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ZYNERGY: AN AI-ENABLED HYBRID SOLAR–HYDROGEN ENERGY SYSTEM WITH IOT SAFETY MONITORING

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Abstract

This paper presents ZYNERGY, an AI-enabled hybrid solar–hydrogen energy system designed to improve short- and long-duration backup capability by combining photovoltaic (PV) generation, maximum power point tracking (MPPT), $LiFePO_4$ battery storage, water electrolysis, hydrogen storage, a Zn–H_2 fuel-cell backup unit, power conditioning, and ESP32-based IoT monitoring. The proposed design uses a 50-W PV panel and a 12-V, 20-Ah $LiFePO_4$ battery, corresponding to a nominal battery energy of 240 Wh. Under an assumed 5 peak-sun-hour condition and a 0.75 system derating factor, the PV subsystem is estimated to produce about 187.5 Wh/day. With an usable-energy factor of 80% and 90% conversion efficiency, approximately 172.8 Wh of battery energy is available, giving an estimated 8.64 h of backup for a 20-W load. The hydrogen subsystem will be analyzed on the basis of a sample of 0.01-kg H_2 which represents chemical energy of 333.3 Wh; at a hypothetical 50% fuel-cell efficiency, 166.7 Wh of electrical energy can potentially be harvested. The ESP32 monitoring layer captures PV and battery electrical parameters, temperature, hydrogen parameters, and fault conditions, while the AI/ML layer extension will enable load prediction, state-of-charge estimation, abnormal condition detection, and energy management. The values are design values and need to be verified by instrumented prototypes.

Keywords:

Green Hydrogen, Photovoltaic System, $LiFePO_4$ Battery, Fuel Cell, MPPT, IoT, ESP32, Energy Management, Hybrid Renewable Energy, Hydrogen Storage

1. INTRODUCTION

The move to shift from the fossil-fuel-dependent electricity production method to renewable energy has brought about the need to store energy. Solar PV systems are promising due to their modularity, less operating emissions, and decentralized uses. However, solar energy is characterized by intermittent nature since electricity generation relies on sunlight and weather. Batteries may solve the problem temporarily; nevertheless, energy storage is still a major engineering issue.

There is another energy storage technique where electrical energy can be transformed to chemical energy by electrolysis and again transformed to electrical energy via a fuel cell. In a hydrogen fuel cell, hydrogen is fed at the anode and oxygen from the air is fed at the cathode to generate electricity, heat, and water as the primary output [1].

India has realized that green hydrogen will play a key role in the country's clean energy ecosystem in the coming years. The National Green Hydrogen Mission has an initial budget of ₹19,744 crores and endeavors to make India a global destination for green hydrogen production, consumption, and export.

The suggested system also makes use of the IoT-based system monitoring facility. The ESP32 microcontroller can be used to measure PV voltage, PV current, battery voltage, battery current, temperature and hydrogen sensors. All the acquired data can be sent to a cloud/dashboard system for remote monitoring purposes. Later on, AI/ML systems can be integrated for load prediction, battery state-of-charge estimation, anomaly detection and predictive maintenance.

2. LITERATURE SURVEY

A vast body of research literature is available that explores architectures that use batteries together with hydrogen systems for addressing the constraints of pure electrochemical energy storage systems due to the emergence of distributed and low-emission energy production systems [19], [20]. Studies related to grid integration demonstrate that power conditioning stages are key for reliable integration of PV output, storage and loads [6]; meanwhile, separate reviews have been conducted of the efficiency, cost and safety issues associated with lithium based storage [5], PEM water electrolysis [3] and hydrogen storage materials [4]. All of these works motivate an approach that involves combining solar, battery and hydrogen technologies.

Distributed sites such as telecom towers, rural health facilities, and off-grid agricultural sites usually use diesel generators as their back-up systems. Battery-only back-up systems address the problem of emissions but suffer from storage duration limitations and cost associated with increasing the storage capacity based on lithium [5].

The National Green Hydrogen Mission in India [7], in addition to similar programs in the EU, the USA, Japan, and South Korea, has started changing the economics of electrolyzer and fuel cell manufacturing through subsidizing early stage capacity and demand [2], [8]. This favorable environment makes one of the key reasons to assess the business opportunities for ZYNERGY instead of waiting for falling prices on hydrogen equipment.

Three main problems limit traditional stand-alone solar power systems. Firstly, the process of solar power generation is unstable since the output of photovoltaics depends significantly on irradiance and temperature and varies during the day time period; thus, it cannot provide enough energy during the night time or in case of low sunlight intensity.

Second, battery-based storage has limited duration; while batteries provide backup power, extending this backup to cover longer low-generation periods requires proportionally larger battery capacity, which increases system weight, cost, and replacement frequency, making batteries alone an inefficient solution for extended autonomy. Third, many small renewable-energy systems lack intelligent monitoring, offering only basic voltage and current regulation without continuous tracking of battery health, hydrogen status (in fuel-cell-integrated systems), or fault conditions. This absence of real-time oversight makes it difficult to detect degradation early, prevent unsafe operation, or

optimize energy usage, ultimately compromising system safety, efficiency, and long-term reliability.

3. SYSTEM ARCHITECTURE AND METHODOLOGY

3.1 SYSTEM COMPONENTS

The Table.11 gives an overview of the main hardware elements of the ZYNERGY system and the function of each element in the process of energy transmission. The Fig.1 illustrates the connection of all these hardware parts, i.e., the use of the solar panels by means of the MPPT controller, their division into the $LiFePO_4$ battery and the electrolyzer, pressurization of hydrogen into the tank, and its return to the DC bus from the Zn-H_2 fuel cell. The ESP32 IoT/AI monitoring block controls these processes with regard to voltage, current, SOC, temperature, hydrogen level/pressure, and faults.

Table.1. Summary of ZYNERGY hardware components and their functional role

Component	Specification/ Role	Function in ZYNERGY
Solar PV Panel	50 W, 12 V	Primary renewable energy source
MPPT Charge Controller	Tracks maximum power point	Optimizes PV energy harvest
$LiFePO_4$ Battery	12 V, 20 Ah	Short-duration energy storage
Electrolyzer	Water electrolysis unit	Converts surplus energy to H_2
Hydrogen Storage Tank	Pressurized, safety-rated cylinder	Secure medium-duration H_2 storage
Zn–H_2 Fuel Cell	Zinc–hydrogen hybrid cell	Converts stored H_2 back to electricity
DC/DC & Power Conditioning	Power-conditioning circuitry	Regulates and conditions DC power
Pure Sine Wave Inverter	AC output conditioning	Delivers grid-quality AC to load
ESP32 IoT Controller	Wi-Fi/Bluetooth microcontroller	Runs AI logic and telemetry upload
Gas/Pressure/Temp Sensors	Continuous analog/digital sensing	Safety monitoring and fault detection

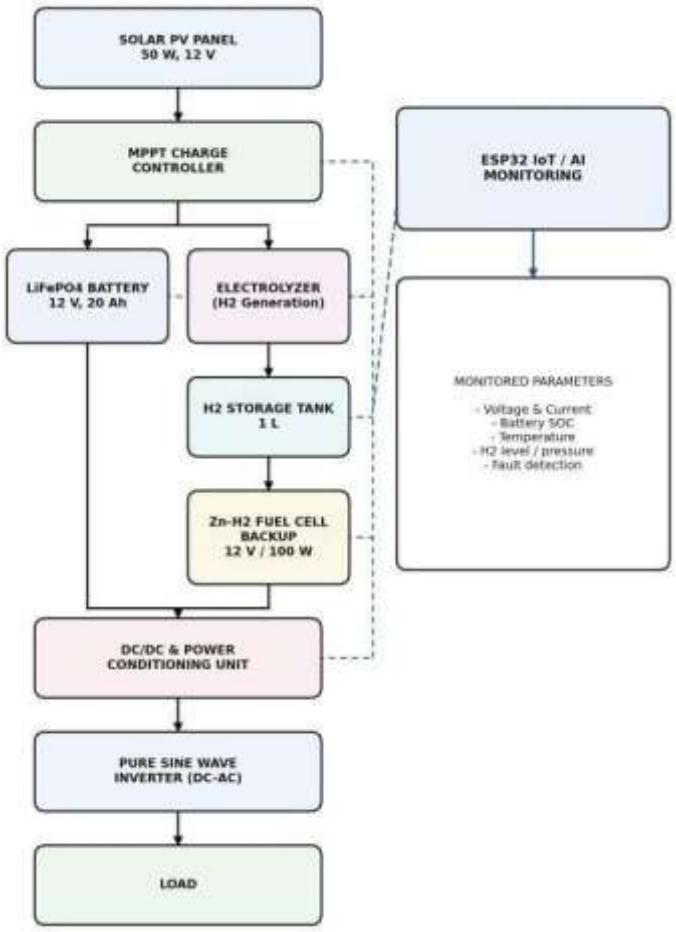


Fig.1(a). ZYNERGY system block diagram: solar-PV power flow through MPPT, battery, electrolyzer and Zn–H_2 fuel-cell backup to the load, with ESP32-based IoT/AI monitoring shown alongside each stage

3.2 METHODOLOGY

The approach followed in the development of ZYNERGY system starts with the generation of electricity through the solar panels and collection of maximum possible electrical power by the MPPT controller, which is then stored in the form of electrical energy in LiFePO4 batteries for direct usage. The surplus electrical power, if any, is supplied to the electrolyzer, which converts the water into hydrogen and oxygen and stores the generated hydrogen gas in a safe cylinder. In the absence of adequate sunlight or any power failure, the hydrogen gas stored acts as an input in the Zn-H2 fuel cell to generate electricity. Throughout this entire operation, the AI algorithms keep on optimizing the flow of electrical power from the three systems.

3.3 CONTROL AND AI OPTIMIZATION LAYER

The intelligence layer operates at the top of the physical power flow infrastructure and takes two types of decisions. First, the dispatch decision determines whether excess solar power will charge the battery, electrolyze, or be dispatched to the load based on the state of charge of the battery, forecasted solar power, and historical loads. The second type of decision is a safety arbitration decision that can supersede any dispatch decision if a sensor reading reaches a certain threshold.

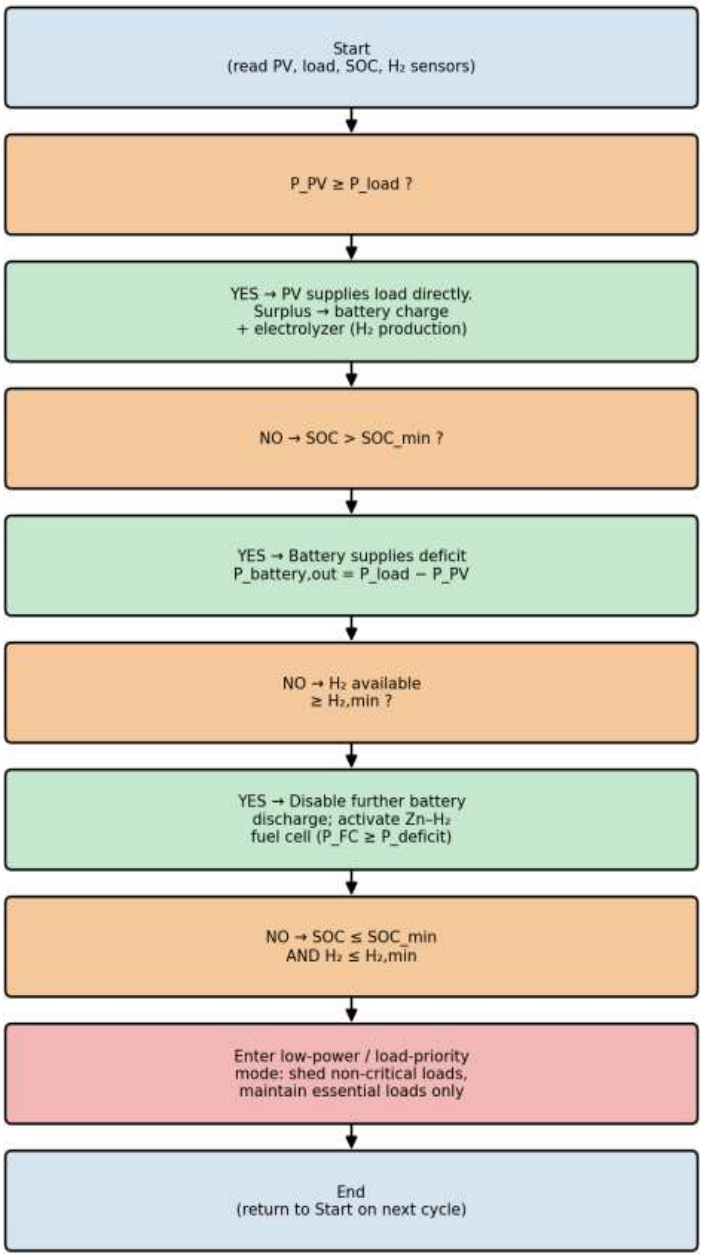


Fig.1(b). Energy Management Decision Flow

3.4 MATHEMATICAL MODEL

The mathematical formulation of the ZYNERGY hybrid energy system represents the transfer of energy from the solar PV power generation to battery storage, hydrogen production, hydrogen storage, and back-up power generation via fuel cell. The model is used for estimating energy generation, storage, hydrogen production, energy recovery, and efficiency of the system.

3.4.1 Solar Photovoltaic Power Model:

The instantaneous electrical power generated by a photovoltaic panel is the product of its terminal voltage and current.

$$P_PV(t) = V_PV(t) \times I_PV(t)$$

where P_PV(t) is the instantaneous PV output power (W), V_PV(t) is the PV terminal voltage (V), and I_PV(t) is the PV output current (A). For a rated 50-W photovoltaic panel: P_PV,rated = 50 W. The actual output varies with solar irradiance, cell temperature, shading, and other environmental conditions. The electrical energy generated during an operating interval from t_1 to t_2 is obtained by integrating the instantaneous power:

$$E_PV = \int_{[t_1,t_2]} P_PV(t)\, dt = \int_{[t_1,t_2]} V_PV(t)\, I_PV(t)\, dt$$

For a simplified daily energy estimation, the peak-sun-hour method can be used:

$$E_PV \approx P_PV,rated \times H_PSH \times \eta_sys$$

where H_PSH is the equivalent peak-sun-hours per day and η_sys is the overall derating factor accounting for system losses. Consider the proposed 50-W PV panel with an assumed 5 equivalent peak-sun-hours and an system derating factor of 0.75.

$$E_PV = 50 \times 5 \times 0.75 \approx 187.5\ Wh/day$$

Thus, the estimated daily electrical energy available from the PV subsystem is approximately 187.5 Wh/day under the stated assumptions. This value is only a design estimate; actual energy generation must be obtained from measured irradiance, PV voltage, and PV current.

3.5 BATTERY STATE-OF-CHARGE MODEL

The battery acts as an intermediate energy-storage element between the solar PV system and the load. Its state of charge (SOC) indicates the percentage of available stored energy relative to the nominal battery capacity. During charging:

$$SOC(t) = SOC(t_0) + [\eta_c / C_nom] \int_{[t_0,t]} I_ch(\tau)\, d\tau$$

During discharging:

$$SOC(t) = SOC(t_0) - [1 / (\eta_d\ C_nom)] \int_{[t_0,t]} I_dis(\tau)\, d\tau$$

Considering both charging and discharging:

$$SOC(t) = SOC(t_0) + [\eta_c/C_nom]\int I_ch(t)dt - [1/(\eta_d\ C_nom)]\int I_dis(t)dt$$

For a discrete-time implementation:

$$SOC(k+1) = SOC(k) + [\eta_c\ I_ch(k)\ \Delta t/C_nom] - [I_dis(k)\ \Delta t/(\eta_d\ C_nom)]$$

The battery controller must maintain the SOC within safe operating limits:

$$SOC_min \le SOC(t) \le SOC_max$$

For example, a preliminary operating window of 20% to 90% may be selected, although the actual limits must be determined from the manufacturer's specifications. The approximate stored battery energy is:

$$E_battery = V_battery \times C_nom \times SOC$$

For the proposed 12-V, 20-Ah $LiFePO_4$ battery:

$$E_battery,nom = 12 \times 20 = 240\ Wh$$

This is the nominal electrical energy rating. The practically usable energy will be lower because of the selected SOC window, conversion losses, temperature, battery characteristics, and other system losses.

3.5.1 Hydrogen Production Model:

The hydrogen subsystem converts electrical energy into chemical energy stored in hydrogen. If the electrolyzer consumes E_el kWh of electrical energy and its specific energy consumption is SEC kWh/kg-H_2, the mass of hydrogen produced is:

$$m_H_2 = E_el / SEC$$

where m_H_2 is the mass of hydrogen produced (kg), E_el is the electrical energy supplied to the electrolyzer (kWh), and SEC is the specific energy consumption (kWh/kg-H_2). If the electrolyzer operates at nearly constant electrical power P_el, the hydrogen production rate can be approximated by:

$$\dot{m}_H_2 = P_el / SEC$$

Appropriate unit conversion is required when P_el is expressed in watts rather than kilowatts. Actual production depends on electrolyzer technology, electrical efficiency, operating temperature, pressure, water quality, current density, and auxiliary power consumption.

3.5.2 Hydrogen Chemical Energy Model:

The energy stored in hydrogen can be estimated from its mass and lower heating value (LHV):

$$E_H_2 = m_H_2 \times LHV_H_2$$

Using the commonly used approximate value $LHV_H_2 \approx 33.33$ kWh/kg:

$$E_H_2 \approx 33.33 \times m_H_2$$

For example, if $m_H_2 = 0.01$ kg: $E_H_2 = 0.01 \times 33.33 \approx 0.333$ kWh ≈ 333.3 Wh. This represents the chemical energy contained in the hydrogen and should not be interpreted as the electrical energy available at the fuel-cell output.

3.5.3 Fuel-Cell Electrical Energy Model:

The hydrogen fuel cell converts the chemical energy of hydrogen into electrical energy. If the fuel-cell electrical efficiency is η_FC:

$$E_FC = \eta_FC \times E_H_2 = m_H_2 \times LHV_H_2 \times \eta_FC$$

For an fuel-cell efficiency of 50% and $m_H_2 = 0.01$ kg: $E_FC = 0.01 \times 33.33 \times 0.50 \approx 0.1667$ kWh ≈ 166.7 Wh.

The 50% efficiency is only an calculation. The actual efficiency of the proposed fuel-cell subsystem must be obtained from its datasheet or experimental testing. The instantaneous fuel-cell output power is:

$$P_FC(t) = V_FC(t) \times I_FC(t);\ E_FC = \int_{[t_1,t_2]} P_FC(t)\, dt$$

3.5.4 Energy Management and Control Logic:

The energy-management controller determines which energy source should supply the load based on PV availability, battery SOC, and hydrogen availability.

1. **Condition 1: Sufficient Solar Power:** If PV power is greater than or equal to load demand, the PV system supplies the load directly. The remaining power is available for battery charging or hydrogen production.

$$P_PV \geq P_load;\ P_surplus = P_PV - P_load = P_battery,ch + P_el$$

2. **Condition 2: Insufficient Solar Power:** If PV power is less than load demand, the power deficit is supplied by the battery when its SOC is above the minimum limit.

$$P_PV < P_load;\ P_deficit = P_load - P_PV = P_battery,out$$

3. **Condition 3: Low Battery SOC:** When the battery SOC reaches its minimum operating limit, further battery discharge is disabled and the hydrogen fuel-cell backup can be activated if sufficient hydrogen is available.

$$SOC \leq SOC_min;\ P_FC \geq P_deficit$$

4. **Condition 4: Battery and Hydrogen Backup Limit:** If both battery SOC and hydrogen availability are below their minimum limits, the system should enter a low-power or load-priority mode, disconnecting non-critical loads while maintaining essential loads.

$$SOC \leq SOC_min\ AND\ H_2 \leq H_2,min$$

3.5.5 Complete Energy Balance:

The overall energy balance of the ZYNERGY system can be expressed as:

$$E_PV,in = E_load + E_battery,stored + E_H_2,stored + E_loss$$

Therefore, the total loss can be estimated as:

$$E_loss = E_PV,in - E_load - E_battery,stored - E_H_2,stored$$

The energy balance equation can be used as a tool for verification of the operation characteristics of the suggested approach. The Fig.2 demonstrates how the 187.5 Wh/day of solar power obtained in Section 3.1 can be distributed between the load, battery storage, hydrogen storage, and system losses. The above distribution is arbitrary and should be substituted with experimental data obtained in a testbed environment.

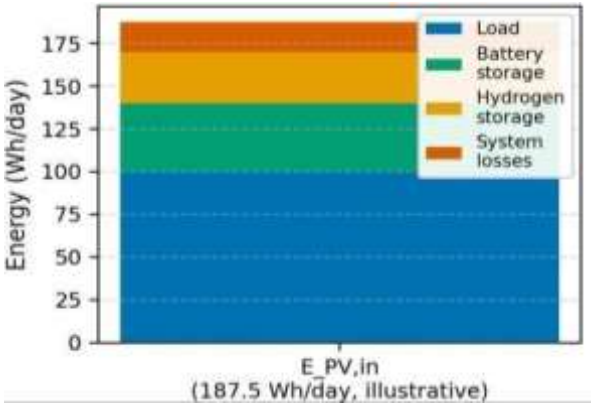


Fig.2. Daily energy-balance breakdown of the 187.5 Wh/day PV estimate across load, battery storage, hydrogen storage, and system losses

3.6 BLOCK DIAGRAM

The block diagram of the ZYNERGY monitoring architecture (Fig.3) centers on the ESP32 [14], which acts as the central monitoring controller. It aggregates PV, battery, hydrogen and fuel-cell sensor data, relays it over Wi-Fi to a monitoring dashboard, and feeds an AI-based extension [17], [18] that performs solar and load prediction, battery SOC/SOH estimation, hydrogen-consumption prediction, abnormal-condition detection and predictive maintenance, as summarized in Fig.3. Hydrogen safety monitoring is particularly important. India's National Green Hydrogen Mission ecosystem already includes R&D activities related to AI-based real-time hydrogen leak detection [16], demonstrating the relevance of intelligent monitoring to hydrogen infrastructure.

4. RESULTS AND DISCUSSION

Four representative operating cases illustrate how the energy-management logic of Section 3.6 responds to changing solar and load conditions. These cases, together with the aggregate results

and comparative analysis below, define the performance envelope of ZYNERGY relative to the backup-power approaches commonly deployed at the distributed sites described in Section 1.1.

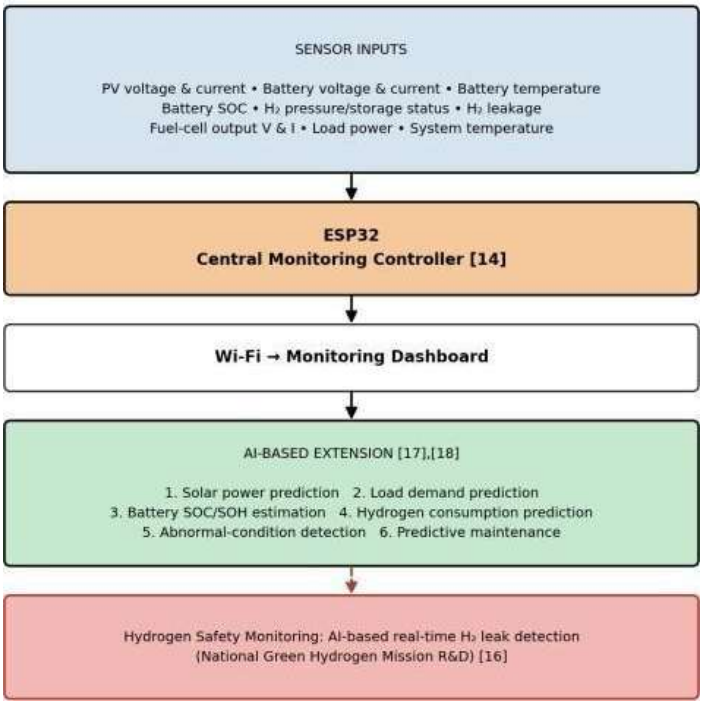


Fig.3. ZYNERGY monitoring and AI architecture: ESP32-based sensor aggregation, Wi-Fi link to the monitoring dashboard, and the AI-based extension for prediction, estimation and fault/leak detection.

4.1 CASE 1: NORMAL DAYTIME OPERATION

Let us assume that P_PV = 40 W and P_load = 25 W. In this case, P_excess = 40 – 25 = 15 W. While the 25 W load is taken care of by the PV system, the other 15 W can be utilized for battery charging and hydrogen production.

4.2 CASE 2: LOW-SOLAR CONDITION

Given that P_PV = 10 W and P_load = 30 W. Power shortage is given as P_deficit = 30 - 10 = 20 W. Battery supplies about 20 W, depending on conversion losses. Operational behavior expected: PV & Battery -> Load.

4.3 CASE 3: NIGHT-TIME OPERATION

When the night comes, P_PV = 0. If the battery SOC is sufficient, then the battery feeds the load. Considering a simplified 20W load and nominal 240 W*hours battery: t = 240 / 20 = 12 h. This is just a nominal-energy calculation. The real backup time would be less as usable SOC, inverter efficiency, conversion losses, and other limitations on the battery operation should be taken into account. Assuming the real energy utilization factor equal to 80% and inverter/converter efficiency of 90%, the usable energy would be equal to E_usable = 240 × 0.8 × 0.9 =

172.8 W*hours. Thus, the time would be approximately: t ≈ 172.8 / 20 = 8.64 h. Fig.4 shows the two runtime calculations side by side.

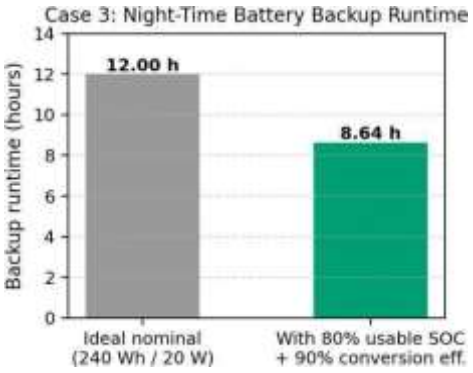


Fig.4. Case 3 battery backup runtime: ideal nominal-energy estimate versus a derated estimate accounting for usable SOC and conversion efficiency

4.4 CASE 4: EXTENDED LOW-SOLAR/EMERGENCY CONDITION

As soon as the state of charge (SOC) of the battery falls below the preset minimum threshold value, the hydrogen system will start if hydrogen is present in adequate amount. The equation of the fuel-cell power is stated by P_FC = V_FC × I_FC. For the considered nominal power level of 100W for the hydrogen backup system: P_FC,rated = 100W. It should be proved through experimentation that actual power output remains this much under operational conditions.

Table.2. Case-wise power balance and expected operation

Case	P_PV (W)	P_load (W)	Net	Expected Operation
Normal Daytime	40	25	+15 W surplus	PV → Load + Battery/ Electrolyzer
Low-Solar	10	30	−20 W deficit	PV + Battery → Load
Night-Time	0	20	−20 W deficit	Battery → Load (≈ 8.6–12 h runtime)
Extended Low-Solar/ Emergency	0	-	SOC ≤ SOC_min	PV → Battery → H_2 Backup → Load

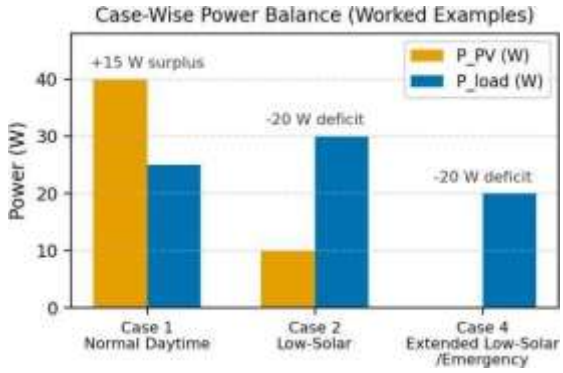


Fig.5. Case-wise power balance for the worked examples in Cases 1, 2 and 4, showing the resulting surplus or deficit

4.5 SUMMARY OF RESULTS

The Table.2 contains all of the main example figures resulting from the modeling. Under the given assumptions, the 50-W PV sub-system delivers around 187.5 Wh/day, while the 12-V 20-Ah LiFePO4 battery delivers nominal 240 Wh, of which around 172.8 Wh can actually be used taking into account the chosen SOC range and conversion losses. The above-mentioned usable energy amount equates to the runtime of approximately 8.64 hours for the 20-W load in the third case, compared to the theoretical nominal-energy-based estimate of 12 h. In the case of hydrogen, the example of 0.01 kg of hydrogen holds approximately 333.3 Wh of chemical energy, of which 166.7 Wh can be converted to electrical energy using 50% efficient fuel cell as an example.

4.6 COMPARATIVE ANALYSIS WITH EXISTING SOLUTIONS

In this section, the paper provides comparisons between four types of backup power solutions applicable for off-grid and disaster-proof needs: diesel generator, battery only, solar plus battery without hydrogen and the suggested ZYNERGY technology. These include backup time duration, emissions, dependency on logistics of fuel deliveries, reaction time and monitoring.

4.6.1 Backup Time Duration:

The diesel generators can function theoretically for unlimited periods of time; however, as far as fuel replenishment will be provided, which is the case in floods, cyclones or road closure – the weak point of using such devices. The battery only and solar plus battery solutions depend on their capacity: extending the autonomy from 6 hours to 3 days will require an enlarged (and accordingly heavier, more expensive) battery.

4.6.2 Emissions During Backup:

The diesel generator produces CO2, NOx, and particulates, and is also very noisy to operate, which is problematic in the case of hospitals, shelters, or residential use during emergencies. Battery only, solar and battery, and ZYNERGY generators are all emission-free as there is no combustion in any of them; ZYNERGY uses the hydrogen fuel cell process, which involves an electrochemical reaction to produce electricity.

4.6.3 Dependence on Fuel Supply:

That is one of the major flaws in the practical use of diesel, because the generator relies on fuel which may be unavailable just when the emergency backup power is needed due to post-calamity road disruptions or fuel shortages and price hikes. Battery-powered, and hybrid PV and battery systems circumvent this issue because they require no external fuel at all. The ZYNERGY system avoids, but doesn't completely bypass, logistics issues by producing its own hydrogen using an electrolyzer.

4.7 REMOTE OR IOT-BASED MONITORING

The majority of small diesel, battery only, and solar+storage configurations provide nothing more than very limited voltage/amp regulation, with no means of constant state observation. This problem will be solved with ZYNERGY, which provides an IoT-based monitoring solution for batteries and hydrogen levels, including artificial intelligence-based analysis.

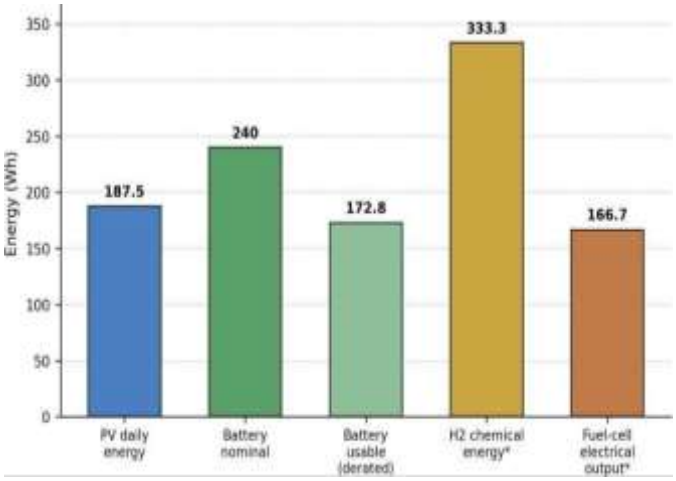


Fig.6. Summary of the energy results of daily PV energy, nominal and usable battery energy, and the hydrogen chemical/electrical energy example from Sections 3 and 4. Values marked * assume m_H_2 = 0.01 kg and 50% fuel-cell efficiency

4.7.1 Response Time:

The diesel generator requires some time for start-up and warming up in order to achieve stable power generation capacity, which causes a brief interruption in the supply of power. The battery-operated systems (battery alone, solar/battery, and ZYNERGY's battery phase) react almost instantly because there is no mechanical start-up procedure involved. In case of ZYNERGY, the battery will react instantly and hydrogen fuel cell will take slightly more time.

5. CONCLUSION

The proposed ZYNERGY system provides an intelligent hybrid renewable energy system which uses AI technology to combine solar photovoltaic generation, $LiFePO_4$ battery storage, hydrogen generation and the Zn–H_2 fuel cell backup system. The mathematical model and case study show how the available solar power is to be smartly allocated between the load, battery charging, and hydrogen generation depending on the operating conditions.

The hybrid design enhances the reliability of energy because battery is used for short-term energy storage, and fuel cell system works as the backup during the period when the solar energy generation is not enough. The ZYNERGY design has various benefits over traditional backup solutions.

Battery and hydrogen storage serve complementary purposes, where the battery is used for fast-acting backup while hydrogen serves for longer-term backup; excess renewable energy can be transformed into hydrogen instead of going to waste; the IoT solution based on the ESP32 allows for real-time monitoring of system parameters; the PV, battery, electrolyzer, storage and fuel cell subsystems can be scaled modularly according to the application; the hydrogen subsystem acts as an additional emergency power source when the solar and battery systems become insufficient; and finally, the design fits perfectly with the Indian National Green Hydrogen Mission.

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