of Proposed Easy-Bike

A three-dimensional model meticulously crafted with a focus on modern utility and sustainability is represented by the compact, simple bike depicted in Figure 3.2. The design was created using AutoCAD software, enabling precise modeling and spatial visualization of the bike's construction and incorporating components. During daylight hours, a rooftop solar panel is positioned to capture solar energy. The solar power system is connected to a Maximum Power Point Tracking (MPPT) charge controller strategically installed within the driver's cabin to optimize real-time energy. This controller optimizes the charging efficacy of the battery by dynamically adjusting voltage and current, thereby enabling more efficient and rapid energy storage.

3.4. Summary

This chapter detailed the design and operational framework of the proposed system, centering around a solar-powered energy architecture regulated by an MPPT charge controller that included an integrated DC-DC boost converter. One of the principal storage units is a lead-acid battery with a voltage of 60V, which is supported by a hybrid charging setup. An ESP32 microcontroller coordinates real-time data collection and cloud connectivity for Internet of Things-based monitoring. An XH-M604 module provides battery protection, and live system feedback is provided by a 20x4 I2C LCD displaying the information. These elements combine to produce a scalable and dependable new energy platform to enable environmentally responsible urban transportation.

Chapter 4

PROJECT IMPLEMENTATION

4.1. Introduction

This chapter presents the implementation aspect of the "Next-Gen Easy Bike with Efficient Solar and Iot-Based Navigation System" project, which transitions from conceptual design and modelling to physical realization. It documents the meticulous execution of the project's primary components, which include software development, electrical cabling, and mechanical construction. The mechanical assembly was composed of the structural integration of the solar module, battery enclosure, and mounting hardware, according to the criteria established in previous chapters. The ESP32 microprocessors, current and voltage sensors, MPPT charge controllers, solar panels, and ancillary modules such as the Neo-8M GPS and XH-M604 battery protection circuit were used to construct the parallel electrical subsystem.

Real-time monitoring, cloud-based data transmission over Wi-Fi, and interaction with the LCD module to display system metrics were all enabled by the software component of the solution, which included the development of ESP32 firmware. The IoT-based system facilitates remote diagnostics and route optimization by collecting data from numerous sensors and transmitting it to a cloud platform for user access. Throughout the implementation process, the design models detailed in Chapter 3 were directly referenced to ensure consistency in architecture and functionality. This stage's interdisciplinary nature demonstrates a solid integration of software, mechanical, and electrical engineering methodologies.

4.2. Required Tools and Components

4.2.1. Solar Panel

The solar panel is a critical system component, converting sunlight into usable electrical energy through photovoltaic (PV) technology. This electrical energy is subsequently stored in the easy bike's battery, which powers the electric drivetrain and other onboard systems. The design significantly reduces dependence on conventional grid electricity by utilizing renewable solar power, thus enhancing overall energy sustainability and operational autonomy.

The integration of solar energy not only lowers operating costs by minimizing fuel or electricity expenses but also contributes to environmental conservation by reducing carbon emissions and fossil fuel consumption. Furthermore, this self-sustaining energy model ensures that the bike can function independently of the national power grid, making it an ideal solution for off-grid or remote areas with limited or unreliable electricity infrastructure. In addition, the solar system is designed to work in tandem with the MPPT charge controller, which ensures that the energy harvested is maximized under varying light conditions. This enhances both the efficiency and reliability of the power supply. Such integration of clean energy technologies positions the easy bike as a forward-thinking solution aligned with global sustainability goals and smart mobility trends.

Figure 4.1: Solar Panel

4.2.2. Battery Protection Circuit

The battery protection circuit guarantees the battery's safe operation. It safeguards the battery from potential hazards, including severe discharge, overcharging, and short circuits. This component is essential for the battery's longevity, which reduces long-term maintenance costs and guarantees reliable performance over time. It does so by protecting the battery.

Figure 4.2: Battery Protection Circuit

4.2.3. ESP32 (Microcontroller)

The ESP32 is a highly adaptable microcontroller that incorporates Wi-Fi and Bluetooth, facilitating the easy integration of IoT capabilities. It is the central controller, enabling communication with external systems such as ThingSpeak and coordinating the bike's electrical systems.

Through its involvement in real-time data collection and control, it guarantees optimal system integration and operation.

Figure 4.3: ESP32 (Microcontroller)

4.2.4. GPS module

This is a critical navigation component that supplies the necessary location data. This module enables the IoT system to optimize routes, monitor the bike's journey, and provide real-time guidance to the rider by facilitating accurate position tracking. Integrating GPS data with IoT-based navigation improves the bike's operational efficiency by ensuring the user follows the most energy-efficient paths.

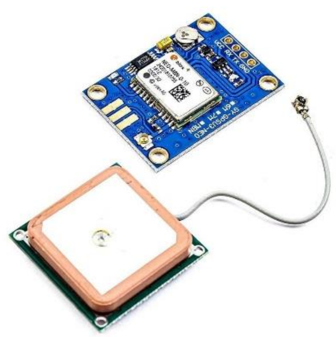

Figure 4.4: GPS module

4.2.5. Capacitors

It is employed to mitigate power fluctuations, thereby guaranteeing dependable and consistent operation. They temporarily store and release electrical energy, when necessary, especially in systems powered by variable sources such as solar energy. The easy bike's performance is safeguarded by capacitors, guaranteeing that energy transfer remains consistent and prevents disruptions.

4.2.6. Inductors

Inductors store energy as a magnetic field when the current passes through them. They regulate the flow of electricity, emphasizing the energy transfer from the solar panels to the battery. They are crucial in preserving the power system's efficacy and smoothing the conversion and storage of energy.

4.2.7. LCD Display

The LCD provides the passenger with critical information, such as the battery, speed, and navigation data. It improves the user's experience by delivering real-time updates, ensuring riders are always informed about the easy bike's performance and operational status. This element facilitates efficient navigation and energy consumption management for passengers.

4.2.8. MOSFET

It regulates the flow of electrical current and the power transfer between this system's solar panels, battery, and other components. Its function is essential in regulating the easy bike's electrical system efficiently and optimally distributing power.

4.2.9. MOSFET Gate Driver

The MOSFET gate driver is responsible for operating the gate of the MOSFET to facilitate proper switching and ensure its correct operation. Controlling the operation of the MOSFETs is essential for ensuring that the electrical components function seamlessly and that power is distributed efficiently throughout the system.

4.2.10. Resistors

Resistors regulate the passage of electrical current, guaranteeing that the system operates within safe electrical parameters. They are essential for preventing potential damage from excessive power flow, protecting sensitive components, and managing voltage and current levels.

4.2.11. Multimeter

The multimeter is critical for measuring the system's voltage, current, and resistance. It enables engineers and technicians to diagnose potential issues, verify the performance of the components, and ensure that the system is functioning as intended during the development and testing phases.

4.2.12. Current Sensor

Current sensors monitor the electrical current traveling through various system components. These sensors are essential for managing the power supplied by the solar panels and stored in the battery, as they provide real-time data on the bike's energy consumption. The current sensor guarantees the system's efficiency by optimizing energy consumption.

4.2.13. Schottky Diode

Schottky diodes prevent the passage of reverse current into the system, safeguarding sensitive components from damage. They permit the passage of current in a single direction, which is essential for the system to operate safely and efficiently and to preserve the integrity of the power flow.

Figure 4.5: Schottky Diode

4.2.14. Connecting Wire

Wires establish connections between the system's diverse electrical components. They are indispensable for transmitting power and signals between the microcontroller, battery, solar panels, and other elements. The quality of the wiring guarantees the system's seamless operation and reduces the risks of electrical failures.

4.2.15. PCB (Printed Circuit Board)

PCBS mounts and interconnects electronic components compactly and efficiently. They optimize space utilization and prevent electrical faults by organizing the system's electrical components and ensuring their secure connection.

4.2.16. Miscellaneous

This category encompasses a variety of minor components, such as screws, connectors, frame and other materials that are necessary for the physical assembly of the system. Although these minor components are essential for the easy bike's construction and incorporation, ensuring all parts are aligned correctly and function as a cohesive unit is crucial.

4.3. Implemented Models

4.3.1. Simulation Model

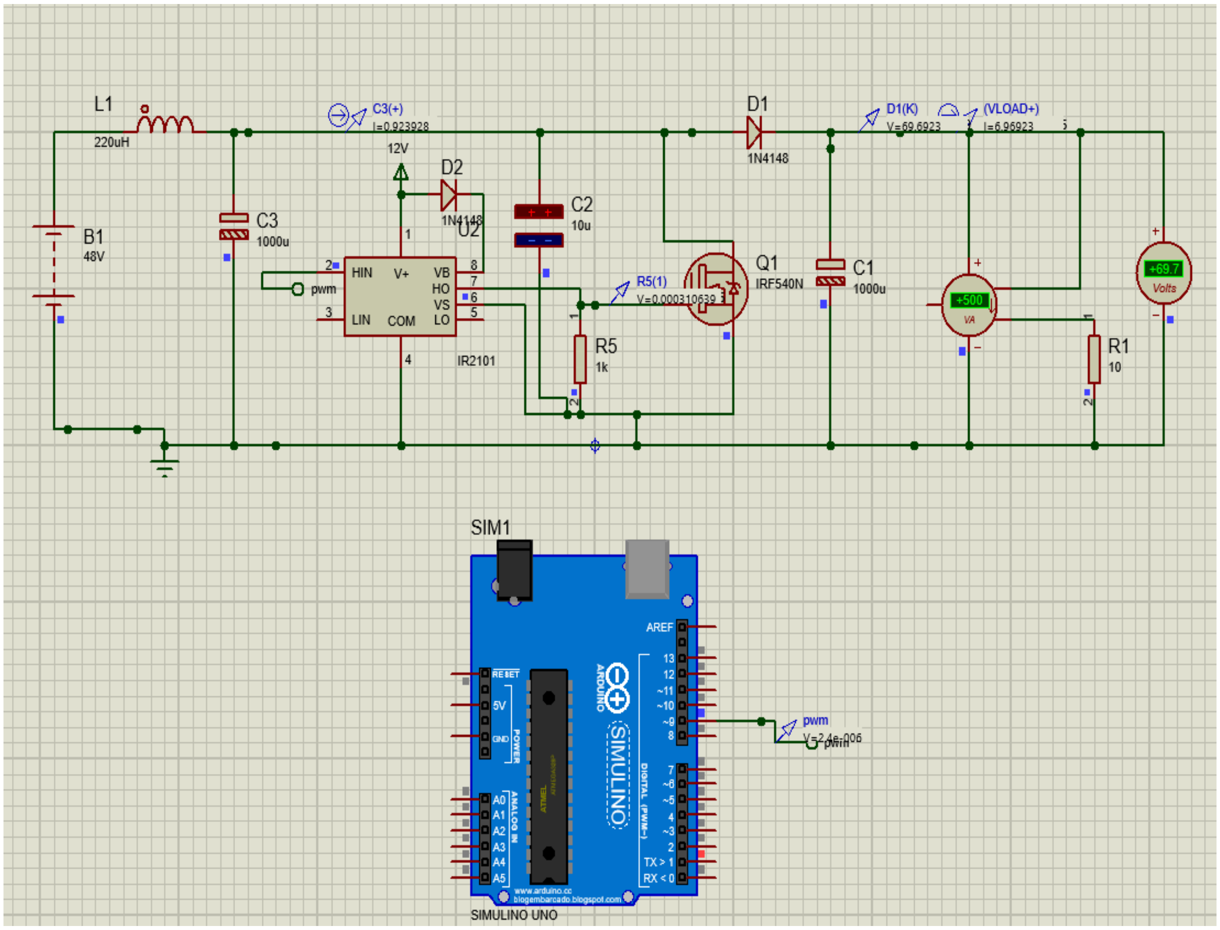

Figure 4.6: Maximum Power Point Tracking (MPPT) Boost Converter

Applying the Perturb and Observe (P&O) algorithm to optimize power extraction, this circuit is an MPPT (Maximum Power Point Tracking) charge controller expressly engineered for solar charging applications. It employs PWM control to implement MPPT logic using an Arduino UNO. The input side is supplied with power from a 48V DC source, typically a solar panel. This power is subsequently amplified by a high-frequency switching converter constructed around an IRF540N MOSFET and a 220µH inductor. The IR2101 gate driver, which is supplied with a PWM signal from the Arduino, is responsible for MOSFET toggling. A bootstrap circuit consisting of capacitor C2 and diode D2 guarantees proper high-side MOSFET operation. The boost converter's output is filtered by a 1000µF capacitor (C1) and then distributed to the battery or load via a sensing resistor (R1).

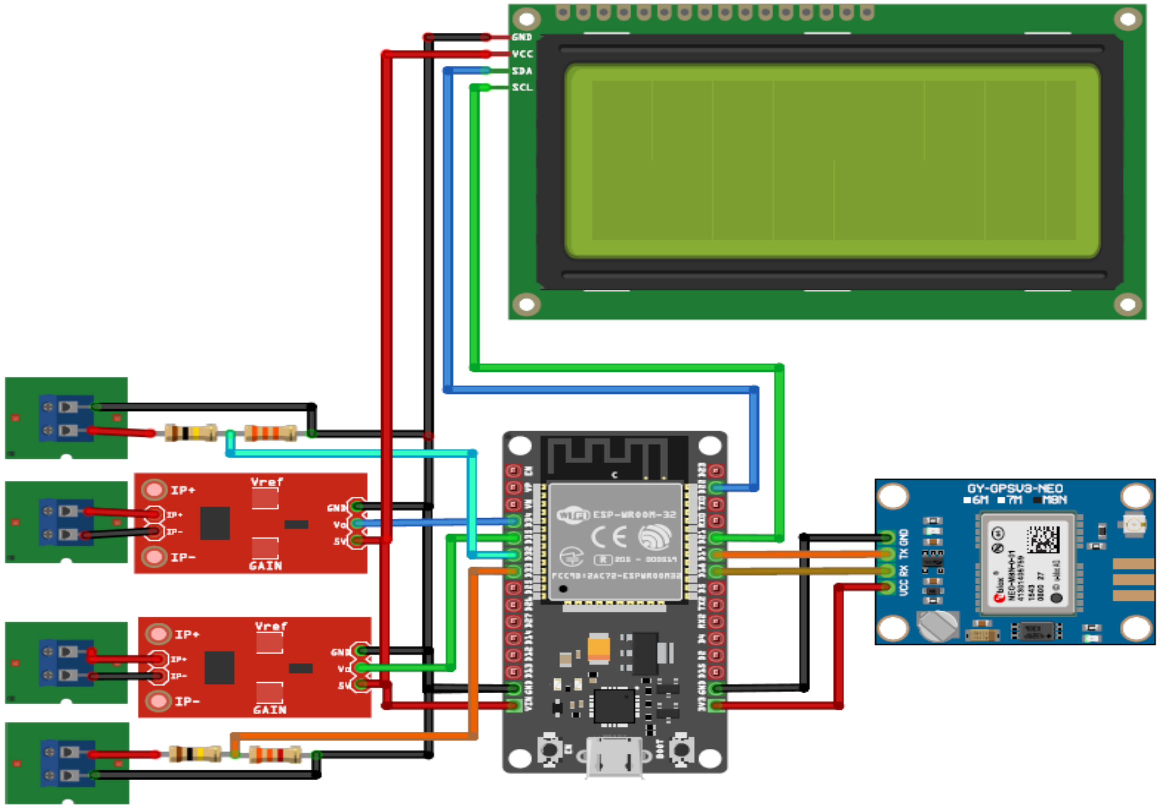

Figure 4.7: Data Logger

This circuit diagram illustrates an advanced data logger system that is ESP32-based and integrated with GPS monitoring. It is intended to capture, display, and potentially transmit real-time data from a solar power system. The ESP32 microcontroller, which is selected for its integrated Wi-Fi and Bluetooth capabilities, is the foundation of this configuration. This makes it an optimal choice for IoT applications. The system interfaces with ACS712 (30a) sensors, which are responsible for monitoring current, and a voltage divider is accountable for sensing voltage at various locations, including the solar panel and battery, allowing for precise energy tracking. Minimal pin utilization and efficient data acquisition are guaranteed by these sensors' communication with the ESP32 via the I2C protocol (SDA and SCL lines).

A 20x4 I2C LCD is connected to enable the user to directly view real-time voltage, current, and power readings, thereby providing immediate, on-site feedback. This improves system usability, particularly in remote or off-grid environments with restricted PC or mobile access. What distinguishes this system is the integration of a NEO-8M GPS module, which communicates with the ESP32 via UART. This module lets the device record the precise geographic location with electrical data, rendering the system more practical.

This system is a powerful, field-deployable solar data logger due to its real-time data display, GPS-based location monitoring, and voltage and current sensing. It can record critical data for system optimization and performance analysis. Additionally, the configuration can be expanded to log data to the cloud using ESP32's connectivity capabilities.

4.3.2. Hardware Model

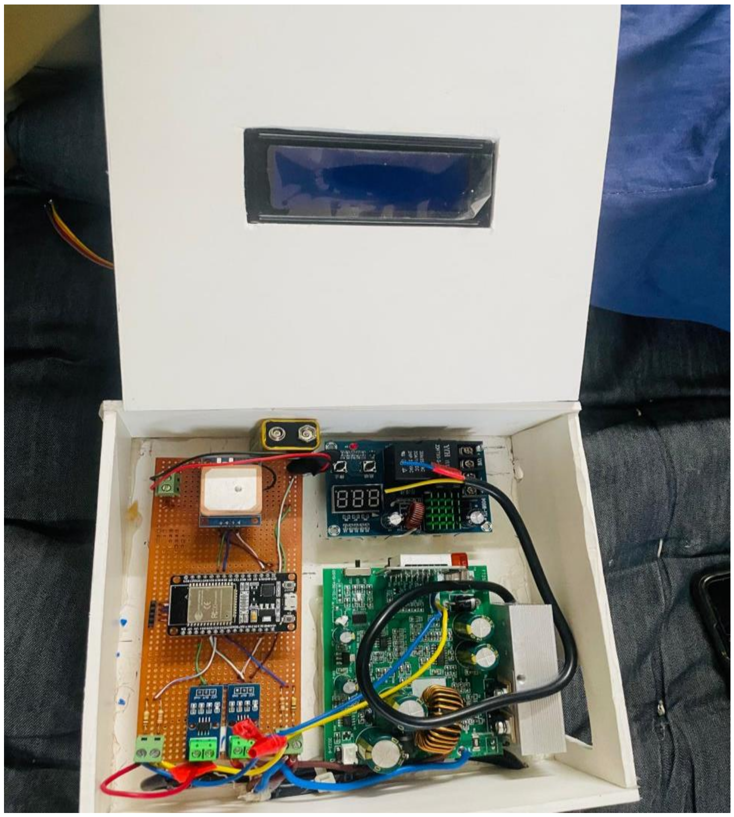

Figure 4.8: MPPT (Maximum Power Point Tracking) Charge Controller

A smart MPPT (Maximum Power Point Tracking) charge controller integrated with a battery protection circuit is contained in a sleek, purpose-built enclosure in this innovative and efficiently crafted project. An ESP32 microcontroller is the central component of the device, which is responsible for real-time monitoring and intelligent power regulation. Location-based solar optimization is facilitated by a GPS module, which improves functionality. A high-efficiency DC-DC Boost converter with a heatsink ensures stable charging under fluctuating solar inputs. At the same time, the custom PCB incorporates voltage regulators, terminal blocks, and sensors with a clean layout. The battery protection circuit enhances system safety and longevity by preventing overcharging, deep discharge, and reverse polarity. An external LCD mounted on the lid enables user interaction and live system data display.

This solution is suitable for real-world solar energy applications with robust and safe energy delivery, demonstrating a combination of precise power management, IoT capability, and innovative electronics. It is also compact and portable.

4.3.3. Final Assembly and Integration

Easy Bike is intended to promote sustainable urban transportation. The initial image depicts the vehicle's final assembly, which is ideal for passenger use due to its compact design, and rooftop solar panel. Power transfer from the solar panel to the battery is optimized by a white MPPT charge controller installed within. The LED screen of the MPPT controller is depicted in the second image, displaying real-time data including input/output voltage, current, and power, which implies efficient energy conversion. This configuration underscores the emphasis of Easy Bike on clean, efficient, and intelligent mobility.

Figure 4.9: Final Assembly

Figure 4.10: LED Display (MPPT Charge Controller Output)

4.4. Summary

This chapter has comprehensively documented the entire implementation process of the proposed solar-powered Easy Bike system, transforming theoretical models into a functional prototype. The development team effectively assembled all mechanical components and interconnected the electrical modules, including the solar charging system, MPPT controller, microcontroller, GPS module, and display interface. The ESP32 microcontroller was programmed to manage sensor data collection and enable wireless communication, allowing for real-time location tracking and IoT-based monitoring of system performance.

Additional measures were implemented to guarantee operational safety and efficiency, including hybrid charging capabilities and battery overvoltage protection. The local display of voltage, current, and power parameters was utilized through the I2C LCD interface, further improving usability. The implementation results demonstrated the system's operational stability and alignment with the intended design objectives. The solution's technical feasibility and suitability for real-world deployment were established during this phase, establishing the foundation for the performance evaluation and testing procedures discussed in the subsequent chapter.

Chapter 5

RESULTS ANALYSIS & CRITICAL DESIGN REVIEW

5.1. Introduction

This chapter provides an in-depth analysis of the results acquired from the Next-Gen Easy Bike, which is equipped with an efficient solar charging system and IoT-based navigation, via simulation models and hardware implementation. Performance, reliability, and efficacy of the designed system are assessed in this chapter under controlled and real-world conditions. For the analysis, simulated outputs from MATLAB/Simulink and Proteus simulation models, such as Maximum Power Point Tracking (MPPT) efficiency and power conversion, are compared with empirical data collected from the physical prototype. Critical reviews of critical performance metrics, including power generation, battery charging efficiency, and IoT system responsiveness, are conducted to evaluate the extent of compatibility between anticipated and actual system behavior.

Furthermore, this chapter addresses the technical obstacles encountered during the implementation process, such as network connectivity issues, hardware integration complications, and limitations associated with solar irradiance variability. The solar-powered Easy Bike is also assessed in terms of its environmental and economic effects compared to a conventional electric easy bike.

The chapter synthesizes these findings to assess the system's weaknesses and strengths, providing valuable insights for future optimization and potential scalability. This assessment is imperative to verify the feasibility and sustainability of using easy bikes equipped with solar and IoT technology in urban and peri-urban settings, particularly in developing countries such as Bangladesh.

5.2. Results Analysis

5.2.1. Calculation

For the calculation, we selected a few sample data points from our actual dataset, which were recorded at specific times throughout the day. Based on these samples, we performed an energy calculation. The sample data is given below.

Table 5: Collected Data

SL No.	Time (H)	Power (W)
01.	11.17	278.61102
02.	11.38	268.28311
03.	11.53	248.0715
04.	12.06	306.82022
05.	12.1	318.97556
06.	12.18	278.82199
07.	12.37	248.40439
08.	12.58	240.17232
09.	13.38	253.46111
10.	13.39	260.74139
11.	13.45	270.66608
12.	14.2	241.90651
13.	14.55	218.37831
14.	15.04	201.69203
15.	15.22	164.55267
16.	15.29	181.19267
17.	16.02	96.44308
18.	16.17	76.30769
19.	16.27	60.95238

Our project collected power data at specific time points rather than continuously. Although this results in minor gaps between measurements, it does not significantly affect the energy calculation, provided that the power variation between the recorded points is smooth and gradual. The Trapezoidal Rule was applied to estimate the total energy delivered by the system. This method is particularly suitable for discretely sampled data, as it approximates the area under the power-time curve by assuming a linear transition between two consecutive measurements. While a higher sampling rate would enhance precision, the selected approach offers a reliable and practical estimation of total energy based on the available sample data. The Trapezoidal Rule to approximate total energy:

$$E = \sum_{i=1}^{n-1} \left(\frac{P_i + P_{i+1}}{2}\right) \cdot (t_{i+1} - t_i)$$

$$=> E = \sum_{i=1}^{n-1} (E_i)$$

Where:

- P_i = power in watts at time t_i
- t_i = time in hours
- n = 19 (so, we have 18 intervals)

Interval 1:

$t_1 = 11.2833$, $t_2 = 11.6333$

$P_1 = 278.61$ W, $P_2 = 268.28$ W

$$So, E_1 = \left(\frac{278.61+268.28}{2}\right) \times 0.35 = 273.45 \times 0.35 = 95.71 \text{ Wh} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Interval 2:

$t_1 = 11.6333$, $t_2 = 11.8833$

$P_1 = 268.28$ W, $P_2 = 248.07$ W

$$So, E_2 = \left(\frac{268.28 + 248.07}{2}\right) \times 0.25 = 258.18 \times 0.25 = 64.54 \text{ Wh} \ldots\ldots\ldots\ldots \; (2)$$

Interval 3:

$t_1 = 11.8833$, $t_2 = 12.1000$

$P_1 = 248.07$ W, $P_2 = 306.82$ W

$$So, E_3 = \left(\frac{248.07 + 306.82}{2}\right) \times 0.2167 = 277.45 \times 0.2167 = 60.11 \text{ Wh} \ldots..(3)$$

Interval 4:

$t_1 = 12.1000$, $t_2 = 12.1667$

$P_1 = 306.82$ W, $P_2 = 318.98$ W

$$So, E_4 = \left(\frac{306.82 + 318.98}{2}\right) \times 0.0667 = 312.90 \times 0.0667 = 20.86 \text{ Wh} \ldots..(4)$$

Interval 5:

$t_1 = 12.1667$, $t_2 = 12.3000$

$P_1 = 318.98$ W, $P_2 = 278.82$ W

$$So, E_5 = \left(\frac{318.98 + 278.82}{2}\right) \times 0.1333 = 298.90 \times 0.1333 = 39.85 \text{ Wh} \ldots(5)$$

Interval 6:

t_1 = 12.3000, t_2 = 12.6167

P_1 = 278.82 W, P_2 = 248.40 W

$$So, E_6 = \left(\frac{278.82 + 248.40}{2}\right) \times 0.3167 = 263.61 \times 0.3167 = 83.48 \text{ Wh} \ldots. (6)$$

Interval 7:

t_1 = 12.6167, t_2 = 12.9667

P_1 = 248.40 W, P_2 = 240.17 W

$$So, E_7 = \left(\frac{248.40 + 240.17}{2}\right) \times 0.35 = 244.29 \times 0.35 = 85.5 \text{ Wh} \ldots\ldots\ldots\ldots (7)$$

Interval 8:

t_1 = 12.9667, t_2 = 13.6333

P_1 = 240.17 W, P_2 = 253.46 W

$$So, E_8 = \left(\frac{240.17 + 253.46}{2}\right) \times 0.6667 = 246.82 \times 0.6667 = 164.54 \text{ Wh} \ldots (8)$$

Interval 9:

t_1 = 13.6333, t_2 = 13.6500

P_1 = 253.46 W, P_2 = 260.74 W

$$So, E_9 = \left(\frac{253.46 + 260.74}{2}\right) \times 0.0167 = 257.10 \times 0.0167 = 4.29 \text{ Wh} \ldots\ldots (9)$$

Interval 10:

t_1 = 13.6500, t_2 = 13.7500

P_1 = 260.74 W, P_2 = 270.67 W

$$So, E_{10} = \left(\frac{260.74 + 270.67}{2}\right) \times 0.1 = 265.70 \times 0.1 = 26.57 \text{ Wh} \ldots\ldots\ldots\ldots\ldots (10)$$

Interval 11:

t_1 = 13.7500, t_2 = 14.3333

P_1 = 270.67 W, P_2 = 241.91 W

$$So, E_{11} = \left(\frac{270.67 + 241.91}{2}\right) \times 0.5833 = 256.29 \times 0.5833 = 149.5 \text{ Wh} \ldots\ldots\ldots\ldots (11)$$

Interval 12:

t_1 = 14.3333, t_2 = 14.9167

P_1 = 241.91 W, P_2 = 218.38 W

$$So, E_{12} = \left(\frac{241.91 + 218.38}{2}\right) \times 0.5833 = 230.14 \times 0.5833 = 134.25 \text{ Wh} \ldots\ldots\ldots\ldots (12)$$

Interval 13:

t_1 = 14.9167, t_2 = 15.0667

P_1 = 218.38 W, P_2 = 201.69 W

$$So, E_{13} = \left(\frac{218.38 + 201.69}{2}\right) \times 0.15 = 210.04 \times 0.15 = 31.51 \text{ Wh} \ldots\ldots\ldots\ldots (13)$$

Interval 14:

t_1 = 15.0667, t_2 = 15.3667

P_1 = 201.69 W, P_2 = 164.55 W

$$So, E_{14} = \left(\frac{201.69 + 164.55}{2}\right) \times 0.3 = 183.12 \times 0.3 = 54.94 \text{ Wh} \ldots\ldots\ldots\ldots (14)$$

Interval 15:

t_1 = 15.3667, t_2 = 15.4833

P_1 = 164.55 W, P_2 = 181.19 W

$$So, E_{15} = \left(\frac{164.55 + 181.19}{2}\right) \times 0.1167 = 172.87 \times 0.1167 = 20.17 \text{ Wh} \ldots\ldots\ldots\ldots (15)$$

Interval 16:

$t_1 = 15.4833, t_2 = 16.0333$

$P_1 = 181.19$ W, $P_2 = 96.44$ W

$$So, E_{16} = \left(\frac{181.19 + 96.44}{2}\right) \times 0.55 = 138.82 \times 0.55 = 76.35 \text{ Wh} \ldots\ldots\ldots\ldots (16)$$

Interval 17:

$t_1 = 16.0333, t_2 = 16.2833$

$P_1 = 96.44$ W, $P_2 = 76.31$ W

$$So, E_{17} = \left(\frac{96.44 + 76.31}{2}\right) \times 0.25 = 86.38 \times 0.25 = 21.59 \text{ Wh} \ldots\ldots\ldots\ldots (17)$$

Interval 18:

$t_1 = 16.2833, t_2 = 16.4500$

$P_1 = 76.31$ W, $P_2 = 60.95$ W

$$So, E_{18} = \left(\frac{76.31 + 60.95}{2}\right) \times 0.1667 = 68.63 \times 0.1667 = 11.44 \text{ Wh} \ldots\ldots\ldots\ldots (18)$$

Therefore, total energy, E $= E_1 + E_2 + E_3 + E_4 + E_5 + E_6 + E_7 + E_7 + E_8 + E_9 + E_{10} + E_{11} + E_{12} + E_{13} + E_{14} + E_{15} + E_{16} + E_{17} + E_{18}$

E = 1145.2 Wh = 1.15 kWh

Finally, Yearly energy = 1.15 kWh/day×365 days = 419.75 kWh

Nevertheless, the estimated energy output increases proportionally when the data collection period is extended to 10 hours per day, which provides a more comprehensive representation of a typical sunny day. The daily energy generation is anticipated to be approximately 2.05 kWh during this extended observation. This value can be used to compute the revised yearly energy output as follows:

10 hours of annual energy consumption equals 2.05 kWh per day

Finally, Yearly energy = 2.05 kWh/day×365 days = 748.25 kWh

This comprehensive data collection enables a more precise and realistic assessment of annual energy generation, particularly in regions that receive abundant sunlight throughout the day.

CO2 Emission factors:

According to the EPA and IEA:

- The coal-based power plant emits 1 kg CO_2 /kWh [27]
- The diesel-based power plant emits 0.73 kg CO_2 /kWh [27]
- The natural gas-based power plant emits 0.44 kg CO_2 /kWh [28]

Therefore, Annual CO_2 reduction:

CO_2 reduction from coal-based power plants = 748.25 × 1 = 748.25kg CO_2

CO_2 reduction from diesel-based power plants = 748.25 × 0.73 = 546.23kg CO_2

CO_2 reduction from natural gas-based power plants = 748.25 × 0.44 = kg CO_2

Energy production cost savings:

According to the BPDB 2022-2023 report, the per-unit energy production cost is 11.03 Taka.[28]

Therefore, the Amount saved per year is = 748.25 ×11.03 =8253.19 taka per year.

5.2.2. Simulated Results

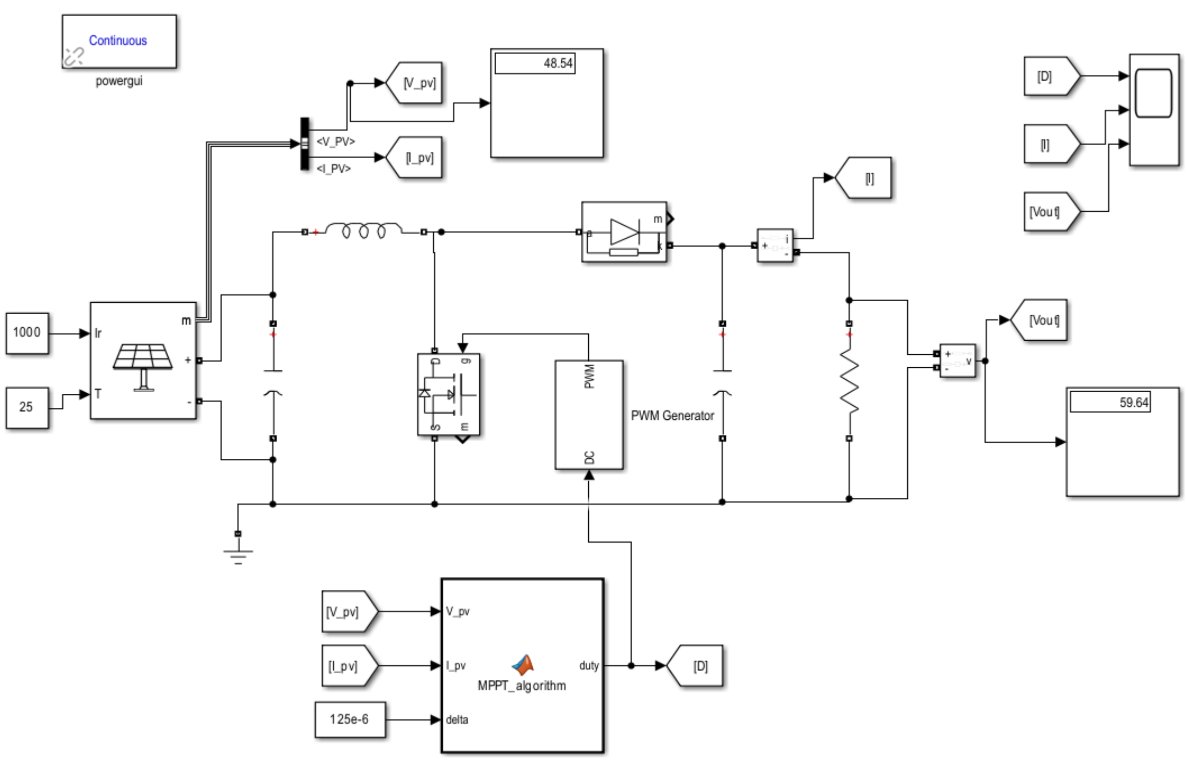

Figure 5.1: Simulink Model of MPPT Charge Controller

This is a Simulink block diagram of a charge controller system that utilizes MPPT (Maximum Power Point Tracking). Electrical power is generated by a solar panel model fed by temperature and solar irradiance. By measuring the voltage and current of the panel, the system provides these values to an MPPT algorithm block. A duty cycle signal is generated by this algorithm and transmitted to a PWM generator, which regulates the power flow by using a switching device. Additional circuit components, such as capacitors, resistors, and inductors, contribute to the stabilization and smoothing of the voltage and current. Additionally, the model comprises display blocks that exhibit voltage and current measurements at various locations, indicating the system's capacity to extract the maximum power from the solar panel.

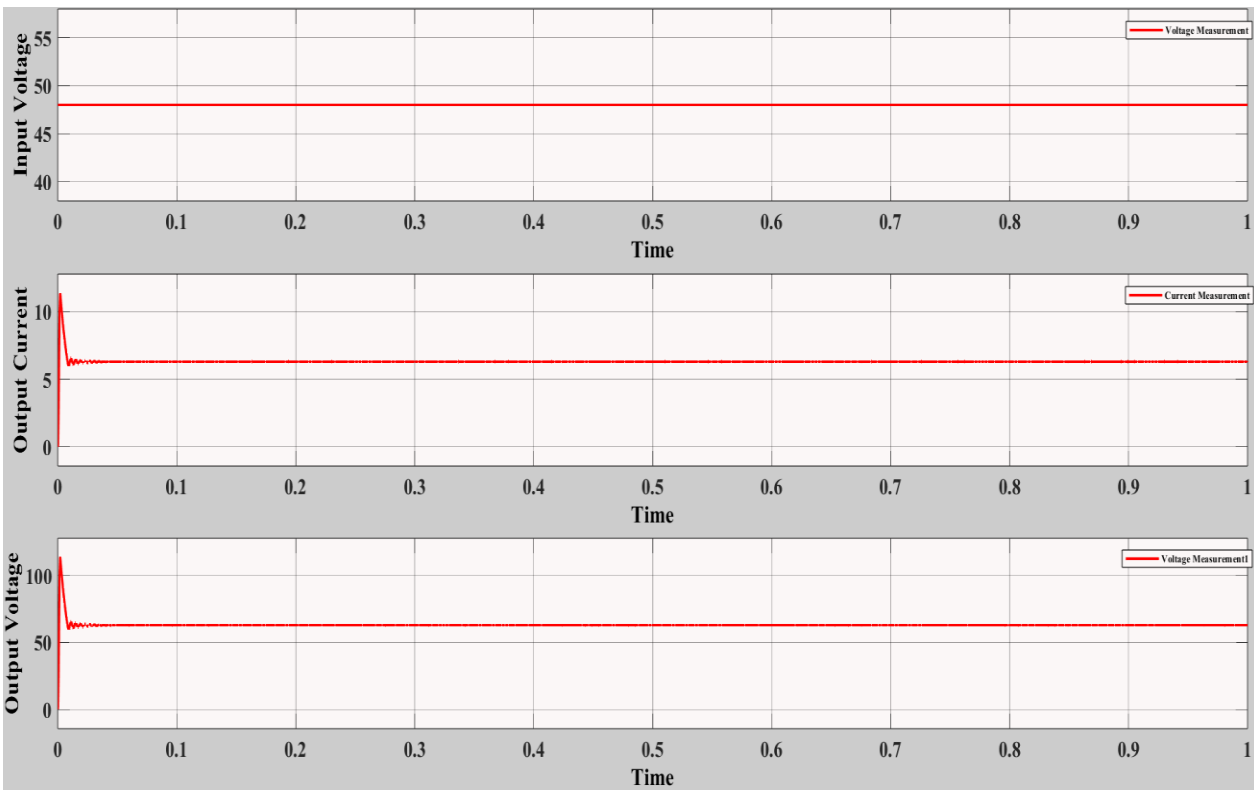

Figure 5.2: Output of MPPT Charge Controller

Three time-based graphs are displayed in this image, which illustrate the dynamic output of the MPPT charge controller system. The voltage in the initial plot stabilizes at approximately 48 volts following an initial transient period. The second plot depicts the current production, which rapidly returns to a consistent value after a brief surge. The third diagram illustrates an additional voltage measurement at a distinct location in the circuit, which stabilized at approximately 58.75 volts following an initial transient. These findings demonstrate the MPPT charge controller's ability to regulate voltage efficiently and current to optimize power extraction and ensure stable operation under the specified circumstances.

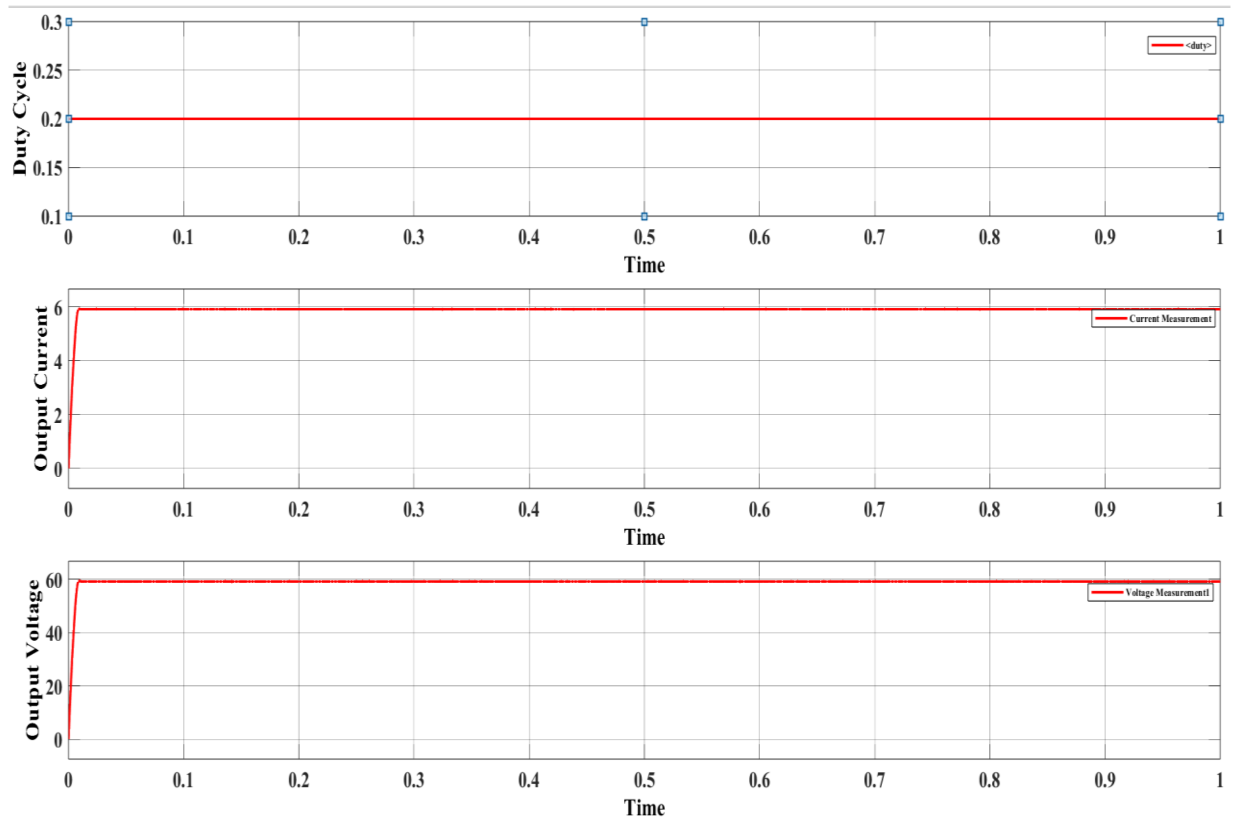

Figure 5.3: Output curve of Voltage, Current and Duty cycle

The transient response of the system over a one-second interval is illustrated in the figure by three graphs. The duty cycle in the upper plot remains constant at 0.2 for the duration of the period, suggesting that the PWM control signal is consistent and unwavering. The output current is illustrated in the middle plot, where it experiences a rapid ascent from near zero to approximately 6 amperes within the first 0.05 seconds. Subsequently, it remains at this level for the duration of the time frame. In the same vein, the output voltage is depicted in the bottom diagram, where it experiences a rapid increase from zero to approximately 60 volts within the first 0.05 seconds before stabilizing. These responses illustrate that the system rapidly achieves stable operating conditions with consistent voltage and current outputs under a fixed duty cycle.

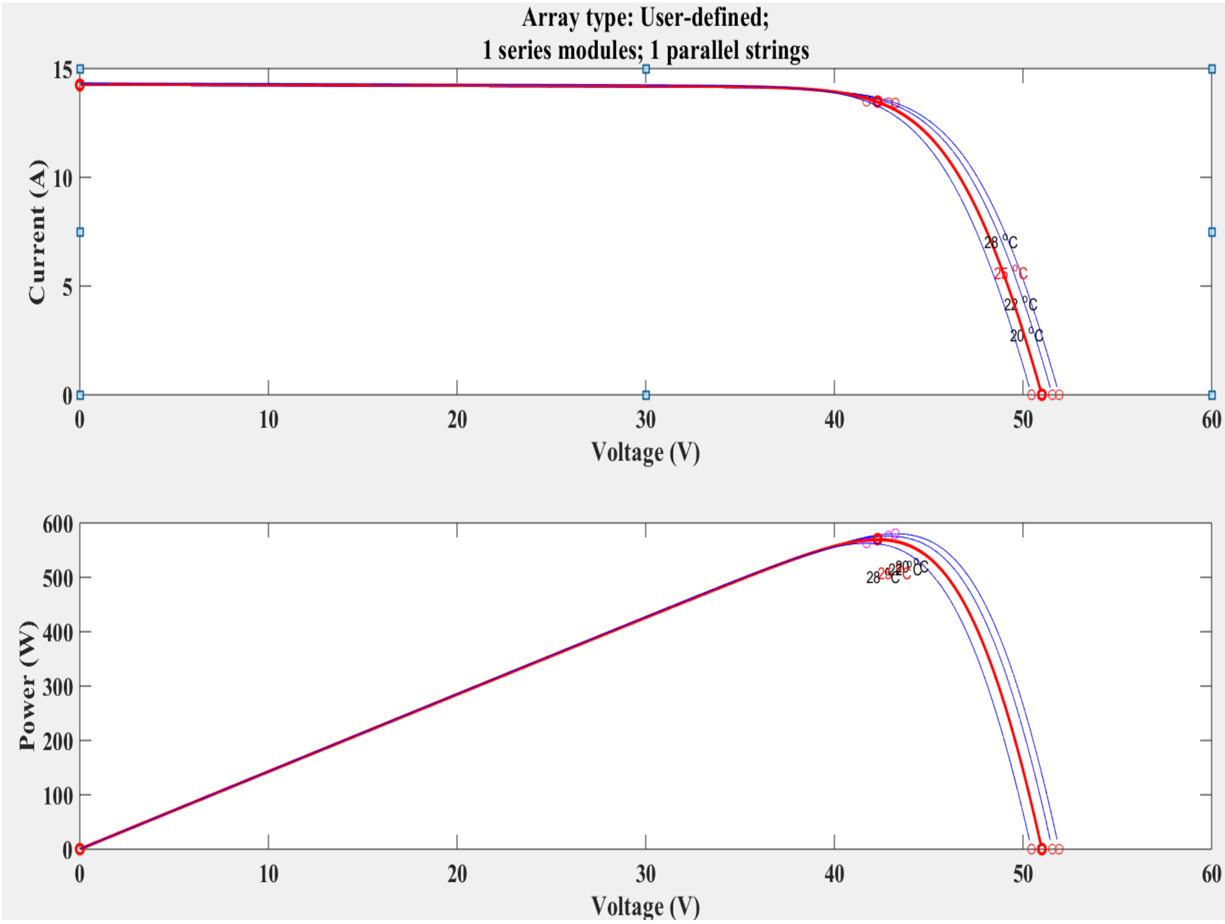

Figure 5.4: Constant Irradiance (1000 W/m2) Varying Temperature

Figure 5.3 illustrates the impact of temperature fluctuations on the efficacy of a solar PV module when subjected to a constant irradiance of 1000 W/m². The current-voltage (I-V) characteristics are illustrated in the upper graph, while the power-voltage (P-V) characteristics are depicted in the lower graph. The maximum voltage output is reduced as the temperature rises from 20°C to 28°C, as the current voltage begins to decline (the knee of the curve). The current remains relatively constant across temperatures; however, the overall power output decreases as the temperature increases because of the voltage reduction. This is demonstrated by the P-V curve, which indicates that the peak power decreases as the temperature increases, underscoring the detrimental effects of elevated temperatures on the efficiency of PV modules.

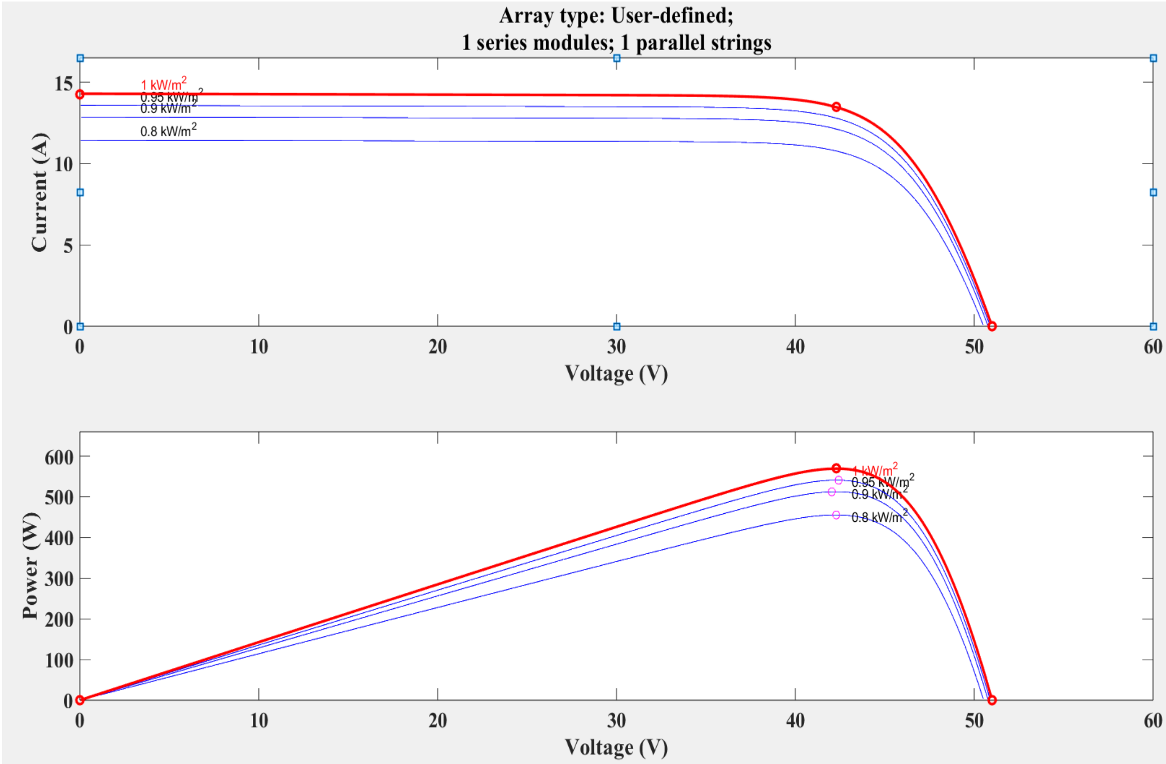

Figure 5.5: Constant Temperature (25 °C) Varying Irradiance

At a constant temperature of 25°C, Figure 5.4 illustrates the impact of varying irradiance on the efficacy of the PV module. As the irradiance decreases from 1 kW/m² to 0.8 kW/m², the current generated by the module significantly decreases, while the voltage remains relatively constant, as demonstrated by the I-V curve. The maximal power output decreases proportionately to the reduction in irradiance, as evidenced by the P-V curve. This suggests that the PV module's power output is significantly influenced by the irradiance level, with higher irradiance resulting in increased current and power generation. In contrast, voltage is less affected by variations in irradiance at a fixed temperature.

5.2.3. Hardware Results

In this project, real-time monitoring and navigation are implemented using an IoT-based platform, ThingSpeak, which enables continuous data acquisition from the MPPT-based solar charge controller. The system is programmed to update data at 15-second intervals, allowing for high-resolution temporal analysis. An essential feature of this system is its ability to acquire geographical coordinates (latitude and longitude) from the GPS module integrated within the IoT setup. These coordinates are transmitted to the server and can be used to navigate to the device's real-time location using digital map services such as Google Maps. This functionality supports remote diagnostics, performance tracking, and solar energy system field validation.

Day-1: 10 May 2025

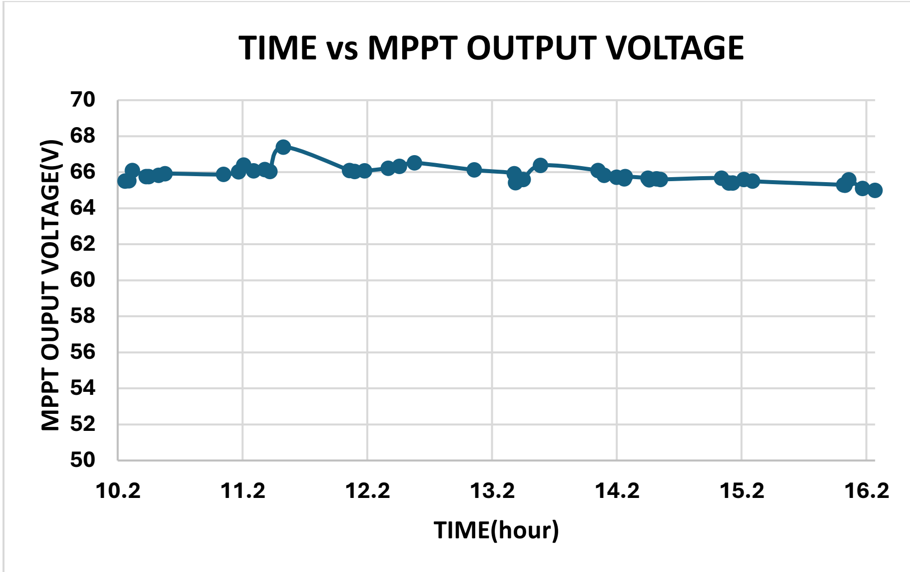

Figure 5.6: Time vs MPPT output Voltage

This figure shows the variation of the MPPT output voltage on 10 May 2025, monitored between 10:20 AM (10.2) to 4:20 PM (16.2). The output voltage remains relatively stable throughout the day, fluctuating between approximately 64.5 V and 67.8 V. A slight increase is observed around 11:20 AM (11.2), where the voltage peaks close to 68 V, possibly due to improved solar irradiance. Following this, the voltage shows minor oscillations but generally trends downward, with around 64.3 V recorded by 4:20 PM. The graph reflects the MPPT controller's ability to maintain a consistent output voltage despite natural variations in environmental conditions. This voltage stability indicates effective regulation and control by the system.

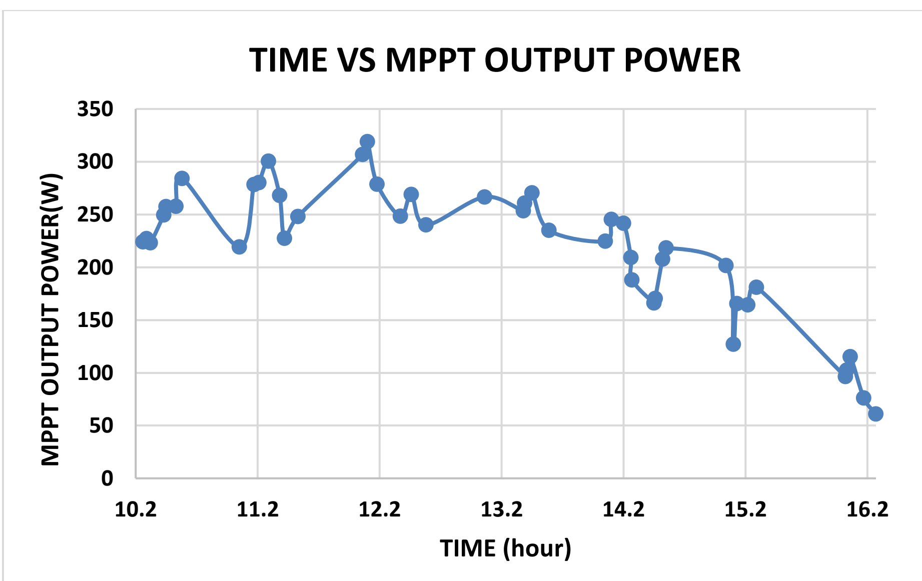

Figure 5.7: Time vs MPPT output Power

This figure represents the MPPT output power variation throughout the day on 10 May 2025, ranging from 10:20 AM (10.2) to 4:20 PM (16.2). Initially, the power output starts at approximately 220 W. It shows a general upward trend until around noon, which peaks at approximately 320 W. This increase corresponds with peak solar irradiance during midday. After this point, the power output declines gradually, dropping to around 260 W at 2:20 PM (14.2) and decreasing more significantly during the late afternoon. By 4:20 PM, the power falls to a low of approximately 60 W. The downward trend in the latter half of the day reflects the natural reduction in solar energy availability. The graph confirms that the MPPT system effectively extracts and regulates power based on real-time solar input despite minor fluctuations, likely due to environmental conditions like intermittent cloud cover.

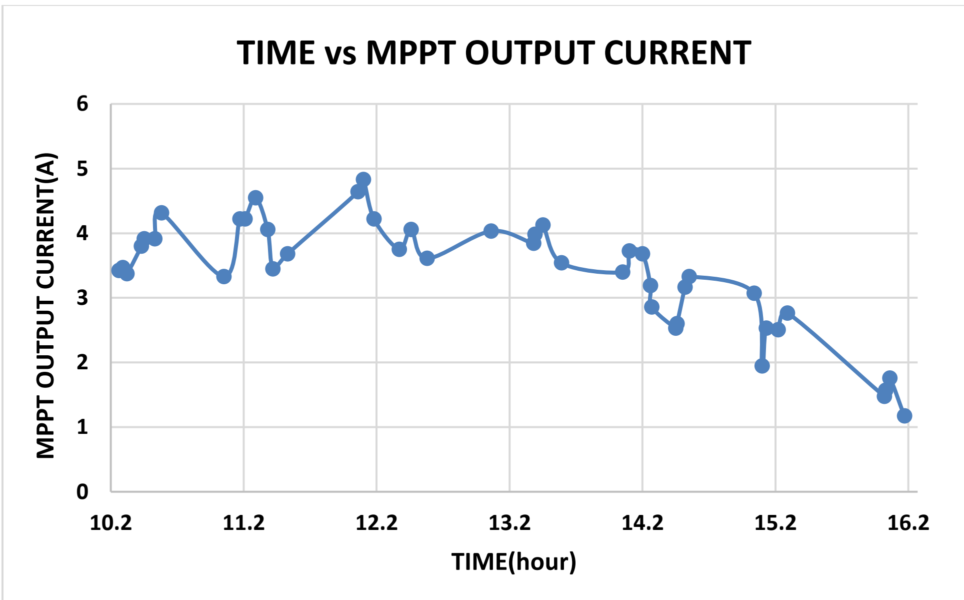

Figure 5.8: Time vs MPPT output Current

This graph gives information about the MPPT output current throughout 10 May 2025, from 10:20 AM (10.2) to 4:20 PM (16.2). The current starts at approximately 3.3 A and gradually rises to a peak of around 4.8 A near 11:30 AM (11.5). Following this peak, the current maintains a relatively stable range between 3.5 A and 4.1 A until about 1:30 PM (13.5). Afterward, a gradual decline begins, with the current decreasing sharply after 3:00 PM (15), eventually dropping to about 1.2 A by 4:20 PM. This current profile aligns closely with the trends seen in voltage and power, indicating the MPPT controller's effective regulation of current to optimize power extraction throughout the daylight period.

Day-2: 11 May 2025

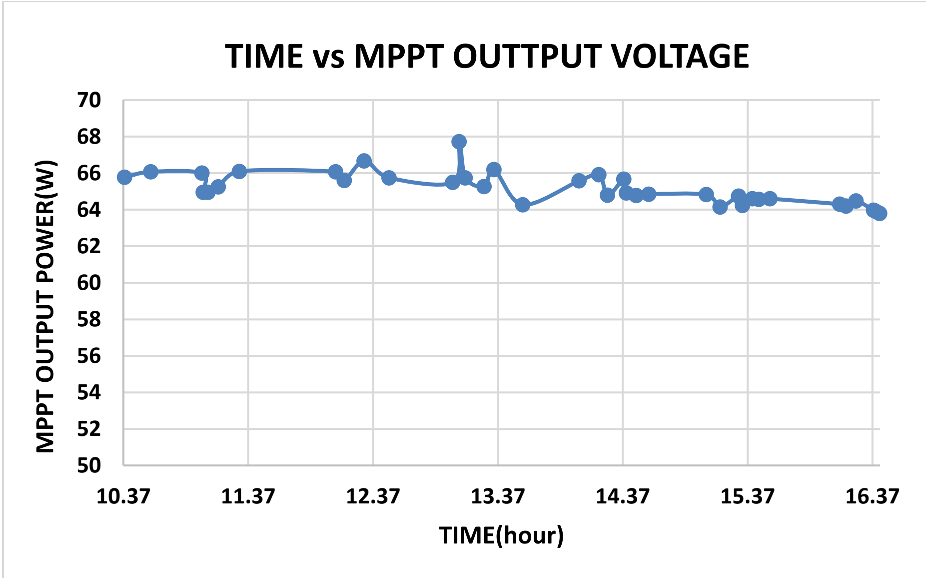

Figure 5.9: Time vs MPPT output Voltage

This graph illustrates the output voltage of the MPPT charge controller over the monitoring period from approximately 10:37 AM (10.37) to 4:37 PM (16.37) on 11 May 2025. The voltage remains relatively stable throughout the day, fluctuating between about 64.0 V and 67.5 V. A slight peak occurs around 12:37 PM (12.37), where the voltage briefly reaches nearly 67.8 V. Overall, the voltage shows minor oscillations. Still, it maintains a consistent level indicative of effective voltage regulation by the MPPT controller. The stability throughout the day suggests consistent solar irradiance with minimal disturbances on this day.

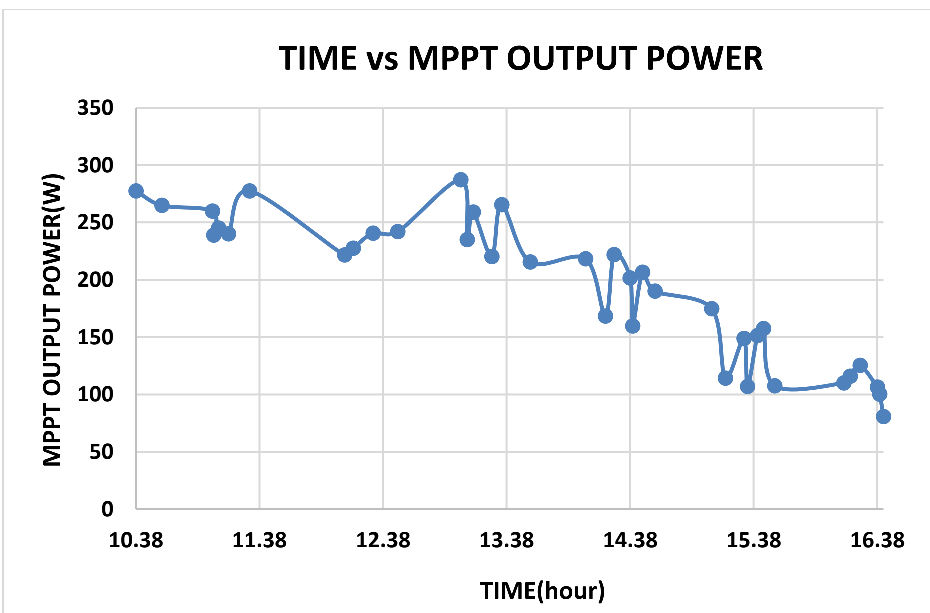

Figure 5.10: Time vs MPPT output Power

This figure shows the MPPT output power between 10:38 AM (10.38) and 4:38 PM (16.38) on 11 May 2025. The power output begins at approximately 275 W. It remains relatively steady with minor fluctuations until about 11:30 AM, when it briefly dips to 240 W before rising again to a peak of around 290 W near 12:45 PM (12.45). Following this peak, a gradual decline in power output is observed, with occasional small dips and recoveries, dropping below 150 W after 3:00 PM (15.0). By the end of the monitoring period, power falls further to approximately 85 W. The pattern reflects typical solar irradiance variation throughout the day, with the MPPT controller adapting in real time to optimize power extraction despite environmental fluctuations.

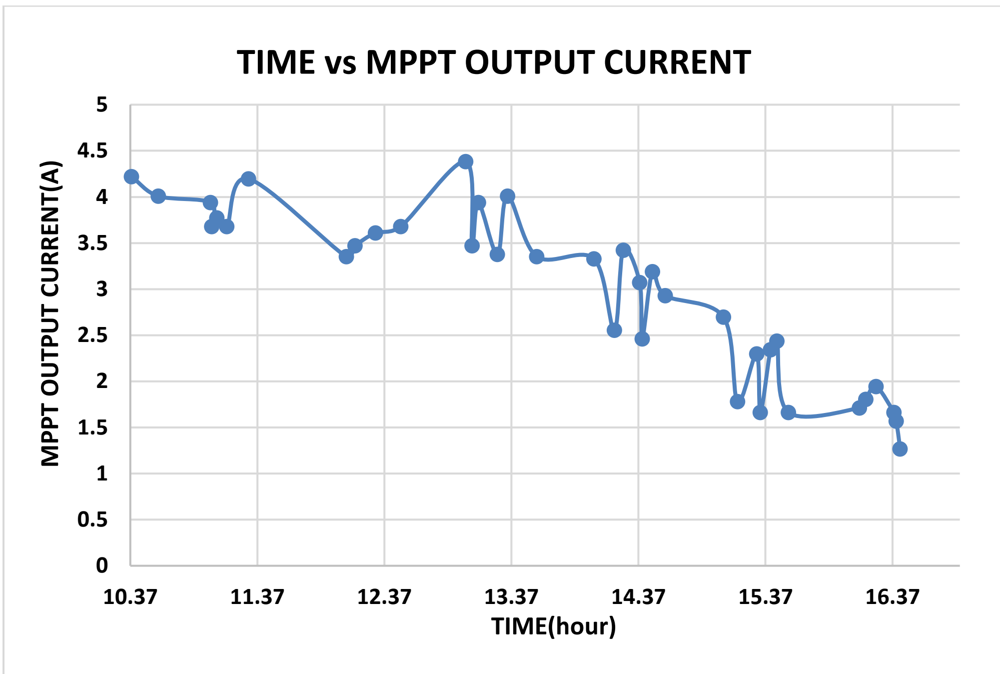

Figure 5.11: Time vs MPPT output Current

This graph illustrates the MPPT output current measured from 10:37 AM (10.37) to 4:37 PM (16.37) on 11 May 2025. The current begins at approximately 4.2 A and remains steady until about 11:30 AM, with minor fluctuations between 3.7 A and 4.3 A. A peak current of around 4.5 A is observed near 12:50 PM (12.5), after which the current gradually declines. From 2:50 PM (14.5) onwards, a more pronounced decrease occurs, with the current dropping below 2.0 A by 4:00 PM (16.0) and settling near 1.3 A at the end of the measurement period. The current profile aligns with the expected daily solar irradiance pattern and indicates the MPPT controller's dynamic adjustment to optimize current flow and maintain maximum power output.

5.3. Comparison of Results

5.3.1. Simulation vs real-life experiment

The Maximum Power Point Tracking (MPPT) charge controller underwent a detailed comparison of MATLAB/Simulink and Proteus simulations, and empirical data obtained from the physical prototype integrated into an IoT-enabled system. The simulation environment functioned as a fundamental validation instrument, modeling the Perturb and Observe (P&O) algorithm to enhance power extraction from photovoltaic (PV) panels. The simulation results indicated that the controller effectively modified the duty cycle of the DC-DC boost converter to stabilize output voltage, current, and power at the maximum power point during a brief transient period, thereby validating the algorithm's theoretical efficacy and the converter's responsiveness. In addition to the simulations, experimental tests were performed utilizing a hardware system integrated with sensors and an ESP32 microcontroller, transmitting real-time measurements to the ThingSpeak cloud platform at 15-second intervals. The empirical data indicated that the MPPT controller sustained output voltage within a range of approximately 64 V to 68 V during daylight hours, aligning with the battery charging requirements. Power output exhibited distinct diurnal variations, reaching a peak around midday in correlation with solar irradiance and progressively declining in the evening. Current measurements displayed profiles that corresponded to dynamic load and irradiance conditions. The results confirmed the MPPT controller's capacity for real-time adaptability and effective energy conversion in varying environmental conditions. Practical factors, such as hardware losses (e.g., MOSFET switching losses, inductor resistance), sensor accuracy limitations, and unpredictable weather events (e.g., intermittent shading and temperature variations), were found to be the cause of discrepancies between simulation and experimental data. These factors did not impact the controller's stability and overall system performance, which only caused minor deviations.

The significant correlation between the simulated and measured outcomes supports the robustness and practical viability of the MPPT controller. This dual-validation approach demonstrates the system's capability to effectively maximize energy harvesting from solar panels under real-world conditions, indicating its suitability for implementing solar-powered urban transportation systems like the Next-Gen Easy Bike. Integrating IoT-enabled monitoring improves system transparency, facilitating remote diagnostics and performance optimization, essential for sustainable and scalable deployment.

5.3.2. Comparison between Solar-Powered and Conventional Easy Bikes

The operational efficiency, energy autonomy, and environmental sustainability of the Easy Bike are significantly enhanced in comparison to its conventional counterpart, which is entirely reliant on grid electricity, because of the integration of a 400Wp solar panel and a Maximum Power Point Tracking (MPPT) charge controller. The demand for non-renewable energy supplies is significantly reduced in Bangladesh, where the national grid is heavily dependent on fossil fuel sources, predominantly natural gas and coal, due to the deployment of solar energy. Solar power directly reduces the Easy Bike's reliance on the grid, thereby reducing its exposure to the frequent power outages and voltage fluctuations prevalent in Bangladesh's energy infrastructure, particularly in peri-urban and rural areas. By continuously monitoring the maximum power point of the photovoltaic panels and dynamically modifying the operating voltage to optimize energy extraction, the MPPT charge controller improves the system's overall efficiency. This results in a more efficient and effective battery cell charging, even in the presence of inconsistent or low sunlight conditions common in Bangladesh due to seasonal fluctuations and frequent monsoon cloud cover. Users who depend on the Easy Bike as their primary mode of transportation rely on its reliability and availability, which are enhanced by this optimization, expanding its daily operational range.

There are substantial economic benefits associated with the solar-powered Easy Bike. Grid reliability remains inconsistent, and the cost of electricity in Bangladesh has been increasing, particularly in urban areas. Solar charging, essentially free after installation, significantly reduces the operational costs for drivers from low-income groups. By inflating their net earnings and decreasing their electricity or fuel expenses, this cost savings can enhance their standard of living. However, the conventional Easy Bike, wholly dependent on grid power, is susceptible to price volatility, supply disruptions, and ongoing electricity costs. Additionally, the operational expenses are further exacerbated by the maintenance obligations associated with the variations in power quality.

In terms of environmental impact, the solar Easy Bike reduces greenhouse gas emissions and local air pollution by reducing the dependence on fossil-fuel-generated electricity. Due to transportation emissions and energy production, Dhaka, the capital of Bangladesh, is subject to some of the most severe levels of air pollution and particulate matter in the world. Cleaner air and enhanced public health outcomes are urgent concerns for the government and civil society, as demonstrated by the contribution of solar-powered vehicles. In addition, the reduction in carbon footprint is consistent with Bangladesh's national climate change commitments, which include its Nationally Determined Contributions (NDCs) under the Paris Agreement. These commitments prioritize the deployment of renewable energy and sustainable urban transport. Moreover, solar Easy Bikes contribute to the sustainability and resilience of energy in the swiftly urbanizing context of Bangladesh. Population growth and urban migration have increased the country's electricity and transportation demand. Integrating renewable energy into transportation systems reduces the burden on the national infrastructure, which is currently grappling with the increasing electricity demand. Also, it enhances national energy security by decreasing reliance on imported fossil fuels. In diverse settings, including peri-urban neighborhoods and rural communities, where reliable and affordable transportation is frequently scarce, the modularity and scalability of solar Easy Bikes facilitate deployment.

To conclude, the solar-powered Easy Bike provides consumers with tangible economic benefits and addresses the systemic challenges that Bangladesh's energy and transportation sectors encounter. Optimizing solar energy utilization through MPPT controllers and decreasing dependence on fossil-fuel-based utility electricity provides a cost-effective, reliable, and cleaner mobility solution that is well-suited to the socio-economic and environmental context of the country. Its implementation has the potential to expedite the adoption of sustainable urban transportation, mitigate environmental degradation, and foster inclusive economic development.

5.3.3. CO_2 emissions

The 400Wp solar panel used in the Easy Bike system can generate about 1.15 kWh of clean energy per day under average sunlight in Bangladesh. This solar energy replaces electricity normally from the national grid, which primarily relies on coal and fossil fuels. In Bangladesh, producing 1 kWh of electricity from traditional sources emits around 0.9 to 1 kg of CO_2. Therefore, each solar-powered Easy Bike helps to avoid about 1.04 to 1.15 kg of CO_2 emissions daily. Using many Easy Bikes across cities and towns can significantly reduce greenhouse gases, helping fight both air pollution and climate change.

Bangladesh faces serious environmental issues due to fast urban growth, more vehicles on the road, and a firm reliance on fossil fuels. Cities like Dhaka are among the most polluted in the world because of factory emissions, car pollution, and power generation. A large part of this pollution comes from transportation. Solar-powered Easy Bikes offer a practical and immediate solution. Using solar energy instead of fuel or grid electricity, they help reduce harmful gases like CO_2 and particles that affect human health.

Bangladesh has also committed to international climate goals like the Paris Agreement and has its own plans, such as the Renewable Energy Policy and the Sustainable Development Goals (SDGs). Solar Easy Bikes support SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). These bikes reduce the need for imported fuel, increase clean energy use, and cut emissions. Solar transport helps the environment and provides social and economic benefits. It lowers the transport cost for drivers and passengers and helps reduce healthcare costs by improving air quality. In addition, solar transport creates green jobs in areas like manufacturing, bike maintenance, and solar infrastructure, helping strengthen the economy.

In conclusion, solar-powered Easy Bikes provide an innovative solution to the big problems of air pollution, climate change, energy use, and city transport. If used on a large scale, they can serve as a model for other developing countries facing similar challenges, showing how clean energy and innovative technology can lead to a better future.

5.3.4. Wide-ranging/Conflicting Technical & Engineering Issues

Despite the evident advantages, the widespread deployment of solar-powered Easy Bikes integrated with IoT-based navigation systems faces several critical technical and engineering challenges that must be addressed to ensure long-term sustainability and scalability. One of the foremost issues is the intermittent and variable nature of solar irradiance, which causes fluctuations in energy generation. This variability necessitates incorporating advanced energy storage solutions alongside hybrid charging architectures integrating solar power with grid backup to guarantee continuous and reliable vehicle operation. Furthermore, battery management presents a complex challenge; commonly used lead-acid and lithium-ion batteries are prone to capacity degradation and shortened lifespan due to repeated charging cycles and environmental factors. Consequently, sophisticated battery management systems (BMS) are essential for longevity, safety, and optimal performance.

In addition, the IoT functionalities embedded within the system rely heavily on consistent and stable internet connectivity for real-time data transmission, remote monitoring, and intelligent navigation. Such connectivity may be sporadic or insufficient in rural and peri-urban areas of Bangladesh, limiting the efficacy of IoT-enabled features. Integrating diverse hardware and software components increases system complexity and elevates initial capital costs, potentially hindering adoption among economically constrained user groups. Regulatory challenges, including the absence of standardized solar electric vehicle protocols and limited local manufacturing capabilities, further complicate large-scale implementation. Overcoming these multifaceted challenges will require coordinated efforts among engineers, policymakers, and industry stakeholders to develop resilient technological solutions, supportive regulatory frameworks, and accessible financing models that collectively foster sustainable and scalable deployment.

5.4. Summary

This chapter presents a comprehensive assessment of the Next-Generation Easy Bike, which incorporates an advanced solar charging system and IoT-based navigation, through empirical analysis and simulation. In a critical comparison, performance metrics derived from MATLAB/Simulink and Proteus simulations are compared to data obtained from hardware implementation. The focus is on parameters such as power generation, battery charging efficiency, and system responsiveness under various operating conditions. Easy Bike's operational efficiency, energy independence, and environmental sustainability are significantly improved compared to its conventional grid-dependent counterpart due to integrating a 400Wp photovoltaic panel and a maximum power point tracking (MPPT) regulated charge controller. Economically, this system provides substantial operational cost savings, which is especially beneficial for low-income consumers in Bangladesh, where intermittent grid reliability and increasing electricity prices are prevalent.

From an environmental standpoint, the solar-powered Easy Bike significantly reduces greenhouse gas emissions by replacing fossil-fuel-derived electricity with pure, renewable solar energy. This closely aligns with Bangladesh's national commitments under international climate frameworks and is consistent with its objectives for sustainable urban development. However, the chapter also elucidates various technical and engineering challenges, such as the dependence on stable internet connectivity for IoT functionality, battery lifecycle limitations, solar irradiance variability, increased system complexity, and regulatory and infrastructural constraints. Coordinated endeavors among engineers, policymakers, and stakeholders will be necessary to establish comprehensive regulatory frameworks, accessible financing mechanisms, and robust technological solutions to address these multifaceted challenges. The sustainable, scalable, and effective deployment of solar-powered Easy Bikes in Bangladesh and analogous developing regions is contingent upon the success of such collaborative endeavors.

Chapter 6

CONCLUSION

6.1. Summary of Findings

The aims of our research are to offer a sustainable urban mobility solution by developing a solar-powered electric Easy Bike integrated with IoT capabilities. During the experiment, we collected approximately 2,000 data points at 15-second intervals to measure the maximum power output of the solar panel. From this dataset, 19 representative samples were selected for energy calculation using the trapezoidal rule, which resulted in a total energy production of approximately 1.15 kWh over 5 hours. The system achieved a peak power output of 308 W and a maximum current of 4.8 A. These results demonstrate the practical application of MPPT (Maximum Power Point Tracking) algorithms to maximize solar energy harvesting. Integrating a hybrid energy system—combining solar and grid power—also ensures reliability under variable weather conditions. The developed IoT framework provided real-time output monitoring of the solar panel, location tracking of the vehicle, and improved safety. The project proves to be technically sound and socioeconomically viable for deployment in urban and peri-urban areas of Bangladesh.

6.2. Novelty of the Work

This project's multidisciplinary framework is among its most distinguished attributes. It offers an integrated solution that combines electrical engineering, renewable energy systems, IoT-enabled communication, and transportation system design. This comprehensive and systems-oriented approach is purposefully developed to address the infrastructural, economic, and technological challenges in developing countries like Bangladesh.

The project incorporates several innovative engineering components that collectively enhance system functionality and sustainability:

- **Dual-Mode Charging (Solar and Grid):** The hybrid charging architecture allows the vehicle to operate using solar and grid power sources, ensuring consistent usability in varying weather conditions and offering flexibility for urban and off-grid deployment.

- **Adaptability to Existing Transport Ecosystem:** The concept is compatible with Easy Bike chassis and operational practices, allowing cost-effective retrofitting of traditional vehicles with minimal transit system disturbance.
- **Open-Source and Locally Reproducible:** The entire system architecture—hardware and software—is based on open-source platforms, enabling local assembly, community-driven innovation, and knowledge sharing without reliance on proprietary technologies.
- **Support for Data-Driven Policy Development:** The system's real-time data can inform city planners and policymakers about designing smarter, cleaner transportation infrastructure, contributing to broader innovative city initiatives.

These engineering strategies contribute substantially to developing sustainable, intelligent, and economically viable transport solutions for low- and middle-income countries. The project meets immediate technical goals and lays the groundwork for scalable and socially impactful mobility innovation.

6.3. Cultural and Societal Factors and Impacts

In Bangladesh, Easy Bikes are essential components of the urban and semi-urban transportation network, offering millions of individuals a cost-effective and easily accessible mode of transportation. Through the implementation of a solar-powered, IoT-enabled alternative, this project improves the existing system and offers numerous tangible advantages. Solar charging significantly reduces energy costs for low-income drivers, providing them with digital tools for route optimization, vehicle diagnostics, and maintenance notifications. This empowers them. In areas where traditional public transport is limited or unreliable, it provides passengers with a more sustainable and secure travel option. The initiative also contributes to national energy security and economic sustainability strategies by reducing reliance on fossil fuels and transitioning to renewable energy, thereby supporting Bangladesh's broader environmental objectives.

6.3.1 Cultural and Societal Factors

Easy Bikes are a culturally accepted and well-established mode of transportation in Bangladesh's urban and semi-urban areas. This project is highly adaptable to the current transportation ecosystem due to its extensive use and familiarity, ensuring seamless integration without requiring behavioral change among users. The project integrates solar energy and IoT-based technologies that considerably reduce daily operational costs and promote socioeconomic empowerment beyond cultural alignment. These innovations equip drivers, particularly those from low-income backgrounds, with navigation, vehicle diagnostics, and predictive maintenance tools, improving income sustainability and augmenting their control over vehicle management. Additionally, the system provides a safe, affordable, and dependable alternative to conventional public transportation in regions where it is unreliable or limited, thereby enhancing the accessibility of mobility for underserved communities.

6.3.2 Environmental Impact

In the context of Bangladesh's urban pollution and energy dependency, the environmental implications of this undertaking are substantial. The system directly supports the country's transition towards healthier energy sources by reducing reliance on conventional grid electricity and fossil fuels using solar-based charging. In the process, it contributes to a quantifiable decrease in noise pollution and greenhouse gas emissions, particularly in densely populated urban areas. The initiative also promotes sustainable resource utilization by implementing modular design principles, which enable the extension of component lifecycles and the reduction of electronic waste. These design decisions encourage environmental responsibility by simplifying the system's maintenance, repair, and upgrading processes, reducing the need for frequent replacements and resource-intensive manufacturing.

6.3.3 Alignment with Professional Standards

The initiative is guided by established industry standards and ethical practices from an engineering perspective, guaranteeing user safety and technical integrity. Integrating embedded electronics, renewable energy systems, and vehicle control mechanisms is consistent with internationally recognized protocols, including IEEE electrical and embedded systems standards. Safety, dependability, and maintainability were prioritized throughout the design process. Furthermore, the project exemplifies the principles of responsible innovation by guaranteeing that the solution is both technologically sound and economically accessible, socially inclusive, and environmentally sustainable. The project demonstrates a comprehensive and ethical approach to sustainable transport system design by adhering to professional norms and addressing the broader societal context of Bangladesh.

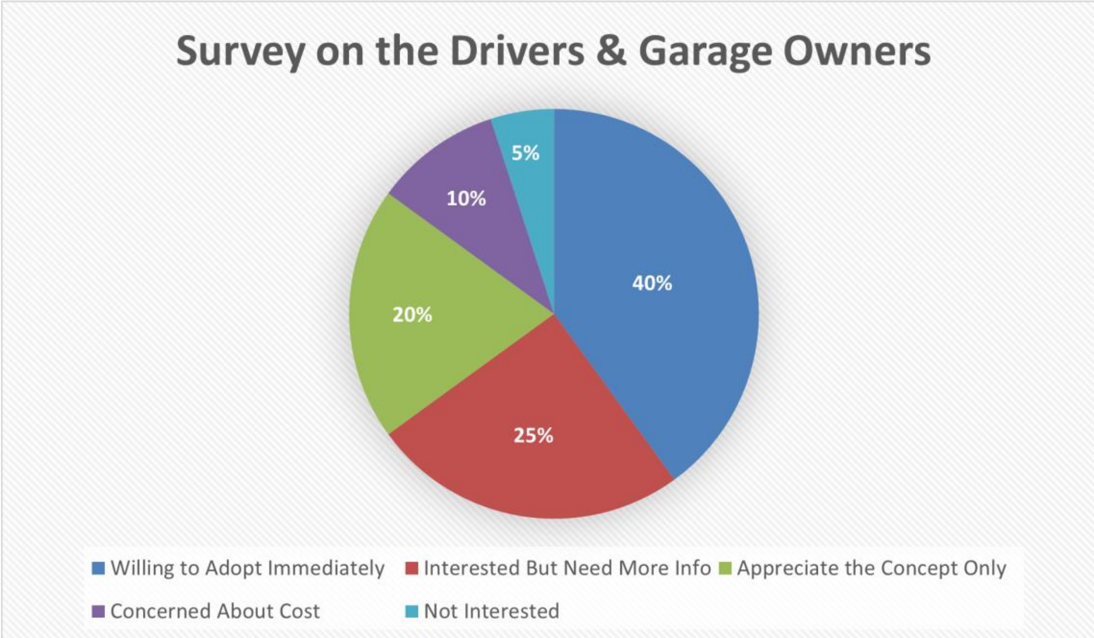

Figure 6: Survey on the Drivers & Garage Owners

Twenty-five participants participated in the "Survey on the Drivers & Garage Owners" pie chart. The results indicate that 40% of respondents are prepared to implement the Next-Gen Easy Bike immediately, while 25% are interested but require additional information before deciding. Additionally, 20% support the concept but have not yet committed, 10% are apprehensive about the cost, and 5% are not interested in adopting the bike. In general, most individuals, 65%, demonstrate interest in adopting technology. However, the need for additional information and cost concerns presents significant obstacles to its widespread adoption.

6.4. Engineering Solution under Professional Practices

To guarantee a sustainable, reliable, and resilient design, the development process rigorously adhered to professional engineering principles at every stage. MATLAB/Simulink was employed to simulate the behavior of electrical models, such as voltage regulation, power flow, and Maximum Power Point Tracking (MPPT), to verify their efficacy under various operating conditions. The initiative ensured safety, interoperability, and efficiency by adhering to recognized IEEE and ISO standards, particularly in embedded electronics and battery management systems. The core engineering principles were maintained throughout, strongly emphasizing promoting social equity, assuring user safety, and minimizing environmental impact. Furthermore, the design included real-time diagnostics, efficient energy conversion strategies, and fail-safe mechanisms, underscoring the design's dedication to responsible, forward-thinking engineering practices.

6.5. Limitations of the Work

- **Lack of Comprehensive Field Testing:** The system has not undergone extensive real-world testing across diverse terrains, climatic conditions, or traffic environments, limiting validation beyond simulated models.
- **Dependence on Mobile Connectivity:** The IoT subsystems rely on continuous GSM/mobile data, which may be unreliable in rural or peri-urban areas. This version did not implement an offline fallback or mesh network.
- **Limited Battery Ageing Analysis:** Battery modelling did not include long-term degradation factors such as capacity fading or thermal effects, restricting lifecycle performance evaluation for large-scale deployments.
- **Constraints in Solar Panel Optimization:** Due to resource limitations, high-efficiency or lightweight PV modules were not used, affecting weight distribution and energy efficiency. Advanced materials remain unexplored.

Although these constraints restrict the current implementation, they provide strategic entry points for additional research and development. Addressing these challenges will be imperative to transform the prototype from a proof-of-concept into a commercially viable, scalable, and robust solution.

6.6. Future Scopes

This initiative establishes a foundational platform for advancing intelligent, sustainable, and inclusive transportation systems. Several strategic directions have been identified for future development, each aimed at enhancing technical functionality and societal impact.

- **Machine Learning Integration:** Incorporating machine learning algorithms presents an opportunity to enable dynamic energy optimization and predictive route planning. By analyzing real-time data such as traffic patterns, solar irradiance, and battery health, the system can make autonomous decisions that improve efficiency and user experience.
- **Community-Based Solar Microgrids:** Deploying solar-powered microgrid stations in remote and peri-urban areas will facilitate localized, off-grid vehicle charging infrastructure. This approach directly supports broader objectives related to decentralized energy access, rural mobility, and renewable energy adoption.

- **Lightweight Chassis Design:** Future enhancements may include fabricating vehicle chassis using advanced composite materials. Reducing structural weight without compromising durability can improve energy efficiency, performance, and overall system sustainability.
- **Mobile Application Development:** Creating dedicated mobile applications for real-time diagnostics, driver training, and fleet management will strengthen operational efficiency. These tools will enable data-driven maintenance practices, enhance driver engagement, and provide critical feedback for system improvement.
- **Vehicle-to-Grid (V2G) Integration:** Integrating V2G technology will allow vehicles to act as mobile energy storage units, capable of returning surplus electricity to the grid. This bi-directional energy flow enhances grid flexibility, supports load balancing, and contributes to a more resilient energy infrastructure.

These future enhancements will collectively improve the system's technological sophistication and reinforce its contribution to clean energy, digital innovation, and sustainable urban development in emerging economies.

6.7. Social, Economic, Cultural, and Environmental Aspects

This section highlights how the project aligns with various UN Sustainable Development Goals (SDGs), promoting long-term transformation.

6.7.1. Sustainability and SDG Alignment

The project meets several sustainability targets through environmentally sound technologies, inclusive economic design, and community-focused deployment strategies.

SDG 7: Affordable and Clean Energy: Integrating photovoltaic (PV) panels and MPPT technology provides a clean, renewable energy source for vehicle operation. This reduces dependency on conventional electricity and fossil fuels, thereby advancing the accessibility and adoption of clean energy solutions.

SDG 8: Decent Work and Economic Growth: This initiative stimulates local employment by creating jobs in vehicle assembly, solar installation, IoT diagnostics, and after-sales services. It also supports entrepreneurship among drivers and small-scale transport operators.

SDG 9: Industry, Innovation, and Infrastructure: The project promotes modular vehicle architecture and local manufacturing, contributing to industrial innovation. It also facilitates infrastructure development by establishing maintenance hubs and localized technology ecosystems.

SDG 13: Climate Action: The project directly reduces greenhouse gas emissions and supports Bangladesh’s commitment to global climate mitigation efforts by replacing fossil fuel-based transport with solar-powered alternatives.

6.7.2. Economic and Cultural Factors

The project's relevance, accessibility, and long-term sustainability within the Bangladeshi context have been meticulously addressed by addressing its economic and cultural dimensions. The system's financial viability is considerably improved by reducing initial capital investment and ongoing maintenance costs using modular and locally serviceable components. This method is feasible for low-income chauffeurs and small-scale fleet operators, effectively reducing the total cost of ownership (TCO). By seamlessly incorporating advanced technological features, the design also maintains cultural compatibility by preserving the visual and functional characteristics of conventional Easy Bikes. This combination of innovation and familiarity ameliorates user acquiescence and resistance to technological change. In addition, the initiative enhances inclusive economic development, notably in urban and peri-urban regions, by providing opportunities for local job creation in driver training, solar panel integration, vehicle maintenance, and IoT system support. The system can be adopted in digitally deprived areas due to its intuitive and accessible user interface, which is characterized by a low learning curve and a straightforward mobile application. This furthers digital inclusivity and is consistent with the national objectives of ensuring equitable access to technology and digital empowerment.

6.7.3. Specific Actions for Sustainability in Bangladesh

The following targeted and actionable strategies are recommended to transform this project from a technical concept into a nationally scalable solution. These initiatives will enhance the project's impact and align with Bangladesh’s national development agenda and global sustainability goals.

- **Deployment of Community-Based Solar Charging Stations:** Implement decentralized, off-grid solar charging hubs in peri-urban and underserved areas. These stations will enable clean, reliable energy access for electric vehicles, reducing dependence on the national grid and supporting local energy independence.

- **Microfinance Support for Solar Conversion:** Collaborate with institutions such as BRAC, Grameen Bank, and other development partners to offer low-interest financing and subsidies. These financial instruments can help drivers and small entrepreneurs transition to solar-powered mobility without high upfront costs.

- **Policy Advocacy and Government Incentives:** Encourage government support through favorable electric vehicle (EV) policies, including import duty exemptions, tax credits, and subsidies for solar and battery technologies. These incentives are vital to encourage early adoption and market penetration.

- **Establishment of Technical Skill Development Centers:** These centers will be dedicated vocational training centers that equip local youth and technicians with solar energy systems, MPPT technology, IoT diagnostics, and battery management skills. This will ensure long-term system sustainability and create employment pathways.

- **Public Awareness and Educational Outreach:** Launch awareness campaigns in schools, universities, and community organizations to promote understanding of sustainable mobility, environmental stewardship, and energy efficiency. Digital media, workshops, and pilot demonstrations can play key roles.

- **Battery Recycling and E-Waste Management Policies:** Work with environmental agencies to establish national guidelines for lithium-ion battery recycling, safe disposal practices, and environmentally responsible e-waste management. This safeguards long-term ecological sustainability and public health.

Collectively, these actions can significantly amplify the project's social and environmental impact, foster innovation at the local level, and pave the way for widespread adoption of clean mobility solutions across Bangladesh.

6.8. Conclusion

The “Next-Gen Easy Bike” project offers a forward-looking and socially responsible response to Bangladesh's transportation challenges. The proposed system moves beyond technical innovation by combining solar photovoltaic technology, real-time IoT integration, and an emphasis on economic inclusivity. It presents a blueprint for transformative urban mobility.

The solution addresses several pressing issues, including carbon emissions, energy inefficiency, and mobility access in underdeveloped communities. Its design ensures cultural relevance, financial accessibility, and technological adaptability, making it well-suited for replication and scaling in similar developing country contexts. Although the project remains in its early development stage, its potential is considerable. With coordinated efforts involving academia, government agencies, industry partners, and local communities, this initiative could evolve into a nationwide innovative transport ecosystem that promotes sustainability, innovation, and equitable growth. The work done here lays the foundation for a cleaner mode of transport and a more resilient, inclusive, and intelligent future for mobility in Bangladesh and beyond.

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Appendix A

Datasheet of the Microcontroller used in the Data Logger

ESP32 Microcontroller Specification

Parameter	Specification
Processor	Dual-core Tensilica LX6 (Xtensa®) at up to 240 MHz
Flash Memory	Typically, 4 MB (external, via SPI flash)
SRAM	520 KB
Wireless Connectivity	Wi-Fi 802.11 b/g/n, Bluetooth 4.2 (Classic and BLE)
Operating Voltage	3.0V to 3.3V
Input Voltage (via VIN)	5V (regulated onboard to 3.3V)
GPIO Pins	34 (with various functions including ADC, DAC, I2C, SPI, PWM, UART)
ADC Channels	Up to 18 channels (12-bit resolution)
DAC Channels	2 channels (8-bit resolution)
PWM Channels	Up to 16
Communication Interfaces	UART, SPI, I2C, CAN, I2S
Timers	Multiple general-purpose and hardware timers
Security Features	Secure Boot, Flash Encryption, Cryptographic Hardware Acceleration
Power Modes	Active, Light Sleep, Deep Sleep, Hibernation
Operating Temperature	-40°C to +125°C (Industrial grade, depending on model)
Package Options	QFN, WROOM-32, WROVER (with or without PSRAM and antenna)
Development Support	Arduino IDE, ESP-IDF, PlatformIO, MicroPython

Fig: ESP32 (Microcontroller)

MPPT Controller Specification

Parameter	Specification
Control Method	Maximum Power Point Tracking (MPPT) using Perturb and Observe (P&O) or Incremental Conductance.
Input Voltage Range	12V – 100V DC (Solar Panel Dependent)
Output Voltage Range	60V DC (Selectable Based on Battery Configuration)
Maximum Current	20A – 60A (Model Dependent)
Efficiency	Up to 98%
Display	LCD/LED Display for Real-Time Monitoring (Voltage, Current, Power, etc.)
Microcontroller	ARM Cortex-M Series or STM32 (High Speed & Low Power)
Operating Temperature	-20°C to 60°C
Protection Features	Overvoltage, Overcurrent, Overtemperature, Reverse Polarity, Short Circuit
Communication Protocols	UART, I2C, RS485 (Optional)
Charging Stages	Bulk, Absorption, Float, Equalization (Configurable)
Cooling	Passive Heatsink / Active Cooling (Fan-Based, Depending on Model)
Mounting	Wall or Onboard Installation
Fault Indicators	LED/Buzzer Alerts for Faults and Protection Events

Fig: MPPT Controller

XH-M609 Battery Protection Circuit Specification

Parameter	Specification
Module Name	XH-M609 Battery Charging Control Protection Module
Input Voltage	DC 12V – 60V
Control Voltage Range	Adjustable within the input range (e.g., set charging start/stop thresholds)
Maximum Current	20A (with appropriate external relay or MOSFET)
Control Accuracy	±0.1V
Display	3-digit 7-segment LED for real-time voltage monitoring
Charging Control Mode	Auto cut-off and auto re-start based on set high and low voltage levels
Battery Types Supported	Lead-acid, Lithium-ion, LiFePO4 (with manual adjustment of voltage thresholds)
Settings	Set upper (stop) and lower (start) voltage thresholds using onboard buttons
Protection Features	Overcharge protection, automatic recovery when voltage drops
Relay Output	Connects/disconnects charging source based on threshold settings
Operating Temperature	-20°C to 60°C
Dimensions	Approx. 81mm × 54mm × 18mm
Mounting	Onboard screw holes for panel or enclosure installation

Fig: Battery Protection Circuit

GPS Module Specification (NEO-8M)

Parameter	Specification
Module Name	NEO-8M GPS Module
Satellite Systems	GPS, QZSS, SBAS (WAAS, EGNOS, MSAS, GAGAN), GLONASS (optional)
Positioning Accuracy	< 2.0 meters CEP
Acquisition Time	Cold Start: < 26 sec, Warm Start: < 25 sec, Hot Start: < 1 sec
Update Rate	1 Hz (default), configurable up to 18 Hz
Communication Interface	UART (Default Baud Rate: 9600 bps), also supports I2C, SPI
Power Supply	3.3V (Recommended), with onboard LDO for 5V input
Current Consumption	~30–40 mA (active tracking mode)
Antenna	External ceramic patch antenna with IPX connector or onboard antenna
Flash Memory	Yes, for configuration storage
LED Indicator	Blinks when GPS fix is acquired
Backup Battery	Yes, for RTC and quick satellite acquisition (Hot Start)
Time Pulse Output	Configurable (for precise timing applications)
Operating Temperature	-40°C to +85°C
Dimensions	Approx. 25mm × 35mm
Mounting	Onboard screw holes for secure enclosure mounting

Fig: GPS module

Appendix B

iThenticate Plagiarism Report

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