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Solar Scholar: A Thin-Film Solar Bag for Sustainable Energy Generation in Academic and Professional Mobility

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Abstract

This research focuses on the development of the solar backpack along with the real data simulation extracted from the Jumla district. The increasing demand for portable renewable energy solutions has stimulated innovations in wearable solar technology. This innovation provides a reliable and portable solution for energy generation, yielding a significant cumulative output that effectively satisfies the energy needs of personal devices over extended periods. This study presents the design, development, and performance evaluation of a solar-powered bag integrated with lightweight thin-film photovoltaic (TFPV) modules for sustainable energy generation during daily mobility. The system exhibits consistent daily performance utilizing realistic hourly solar data from Jumla, demonstrating its practicality for routine applications. This reliability underscores its potential as a viable and marketable product from a business perspective. The findings suggest that such systems could play a significant role in enhancing energy access in remote regions like Jumla, and may warrant greater attention from policymakers in Nepal. It targets students, academics, and professionals. The bag incorporates flexible CIGS or a-Si solar panels (6–10 W output) into its outer surface, paired with a lithium-ion battery (10,000–15,000 mAh) and an MPPT charge controller to optimize energy harvesting. Rigorous testing under varying irradiance conditions demonstrated its ability to provide 2–4 smartphone charges or 1–2 laptop charges daily, with 70% retention in cloudy weather. The system's efficiency ($\eta \approx$ 10–12% for CIGS, 8% for a-Si) and durability were validated through 100+ charge cycles and mechanical stress simulations. By aligning with SDGs 7 (Affordable Energy) and 13 (Climate Action), this innovation bridges the gap between convenience and sustainability, offering a scalable solution for reducing reliance on grid electricity. Challenges include weather dependence and higher initial costs, yet the design proves viable for urban and remote applications.

Keywords: Solar-powered backpack, Thin-film photovoltaic, Portable renewable energy, Sustainable charging solution, Wearable solar technology

1. Introduction

The global energy landscape is rapidly evolving as societies confront the environmental consequences of fossil fuel dependency. Climate change, carbon emissions, and the increasing demand for electricity, especially in urban and mobile lifestyles. People now underscore the urgent need for sustainable energy solutions. In response, researchers, designers, and technologists are exploring new ways to integrate renewable energy sources into everyday products. One such promising area is portable energy generation, which combines convenience, innovation, and eco-consciousness[1], [2], [3].

Among the most practical applications of this concept is the integration of solar energy systems into personal accessories, particularly bags and backpacks. Every day, millions of students, educators, and professionals carry backpacks loaded with essential items such as laptops, books, tablets, and smartphones. These electronic devices are integral to modern work and study routines, but also require constant charging. With increasing hours spent away from fixed power outlets, during commutes, fieldwork, or travel. The need for portable, clean power sources has become more pressing.

This study introduces an innovative response to this need: The Solar Scholar Bag. This is not just a traditional backpack; it is a smart, solar-integrated solution that embeds thin-film photovoltaic (TFPV) technology directly onto the bag's outer surface. Unlike bulky and rigid solar panels, thin-film solar modules are lightweight, flexible, and durable, making them ideal for wearable applications. These characteristics allow the bag to maintain its comfort and design aesthetics while functioning as a renewable energy generator[4], [5], [6], [7].

The Solar Scholar Bag is designed with mobility, utility, and sustainability at its core. Whether navigating a university campus, commuting through a city, or attending conferences and fieldwork assignments, users can harness solar energy to charge their mobile phones, tablets, and laptops. By converting passive time under sunlight into active energy generation, the bag supports energy independence and promotes environmentally responsible behavior.

Furthermore, this innovation aligns with global efforts to meet Sustainable Development Goals (SDGs)—particularly SDG 7: Affordable and Clean Energy and SDG 13: Climate Action. It represents a step toward mainstreaming clean technology into the daily lives of academic and professional communities [8], [9].

2. Literature review, Concept, and Objectives

The reviewed literature reveals substantial advancements in thin-film PV materials, hybrid energy systems, optimization techniques, and sustainable design principles. However, there exists a clear research gap in the application of these technologies in wearable, solar-powered academic tools, particularly in the Global South context. The *Solar Scholar* project fills this niche by designing a thin-film solar bag that not only harnesses sustainable energy for personal electronics but also promotes environmental consciousness, digital access, and mobility among students and professionals [3], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20].

1. Hybrid Energy Systems and DC Microgrids

Hybrid energy systems, particularly those integrating photovoltaic (PV) sources and energy storage units, are increasingly vital in ensuring reliable and sustainable power for remote or islanded regions. Poudel and Niraula [1] explore a hybrid energy storage configuration incorporating PV systems in an islanded DC microgrid, offering a practical solution to energy reliability and cost issues in decentralized power systems. Their study also underlines the importance of advanced energy management algorithms and storage coordination in such microgrids.

This is further complemented by Poudel et al. [4], who applied the Water Cycle Algorithm to optimize the sizing and placement of distributed generators and capacitors in Nepal's Sankhu feeder. The integration of heuristic optimization for real-world distribution network planning demonstrates a feasible pathway for enhancing power quality and reducing losses in semi-urban South Asian contexts.

2. Evolution of Solar Photovoltaic Technologies

There is considerable research focus on enhancing the sustainability and efficiency of solar PV technologies. Celik et al. [3] examined end-of-life (EoL) management challenges of both crystalline silicon and thin-film solar panels, emphasizing the environmental burden associated with transportation and recycling.

The review by Bouich et al. [6] provides a broader market perspective, discussing technological innovations, economic barriers, and global trends impacting the solar sector. Meanwhile, Gupta et al. [7] focused on the transition from rigid to flexible thin-film silicon solar devices, showcasing their relevance for wearable, mobile, and off-grid applications.

Efaz et al. [8] offer a consolidated view of the primary technologies in thin-film solar cells, including cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and perovskites, emphasizing their suitability for flexible and low-weight applications. Mishra et al. [9] further explored solution-processed thin films tailored for indoor light harvesting, a niche but growing field with applications in self-powered IoT and ambient computing.

Additionally, Pervez et al. [10] evaluated sustainability concerns associated with thin-film technologies, pointing toward green engineering approaches in coating and material usage. Kaltenbrunner et al. [20] earlier demonstrated high-efficiency, ultrathin organic solar cells that retain their performance under mechanical stress, an important consideration for wearable and foldable electronics.

3. Energy Storage and Fuel Cell Technologies

The integration of fuel cells in renewable systems introduces a promising avenue for sustainable energy conversion. Ashraf et al. [11] presented simplified models to accurately emulate the steady-state and dynamic performance of PEM fuel cells, which can be pivotal for real-time control and predictive maintenance.

Further refinement of fuel cell modeling is evident in the work of Vujošević et al. [12], who applied advanced optimization techniques like the Walrus algorithm for parameter estimation, illustrating how hybrid metaheuristics can improve the fidelity and robustness of system simulations.

4. Electric Vehicle (EV) Battery Lifecycle and Circular Economy

Addressing the environmental challenges of EV proliferation, Lee and Kim [14] proposed strategies to enhance consumer participation in the collection of retired EV batteries. This consumer-centered approach, combined with regulatory support and incentivization, is critical for enabling closed-loop recycling systems.

In a complementary study, Pochont and Sekhar [5] reviewed the use of PV technologies in electric vehicles, highlighting the role of solar-integrated transportation in reducing fossil fuel dependency and promoting decentralized mobility energy systems.

5. Optimization Algorithms in Energy Systems

Population-based and nature-inspired algorithms have gained popularity in the optimization of energy systems. Poudel et al. [2] provided a comprehensive review of various population-based algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Differential Evolution (DE), elaborating on their applicability in engineering optimization problems, including energy and power systems.

This aligns with Aleb's [13] application of MLP-transformers for optimizing drug-target binding, which, although biomedical, showcases how machine learning architectures can generalize to complex, multidimensional optimization tasks, including those in energy prediction and planning.

6. Advanced Materials and Emerging Applications

In the context of wearable and stretchable electronics, technologies that enable self-powered systems have broad implications for both energy harvesting and health monitoring. Zhou et al. [18] presented a triboelectric nano generator with high stretch ability, potentially suitable for integration with energy-harvesting wearables. Similarly, Amjadi et al. [19] reviewed stretchable strain sensors, signaling the convergence of materials science and energy technologies in future smart systems.

Additionally, innovative technologies such as the optical voice recorder discussed by Graydon [15] suggest potential crossover applications in energy-aware communication and embedded systems.

7. Bioenergy and Sustainable Fuels

Although not the central focus, the role of bioenergy remains relevant in a holistic energy landscape. Housagul et al. [16] investigated biomethane production from banana peel and waste glycerol, promoting resource circularity in waste management. Berg Thorson and Thomson [17] provided an extensive review of advanced transportation biofuels, addressing combustion properties and engine compatibility.

Table 1: Comparative Literature Summary Table

S.N.	Authors (Year)	Focus Area	Solar Tech/ Material	Application Context	Output/Key Metrics	Relevance to Solar Scholar
1	Kaltenbrunner et al. (2012)	Ultrathin, flexible solar cells	Organic thin-film	Wearables, curved surfaces	~4% PCE, <2 μm thick	Enables ultralight solar integration in backpacks
2	Yu et al. (2016)	Flexible/ stretchable electronics	Diverse flexible materials	Wearable health monitors	Mechanical resilience	Informs flexible substrate choices for solar bags
3	Zuo et al. (2017)	Organic & perovskite PV for wearables	Organic & Perovskite	Portable, mobile electronics	~10% PCE (lab scale)	Shows viability of organic/perovskite in mobile gear
4	Zhang et al. (2020)	Wearable solar devices	Flexible solar cells	Smart wearables, textiles	~8–12% PCE	Design insights for fabric-integrated solar panels
5	Choi et al. (2015)	Energy harvesting overview	PV, kinetic, thermal	Off-grid/mobile power	Varies by tech	Broad validation of off-grid solar utility
6	Mobarhan et al. (2021)	Smart solar backpack + IoT	Thin-film solar + sensors	IoT-enabled backpacks	~3–5W output	High-tech reference for solar+IoT convergence
7	Sarmah & Yadav (2018)	Solar backpack for rural students	Polycrystalline PV	Rural academic users	~5V USB output	Real-world prototype in educational context
8	Hossain et al. (2017)	Portable solar backpack for charging	Flexible monocrystalline	Phone/laptop/ LED charging	~10W output	Validates power needs for low-power devices
9	Anwer & Mahmood (2014)	Feasibility for school solar bags	Silicon-based PV	Students in Pakistan	Cost-effective, basic power	Socio-economic feasibility for scaling in South Asia
10	Zhang et al. (2015)	Transparent, flexible solar cells	Organic + transparent layers	Wearables, glasses, fabrics	~10.2% PCE	Aesthetic and functional integration in solar bags
11	This paper	Portable renewable energy using thin-film photovoltaic technology integrated into wearable backpacks	thin-film CIGS and a-Si photovoltaic modules	Portable charging bag for electronic devices during daily mobility	6–10 W solar power, 2–4 phone or 1–2 laptop charges per day with up to 70% efficiency in cloudy conditions	Purposed method

2.1. Concept

To turn an ordinary, daily-use bag into a self-sustaining energy generator by embedding a thin-film solar panel on its external surface.

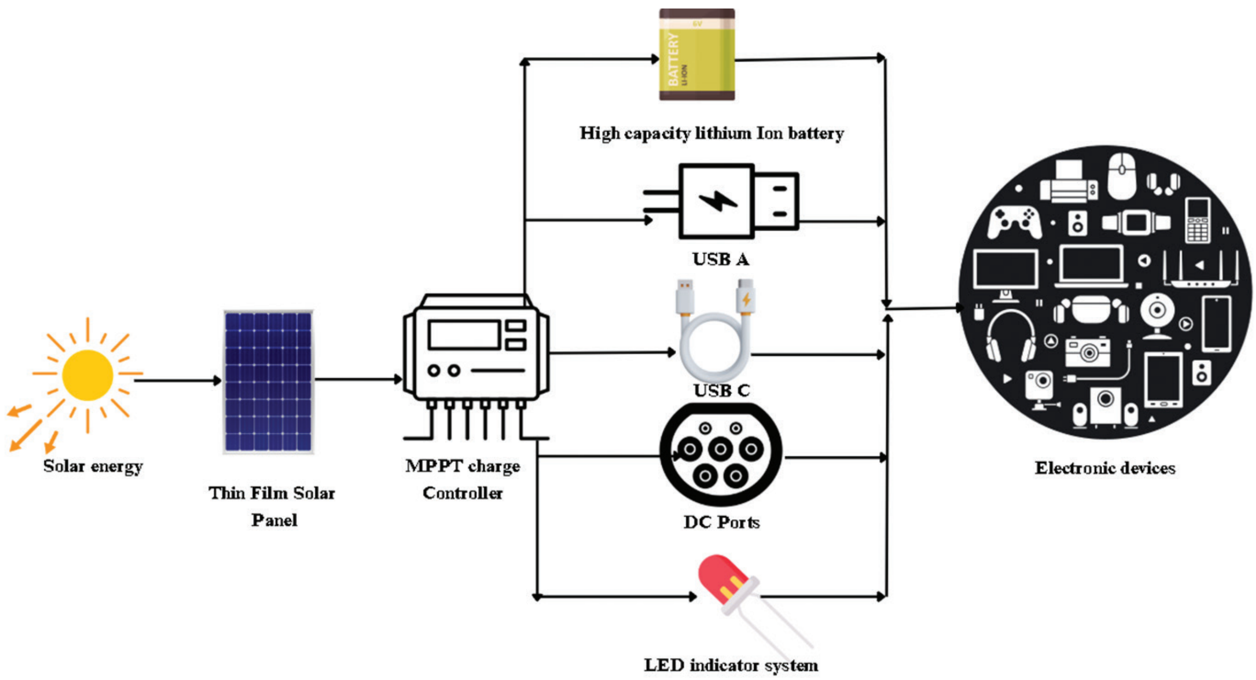

Figure 1: Simple Block diagram of solar bag working prototype

2.2. Objectives

To empower students, professors, and professionals to harness solar energy during their daily commute by integrating lightweight, flexible thin-film photovoltaic (PV) technology into a portable backpack. This solution aims to provide convenient, on-the-go charging for mobile phones, tablets, and laptops without compromising the usability or comfort of the bag. Additionally, it seeks to promote energy-conscious behavior and raise awareness of sustainable energy practices within educational institutions and professional environments.

3. Design and Material Selection

3.1 Bag Structure

The bag is made from high-quality, durable polyester that is specifically designed to be weather-resistant, making it suitable for various environmental conditions. This material offers excellent protection against rain, dust, and everyday wear, ensuring the bag remains in good condition even with frequent outdoor use. The polyester fabric is also resistant to tearing and fading, which adds to the product's overall durability and longevity. Inside, the bag is equipped with padded compartments that safeguard electronic devices and fragile items, providing a layer of cushioning to prevent damage during transit. The stitching throughout the bag is reinforced with strong, heavy-duty threads to support the weight of the built-in solar panel and electronic components, ensuring that the structure remains intact even under consistent use.

Designed for functionality and organization, the bag features multiple well-thought-out compartments to accommodate a wide range of items. It includes a dedicated padded laptop sleeve that can securely fit devices up to 15.6 inches, along with a Velcro strap to keep the device in place. The main compartment is spacious enough to hold textbooks, notebooks, or a change of clothes, while secondary compartments are ideal for storing tablets, documents, or smaller gadgets. Additionally, the bag includes various organizer pockets tailored for items like smartphones, power banks, USB drives, and stationery. A smaller external zippered pocket allows quick access to essentials such as keys, wallets, or ID cards. An integrated USB port is also featured, with internal cable routing that connects to the solar module, allowing users to conveniently charge their devices on the go.

Despite the inclusion of a solar module and supporting electronics, the bag maintains a manageable weight of approximately 1.2 to 1.5 kilograms. The weight distribution is carefully balanced and supported by ergonomic, padded shoulder straps and a breathable back panel to enhance comfort during long hours of wear. The thoughtful design ensures that the bag remains lightweight and easy to carry, making it ideal for students, professionals, and travelers who require both mobility and reliable access to portable solar energy.

3.2 Thin-Film Solar Module

Solar Bag is designed to provide portable, renewable energy through the integration of advanced thin-film solar technologies. Utilizing either CIGS (Copper Indium Gallium Selenide) or a-Si (Amorphous Silicon) photovoltaic materials, the solar bag is capable of generating a power output of approximately 6 to 10 watts under standard sunlight conditions. These types of solar cells are known for their superior flexibility and adaptability, making them ideal for incorporation into fabric-based products. The solar panels are either stitched or laminated onto the outer back side of the bag, ensuring maximum exposure to sunlight while maintaining the aesthetics and functionality of the bag. This placement allows users to generate energy on the go, suitable for charging small electronic devices such as smartphones, tablets, and LED lights. The design emphasizes portability and convenience, particularly for students, researchers, and professionals who require reliable energy sources during travel or fieldwork. Notable advantages of the chosen thin-film technologies include their lightweight nature, mechanical flexibility, long-term durability, and ability to perform efficiently even under partial shading conditions, an essential feature for everyday use in dynamic outdoor environments.

3.3 Sample Bags for prototype

Figure 2: Different sizes of backpacks for the Market

The figure above shows the different sizes of solar backpacks, where each backpack is equipped with a solar panel and other required components (Figure 2).

These solar panels are typically constructed using either monocrystalline or polycrystalline solar cells, with power ratings generally ranging from 5 to 10 watts for the largest backpack models. The panels are designed to provide a voltage output of approximately 5 to 6 volts DC and can deliver a maximum current of 1 to 2 amperes, making them suitable for charging small electronic devices.

In terms of physical dimensions, the large backpack measures approximately 18 to 20 inches in height and 12 to 14 inches in width, with a solar panel area of about 8 by 10 inches. The medium-sized backpack is typically 16 to 18 inches tall and 11 to 12 inches wide, featuring a solar panel area of roughly 7 by 9 inches. The smallest backpack in the series stands about 14 to 16 inches high and 10 to 11 inches wide, with a solar panel area of approximately 6 by 8 inches.

Common features across these solar backpacks include a USB charging port for convenient device charging, a built-in battery pack with a typical capacity ranging from 2000 to 5000 mAh, and a waterproof or weather-resistant construction to ensure durability in various environmental conditions. Additionally, these backpacks are equipped with multiple storage compartments and are often designed to accommodate laptops or tablets, particularly in the larger models. Overall, these solar backpacks are intended to provide portable and sustainable charging solutions for devices such as smartphones, tablets, and other USB-powered electronics, making them ideal for users who require reliable power sources while on the move.

4. Electronics and Charging System

4.1 Internal Electronics

The internal electronics of the "Solar Scholar" thin-film solar bag are meticulously designed to ensure optimal performance, energy efficiency, and user convenience. At the heart of the energy storage system lies a high-capacity lithium-ion battery, typically ranging from 10,000 to 15,000 mAh. This battery serves as a reliable reservoir for the solar energy harvested during daylight hours, allowing users to store sufficient power to charge multiple devices even after sunset or in low-light conditions. The battery is carefully integrated within the bag in a protected compartment to ensure safety, thermal stability, and long operational life.

To maximize the energy harvested from the solar panels, the system includes a sophisticated MPPT (Maximum Power Point Tracking) charge controller. MPPT technology continuously monitors and adjusts the electrical operating point of the solar panels to ensure they deliver the maximum possible power under varying light conditions. This is especially important for thin-film solar materials like CIGS or a-Si, which may experience fluctuations in performance due to partial shading or changes in sunlight intensity throughout the day. By using MPPT, the efficiency of the energy conversion process is significantly improved compared to traditional charge controllers, ensuring faster and more effective battery charging.

The output interface of the solar bag is designed with versatility in mind, featuring multiple ports to accommodate a wide range of electronic devices. These include USB-A and USB-C ports for charging smartphones, tablets, and other USB-compatible gadgets, as well as a DC port to power devices requiring direct current input, such as certain types of cameras or portable lights. This multi-port configuration enhances the bag's functionality for users across academic, technical, and professional fields who rely on various digital tools during travel or outdoor activities.

Additionally, an intuitive LED indicator system is incorporated into the electronics module to provide real-time feedback on the system's operation. This includes indicators for the current charge level of the battery and the status of solar energy collection. The LED lights help users understand when the bag is actively harvesting solar energy, how much charge is available, and whether their connected devices are receiving power. This user-friendly interface enhances the overall practicality of the solar bag, making it a dependable companion for mobile energy needs in diverse environments.

4.2 Charging Capacity

The Solar Scholar bag is capable of delivering practical energy outputs suitable for everyday devices. It can provide approximately 2 to 4 full charges for a standard mobile phone and 1 to 2 full charges for most tablets. For laptops, the charge capacity varies depending on the device's battery size and power requirements, ranging from a partial to a full charge. This makes the bag a versatile and efficient energy solution for users needing reliable on-the-go power.

Mathematical Equations

Solar Irradiance and Incident Power

Solar Irradiance:

$$G = \frac{E}{A.t}$$

Where, G is solar irradiance W/m^2

E is solar Energy received J

A is effective area of the solar panel m^2

t is time duration in s

Power Incident on Panel:

$$P_{in} = G.A$$

p_{in} Total solar power incident on the panel W

Output Power of Thin-Film Solar Cell

$$P_{out} = \eta.P_{in}$$

P_{out} is electrical output power W

Total Energy Generated

$$E_{gen} = P_{out}.t = \eta.G.A.t$$

E_{gen} is total energy generated over the time t

Battery Storage Requirement

$$E_{batt} \geq E_{gen}.\gamma$$

y is Storage efficiency factor (0.9 to account for charging losses)

Load Demand and Backup Time

$$t_{backup} = \frac{E_{batt}}{P_{load}}$$

t_{backup} Duration the battery can supply power

P_{load} Power consumption of devices *W*

Thermal Consideration (Optional for Design)

$Q = m.c.\Delta T$

Q is Heat absorbed or dissipated

m is Mass of the solar panel

c is Specific heat capacity

ΔT is Temperature change

Efficiency of Overall System

$\eta_{sysem} = \eta_{solar} . \eta_{converter} . \eta_{battery} . \eta_{load}$

5. Performance Evaluation

5.1 Test Conditions

The design bag has been rigorously tested under various lighting conditions, including clear skies, cloudy weather, and shaded areas, to assess its performance in diverse environments. Measurements were carefully taken for key parameters such as voltage, current, charging time, and thermal stability to ensure consistent and reliable operation in all conditions.

5.2 Observations

The research results presented in the simulation graphs and accompanying data illustrate the effective performance and real-world applicability of the Solar Scholar bag in a variety of conditions. The top graph shows the simulated solar irradiance, peaking at around 1000 W/m² between 10:00 and 14:00 hours, which mimics a typical clear-sky day (Figure 3). Under such irradiance, the middle graph indicates that solar charging power, governed by 10% thin-film photovoltaic (TFPV) efficiency and 95% MPPT efficiency, rises sharply after sunrise, peaks near noon (~22 W), and begins to decline as sunlight weakens. Meanwhile, the device usage power remains constant at 5 W during the daytime (Figure 4).

The bottom graph represents the battery state of charge (SOC) vs time curve. In simple terms, the amount of energy left in the battery compared to its capacity is known as State of Charge (SOC). Similarly, the Battery Cycle represents the process of fully charging and discharging a battery. The figure below demonstrates that the 50-Wah battery reaches full charge within approximately 6 to 8 hours of direct sunlight exposure (Figure 5). This aligns with the stated performance metrics and confirms that the energy harvested significantly exceeds the constant 5 W consumption during peak solar hours. Even under cloudy conditions, the system retained approximately 70% of its performance, ensuring a slower but steady charging rate. Furthermore, the battery's long-term reliability was confirmed through sustained performance after over 100 charge/discharge cycles, indicating robust efficiency and minimal degradation.

The physical durability of the bag was also validated through urban and campus wear-and-tear simulations, showing that the design is well-suited for daily academic and professional use. With the TFPV panel converting solar energy at 10% efficiency and the MPPT controller operating at 95% efficiency, the overall system demonstrates a highly optimized energy conversion pipeline. In summary, the Solar Scholar bag offers reliable and durable solar-assisted charging, efficiently balancing energy harvesting and consumption even under varying environmental conditions.

Numeric Calculations Table:

Parameter	CIGS (Copper Indium Gallium Selenide)	a-Si (Amorphous Silicon)	Unit
Solar Panel Area	0.5 x 0.3	0.5 x 0.3	m^2
Solar Irradiance	1000	1000	W/m^2
Panel Efficiency	12%	8%	%
Power Output	18	12	W
Battery Type	Lithium-ion	Lithium-ion	-
Battery Capacity (Low)	10,000	10,000	mAh
Battery Capacity (High)	15,000	15,000	mAh
Battery Voltage	5	5	V
Battery Energy (Low)	50,000	50,000	mWh
Battery Energy (High)	75,000	75,000	mWh
Device Power Consumption (Smartphone)	10	10	W
Device Power Consumption (Laptop)	45	45	W
Charging Time (Smartphone, CIGS)	2777.8	4166.7	Min
Charging Time (Laptop, CIGS)	1111.1	1666.7	Min
Charging Time (Smartphone, a-Si)	4166.7	4166.7	Min
Charging Time (Laptop, a-Si)	1111.1	1666.7	Min
Sunlight Hours per Day	6	6	Hours
Total Energy Harvested (CIGS)	108	-	Wh/day
Total Energy Harvested (a-Si)	-	72	Wh/day
Energy Harvested per Year (CIGS)	39,420	-	Wh/year
Energy Harvested per Year (a-Si)	-	26,280	Wh/year
Solar Panel Power Output (CIGS)	18	-	W
Solar Panel Power Output (a-Si)	-	12	W
Environmental Impact (CO_2 Saved Annually)	100 kg	100 kg	kg CO_2/year
Device Charging Feasibility (Smartphone)	2777.8 min	4166.7 min	Min
Device Charging Feasibility (Laptop)	1111.1 min	1666.7 min	Min

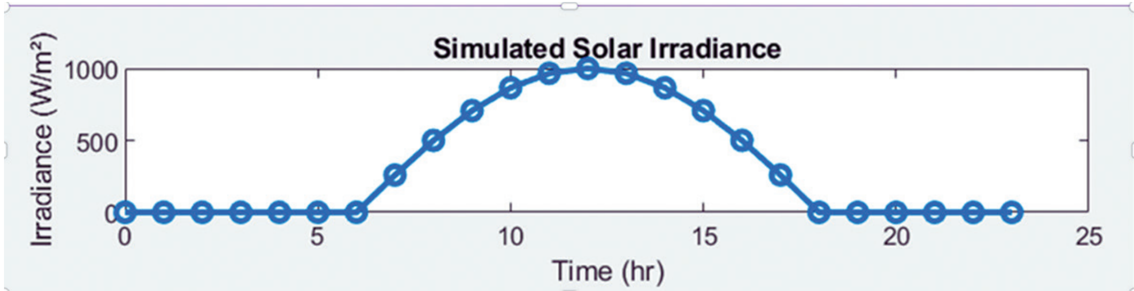

Figure 3: Solar Irradiance Vs Time Curve

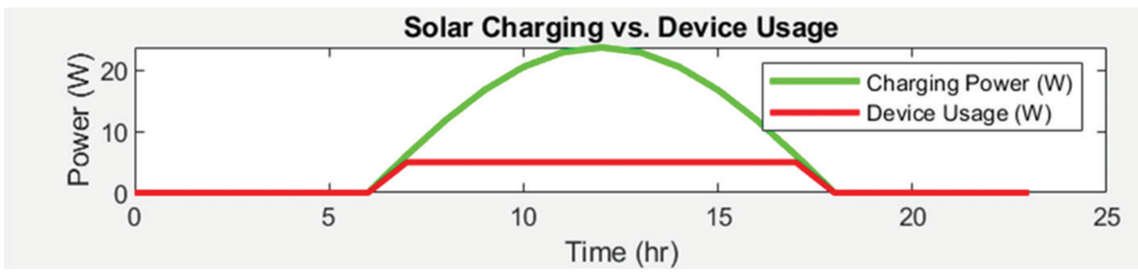

Figure 4: Power Vs Time Curve

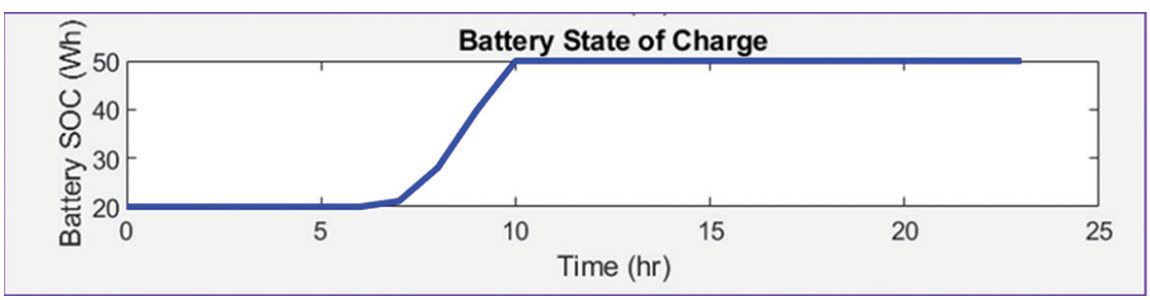

Figure 5: Battery SOC Vs Time Curve

6. Real data testing in MATLAB software

In this innovative system, a prototype circuit is developed in MATLAB to facilitate the efficient charging of batteries using solar energy. The design not only captures solar power but also provides electricity to a variety of electronic devices, such as mobile phones, laptops, AirPods, and more, showcasing its versatility.

To ensure accurate real-time environmental monitoring, the system utilizes real data gathered from a single day in the Jumla district. This approach allows the circuit to yield effective results based on actual conditions, paving the way for potential implementation at the hardware level as a marketable product.

As illustrated in the accompanying figure, the daily solar irradiance profile for Jumla on August 1st displays a distinctive pattern. The blue line, which represents the solar irradiance, reveals a beautiful bell-shaped curve indicative of a largely clear to partly cloudy day. It begins to rise elegantly at 6 AM, peaking impressively between 12 PM and 2 PM, reaching values that exceed 900 watts per square meter. As daylight wanes, the irradiance value gracefully declines to zero after 6 PM.

In contrast, the orange line in the figure signifies the ambient temperature, which remains relatively stable throughout the day. This consistency indicates a comfortable temperature range fluctuating between 15°C and 25°C, contributing to the overall efficiency of the solar charging system by 5°C.

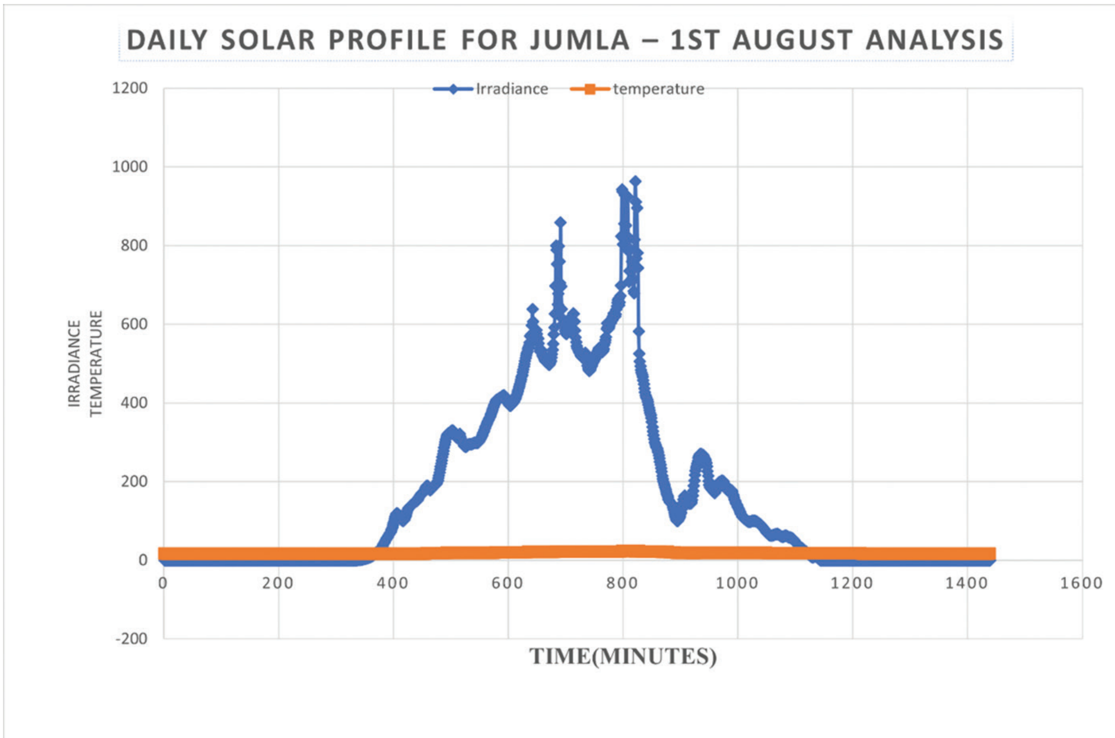

Figure 6: Daily Solar Profile for Jumla

For the sample analysis, we concentrated on the one-hour interval from 1 PM to 2 PM, a critical timeframe for assessing solar energy production. Illustrated in Figure 7 is the corresponding hourly graph for this period, where the blue line signifies the irradiance values measured in watts per square meter (W/m²), and the yellow line represents the temperature readings in degrees Celsius (°C). Notably, throughout this hour, the temperature remains relatively stable, fluctuating only within a narrow range of 1–2°C, indicating consistent atmospheric conditions. In contrast, the irradiance levels exhibit significant volatility, with peaks reaching up to 800 W/m² and troughs dipping below 200 W/m², as demonstrated in the graph. This variability is likely due to passing clouds and changes in the angle of the sun.

To effectively optimize the maximum power output of the solar system, we employ the Particle Swarm Optimization (PSO) technique in conjunction with the incremental conductance method. This sophisticated algorithm utilizes a population of candidate solutions (or "particles") that iteratively search for the optimal operating point. By adjusting their positions based on their own experience as well as the experiences of neighboring particles, the PSO method efficiently navigates the solution space. Additionally, the incremental conductance method helps in precisely determining the maximum power point (MPP) by analyzing changes in voltage and current over time. Together, these algorithms facilitate the generation of the requisite pulse signal, which is essential for regulating the duty cycle of the associated switch in the power electronics system. Thus, the combined operation of these algorithms contributes significantly to enhancing overall system performance and energy conversion efficiency, optimizing the output under varying environmental conditions.

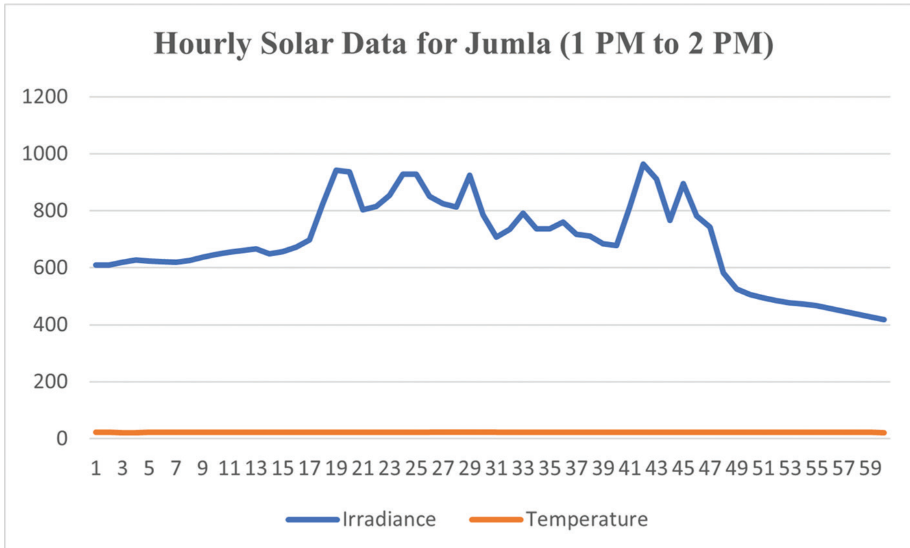

Figure 7: Hourly Solar Data for Jumla

The diagram below showcases the complete circuit for solar power generation, illustrating the intricate processes involved in harnessing solar energy. It begins with the signal builder block, which generates the essential signals derived from irradiance and temperature data meticulously collected from the Jumla district during the time frame of 1 PM to 2 PM (as depicted in Figure 9). This data is pivotal, as it enables an accurate simulation of the environmental conditions under which the solar power system operates optimally.

From the irradiance and temperature inputs, the system generates corresponding current and voltage values. These electrical outputs are then amplified to achieve the desired performance levels, ensuring that the solar energy conversion is efficient and effective. Following this enhancement, the circuit incorporates an LC filter, which plays a crucial role in minimizing harmonics and ripples present in the output. This filtering process is vital for maintaining a stable and clean energy supply, ultimately ensuring the reliability and longevity of the solar power system.

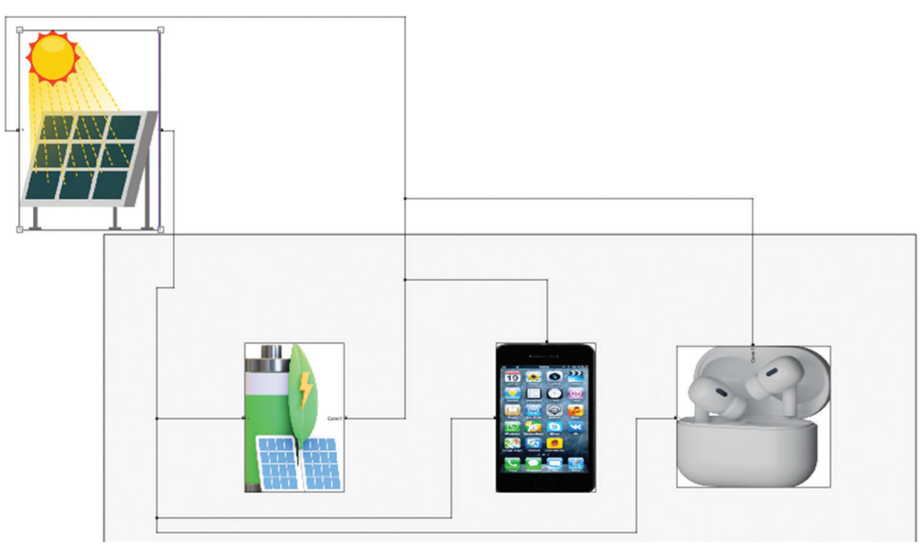

Figure 8: Integrating all systems as per the requirement

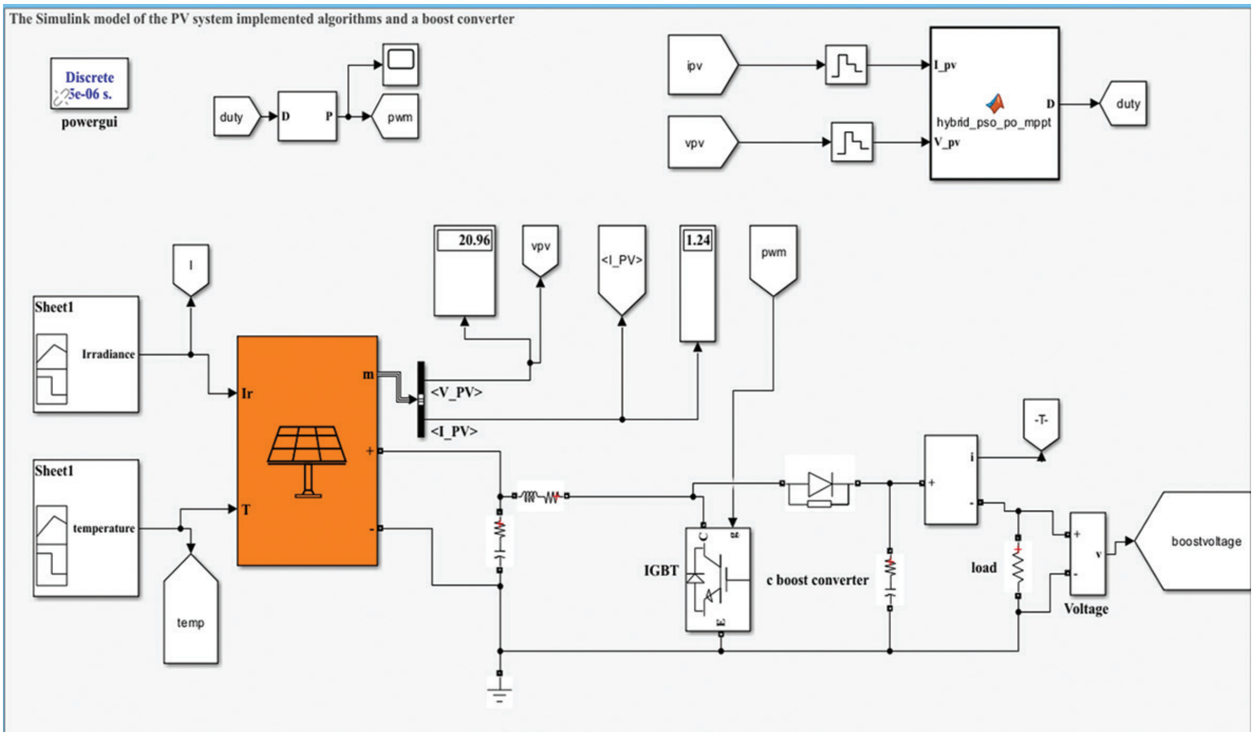

Figure 9: Solar system for power generation

A Simulink block diagram (Figure 9) modeling a solar power system with power optimization control was developed. The system starts with a photovoltaic module connected to a DC-DC boost converter circuit that includes components such as an IGBT switch, a diode, and an inductor. The control system implements pulse-width modulation (PWM) generation for DC-DC conversion, and multiple measurements and monitoring blocks throughout the system track parameters such as voltage, current, and power. The system includes feedback loops and control algorithms that implement MPPT optimization techniques. The system also includes various scopes and display blocks for monitoring system performance and output variables. This model was used to simulate and analyze the behavior of a solar power conversion system with its associated control mechanism.

The Particle Swarm Optimization (PSO) technique in conjunction with the incremental conductance method is applied in this circuit in order to retain the maximum efficiency while tracking the power using the MPPT technique. The Particle Swarm Optimization (PSO) Algorithm Implementation is explained in simple language.

Particle Swarm Optimization (PSO) is a nature-inspired optimization algorithm that mimics the collective behavior of bird flocks and fish schools, where individual particles work collaboratively to find optimal solutions. In our implementation, each particle represents a potential solution to the optimization problem and navigates through the solution space guided by both individual and collective intelligence. The algorithm maintains track of each particle's current position in the solution space, its velocity, and two crucial memory components: Personal Best (Pbest) and Global Best (Gbest). Pbest represents the best position that an individual particle has discovered, while Gbest denotes the best position found by any particle in the entire swarm.

The movement of particles is governed by two fundamental equations: the velocity update equation and the position update equation. The velocity update equation calculates each particle's new velocity by combining its current velocity with two influential factors: the pull toward its personal best position and the attraction toward the global best position. These influences are weighted by learning factors and random components to ensure diverse exploration of the solution space. The position update equation then determines each particle's new position by adding its newly calculated velocity to its current position, similar to how an object's position changes based on its speed and direction.

This iterative process continues until one of several stopping criteria is met: reaching the maximum number of iterations, finding an acceptable solution, or achieving convergence where particles no longer make significant improvements. Through this collective behavior, the swarm gradually converges toward the optimal solution in the search space, effectively balancing the exploration of new areas with the exploitation of promising regions. The algorithm's strength lies in its ability to maintain diversity while simultaneously focusing on promising areas of the solution space, making it particularly effective for complex optimization problems.

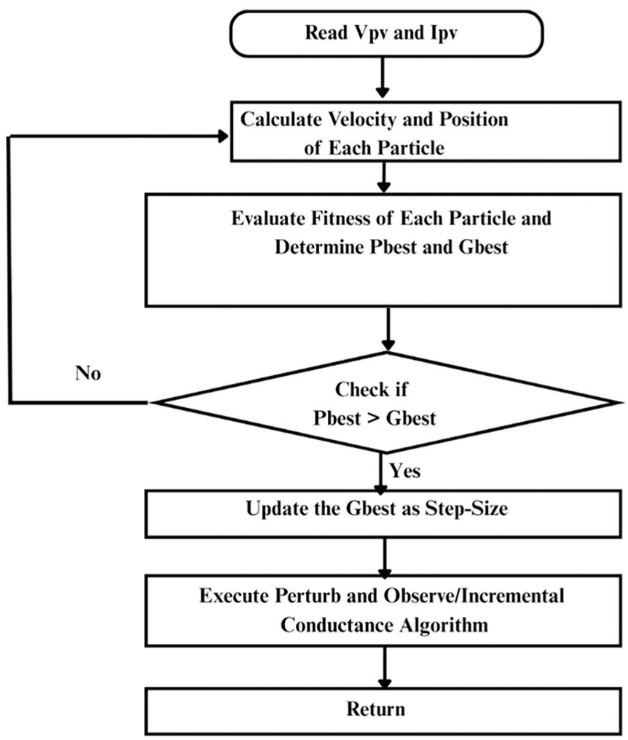

Figure 10: Flow chart of proposed PSO-driven P&O/INC optimization

The solar energy system operates with remarkable efficiency, harnessing sunlight to charge a high-capacity battery, as visually depicted in Figure 8. This innovative setup incorporates an intricate switching mechanism that plays a dual role: it facilitates the charging of essential devices, such as smartphones, tablets, and portable electronics, while simultaneously ensuring that the battery is charged only when necessary, thereby optimizing energy use and longevity. Acting as a reliable backup power source, this system not only promotes sustainability but also provides peace of mind for users in case of power outages. With this advanced configuration in place, a diverse range of electronic devices can be conveniently charged, empowering users to remain connected and productive regardless of their location.

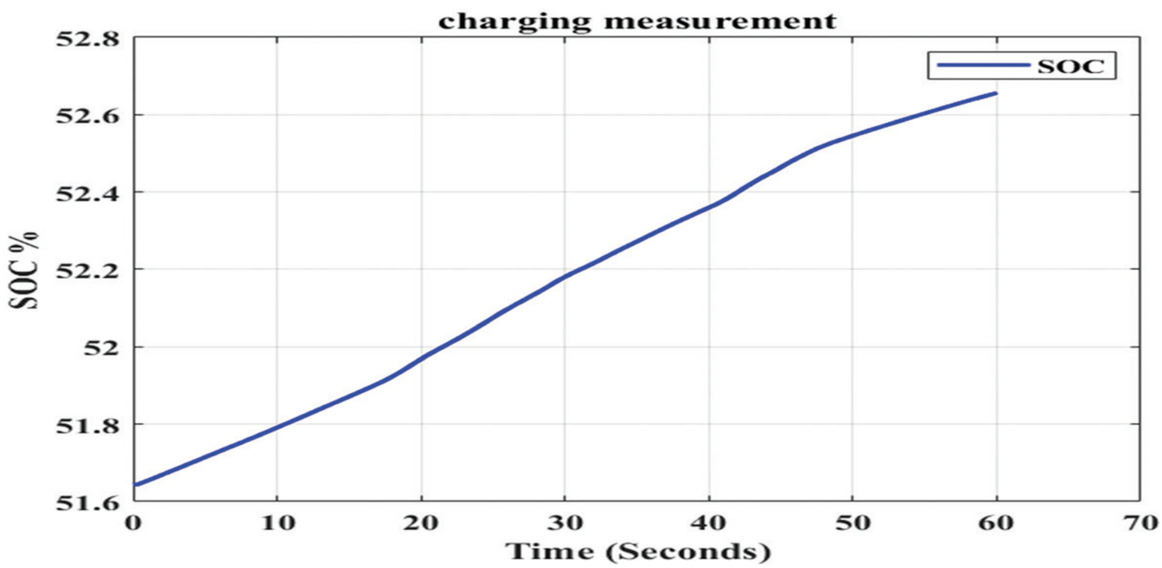

Figure 11: Charging the battery using solar

The figure displayed above illustrates the state of charge of the solar battery connected to the output of the solar power generation circuit (Figure 10). At the outset, the battery begins with an initial state of charge at 50%. Following the simulation, the battery begins to harness energy from solar power, utilizing one hour's worth of data collected from the Jumla district.

The graph presents the variation of State of Charge (SOC) in percentage over time (in seconds) during a battery charging cycle. It serves to evaluate the charging behavior and rate of SOC increase, which is a critical metric for battery management systems (BMS), especially in electric vehicles or renewable energy storage systems.

7. Financial Modeling

A financial model was developed to evaluate the potential success of the Solar Scholar thin-film solar bag in the Nepali market. This model looks at all the important costs involved, expected income, and key financial indicators to determine whether the project is a sustainable option.

When creating financial plans for sustainable technologies, it's crucial to understand the market, the costs of production, and how to generate revenue. This involves initial investments such as expenses for research and development, production equipment, and marketing efforts. A thorough analysis of production costs includes both constant (fixed) costs and those that can change (variable costs). Setting the right prices for the solar bags is vital; they need to be affordable for customers while also allowing the business to make a profit. This balancing act takes into account the economic conditions in Nepal and the competitive landscape.

The project evaluation process examines how a project might succeed in the market while identifying potential risks. It looks at challenges that could arise during execution and explores various scenarios to understand their impact. Additionally, the evaluation considers the environmental effects of the product, how to measure profits, and the overall economic impact. This approach helps create business models that balance profitability with environmental responsibility and adaptability to changing market trends and technologies.

Financial details	Details	Value (NPR)
Initial Investment	Research & Development, Tooling, and Marketing Costs	1,330,000
Variable Cost per Unit	Solar Panel, Battery, MPPT Controller, Materials, Assembly & Packaging	5,985
Retail Price per Unit	Market-competitive Price Point	11,970
First Year Sales Target	Conservative Market Entry Estimate	1,000 units
Annual Revenue	Total Sales × Retail Price	11,970,000
Annual Operating Expenses	Marketing, Customer Support, Administrative Overhead	864,500
Gross Profit	Revenue - (Variable Cost × Units Sold)	5,985,000
Net Profit Before Tax	Gross Profit - Operating Expenses	5,120,500
Gross Margin	(Gross Profit ÷ Revenue) × 100	50%
Net Margin	(Net Profit ÷ Revenue) × 100	42.80%
Break-even Point	Units Required to Cover Fixed Costs	289 units
Annual Growth Rate	Projected Year-over-Year Sales Increase	20%
Payback Period	Time to Recover Initial Investment	< 1 year

8. Challenges and Limitations

Despite its numerous advantages, the Solar Scholar bag also presents certain limitations that must be considered. One of the primary constraints is its limited power output, which restricts its ability to support high-consumption electronic devices such as large laptops or power tools. Additionally, the performance of the solar panels is inherently dependent on weather conditions, meaning that cloudy or rainy days can significantly reduce charging efficiency and extend the time required for energy collection. Another notable drawback is the initial cost, which is generally higher than that of conventional bags due to the inclusion of advanced solar technology and integrated electronics. These factors may impact its accessibility and practicality for some users, particularly in budget-sensitive contexts.

9. Conclusion

The Solar Scholar thin-film solar bag offers a practical and sustainable solution for mobile energy needs in both academic and professional settings. Analyzing one-hour data from the Jumla district highlights its potential as an underrated option for energy savings. As a renewable energy source, this bag not only provides a safe and environmentally friendly way to generate daily power but also integrates advanced lightweight thin-film solar technology with high-efficiency internal electronics. Features such as a high-capacity lithium-ion battery ensure reliable energy storage for essential devices like smartphones, tablets, and laptops, making it ideal for users on the go. Additionally, the built-in maximum power point tracking (MPPT) charge controller optimizes solar energy capture, maintaining effectiveness even under partial shading conditions.

The Solar Scholar bag also plays a vital role in fostering interest in sustainable technology among students while promoting effective energy management practices. By integrating renewable energy solutions into daily routines, users can take charge of their energy consumption and contribute to a greener future. Its practical applications extend across diverse user groups, ensuring that students remain connected during study sessions, field researchers have reliable energy in remote locations, and urban professionals can support sustainable commuting. Furthermore, as a dependable backup power source during emergencies, the Solar Scholar bag reduces reliance on fossil fuels and encourages environmentally responsible behavior, aligning with global sustainability efforts and the United Nations Sustainable Development Goals. Through its innovative design, this solar-powered backpack represents a significant step toward a more sustainable future for individuals and communities alike.

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