C. Vimalraj[1],

Murugesan Srinivasan[2],

S Aruna[3],

T.Vinoth Kumar[4]

AI Algorithms for Advanced Energy Management Strategies of Hybrid Solar Systems

Journal of Electrical Systems

Abstract: - This paper presents a comprehensive energy management mechanism for hybrid solar systems from different aspects of solar energy generation, battery storage, and grid coupling. The proposed system operates through on advanced modes—Hybrid, Smart, and Power Conditioning Unit (PCU)—which are used for power distribution in real-time for the uninterrupted supply of energy. Utilizing Maximum Power Point Tracking (MPPT) controllers, inverters, and smart algorithms such as Reinforcement Learning (RL) and Fuzzy Logic, the system reaches high efficiency, adaptability, and sustainability. The hybrid mode here helps to distribute energy flows among local solar power, batteries, and the grid, while the smart mode adjusts resource allocation from the grid dynamically based on real-time weather and environmental conditions to optimize the use of renewable energy as well as maintain the battery health. PCU mode prioritizes avoiding grid outages and low solar with very low availability & resource preservation. This research illuminates the pivotal function of intelligent hybrid systems in enhancing sustainable energy solutions, thereby facilitating the generalized employment of renewable energy.

Keywords*:* Hybrid Solar Energy Systems, Energy Management Optimization, Reinforcement Learning (RL), Fuzzy Logic Control, Smart Grid Integration

1. INTRODUCTION

The energy transition has emerged as a key issue in the global search for sustainable development and energy security. Among the most abundant and clean forms of renewable energy and also near-inexhaustible nature, solar power stands out. Solar energy is one of the main pillars of the renewable energy sector, providing significant potential to transition away from fossil fuels and decrease greenhouse gas emissions. Nonetheless, harvesting solar energy have many challenges due to the intermittency nature of solar energy which relies on external characteristics like sun light intensity, duration and weather conditions. These challenges highlight the necessity for intelligent systems and advanced technologies that can maximize the harvesting, storage, and distribution of solar energy.

Photovoltaic (PV) systems harness solar energy by converting sunlight directly into electrical energy by utilizing the photovoltaic effect. They are a cornerstone of renewable energy infrastructure, used in residential, commercial and utility-scale situations. PV systems are widely used but have limitations, especially when solar generation is hampered due to cloudy days, nighttime, and seasonal variation. As a response to these challenges, hybrid energy systems combined with solar power and smart grids are gaining a significant momentum, providing an effective tool for balancing the steady supply of electricity from the grid and alternative sources and contributing to the grid based renewable systems and technologies development.[1]

[1]Associate Professor, Department of Electrical and Electronics Engineering, Builders Engineering College (Autonomous), Kangeyam- 638108 Tamil Nadu, India drcvimalraj@gmail.com
[2]Professor, Department of Electrical and Electronics Engineering, Builders Engineering College (Autonomous), Kangeyam, Tamil Nadu, India -638108 , Tamilnadu, India srinimeha@gmail.com
[3]Assistant Professors(SG) Department of Electrical and Electronics Engineering, Dr. N.G.P Institute of Technology , Coimbatore-641004, Tamilnadu, India arunasubra1985@gmail.com
[4]D. Associate professor, Department of Electrical and Electronics Engineering, RVS College of Engineering and Technology,Kumaran kottam campus,Coimbatore-641402.Tamil Nadu, India. tvinoth15f@gmail.com

A smart grid is one of the advanced technologies that you will use to manage energy. Due to their capability to flexibly control power flows, smart grids are suitable for the integration of solar energy for both grids and off-grids. [2] By using intelligent automation, these grids help to make maximum use of solar energy providing a balance between supply and demand, reducing wastage and decreasing reliance on non-renewable energy. [3]

This work highlights the coupling of all the key elements like MPPT controllers, inverters, solar panels, battery, etc. in Smart grid environment. The study of these key components is significant to overcome the environmental threat of solar energy use and to achieve smooth operation in hybrid energy systems.

2. LITERATURE REVIEW

It has been a widespread research area to utilize renewable energy sources so in combination with adaptive load-sharing mechanisms and EV charging in order to increase the efficiency and sustainability of both modern society and the related power systems.[4,5] In this review, we highlight the key contributions made in these areas, highlight progress, as well as areas of opportunity that remain.

This study addresses few adaptive load-sharing strategies that play an important role in the balancing of energy supply and demand between these two sources of systems. Hu et al. (2021) designed a microgrid-based predictive control algorithm suggesting reliable resilience and energy efficiency of microgrids. Similarly, Chen et al. to achieve for enabling stability and power loss reduction of hybrid AC/DC microgrids, they proposed a non-centralized load-sharing method in [6]. However, these studies are focused on microgrid but large-scale hybrid system implementations are lacking.

Additionally, renewable energy-solar power in particular-is not always found easily into these existing grids, starting with the fact that renewable energy is intermittent. It pointed out MPPT algorithm plays a significant role in improving the effectiveness of PV system under different environmental condition [7]. Additionally, Ahmed et al. [8] discussed hybrid energy systems such as combined solar and wind energy systems, emphasizing the requirement of effective energy management techniques for managing variability. These breakthroughs showed promising results, but the full incorporation of PV systems into hybrid configurations still needs deeper study.

The growth in EVs will have to be matched by smart charging regimes to stop the grid becoming overloaded. Wang et al. [9] proposed a real-time pricing mechanism for electric vehicle (EV) charging to promote off-peak charging while minimizing peak demand. He proposed a vehicle-to-grid (V2G) architecture, which brings a two-way energy exchange capability between EVs and the grid, improving grid stability. But challenges remain when it comes to large-scale implementation of these solutions, especially for off-grid and hybrid systems.

Dynamic energy management as a solution is to be linked through the smart grids that fulfilled the role of complex monitoring and control systems. Information and communicating technology (ICT) plays a significant part in smart grids development as argued in [10, 11] where a need for standardization in terms of communication protocols for integrating distributed energy resources was highlighted. Similarly, Zhang et al. (2021) of the potential benefits of artificial intelligence in predictive maintenance and load forecasting for smart grids. Though powerful, the incorporation of these technologies in hybrid energy systems and EV charging infrastructure is still immature. [12]

Although there are algorithms for adaptive load-sharing and optimized electric vehicle charging, energy management is not widely implemented and there are still some constraints that underlie this in the literature. Most developed solutions are microgrid specific; thus scaling them up for hybrid energy application can be a challenge. In addition to this, the interoperability of the components of such systems is a challenge, as if we want the different renewable energy sources, battery storage mixers, and the grid infrastructure to work together--after all--then we need standardized protocols to allow each piece of the system to talk to others. Another major concern is the economic viability, as the cost of introducing smart grid technologies and EV charging infrastructure is high. This high cost creates an urgent need for cost-effective strategies that would render such systems accessible and practical on a larger scale.

The present research is focused on addressing these challenges by offering novel solutions to make hybrid energy systems more exploitable and efficient. The work also examines hybrid systems combining solar, grid, and battery power to manage smooth transitions between energy sources in changing operating conditions. The goal of the system is to use real-time feedback and control systems embedded in a smart grid infrastructure to optimize energy usage with proper planning, so as to be less dependent on fossil/other non-renewable energy resources. This study, using this approach, aligns with the broader context of sustainable energy scheduling by increasing the robustness of grid against failure, the lower the emission of green house gases, and the higher the path to scale the solutions for future energy ecosystem.

3. METHODOLOGY

3.1 System Design Overview

The paper suggests a hybridization of PV arrays, maximum power point tracking (MPPT) controllers [13], inverters, battery storage systems, and the grid. Energy transfer between these components is depicted in the block schematic, Fig. [1]. Owing to the virtual control of sub-segments and operated dynamically, it can aid the user with varying environmental and load conditions when distributed controlled energy approaches the local grid, via optimized energy distribution to reduce dependence on the grid and operation costs.

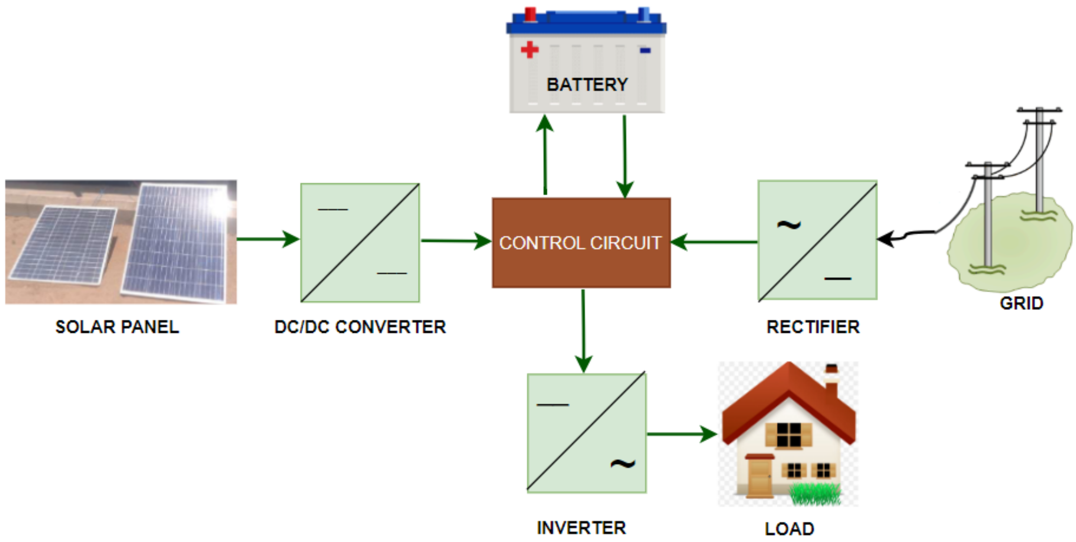

Fig.1. Block diagram of proposed system

Photovoltaic (PV) System

The main renewable energy source, of course, is the solar PV system that converts sunlight to electrical energy. The PV system efficiency relies on input parameters like solar irradiance and temperature. The PV modules are connected to MPPT controllers designed to maximize energy extracted from the modules according to changing conditions. PV system contains some modules which are connected in series and parallel for achieving the desired voltage and current levels.

MPPT Controllers (Maximum Power Point Tracking)

To maximize the energy output, MPPT controllers are necessary. MPPT algorithms work to extract maximum energy by frequently changing the operating point of the PV array in accordance with the instantaneous environmental conditions. The proposed system uses a very simple Efficient Perturb and Observe (P&O) MPPT algorithm. It regulates the DC output from a PV system to provide a stable input to the inverter.

Battery Storage System

Batteries harvest any excess energy produced during peak solar hours and disburse that energy at times when solar production is deficient. Lithium-ion batteries are used as they have high energy density, are efficient and have a long lifecycle. Capacity of the battery bank is 10 kWh, assumed to be configured to meet both load and EV charging needs. The battery management system (BMS) of the battery keeps track of charge and discharge cycles to avoid situations of overcharging and deep discharge which can damage the battery and thereby extending its life.

Inverters

Inverters that couple direct currents (DC) power from the PV system with battery and convert it to alternating current (AC) power, which is then fed into the grid or consumed locally. The presented approach utilizes a multi-source capable hybrid inverter. Inverter's energy efficiency is greater than 95%, which means less energy loss. The inverter has the capability to synchronize with the grid, which allows it to transition between the on-grid mode and off-grid mode.

Grid Connectivity

Grid access acts as a backup, as an energy source when demand is high and renewable production is low. The system lights up the homes with other than the grid as required optimizing on cost and availability of the renewable sources.

3.2 A Generic Adaptive Load-Sharing Mechanism

In this case, the energy reference for each source is dispersed uniquely based on the energy disposition with an adaptive load-sharing algorithm applied to distribute energy among the PV system, battery storage, and the grid. And in any case there are two goals: to increase the share of renewables, but still to keep the power supply reliable. The algorithm [14] functions according to the below principles:

Sensors continuously monitor solar generation, battery charge levels, and load demand. All renewable energy produced from the PV system is utilized to the maximum extent to supply loads, and any surplus energy is used to charge the batteries.When solar output is low, it switches to battery power or grid supply, reducing energy expenses.

Scenarios:

- A lot of sunshine: Excess sunlight loads internal batteries or electric automobiles.
- Low Solar Generation: Continuity of power with battery, grid supply
- Hybrid Mode: The system utilizes the power of all sources as needed depending on demand and availability.

3.3. WORKING OPERATION

A few real-time challenges that the proposed hybrid solar system would need to deal with are fluctuating solar energy, varying load demands, and grid outages. This solution addresses the described control in a rational manner with the use of Reinforcement Learning [15] towards the controllability aspect and Fuzzy Logic [16] towards handling uncertainties and non-linearities of the environment. In combination, these methods can allow for optimal distribution of power between solar panels, batteries, and the grid.

3.3.1 Reinforcement Learning (RL)

A machine learning technique in which an agent learns to perform actions in an environment in a sequential manner by maximizing a reward function. For a hybrid solar power system, the agent is actually the energy management system while the environment includes panels, battery, grid, and load. Operating states are identified by the status of solar panels, grid, battery voltage (e.g. >14.5V, 11.8V, or critical), and load demand (low, medium, high). The agent acts by choosing the correct power source (solar/grid/battery) and managing energy flows on the fly. The reward function can promote actions that use as much renewable energy as possible and reduce reliance on the grid while providing power without damaging the batteries.

3.3.2 Fuzzy Logic Integration

The RL framework is extended to Fuzzy Logic to improve the decisions on variable sunlight reaching the panels and Load demand variability. Fuzzy logic is a very useful area which allows the system to make decisions based on approximate conditions, unlike traditional binary logic.

Inputs:

Renewables Availability: Low, Medium or High (Solar Power)

Battery State of Charge [17] SOC: Low, medium, or high battery state of charge

Load Demand — low, medium or high.

Rules:

Suppose the solar power is high and battery charge is low, you can charge the battery from the solar energy. The voltages used to trigger the grid power switch are used are general, if the battery voltage drops below 11. 8V, switch to grid power to protect the battery. if solar is greater than the load and the battery voltage is greater than 14.5V, disconnect the grid and use solar priority

If solar is not enough to supply load demand, combine battery and solar power to make sure to supply uninterrupted.

Outputs:

Decides which power to use for load. Should I charge the battery and from which source (solar or grid)[18] Real time based transition between Energy Source.[19]

3.3.3 Operational Workflow

The AI algorithm consists of three main steps:

Initialization:

Set up RL states, actions, reward function. Define rules for fuzzy inference involving solar power availability, battery voltage, and load demand for making decisions. [20]

Training:

Train the RL agent on the simulated data. This information consists of solar irradiance from the previous years, available performance data of the batteries and grid based data. It saves your time to test the agent on many scenarios such as grid outages, overloaded, solar power fluctuating.

Deployment:

Deploy the trained RL agent on real-time application for dynamically managing power scheduling. Perform online reinforcement learning to constantly update the agent to learn new conditions.

3.3.4. Hybrid Mode Expansion

The charger is in the system that charges the battery from the solar collection panel and from grid when in operation. The controller, when there is excess energy produced by the solar panel which is not being utilized by the load, would then focus on charging the battery. When the grid is providing power, it directly controls the charger to adjust the charge for batteries so that the batteries can be sufficiently charged with grid power and take maximum advantage of it from renewable energy sources. (Fig.2.)

So, a solar power system with well-connected batteries and connected to the grid will provide well flexibility, resilience, and efficiency regarding electricity generation, storage, and consumption at different levels and conditions. It also enables self-sufficiency by utilizing renewable energy and has the ability to be a backup power supply for grid outages or fluctuations.

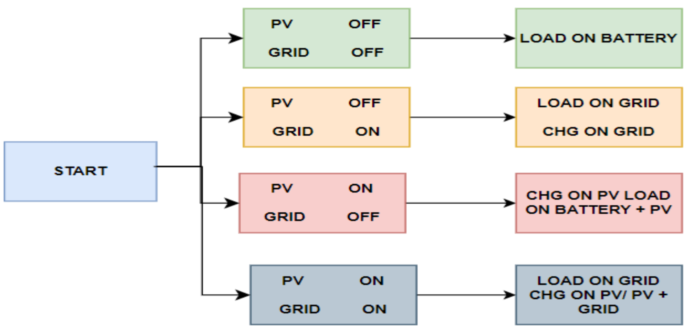

Fig.2. Hybrid Expansion mode

Solar Panel and Grid Both Off

This situation usually happens overnight or when solar generation is off and grid power is not available from an outage or when intentionally disconnected. Here, the battery is exclusively powering the load. Hence the battery releases the energy charged inside it to supply the power required for the load. It is essential for providing uninterrupted power supply when the solar panel or the grid is unavailable.

Solar Panel Off, Grid On

If, the solar panel is not generating electricity but the grid is present and giving power, the load will take electricity directly from the grid. Most systems have a transfer switch that automatically alters the electricity source from the grid or battery, depending on availability. This approach makes sure that the load gets power without any interruption.

Solar Panel On, Grid Off

If the solar panel is generating power, but the grid is unavailable then the load is powered largely from the solar panel in this case. Any surplus solar energy produced beyond the immediate needs of the load is used to charge the battery. It enables the system to capture excess solar energy, which can then be used later, at night, or on cloudy days, when solar generation is scarce or non-existent.

Solar Panel and Grid Both On

The grid primarily supplies the load when the solar panel is producing energy and the grid is on. This is particularly beneficial in periods of high load or if the solar generation cannot fulfil the demand. At the same time, the surplus solar energy produced is used to charge the battery. The battery is basically the buffer, storing overflow energy from your solar panels.

3.3.5. Smart Mode Expansion

The smart mode uses the sources available as effectively as possible with regard to efficiency, reliability, and sustainability. The system will supply energy to the load through the use of renewable energy hubs to the greatest extent and hence leading to minimum utilization from the external source and also making sure that uninterrupted power supply to the load. (Fig.3.)

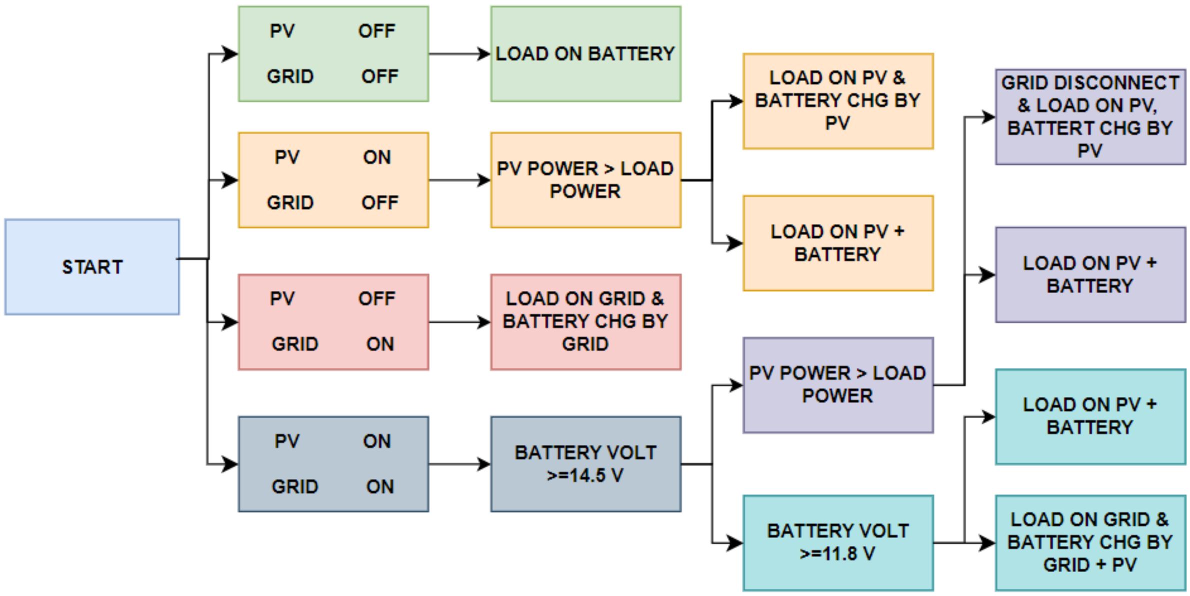

Fig.3. Smart Expansion Mode

Load On, Grid Off, Solar Exceeds Load Power

If the load is running and the grid connection is faulty, but there is more solar power available than what is being fed to the load, the best approach is to use the excess solar energy to power the load. At the same time, excess energy goes to charge the battery and store it for later.

Load On, Solar and Battery Energy Supply

The system automatically adds the battery power when solar power alone is insufficient to supply the load. The system supplies the load with the power coming from the renewable energy source, or, if it is not producing power, it supplies it with stored energy from the battery to ensure that it never runs out.

Solar and Grid On, Battery Voltage ≥ 14.5V

The battery is active once it has both solar and grid power sources available, and the voltage is 14.5 volts or greater, indicating a fully charged battery. This is also called the battery health threshold voltage which means that the battery still has a lot of energy stores to operate the device. Finally, if under these circumstances the amount of solar power generated is greater than the load demand and the battery is in an active state, then the system allocates solar energy for use. It even decouples from the grid, making sure that the load gets power from solar primarily (and at the same time, the rest of the energy available charges the battery further).

Solar production is greater than load, and battery voltage is less than 14.5V

When the solar power is great enough to power the load but the battery voltage is still not enough to reach the activation threshold, so the final option is taken. Here, the system remains connected to the grid and continues to draw power from solar and battery to meet the load.

Battery Voltage at 11.8V

An 11.8-volt battery is low and close to being discharged at 12.0 volts, which is the threshold for the bottom of most battery industries. Now, the system prioritizes conserving battery health and will extend its lifespan. To avoid further discharging the battery and supply continuous power to the load, the battery and solar panels power the load.

Grid Powered Load, Charging from Battery

The grid power is used to supply the load when the battery voltage is lower than the set threshold conditions and grid connection is present. Moreover, it charges the battery using both grid and solar energy so that it can recycle its energy and be used at a later time.

3.3.6. PCU Mode Expansion

PCU (Power Conditioning Unit) mode is an important mode of operation in Solar Power applications which manages the supply of power from different sources. This mode automatically handles the power flow depending on the solar panel state, the state of the grid and the state of the battery (Fig.9.3)

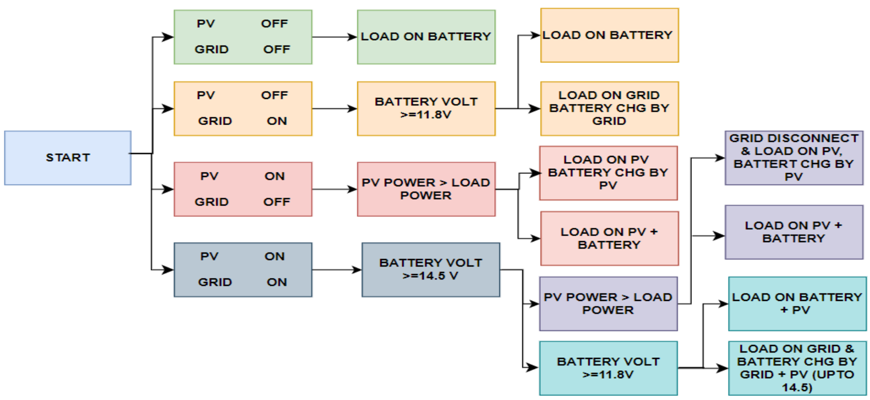

Fig. 9.3 PCU Mode Expansion

Solar Panel Off, Grid On, Battery Voltage at 11.8 Volts

The point at which the solar panel is inoperative (meaning low or zero solar irradiance) and the grid is connected is the critical decision point in the system. At 11.8 volts, it decides whether it can run the load off battery or go back to the grid. Eleven-point-eight volts is the threshold for a battery state of charge (SoC) which is considered low, or poor charge. Now in this case the system checks whether the battery capacity is enough to support the load, the system evaluates if it does not compromise the battery life and overall health to power the load from the battery.The logic of this decision comes from the simple principle of favoring the use of your stored energy from prior times (solar generation during the day, like a big battery) rather than drawing energy from the grid whenever possible, to directly utilize the solar energy that you have and to reduce reliance on the grid in those moments when there is low solar availability. On the other hand, if the system finds that the battery capacity will not be sufficient to sustain the load for the required time, or if it detects that discharging the battery to those lower levels carries any risk, it will move the load to grid power and charge the battery to raise the charge level.

This is because leaving the battery free will ensure that it lasts longer and is available for solar generation – we can never be sure how much solar generation there will be, particularly on dark days or seasons, and our battery is a reserve for those days.

Battery Voltage Condition False

This is a state that occurs when the battery voltage drops below a defined value, which shows a depleted state or insufficient charge level to sustain the load. In these cases, the system uses grid supply to power the load, while also attempting to store any excess energy into the battery.This means that the system justly ensures that the battery never gets discharged too deeply, which could harm it, and also hurt its performance and life span.

Additionally, utilizing grid charging when solar availability is low is one way to optimize storage capacity for later peak demands and periods of greater solar generation.This working mechanism reflects an energy management strategy that focuses on optimum handling of energy where system takes decisive action according to available conditions defined in this example to user load requirements and provides the energy from available resources such as battery bank to save electricity from the grid.

Load Grid Powered, Battery Grid Charged

If solar power is not being generate from the solar panel while the battery does not have enough charge to support the load, the system draws power from the grid to meet the demand. At the same time, it draws power from the grid to refuel the battery, replenishing its energy bank for future use. It is a sort of contingency mode to maintain electrical output (in case of zero solar input or the batteries can't supply enough current.)Although such dependence on grid power is a moving away from renewable energy, it shows the resilience of the system and capability of working in more team-oriented situations, giving guarantees of greater reliability and availability.Here, the focus is on fulfilling load demands and recharging the battery with grid supply, ensuring the system keeps running and reducing the risk of energy deficit when there may be a low solar irradiance or battery supply.

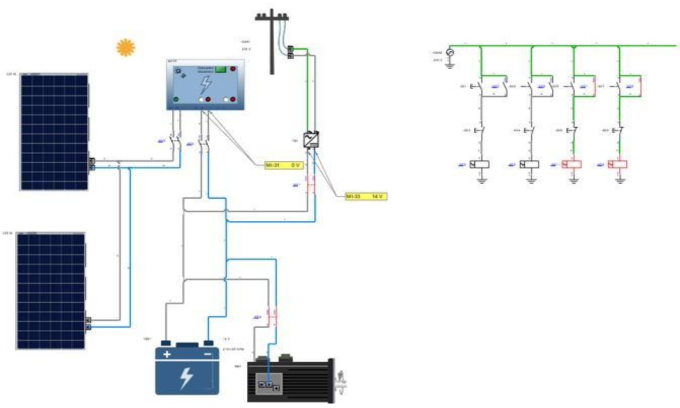

Fig.4 PV and Grid OFF

3.3.7. SIMULATION

PV and Grid OFF

The results are obvious in the simulation under solar panel on and grid off condition. Solar panels are capable of generating electricity as long as they are powered by sunlight, regardless of whether they are connected to the grid or not. Yet, with no grid connection, this surplus energy cannot be exported, thus, representing a challenge to maximise efficiency. This is where batteries come in very handy to store the extra energy and use it when you are not generating enough energy on cloudy and rainy days or nighttime. However, power outages could still emerge during prolonged periods of cloud cover or at night. This makes the effective implementation of energy storage and management systems crucial to ensuring a reliable off-grid power supply. (Fig.4)

Grid – ON, PV – OFF

When we simulate shutting off the solar panels and only the grid is supplying power a few things are likely to occur(Fig.5). With the solar panels not producing electricity, we'll have to rely more on the normal power from the grid. That could mean higher electricity bills, especially when many people are using power at the same time. On the plus side, the electricity from the grid is usually quite reliable, so power outages shouldn't be too frequent. However, we can lose the opportunity to save money and to help environment by the using clean energy, if there is no solar power. So, what the simulation teaches us is both the advantages, and what we should avoid if we depend only on the grid when solar panels goes off line.

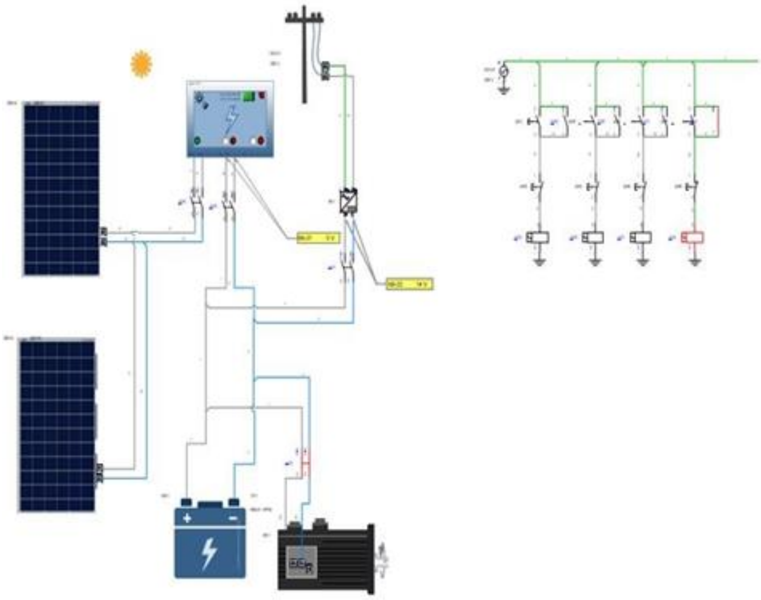

Fig.5. Grid ON PV OFF

PV – ON, Grid – OFF

In the simulation of solar panel (Fig.6) on and grid off condition, the panel produces electric energy if exposed to sunlight which can be used to power devices or used to charge batteries. But if disconnected from the grid, not only can any surplus energy not be exported — it may also result in an expensive waste of energy or energy storage. It finesses efficiency based on sunlight and energy demand. The solar plant may not be able to operate at full capacity without backup power sources to maintain reliability at low sunlight or high demand periods. In essence, solar panels represent renewable energy; however, as with all forms of energy production, the more solar panels that augment the supply the harder it becomes to manage the surplus, and reliability without a grid connection becomes a non-debatable challenge.

All of the components were connected according to the circuit diagram. This is the project hardware connections & prototype as shown in the Fig 7.

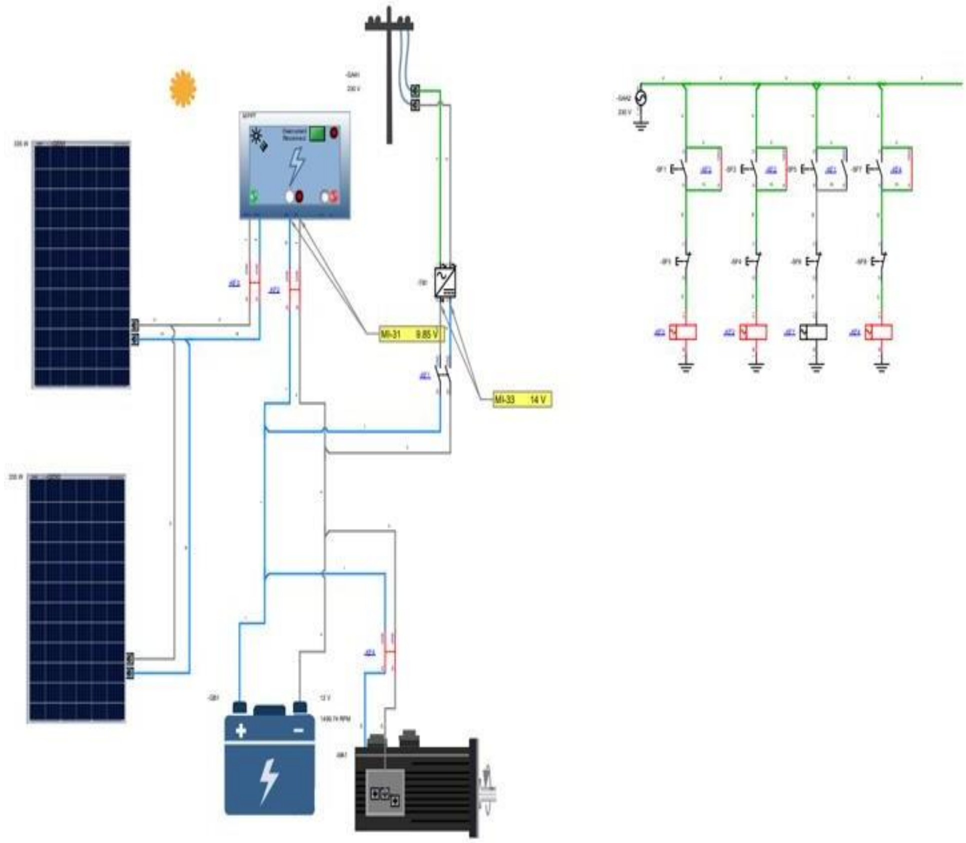

Fig. 6. PV – ON, Grid – OFF

Fig.7 Hardware kit

CONCLUSION

In this paper, an intelligent hybrid energy system comprising of solar, battery and grid has been proposed to overcome the challenges of traditional energy management. Dynamic modes—Hybrid, Smart, and PCU—allow the system to optimally use energy and adapt to different conditions. With integral MPPT controllers, Reinforcement Learning and Fuzzy Logic algorithms, the system continuously allocates resources, will be able to run 24/7 power supply and maintain the health of the battery. In addition to improving compatibility and reducing strain on the grid, the framework also contributes to sustainability by ensuring a more efficient use of renewable resources. The system is confirmed to be resilient to extortion and cost-effective in real-world applications via simulation results and has the potential to revolutionize energy management. The study emphasizes the need for intelligent hybrid systems like these, for reliable and sustainable energy solutions ranging from home systems to larger industrial enterprises.

REFERENCES

[1] M. A. Vaziri-Rad, “Excess electricity problem in off-grid hybrid renewable energy systems: A comprehensive review from challenges to prevalent solutions,” IEEE Trans. Sustain. Energy, vol. 14, no. 3, pp. 1052–1061, Mar. 2023.

[2] C. Ceylan, “Green hydrogen-based off-grid and on-grid hybrid energy systems,” Renewable Energy Reviews, vol. 12, pp. 68–76, Feb. 2023.

[3] S. Ma, A. Ahmed, “Fuel cell-battery hybrid systems for mobility and off-grid applications: A review,” Journal of Renewable Energy Systems, vol. 9, pp. 112–130, Dec. 2021.

[4] B. Zhang et al., “Optimization techniques for electric vehicle charging in on-grid and off-grid systems,” IEEE Trans. Ind. Appl., vol. 59, no. 5, pp. 1248–1260, Sep. 2022.

[5] C. Vimalraj et al., “Economic analysis and effective energy management of fuel cell and battery integrated electric vehicle,” Journal of Energy Storage, vol. 101, Part A, Nov 2024

[6] J Hu et al., “Model predictive control of microgrids – An overview”, Renewable and Sustainable Energy Reviews, Vol 136, Feb 2021,

[7] R. Das and A. Mukherjee, “Effectiveness of MPPT algorithms under varying environmental conditions,” IEEE Trans. Energy Conversion, vol. 36, no. 5, pp. 801–810, Sep. 2023.

[8] A. Ahmed, F. Hussain, and P. Kumar, “Integration of PV and wind energy for hybrid energy systems: A technical and economic review,” Energy Conversion and Management, vol. 154, pp. 484–495, Jan. 2022.

[9] D. Wang et al., “Intelligent EV charging and load management in smart grids,” IEEE Trans. Transport Electrification, vol. 6, no. 2, pp. 174–186, Apr. 2020.

[10] “State-of-the-art in adaptive load sharing and EV charging optimization for on-grid and off-grid systems,” Renewable Energy Research Journal, vol. 15, pp. 23–33, 2019.

[11] M. Chen et al., “Non-centralized load-sharing techniques for hybrid AC/DC microgrids,” IEEE Trans. Power Electron., vol. 35, no. 3, pp. 562–578, Feb. 2021.

[12] Z. Zhang et al., “AI-based predictive maintenance and load forecasting for smart grids,” IEEE Access, vol. 8, pp. 157624–157634, Aug. 2021.

[13] Amit Kumer Podder et al., “MPPT methods for solar PV systems: acritical review based on tracking nature”, IET Renew. Power Gener., Vol.13, no. 10, May 2019

[14] K. Liu et al., “Predictive control algorithms for microgrid resilience and efficiency,” IEEE Trans. Sustain. Energy, vol. 13, no. 2, pp. 1324–1335, Apr. 2021.

[15] J. Kaur et al., “Energy management in hybrid solar energy systems: A reinforcement learning approach,” Journal of Clean Energy Research, vol. 17, pp. 76–89, Feb. 2022.

[16] P. Singh et al., “Fuzzy logic controllers in hybrid solar systems for efficient energy management,” IEEE Trans. Energy Management, vol. 8, no. 3, pp. 214–225, Jun. 2020.

[17] Wei Zhou et.al, “Battery behavior prediction and battery working states analysis of a hybrid solar–wind power generation system”, Renewable Energy, Vol. 33, no.6, Pp 1413-1423, 2008,

[18] S. Rao et al., “Hybrid renewable energy systems: Optimal design and control for PV and battery integration,” Renewable Energy Systems Journal, vol. 14, pp. 45–53, Jul. 2021.

[19] Y. Wang and T. Lin, “Real-time pricing mechanisms for EV charging optimization in smart grids,” IEEE Trans. Ind. Informatics, vol. 15, no. 5, pp. 3456–3464, May 2020.

[20] N. Patel et al., “Artificial intelligence in renewable energy systems: Applications and challenges,” IEEE Access, vol. 9, pp. 112304–112318, Jun. 2021.