OPTIMAL SIZING OF THE AUTONOMOUS SOLAR HYDROGEN HYBRID POWER PLANT

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Abstract:

Global warming underscores the need for alternative energy sources, with Kerala embracing solar rooftop installations due to shade-free rooftops, with remote areas using autonomous systems. This paper optimizes a hybrid solar photovoltaic (PV) power plant, integrating solar panels, an electrolyzer (ELZ), and a proton-exchange membrane fuel cell (PEMFC). The system is designed to handle worst-case scenarios, maintain performance during low sunlight and high energy demand, and minimize system cost. The paper employs Linear Programming (LP) formulation, a mathematical method used to optimize component sizes within the system. This approach helps balance the need for efficiency and cost-effectiveness, eliminating the issues of oversizing (which would lead to unnecessary expenses) and undersizing (which would result in non-optimal operation). As a result, the optimized hybrid system not only reduces costs but also improves efficiency by more than 5%, making it a viable solution for reliable energy supply in both remote and conventional energy-challenged areas.

Index Terms—PV system, Fuel cell, Electrolyzer, Hybrid system, System sizing, Linear Programming Optimization

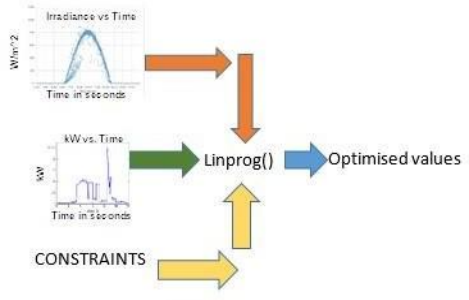

Fig. 1. Graphical Abstract

A. I. INTRODUCTION

The utilization of an integrated renewable energy generation system is viewed as a critical step toward reducing reliance on finite fossil fuels used for power generation. However, because renewable energy sources (RES) such as wind and solar energy are intermittent, increasing their penetration in the traditional grid will cause reliability and quality difficulties. As a result, a reliable method of determining the availability of energy resources is critical to ensuring that energy demand constantly equals supply.

Significant advancements in renewable energy (RE) technology have been made as a result of the growing urgency to battle climate change and the demand for sustainable energy solutions. The current research offers numerous advancements in reaching the United Nations Sustainable Development Goals [1], [2], [3], [4] and could help expedite the widespread use of fuel cell electric vehicles (FCEVs). Energy plays a crucial role in driving socio-economic development, and the future lies in RES.

Numerous investigations have been conducted to examine which hybrid energy sources operate best in the Gulf region. [5], [6], [7]. Conversely, the declining costs of RE and the advancements in this sector suggest that countries with available resources will likely adopt RE as their primary energy source [8], [9].

Carbon emissions have surged from 47.02 million to 586.4 million tons between 1970 and 2021, showing a remarkable increase of over 11 times since 1970 [10]. Simultaneously, scientists are actively exploring the incorporation of energy storage technologies, including cutting-edge batteries, supercapacitors, and hydrogen storage. This makes it possible to seamlessly include intermittent renewable energy sources, which eventually increases the dependability and flexibility of the system [11], [12].

India is actively exploring alternative fuels such as ethanol, biodiesel, methanol, compressed natural gas, solar energy, and hydrogen to decarbonize the energy sector and address issues related to greenhouse gas emissions, air quality, and global warming. Solar and wind power are two established renewable energy sources that are extensively utilized for various applications. They can be integrated with other energy sources in hybrid or independent setups to guarantee a reliable and sustainable energy provision [13].

In the state of Kerala in India, 80% of consumers are domestic, and integrating renewable energy with the grid is crucial. Solar photovoltaic (SPV) power generation is a promising alternative for conventional electricity generation in Kerala, as it can support local priority loads and feed energy back into the grid. Off-grid installations are also needed due to grid outages in many areas. The focus lies on creating an optimization model and use simulation tools that take into account factors such as weather conditions, load profiles, and component characteristics. As in [14], [15], [16] the ultimate aim is to achieve an optimal design and sizing of hybrid systems, resulting in significant enhancements in efficiency and cost.

This study focuses on maximizing the energy production of a solar fuel cell hydrogen power plant in Kerala. The price of electricity produced using fuel cells (FC) has significantly decreased over the years, dropping from $110 per kilowatt (kW) in 2004 to $56.6 per kW in 2012, and is expected to continue decreasing in the coming years [17].

Fuel cells operate at an efficiency range of 40% to 60%, outperforming combustion engines (25%) and RE power plants by a significant margin [18]. An energy management plan recommends that the battery be charged by the fuel cell on a regular basis when the PV generation is not enough to meet the load demand, in order to keep the state of charge of the battery above 40% considering the time it takes for the fuel cell to reach its maximum power output.

Hydrogen storage tanks offer numerous benefits compared to batteries, including their superior storage capacity and longer lifespan. Integrating hydrogen refuelling stations with RE sources like solar and wind power is essential in distant or remote areas [19]. The combination of Hydrogen Storage Systems (HSS) with renewable distributed generation is suggested in several studies to enhance the efficiency of renewable systems [20], [21]–[23], [24]. Additionally, a multi-objective dispatching scheme is detailed in another study for the optimal functioning of an integrated energy system comprising a wind turbine [25], a photovoltaic plant, and hydrogen storage equipped with electrolyzer, fuel cell, and storage.

The study in [26] analyzed the economic aspects of producing hydrogen via electrolysis and lowering the cost of hydrogen production. A comparative study in the field of energy storage, examining the differences between hydrogen based and battery based solutions is given in [27]. The research model effectively determined the best setup for a hybrid system, utilizing resources such as wind, solar, and geothermal energy to achieve an optimal configuration. An examination of the Asian continent reveals that South Korea, China, and Japan account for the majority of the region’s installed hydrogen stations [28].

RES are influenced by site-specific meteorology and can be inconsistent [29], [30]; energy storage technologies are commonly employed to stabilize power outputs and improve system reliability [31], [32]. The findings will help enhance the progress of sustainable energy solutions customized for Kerala’s distinct environmental and energy conditions. By maximizing the energy efficiency of the electrolyzer and fuel cell elements, this research seeks to establish a method for the effective and expandable creation of self-sufficient solar fuel cell hydrogen power stations, supporting a cleaner and more sustainable future.

The research in [33] makes use of HOMER and the performing platform, a sophisticated system that combines optimal dispatch strategies to assess plant performance. The study covers various factors such as sensitivity analysis and market conditions, operational limitations, and the impact of capacity based incentives.

Solar integrated with green hydrogen technology systems often face the challenge of either being oversized, resulting in high expenses, and surplus energy generation, or undersized, causing inadequate operational power deficiencies for their designated functions [34]. To overcome these obstacles and optimize the advantages of renewable energy-powered systems, it is crucial to precisely calculate the optimal size of the solar hybrid power plant and combine it with a robust energy management strategy [35].

B. FORMULATION AND APPROACH

The aim of the study is to fine-tune the dimensions of an autonomous solar-electrolyzer-fuel cell hybrid power plant to reduce investment through design optimisation. Utilizing the Direct Normal Irradiance (DNI) data from Trivandrum in 2020, the month with the lowest irradiation is identified, providing insight into the worst-case scenario for system design. The optimal size of the electrolyzer and fuel cell are determined using linear programming methods implemented in MATLAB, ensuring high efficiency and system performance.

Here data is collected on the DNI readings of the year 2020 in Trivandrum using US-NREL metrological site [35] and found that the worst irradiation occurs in the month of June which is the rainy season and maximum irradiance occurs in the month of February.

I. Methodology

System Description

The test system considered here is a 2kWp solar PV array connected to an electrolyzer which stores the hydrogen in a tank which is in turn feeds the fuel cell and load. A generalised diagram is given in Fig 1.

Based on the average daily solar irradiance available at Trivandrum, the solar PV array of 2KW capacity is expected to generate maximum of 10 kWh and hence the electrolyzer tank is sized to store 10 kWh. In general, from this 10 kWh generated daily, 5 kWh is supplied under day light and the rest 5 kWh are stored in the tank in order to consume it under night condition when there is no solar irradiance.

For a 2kWp solar array, the maximum load in the load profile selected is 580W. Water splitting electrolyzer selected is a discrete regenerative PEM type because its efficiency is higher than the presently available Unitized Regenerative PEM technology (URPEM).

Optimization of the power of the electrolyzer and energy of the fuel cell are done. So, considering the maximum possible values of the constraints for power of the electrolyzer, lower bound is set at 0kW and upper bound at 2kW and the minimum energy of fuel cell is considered to be 1kJ (0.000278kWh) and maximum to be 37.8MJ (10.5kWh).

Minimum energy of fuel cell = 0.000278x60x60 = 1kJ

Maximum energy of fuel cell = 10.5x60x60 = 37.8MJ

The solar data and load data are collected from the solar and load profiles obtained in a worst case condition during the month of June, 2020 at Trivandrum in Kerala.

Design of the MPPT

The design of the MPPT for Solar-ELZ system is significant as it reduces the overall cost of the system. The I-V curve of the solar PV system is referred. The Solar PV system is a constant current source with the impedance determined by the irradiance falling on it. From analysing the performance characteristics of the ELZ, it is clear that it is a constant current load with charging terminating at its full capacity voltage. The performance characteristics of the ELZ is thus in perfect match with that of the Solar PV system. Hence, only an impedance matching is needed and thus one can avoid the use of comprehensive MPPT electronics.

That is, optimally sized electrolyzer system tracks the maximum power point of the PV system very closely without the additional control device and under wide irradiance interval. With such a method very high transfer efficiencies of the whole PV/Electrolyzer system can be achieved for any irradiance level. After identifying the optimal sizing, the electrolyzer can be directly connected to PV array. Such systems have simple structures and there is no need for an additional requirement of other control devices.

Optimisation and Approach

The location based sizing of the autonomous solar electrolyzer-fuel cell hybrid power plant optimizes the investment for the fuel cell by avoiding the oversizing of electrolyzer fuel cell system and matching with the source impedance. In order to achieve this, the work focuses on the worst case condition of solar DNI.

The aim is to optimize the fuel cell size and also the electrolyzer size. The optimal sizing results may work not only for the current simulation year but also other years in any climatic conditions. Here, the case of worst condition is analysed. Optimally sized electrolyzer integrated with solar PV array provides high conversion efficiencies. Because energy systems have a dynamic, linear nature and must be optimized, the linear programming method is employed.

The behaviour of electrical loads is random based on human affinity. The fuel cell is optimized in size so that its behavior matches with the load profile, where a daily average load profile is taken for simulation.

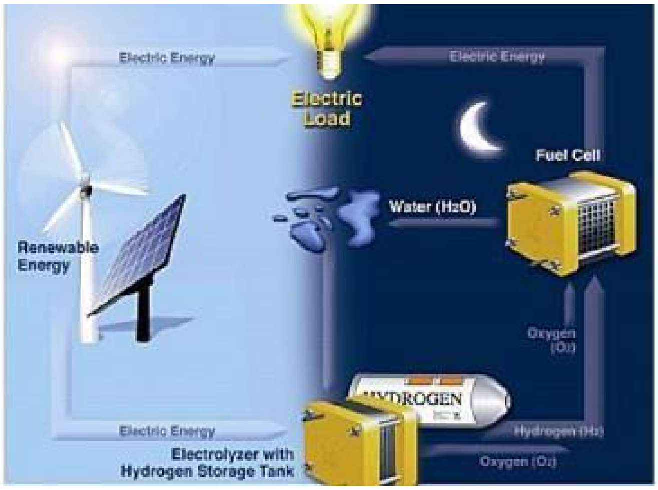

Fig. 1. Solar Hydrogen energy cycle

A simple linear programming (LP) is chosen and is implemented using linprog() function in MATLAB.

System optimisation using HOMER does not optimize the system and does not takes into account the sizing of elements. Here, the optimization is more concerned with the total cost of the project, i.e. it looks for the cheapest feasible system. Similarly RETSCREEN performs prefeasibility studies on energy models and does not optimise the size of subcomponents using integrated energy optimisation techniques.

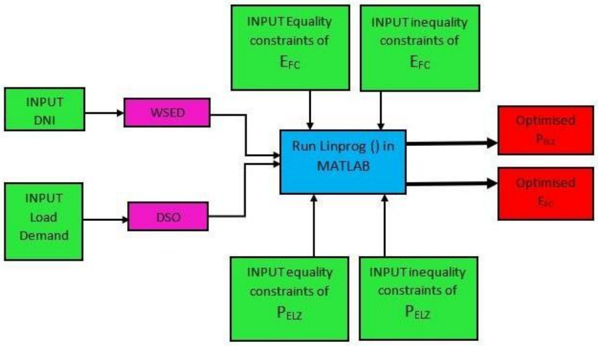

Fig. 2. The general block diagram of the optimisation flow

This paper performs efficient component wise sizing that involves predictive and real-time analysis of the system. An integrated system consists of demand, supply side management, and energy resources. Considering the general unavailability of an optimisation system, here a different and novel approach is used. The unit wise sizing is done considering the worst cases so that overall cost of the integrated system is optimised.

The general block diagram of the optimisation flow is given in Fig. 2. In this block diagram, the complete optimisation flow is explained, in which DNI and Load are the input parameters used in the optimisation. The DNI was selected based on the WSED (Worst Case Solar Energy data) and load was selected based on DSO (Demand Side Objective). To run optimisation in MATLAB using linear programming, one equality constraint and two inequality constraints were formulated based on the condition of energy of fuel cell and power of the electrolyzer. This provides the optimised values of power of the electrolyzer and energy of the fuel cell.

C. Problem Formulation

The objective function is to minimize,

$$\min f \quad x = \min(P_{elz}\Delta t, E_{fc})$$

subject to:

$$Ax \leq B$$

$$A_{eq}x = B_{eq}$$

$$lb \leq x \leq ub$$

where the decision variable is given by,

$$= \left[\begin{matrix} (0), \quad (1), \dots\dots \quad P_{elz(k-1)}, 0 \\ E_{fc}(0), E_{fc}(1), \dots\dots\dots\dots E_{fc}(k-1), E_{fc}(k) \end{matrix} \right] \tag{1}$$

Data used in linear programming is available in an interval of 10 minutes. So for a complete day, N=144. We have 2N+1 variables. Therefore

$$f = [\Delta t, \dots, \Delta t, 1, 1, \dots, 1]^T \tag{2}$$

Time interval Δ t = (10 minutes)x(60 sec) = 600 sec. The optimization through linear programming is done using one equality constraint and two inequality constraints.

$$-E_{fc}(k) + E_{fc}(k+1) = -P_l(k)\Delta t \qquad \forall k = 0, \dots, N \tag{3}$$

Here is the energy of the fuel cell and is the power of the load.

$$P_{elz}(k) \le P_s(k) \qquad \forall k = 0, \dots, N \tag{4}$$

Here is the power of the electrolyzer and is the power of the solar.

The fuel cell is not allowed to discharge completely so as to maintain a reserve; hence, the final capacity is kept between 30% and 70%.

$$20 \le E_{fc}(k) \le 400 \qquad \forall k = 0, \dots, N \tag{5}$$

The power of electrolyzer, and energy of fuel cell, are limited by upper and lower bounds as below;

$$Pelz_{min} \le Pelz(k) \le Pelz_{max} \tag{6}$$

$$Efc_{min} \le efc(k) \le Efc_{max} \tag{7}$$

Equations from (1) to (7) is considered to form an optimization program. The equality constraint (3) in matrix vector form using x is defined as

$$\begin{bmatrix} 0 \cdots 0 -1\ 1\ 0 \cdots 0 \\ 0 \cdots 0\ 0 -1\ 1 \cdots 0 \\ \vdots \\ 0 \cdots 0\ 0\ 0\ 0 \quad -1\ 1 \end{bmatrix} \begin{bmatrix} (0) \\ Pelz(1) \\ \vdots \\ Pelz(k-1) \\ (0) \\ Efc(1) \\ \vdots \\ Efc(k-1) \\ (\ ) \end{bmatrix} = \begin{bmatrix} -P(0)\Delta t \\ \vdots \\ -P(k-1)\Delta t \end{bmatrix} \tag{8}$$

This will give A_{eq} and B_{eq}. Similarly for inequality constraints (4) and (5) in matrix vector form using x are defined as

$$\begin{bmatrix} 1\ 0 \dots\ 0\ 0\ 0 \dots 0 \\ 0\ 1 \dots\ 0\ 0\ 0 \dots 0 \\ \vdots \\ 0 \dots\ 1\ 0\ 0 \dots 0\ 0 \\ 0\ 0 \dots 1\ 0\ 0 \dots 0 \end{bmatrix} \begin{bmatrix} (0) \\ Pelz(1) \\ \vdots \\ Pelz(k-1) \\ Efc(0) \\ Efc(1) \\ \vdots \\ Efc(k-1) \\ Efc(k) \end{bmatrix} \le \begin{bmatrix} (0) \\ \vdots \\ Ps(k-1) \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} 0\ 0 \dots 0\ 0\ 0\ 0 -1 \\ 0\ 0 \dots 0\ 0\ 0\ 0\ 1 \end{bmatrix} \begin{bmatrix} (0) \\ Pelz(1) \\ \vdots \\ Pelz(k-1) \\ Efc(0) \\ (1) \\ \vdots \\ Efc(k-1) \\ Efc(k) \end{bmatrix} \le \begin{bmatrix} 20 \\ 400 \end{bmatrix} \tag{10}$$

The upper and lower bounds expressed by (6) and (7) in matrix form is defined as

$$lb = |P_{min} \dots P_{min}\, E_{min} \dots E_{min}|^T \tag{11}$$

$$ub = |P_{max} \dots P_{max}\, E_{max} \dots E_{max}|^T \tag{12}$$

The equation (8) gives A_{eq} and B_{eq}. Equations (9) and (10) are concatenated to obtain A and B. Lower and upper bounds are given by (11) and (12).

The function linprog() in MATLAB is used for minimization.

D. RESULT AND DISCUSSION

After examining the body of research on Integrated Energy Optimization Systems (IEOS) for standalone applications, it was found that an IEOS framework supporting solar energy integration consists of four main components: the Worst Case

Solar Energy Determination (WSED) on the location, demand Side Optimisation (DSO), and the Power Supply and Energy Storage Optimisation (PSO & ESO).Every component must have the ideal size before beginning the IEOS design process. To power a household load, the effort entails optimizing a hybrid solar-hydrogen power plant's componentry

Fig. 3. DNI of selected months for the year 2020

Input DNI & Worst case Solar Energy Data (WSED): Accurate resource availability decreases the requirement for storage and other reserves, allowing the energy sector to minimize power swings while ensuring system reliability. It was found that matching source and demand lowered the need for storage by 10%-20% and the levelized cost of energy (LCoE) by roughly 10%.

To optimise the size of the Electrolyzer, solar irradiance data was initially gathered from the US-NREL [35] facility. DNI of selected months during the year 2020 at 10-minute intervals. Data was collected on DNI readings for the year 2020 in Trivandrum at latitude 8.490327°N and longitude 76.949096°E using the NREL metrological site, and it was discovered that the worst irradiation occurs in June, which is the rainy season, and the maximum irradiance occurs in February. From this data, the DNI for day 12 was taken for finding the storage capacity (Since worst case condition is the aim, day 12 data was found suitable when compared with the first 15 days of the month June). Solar PV array of 2kWp capacity is used which generates electricity on an average at 10 kWh per day. This electricity is stored as hydrogen.

The Fig. 3. shows the maximum DNI of each month for the year 2020 and Fig. 4. DNI of two months each with high DNI (January And February) and low DNI(May and June).

DSO: DSO is the process of using energy more efficiently by managing client energy use to lower energy prices and emissions. Storage batteries are frequently over-sized in resource constrained grid areas, such as off-grid rural villages, to improve power system reliability.

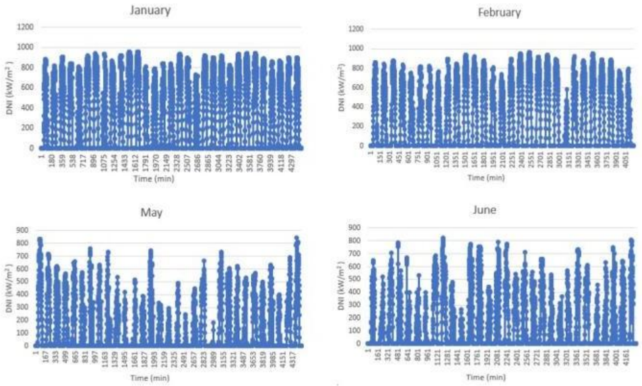

Fig. 4. DNI of January, February, May and June months for the year 2020

DSO can serve as an energy buffer, lowering the capital and operating expenses of the power system. For performing DSO, the residential load demand is determined for a typical house-hold. The daily average demand is identified for a worst case. This data is used to optimise the size of HESS using linprog in MATLAB. The inequality and equality constraints are also fed into MATLAB as input. For this research work ,a load profile of a typical residential household in Trivandrum district in the state of Kerala in India is considered was the load profile was estimated to be as depicted in Fig.5.

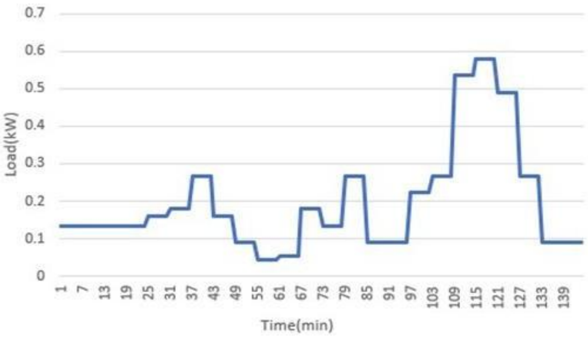

Fig. 5. Average load profile

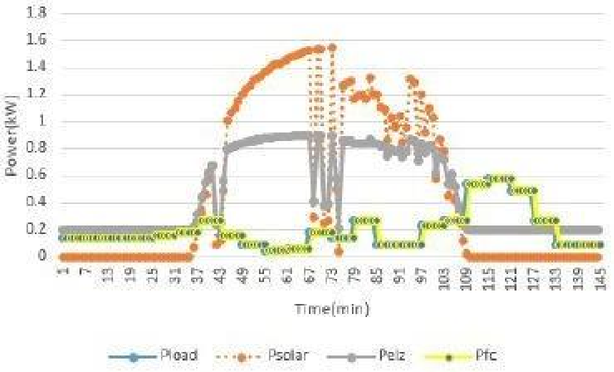

Fig. 6. Output of the simulation

E. Experimentation and validation

PSO (Power Supply Optimisation) & ESO (Energy Storage Optimisation) are done using linprog(). Data used is that of a household situated in Trivandrum district of Kerala. Houehold has an RE plant. Inorder to obtain energy, storing of hydrogen is necessary. For the storage of hydrogen the capacity of the fuel tank plays a crucial role. For making it cost effective, here optimization of fuel cell capacity is done.

The objective function is considered for minimising the power of the electrolyzer and energy of the fuel cell. This will in turn optimise the hydrogen tank capacity also

From Fig.6. it is clear that from 0hr – 7hr solar radiation is not available/minimum . During this time there are only critical loads as it is the starting of a day. From 7 am – 6pm, it shows a stochastic variation in power. From evening 6pm, solar power is falling down. After 6pm there is no generation of solar power due to non-availability of essential solar radiation. The optimized power of electrolyzer is also shown in the Fig.7. The maximum value of the power of the electrolyzer is 580.25W . The minimum capacity of the electrolyzer stack is therefore fixed at 580W.

For producing maximum quantity of hydrogen during nominal conditions two more stacks are connected in parallel so that total capacity becomes 1740W and integrated with 2kW solar PV array. The load profile is also depicted in the Fig.7. The optimized energy of the fuel cell is given in Fig.8. Here the objective constraints in MATLAB limit the final value of E(N) to lie between 20kJ and 400kJ so that complete discharge of the fuel cell is avoided. The optimized capacity of hydrogen tank is determined and is 17267.32Wh. (The hydrogen tank therefore has a capacity of 17 to 20 kWh). As it reaches the end of the day, it has become steady and stopped at final value (Fig 8).

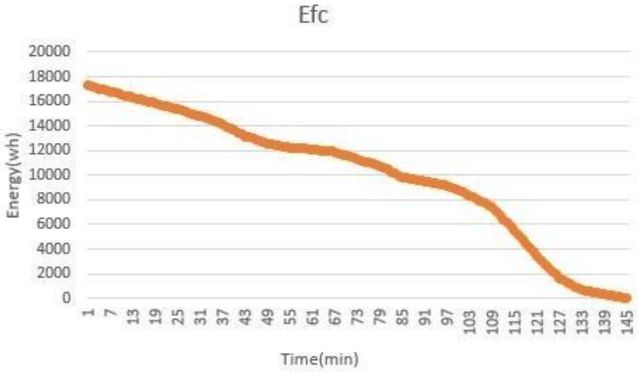

Fig. 7. Energy of fuel cell obtained from simulation in MATLAB

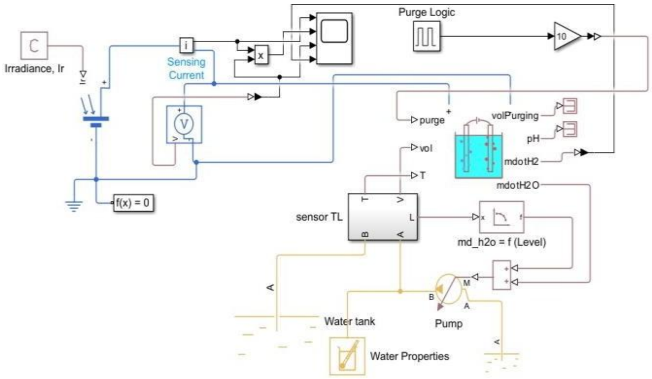

Fig. 8. Solar-Electrolyzer-Fuel Cell Model in MATLAB SIMULINK

1) Analysis in MATLAB simulink: To verify the results obtained, analysis is done using SIMULINK model of the Solar-Electrolyzer-Fuel Cell as given in Fig.8 . The Solar PV array of capacity 2kW @STC (Standard Test Condition) is used with open circuit voltage of 480V DC . The applied parameters are given in Table.I .

The PEM electrolyzer used is a series connected topology of 200 cells. The internal resistance determines the power capability of the Electrolyzer. The initial parameters used are given in Table.II.

TABLE I
Parameters Of The Solar PV Array Model Used In Simulation

Parameter	Value	Units
Diode saturation current Is	3.15e-07	A
Diode saturation current Is2	-	A
Solar generated current for measurement	8	A
Irradiance used for measurement	1000	W/m^2
Series resistance	0.0042	ohm
Parallel resistance	10.1	ohm
Number of series connected cells in a string	700	
Number of strings	1	

TABLE II
Parameters Of The PEM Electrolyzer Model Used In Simulation

Parameter	Value	Units
Assumption pH	Constant	
Resistance	variable	ohms
sCross-sectional transport area	0.01	m2
Distance anode-cathode	0.0002	m
Number of cells	200	
Initial pH	6	
Constant pH	6	

TABLE III
Result of Simulation done In Matlab

Resistance of Elz stack(Ohms)	0.16423	0.16	0.14
Voltage(V)	185	187.7864	175.661
Current(A)	7.8	7.993	7.999
Power(W)	1443	1502	1405
Hydrogen gas Produced(gmol/s)	0.016712	0.017	0.167
Remarks	*Undersized*	*Optimized*	*Oversized*

Here, three conditions are applied as given in Table.III. From the result obtained, it is clear that the optimised size of the Electrolyzer directly coupled to the PV Array gives maximum yield of Hydrogen gas and allows maximum power yield from Solar PV Array. The power yield and hydrogen gas yield are correspondingly reduced when the electrolyzer stack is undersized and oversized. The optimized hybrid system not only reduces costs but also improves efficiency above 6%, making it a viable solution for reliable energy supply in both remote and conventional energy-challenged areas.

F. CONCLUSION

The following conclusions can be drawn:

• Uncertainty in the power system can be reduced if integrated RES are optimised. For mini-grids that use solar energy as the primary supply source, it is beneficial to optimise the supply and load consumption since the former dictates how the latter is used. In addition, load consumption is harder to predict due to the unpredictable nature of energy use by consumers.

• Advances in grid technology and communication, a diverse energy mix, and more interconnections require the new EOSs to interact with both the supply and demand sides of the grid. • For efficient energy scheduling and utilization, Worst case SE data should be integrated with demand side (DS) data.

• Renewable smart hybrid mini-grids (RSHMGs) have the necessary technology and infrastructure for solar energy integration. They also present realistic options for grid extension. The components are optimised to achieve energy balance. • Constraints and objectives specific to the case study or locality often influence the strategy chosen.

•Hydrogen Fuel Cell Energy System (HFES) is seen as a critical component of future hybrid energy systems. However, there are possible difficulties with capital and operating expenses, safety dangers, and environmental effect, owing mostly to its capacity. The adoption of an IEOS can help to mitigate these concerns by minimizing the necessary capacity, optimizing the Electrolyzer and Fuel Cell discharging processes for maximum efficiency, and preventing the HESS from over-sizing, under-sizing, or overheating.

• IEOS can both prevent an energy mismatch between supply and consumption.

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