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Modeling, analysis and design of Solar PV based hydrogen energy storage system for residential applications

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Abstract

This research article presents the mathematical modeling, analysis and design of solar photovoltaic (PV) based hydrogen energy storage system with fuel cell for residential applications. The analysis is carried out for a rooftop solar power plant, considering the average annual radiation in Madurai city, located in the southern part of India. For performing this analysis, a mathematical model for polymer electrode membrane (PEM) electrolyzer, metal hydride hydrogen storage tank and PEM fuel cell is developed and simulated. A typical day time and night time load is considered. A detailed investigation is conducted on the production, storage and utilization of hydrogen for different operating conditions. For real time implementation of the standalone renewable system, design calculation is required to reduce the complexity in identifying the rating of all the components. To meet the residential load considered, the required number of cells in electrolyzer and fuel cell are calculated as 32 and 20 respectively. Moreover, the rating of PV panel required is 1.5kW and 4 numbers of 2000 litre capacities of metal hydride storage tank are needed. The response of the interconnected electrolyzer, metal hydride and fuel cell model were also discussed. This system is emission free and effective for residential applications.

Keywords

Mathematical model, PEM electrolyzer, Metal hydride, PEM fuel cell, Solar energy.

1.Introduction

In the recent days, the usage of renewable energy resources is drastically increasing due to the increase in electrical energy demand [1]. Moreover, the efforts taken to reduce the emission of harmful gases and the effect of climate changes on the world have made us to move forward on the energy production through renewable resources [2]. But the renewable resources are fully dependent on the weather and it leads to an inherent intermittency in availability [2]. This drawback is overcome by energy storage technology and one of the most common storage devices is among batteries [3]. These batteries are highly expensive and are not suitable for long-term storage. Hydrogen which is a clean energy carrier can be used for energy production [4]. But the barriers to hydrogen storage, pose serious challenges for the development of fuel cell technologies needed for several applications [5]. Hydrogen storage is an important methodology required for the improvement of hydrogen and fuel cell technologies [5]. The development of hydrogen storage methods that have potential for higher energy density is an important challenge faced by scientists presently [6]. This motivated to do research on fuel cell with electrolyzer and metal hydride-based hydrogen storage tank.

In the existing literature, techno-economic analysis, response of an integrated hydrogen storage system with renewable system and optimizing the response of integrated system are presented [7, 8]. For real time implementation, design calculation is required to find out the rating and sizing of solar photovoltaic (PV) power plant, polymer electrode membrane (PEM) electrolyzer, metal hydride storage tank and PEM fuel cell which is not presented in literature. This motivated to focus on the design of standalone solar PV based hydrogen energy storage system with fuel cell for residential applications.

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The objective of this research work is to find the sizing of PEM electrolyzer, metal hydride and PEM fuel cell integrated with a solar PV system needed for a typical residential load. To achieve this, first load analysis is carried out for a residential application. Next, energy produced by standalone rooftop solar power plant is calculated, considering the average annual solar radiation in Madurai city of Tamilnadu located in the southern part of India [9]. Then, the excess energy produced during day time by the solar PV system is found out which is converted as hydrogen energy using electrolyzer [10]. To meet out the night time load, the size of fuel cell and the sizing of electrolyzer to meet out the hydrogen requirement of fuel cell are estimated [11]. The required rating of solar PV system and size of hydrogen gas storage tank are also identified. For doing all these analyses, a detailed mathematical modelling is required. Hence, in this paper the mathematical modeling of PEM electrolyzer, metal hydride and PEM fuel cell is also presented.

This paper is organised as follows. The literature review on PEM electrolyzer, metal hydride storage tank and PEM fuel cell integrated with renewable energy sources is presented in section 2. Section 3 contains the residential load calculation and mathematical models of PEM electrolyzer, metal hydride storage tank and PEM fuel cell. The simulated results of PEM electrolyzer, metal hydride tank and PEM fuel cell are presented along with rating as well as sizing calculation of solar PV system, PEM electrolyzer, metal hydride tank and PEM fuel cell in section 4. The integrated model is also presented in section 4. In section 5, the discussion of obtained results in conjunction with the advantages and limitation of hydrogen energy storage system is presented. Section 6 concludes the research work and presents the future scope.

2.Literature review

Several research works on renewable energy systems with integrated hydrogen energy storage system are carried out in literature. A combined system [6] of solar and hydrogen production has a better performance and offers a suitable sustainable solution for hydrogen production with improved energy efficiency. An energy system comprising of solar panel, wind turbine generator, biogas generator and fuel cell is evaluated for both standalone and on-grid applications [1]. An optimal configuration of the system is developed to meet the electricity demand for both economic and environmental point of view. A study of the hydrogen storage system for compensating the energy supply and demand on a large scale with the renewable system for California is analyzed [12]. A review is carried out on the different sources of hydrogen production, long term storage, safe transportation, and the methods for purifying the hydrogen gas are compared [4]. The configuration of the hydrogen production system based on biomass gasification, solar PV and geothermal energy is also investigated [13]. For the three configurations, parametric analyses and the effect of system efficiency are discussed.

A case study on electricity generation in South Australia State [2] by using hydrogen for long lasting storage application is discussed. For generating the hydrogen gas from electrolyzer, solar and wind energy is used. The battery and the battery integrated with hydrogen storage systems are compared on a techno-economical point of view and it is found that the integrated battery hydrogen system is costlier compared to battery energy storage system but have the advantage of both the storage system. An energy review and an initial economic analysis are conducted on hydrogen-based micro-grids in buildings during weekends. It is concluded that the design achieved an annual energy production, higher than the nominal power plant [14]. Similarly, on techno-economic point of view the hybrid renewable system with a fuel cell is investigated for Bozcaada Island in Turkey [7]. The study concluded that this method is expensive. A study is carried out on the technical feasibility of PV-based off-grid system with battery and hydrogen storage system [15]. In the same way, the technical feasibility of hybrid solar PV/hydrogen fuel cell is examined [8].

On the basis of literature reviews, it is understood that the storing energy in the form of hydrogen is a more promising system for long term storage. An optimized design of an off-grid solar panel with fuel cell and diesel generator [10] is presented. A standalone power source combined of solar/wind/fuel cell/battery [16] is constructed and experimentally verified under different environmental conditions. A low voltage energy management control system [17] is designed and simulated for the hybrid PV-fuel cell power source to meet the power demand. For hybrid energy storage system applications, the various energy storage coupling architectures, energy management models and the basic principle for power flow decomposition on the basis of peak shaving and double low-pass filtering are discussed [18]. A study [19] presents the fuel cell application as a backup power system for the grid to meet the power demand. Simulation work is carried out on the multi-objective optimization of fuel cell-based hybrid energy storage systems and battery management systems [20]. Economic analysis is carried out for the grid connected fuel cell system with combined heat and power system [21]. A renewable PEM fuel cell system [11] to produce 1kW output is designed and the requirements of hydrogen in the tank are calculated for solar irradiance in Damascus city. In literature [22], the electrical energy produced by solar PV is stored in batteries and excess energy is converted as hydrogen gas by PEM electrolyzer. The literature [21] provides review on the latest developments in hydrogen energy storage system.

A detailed mathematical model of PEM electrolyzer at different operating conditions is provided and efficiency calculations are carried out in the literature [23−26]. In addition to the mathematical model, the performance effect of various parameters such as working temperature, pressure, membrane thickness, height and width of the channel, and current density are analyzed [27]. Moreover, the energy and energy efficiency of the electrolyzer are investigated. In the same way, the mathematical model of metal hydride [28] for both hydriding and dehydriding process is developed. Further a numerical simulation is presented for charging process in a metal hydride tank using the cooling water jacket and fins [29]. The hydrogen compressor technology on metal hydride is reviewed [30] based on the fundamental aspects of materials and the design features. Performance of the metal hydride tank from a thermodynamic viewpoint is assessed. The thermal management on the integrated system composed of a metal hydride tank and fuel cell is discussed [31]. The dissipated heat from the fuel cell is removed by using water and circulated in metal hydride storage tank for releasing the hydrogen gas. The proportional, integral and derivative (PID) controller is designed for hydrogen supply system [32]. An investigation of the controlling the properties of metal hydrides for stationary applications, integration with fuel cell and their operation are discussed [33].

A review of PEM fuel cell applications, fundamentals for the design, control optimization, and reduction in cost are presented in [34]. Also, it describes the significant potential of machine learning, deep learning and artificial intelligence (AI) methods in fuel cell-based system. A design of metal based monolithic fuel cell is presented [35] for transportation application. A mathematical model of a fuel cell and an analysis of electrochemical reactant flow dynamics are specified in the literature [36−39]. The fundamentals of non-traditional energy processes are discussed [40]. A high precision analysis of PEM fuel cell is carried out in [41]. Further, a wide review is conducted on fuel cells for the processing methods, thermal management, and various components of integrating systems with fuel cell [5]. In the study, the system modeling, optimization, feasibility, and current status of commercialization of the system are considered. A review on the fuel cell technology [41] on cost, performance and improvement still need of hydrogen fuel cell are addressed.

From the aforementioned literature review, it is observed that the hydrogen energy storage system will play a key role in future energy systems. Since it has high gravimetric energy density, no self-discharge problems and independency in supply duration [28], the system is more attractive. In the existing literature, techno-economic analysis, response of integrated hydrogen storage system with renewable system and optimizing the response of integrated system are presented. But for real time implementation, design calculation is required to find out the rating and sizing of solar PV system, PEM electrolyzer, metal hydride storage tank and PEM fuel cell which is not available in the literature. Hence, this paper deals with the detailed mathematical modeling of PEM electrolyzer, metal hydride tank and PEM fuel cell in addition to the analysis of the system for various temperatures and pressure levels. This paper also provides a complete design of PEM electrolyzer, metal hydride tank and PEM fuel cell with a solar PV system for a residential application.

3.Methods

As a detailed design analysis for the hydrogen storage system with renewable systems is not presented in the literature, this research paper presents the design of standalone solar PV based hydrogen energy storage system with fuel cell for residential applications and the graphical diagram is presented in *Figure 1*.

The energy generated from the solar panels is used for meeting the day time load and the excess energy is saved as hydrogen gas in metal hydride storage tank using an electrolyzer. During nighttime, the stored hydrogen energy is transformed into electrical energy using fuel cell to meet the demand. The steps followed for the design of standalone solar PV based hydrogen energy storage system are:

1. Calculate the daily load consumption for a residential application.
2. Calculate the energy production from a Solar PV system for average solar irradiation level.
3. Compute the performance of a hydrogen storage system using mathematical modeling technique.
4. Determine the sizing and rating of the components of the hydrogen storage system and solar PV panel.

The domestic energy consumption per day for residential applications is listed as for daytime (6 am to 6 pm) and night-time (6 pm to 6 am) in *Tables 1* and 2 respectively.

Design of standalone solar PV based hydrogen storage system with fuel cell for residential applications is done by considering the solar irradiance values in Madurai city located in the southern part of India [9] with a latitude 9.95 and longitude 78.15. The annual average solar radiation (R) for Madurai city is 5.38kWh/m^2/day. Considering a 1.5kW rooftop solar PV system for domestic usage, the energy produced from the PV system using average radiation obtained from the values in *Figure 2* as shown in Equation 1.

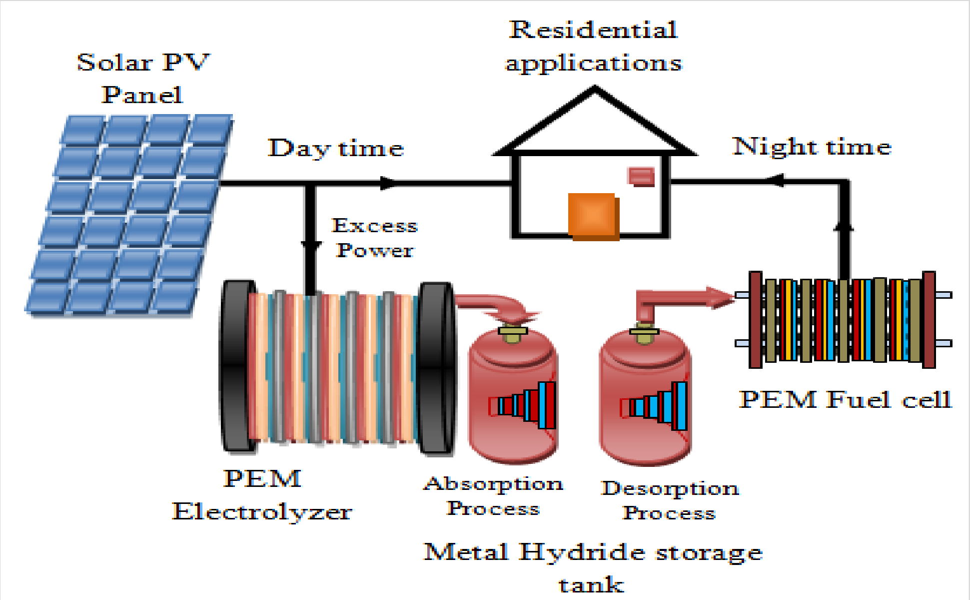

Figure 1 Graphical diagram of standalone solar PV based hydrogen storage system

Table 1 Average energy consumption during day time per day for a typical residential load

S. No.	Appliances	Power consumption (W)	Quantity	Usage time (Hours)	Energy required (Wh)
1.	Fridge	400	1	12	4800
2.	Ceiling Fan	70	1	8	560
3.	46-inch LED TV	70	1	3	210
Total					5570

Table 2 Average energy consumption during night time per day for a typical residential load

S.No	Appliances	Power consumption (W)	Quantity	Usage time (Hours)	Energy required (Wh)
1.	Fridge	400	1	12	4800
2.	Ceiling Fan	70	2	12	1680
3.	Tube Light	22	1	4	88
4.	CFL lamp	15	3	4	180
5.	46-inch LED TV	70	1	2	140
Total					6888

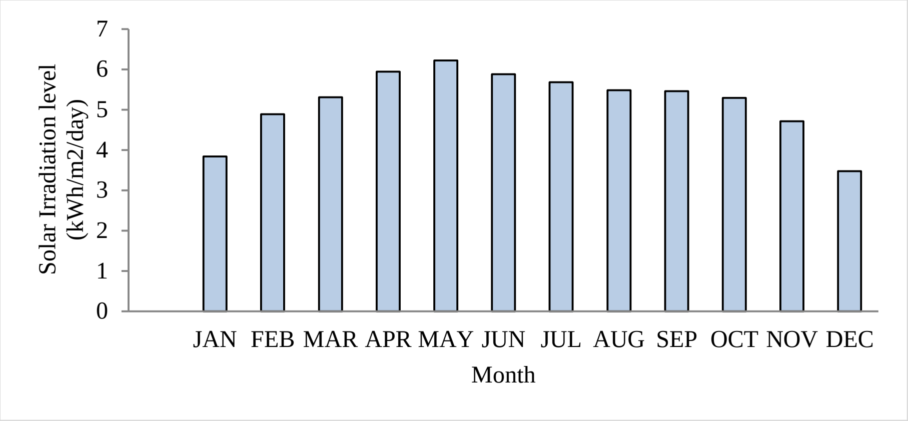

Figure 2 Average monthly solar radiation in Madurai city

$$E_{PV} = P_{PV} \times R = 1.5 \times 5.38$$
$$E_{PV} = 8.07 kWh/day \tag{1}$$

The total energy produced by solar PV rooftop system is obtained as 8.07kWh/day. From *Tables 1* and *2*, it is found that, 5.57kWh of energy is required for daytime and 6.88kWh is needed for night-time. Using solar PV rooftop power plant, after utilizing it for day time, the remaining unused energy is 2.5kWh. The remaining energy is converted as hydrogen gas and stored in a metal hydride storage tank using an electrolyzer. The stored hydrogen energy is utilized using fuel cells to meet the energy requirement during night-time. For designing the system, a detailed analysis on the performance of the electrolyzer, metal hydride storage tank, and the fuel cell is required.

3.1Mathematical model of Hydrogen Energy storage system

3.1.1 Mathematical model of PEM Electrolyzer

Water electrolysis is used to produce hydrogen by dissociation of water molecules into hydrogen and oxygen on applying electrical energy. The PEM electrolysis is ecologically clean and compact compared to the traditional electrolysis methods [24]. A dynamic model for PEM electrolyzer is developed on the basis of electrochemical reaction given by Equation 2

$$H_2O \rightarrow H_2 + 0.5O_2 \tag{2}$$

The water is introduced at the anode side; it separates as hydrogen ions and oxygen gas. At the cathode side, the positive hydrogen ions recombine and form hydrogen gas. The reaction rate of hydrogen and oxygen is calculated as in Equation 3

$$H_{2,g} = \frac{nI}{2F}\eta_F , O_{2,g} = \frac{nI}{4F}\eta_F \tag{3}$$

The rate of hydrogen production from electrolyzer is obtained from equation (3), where I is the supplied current to electrolyzer and Faraday's efficiency as η_F. The voltage required for the PEM electrolysis is expressed in Equation 4.

$$V_{el} = E + V_{act} + V_{ohm} + V_{conc} \tag{4}$$

According to the Nernst equation, the equilibrium voltage is given in Equation 5.

$$E = 1.48 - 0.85 \times 10^{-3}(T - 298) + 2.3\frac{RT}{4F}\left[log\left(\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}}\right)\right] \tag{5}$$

Where Universal gas constant R is 8.3145Jmol^{-1}K^{-1}, Faraday constant F is 9.6485×10^{4} Cmol^{-1}, absolute temperature T is 80°C, $P_{H2,}$ P_{O2} and $P_{H2O}$are the partial pressure of hydrogen, oxygen and water respectively. The Activation loss [11] is given by Tafel equation as represented in Equation 6.

$$V_{act} = \frac{RT}{\alpha nF} ln\left(\frac{J}{J_o}\right) \tag{6}$$

Where α is the electrons transfer coefficient and for electrochemical reaction α is 0.5. J_o is the exchange current density and its temperature dependence is modeled through an Arrhenius type relationship and is given as:

$1.08 \times 10^{-17} exp^{0.086T}$

The ohmic over potential is obtained by transportation of hydrogen ions [24] is obtained as in Equation 7.

$$V_{ohm} = J\frac{t_{mem}}{\sigma_{mem}} \tag{7}$$

Where J is current density A/cm^2, σ_{mem} the membrane conductivity and is given in Equation 8

$$\sigma_{mem} = (0.005139 \times \lambda_{mem} - 0.003260)\, exp^{\left[1268\left(\frac{1}{303} - \frac{1}{T}\right)\right]} \quad (8)$$

λ_{mem} represents membrane's hydration and is expressed in Equation 9.

$$\lambda_{mem} = 0.043 + 17.81 \times a - 39.85 \times a^2 + 36 \times a^3 \quad (9)$$

Where a is the membrane water activity. Assuming that the electrolyser membrane operates under 100% humidification, the value of a=1.

The concentration loss is given in Equation 10.

$$V_{conc} = -\frac{RT}{nF} ln\left(1 - \frac{J}{J_L}\right) \quad (10)$$

J_L is the supplied maximum current density to the electrolyzer which is assumed to be 1.7A/cm^2. It shows the maximum production rate provided by the electrolyzer. The electrolyzer efficiency η is represented in Equation 11 by dividing the minimum voltage by the operational voltage [11].

$$\eta = \frac{1.48}{V_{el}} \times 100\% \quad (11)$$

3.1.2 Mathematical model of metal hydride based hydrogen storage tank

The storage medium of hydrogen consists of various metal hydrides like MgH_2, $NaAlH_4$, $LiAlH_4$, $LaNi_5H_6$ which are used at different degrees of efficiency. In this research work, a reactor in the shape of cylinder is considered which contain porous filled with $LaNi_5$. For absorption and desorption process, the external surface of reactor is circulated by cool and hot water respectively. To develop the mathematical model, few assumptions are taken as referred in [28].

3.1.2.1 Mass balance equation for gaseous hydrogen

Equation 12 represents the absorption process,

$$\frac{dm_{H_2g}}{dt} = f_{inH_2} - rm_S \frac{MW_{H_2}SC}{MW_{MH}} \quad (12)$$

Equation 13 represents the desorption process,

$$\frac{dm_{H_2g}}{dt} = -f_{outH_2} - rm_S \frac{MW_{H_2}SC}{MW_{MH}} \quad (13)$$

Where $f_{inH2}$and f_{outH2} are inlet and outlet flow rate of hydrogen gas in kgs^{-1}, r is rate of reaction in gMHgs^{-1}s^{-1}, m_s is mass of solid phase assumed as 143 kgs, MW_{H2} is the molecular weight of hydrogen gas and MW_{MH} is for metal hydride and they are assumed to be0.002 $kg_{H_2} mol^{-1}_{H_2}$ and0.432 $kg_{MH} mol^{-1}_{MH}$ respectively [28]. The stoichiometric coefficient (SC) is taken as 3 $mol_{H_2} mol^{-1}_{MH}$.

3.1.2.2 Mass balance equation for metal hydride

The mass balance equation for solid phase is expressed as in the Equation 14,

$$\frac{dm_{MH}}{dt} = rm_s \quad (14)$$

For both absorption and desorption process.

3.1.2.3 Energy balance equations

To find out the temperature in the reactor, the energy equation [28] is expressed as

Equation 15, for absorption process,

$$\left(m_{H_2g}C_{pH_2} + m_sC_{ps}\right)\frac{dT}{dt} = f_{inH_2}c_{pH_2}\left(T_{in} - T\right) + AU\left(T_{wa} - T\right) - \Delta H_d rm_s \frac{SC}{MW_{MH}} \quad (15)$$

Equation 16, for desorption process,

$$\left(m_{H_2g}C_{pH_2} + m_sC_{ps}\right)\frac{dT}{dt} = AU\left(T_{wd} - T\right) + \Delta H_d rm_s \frac{SC}{MW_{MH}} \quad (16)$$

Where, C_{pH2} is specific heat of hydrogen gas and C_{ps} is for solid phase and are equal to 14,300 $Jkg^{-1}_{H_2}K^{-1}$ and 355 $Jkg^{-1}sK^{-1}$ respectively.

The area of reactor A is 5.4 m^2, U is overall heat transfer coefficient and is equal to 243Wm^{-2}K^{-1}, Enthalpy at absorption (ΔH_a) and desorption (ΔH_d) stage are -30,478 $Jmol^{-1}_{H_2}$ and 30,800 $Jmol^{-1}_{H_2}$ respectively. The temperature of cooling water T_{wa} is 298K, the temperature of heating water T_{wd} is 353K and inlet temperature of hydrogen gas, T_{in} is 290K.

3.1.2.4 Reaction kinetics

In literature, various expressions for reaction equations are available for sorption process. Generally, the reaction equations for $LaNi_5$ hydrogen system [28] are stated as in the Equation 17 and Equation 18 for both absorption and desorption process respectively.

$$r = C_a e^{-E_a/RT} \ln\left(\frac{P_a}{P_{eq}}\right)\left(1 - \frac{m_{MH}}{m_s}\right) \quad (17)$$

$$r = C_d e^{-E_d/RT} \ln\left(\frac{P_d - P_{eq}}{P_{eq}}\right)\left(\frac{m_{MH}}{m_s}\right) \quad (18)$$

Where E_a and E_d are activation energy for hydride and dehydride process and are equal to 21,170 $Jmol^{-1}_{H_2}$ and 16,420 $Jmol^{-1}_{H_2}$ respectively and the kinetic constants for both absorption C_a and desorption C_d are 59.2S^{-1} and 9.6S^{-1}. P_{eq} is pressure at equilibrium state, m_s is mass constant of solid material and m_{MH} is the variation in mass current in metal hydride tank.

3.1.2.5 Equilibrium pressure

As stated in Van’t Hoff relation, the plateau pressure for $LaNi_5$depends on temperature. The pressure at equilibrium state is depend on the temperature and concentration of hydrogen and is represented as Equation 19, for absorption and Equation 20, for desorption.

$$P_{eq} = e^{\left(\frac{\Delta H_a}{RT} - \frac{\Delta S_a}{R} + sl\left(\frac{m_{MH}}{m_s} - 0.5\right)\right)} P_o \qquad (19)$$

$$P_{eq} = e^{\left(-\frac{\Delta H_d}{RT} - \frac{\Delta S_d}{R} + sl\left(\frac{m_{MH}}{m_s} - 0.5\right)\right)} P_o \qquad (20)$$

Where, the entropy at absorption ΔS_a and desorption ΔS_d stage are -108 $Jmol_{H_2}^{-1} K^{-1}$ and 108 $Jmol_{H_2}^{-1} K^{-1}$ respectively. Assumed reference pressure P_0 is 1 bar and the Plateau slope coefficient sl is 0.13.

3.1.2.6 Ideal gases state equation

$$m_{H_2 g} = \frac{PV_g}{RT} MW_{H_2} \qquad (21)$$

Where P is operating pressure, V_g is volume of reactor and is taken as 0.0172 $m^3_{H_2}$, R is Universal gas constant.

3.1.3 Mathematical model of PEM Fuel cell

An electrochemical reaction is carried out on a fuel cell to produce electrical energy. In the PEM Fuel Cell, solid polymer membranes function as an electrolyte in the form of a thin, permeable sheet. Platinum is placed in between the two electrodes, which speeds up the reactions at the electrodes. The pressurized hydrogen gas is applied at the anode side and the oxygen (air) is on the cathode side [37&38]. Equation 22 represents that the hydrogen is dissolved at the anode and yields electrons as well as hydrogen ions.

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad (22)$$

These yielded electrons move from anode to cathode through an external circuit. The hydrogen ions move to the cathode through the electrolyte. At the cathode, oxygen gas reacts with the entering hydrogen ions and produce water as a by-product as expressed in Equation 23.

$$2H_2 + O_2 \rightarrow 2H_2O + Heat \qquad (23)$$

The electron flow provides power to the load. Thus, fuel cell generates DC voltage with very less pollution and produces a harmless by-product as water.

Generally, the performance of fuel cell is highly non-linear. On increasing the current value, the cell voltage decreases. Based on the characteristics of fuel cell, the polarization curve (I-V curve) is obtained. The potential of a single cell V_{cell}, is expressed [36−38]as in Equation 24.

$$V_{cell} = E - V_{act} - V_{ohm} - V_{conc} \qquad (24)$$

The cell potential E (Nernst equation) is written based on the cell temperature and partial pressures are given in Equation 25.

$$E = E_o - 0.85 \times 10^{-3}(T - 298.15) + \frac{RT}{2F} ln\left(\frac{P_{H_2} \times P_{O_2}^{1/2}}{P_{H_2O}}\right) \qquad (25)$$

Where E_o represents the referred potential which is taken as 1.229V at unity activity.

V_{act} Activation losses taking place due to the slowness of reaction on the electrode surface. It is analysed by Tafel’s equation as presented in Equation 26.

$$E_{act} = \xi_1 + \xi_2 T + \xi_3 T(ln(CO_2)) + \xi_4 T(ln(i)) \qquad (26)$$

Where ξ_1 to ξ_2 represent constant parametric coefficients [37], i is the current in cell and CO_2 is the oxygen concentration which is depends on stack temperature, it is assumed as 353K and is expressed as in Equation 27,

$$CO_2 = \frac{P_{O_2}}{5.08 \times 10^6 e^{(-498/T)}} \qquad (27)$$

$$V_{act} = -E_{act} \qquad (28)$$

The ohmic loss represents the membrane resistance [11]. Thus, ohmic loss is specified as in Equation 29.

$$V_{ohm} = i(R_m + R_c) \qquad (29)$$

Where, R_c is the constant part of cell’s resistance and R_m is the membrane resistance which depends on the temperature and the membrane hydration level ψ as given in Equation 30.

$$R_m = \frac{\rho_m l}{A} \qquad (30)$$

Where l is the membrane thickness and is taken as 178µm, A is the active area of cell in cm^2, specific membrane resistance $\rho_m$in Ω *cm* is given as in Equation 31.

$$\rho_m = \frac{\left(181.6\left[1 + 0.03 \times \left(\frac{i}{A}\right) + 0.062 \times \left(\frac{T}{303}\right)^2 \times \left(\frac{i}{A}\right)^{2.5}\right]\right)}{\left(\left[\psi - 0.634 - 3\left(\frac{i}{A}\right) \times exp^{\left[\frac{4.18 \times (T-30)}{T}\right]}\right]\right)} \qquad (31)$$

An adjustable parameter Ψ is ranges from 10 to 23. Due to flow resistance, the constant pressure cannot deliver oxygen and nitrogen inside the cell. It generates losses in concentration voltage. Thus, the concentration loss corresponds to the limit of reactants mass transfer. Thus, the concentration loss is represented by Equation 32.

$$V_{conc} = -B\ ln\left(1 - \frac{j}{j_{lim}}\right) \qquad (32)$$

Where, j is the current density driven from the cell in mA/cm^2 and the maximum current density determined from the cell is about 1500 mA/cm^2. It is the limit found by the limiting current density.

4. Results

4.1 Simulation of PEM electrolyzer

The Simulink diagram of PEM electrolyzer is shown in *Figure 3* and the characteristics curve is shown in *Figure 4*. The polarization curves for different temperature show that as on increasing the current density, the corresponding cell voltage also increases. At higher value of current density, the water molecules are separated as a greater number of hydrogen ions and oxygen and hence it produces high voltage. On increasing the temperature, the cell voltage starts to decreases. It is due to the Gibbs free energy reduction and hence increases the cell performance and energy conversion. As shown in Figure 4, at a temperature of 343K the cell voltage is 1.948V and at 373K the observed cell voltage is 1.828V. *Figure 5* shows the temperature impact on the cell efficiency. At low current density, the efficiency reaches higher values as a result of heat absorption in the cell and later it slowly reduces on increasing the current density.

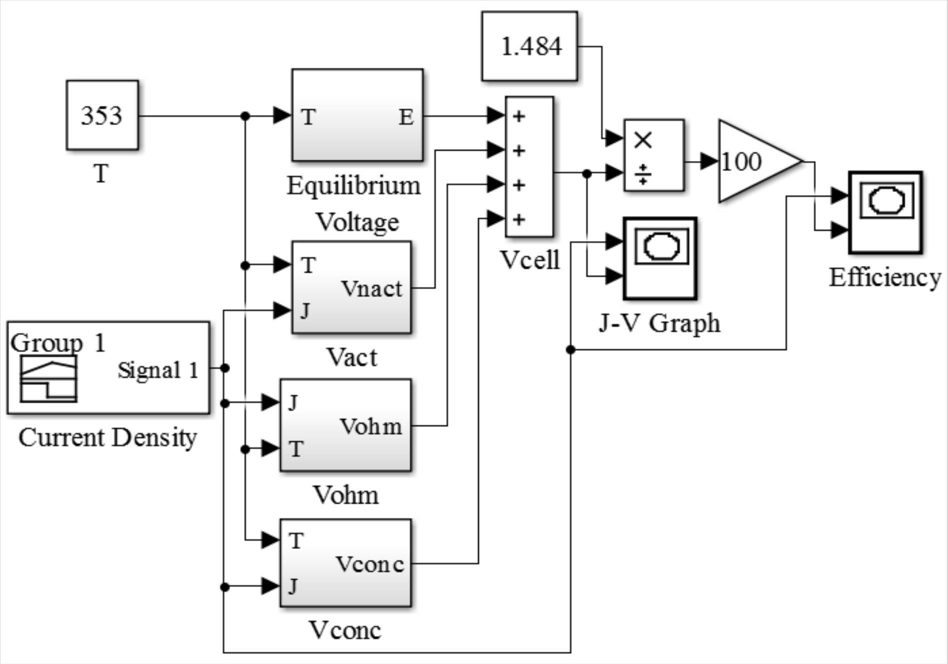

Figure 3 Simulink diagram of PEM Electrolyzer

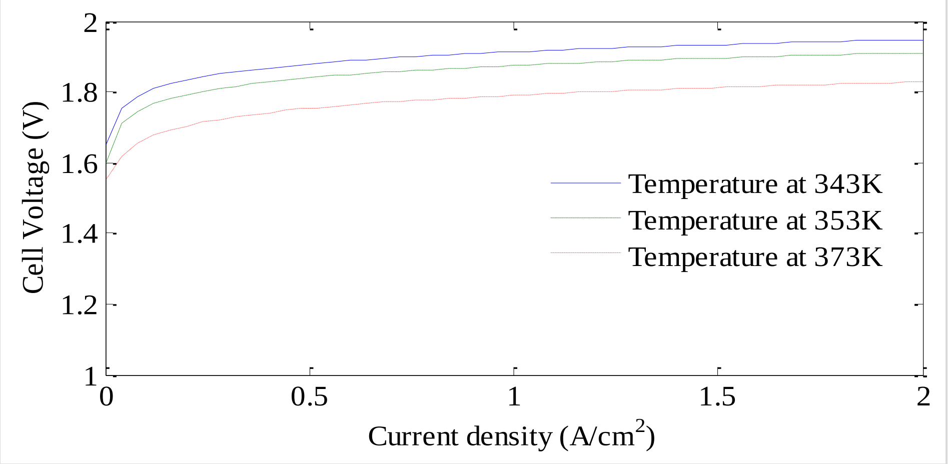

Figure 4 J-V characteristics of PEM Electrolyzer

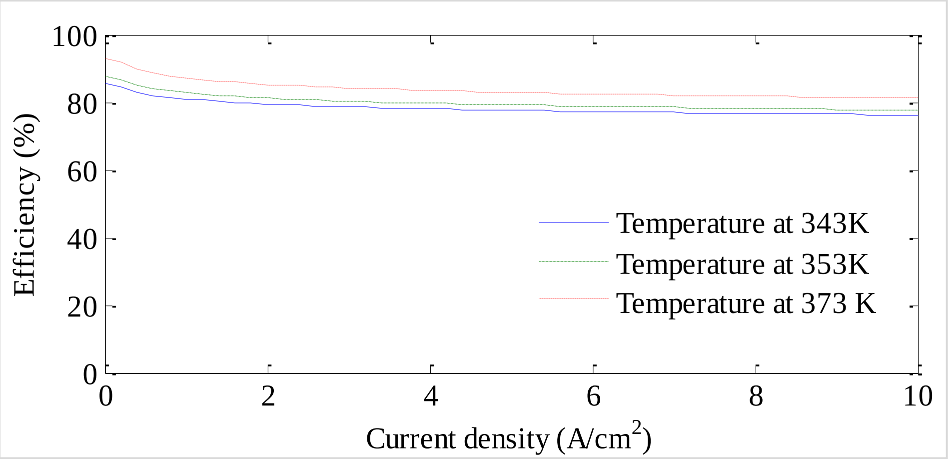

Figure 5 Efficiency curve of Electrolyzer cell

4.2 Simulation of metal hydride storage tank

4.2.1 Simulation of absorption process

The Lumped model of Metal hydride tank is chosen for simulation as it improves the design of hydrogen storage/compression process. The Simulink diagram of absorption process is displayed in *Figure 6.*

$LaNi_5$ material is used for the hydride formation since this material has higher cycling resistance and gas impurities resistance but the plateau slope and hysteresis are low. In this simulation, the hydrogen storage capacity is taken as 1.39wt% and the mass production of hydrogen in metal hydride form is $143kg_{MH}/h$. A multi tubular reactor holds the $LaNi_5$. This reactor can store large amount of solid material and it is same as shell and tube type heat exchanger. The hydrides are located within the tube and cooling/hot water is circulated at the outer surface of the tank. Thus, all the tubes are modelled as a cylindrical reactor and diameter of tubes are considerably taken as small. This is to raise the value of inner conductance and area of the heat transfer region.

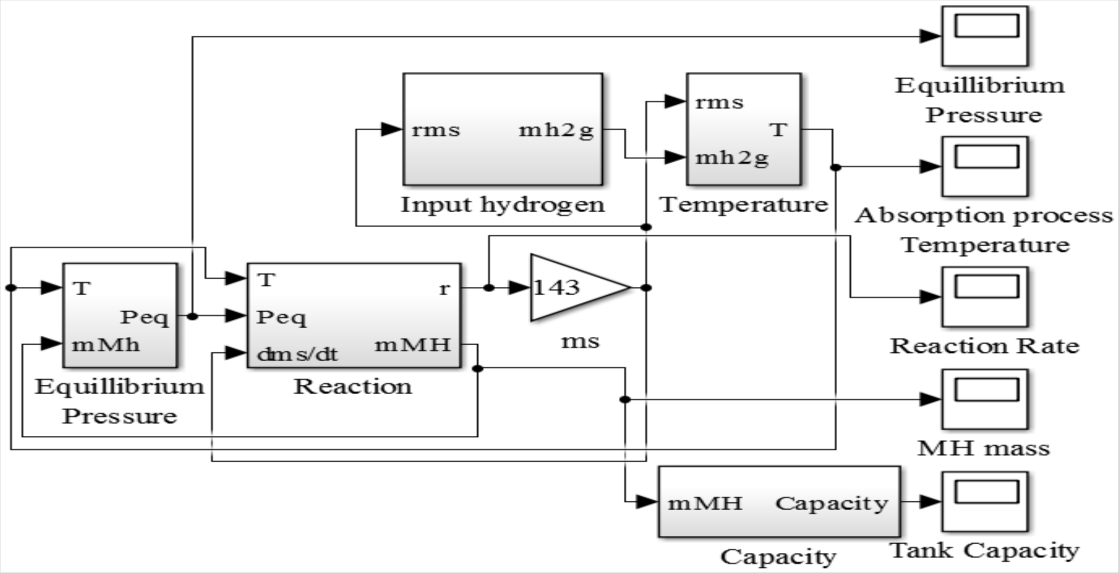

Figure 6 Simulink diagram of Metal Hydride hydrogen storage tank during absorption process

The simulation work is conducted with the following initial conditions, the mass of metal hydride is assumed as $m_{MH(initial)}=27kg$ and the reactor temperature as $T_{a(initial)}=T_{wa}$. The simulation result in *Figure 7* shows the variation in mass of metal hydride stored with respect to time for various temperatures. The maximum hydrogen storage capacity of reactor has been reached in 1000 seconds at a temperature of 298K.It reveals that for hydrogen at lower temperature stores quickly in the metal hydride storage tank compared to the higher temperature.

In the absorption stage, the initial bed temperature is cool water temperature. As the gaseous hydrogen penetrates into tank, the exothermic reaction takes place. The reaction rate is improved and produces the heat. The circulating cooling water is not able to remove all the heat produced during the exothermic reaction, as a result the bed temperature raises up to 320K is shown in *Figure 8*. This raise in tank temperature leads to an equivalent rise in equilibrium pressure and is shown in *Figure 9*. As the absorption process continues, the rate of reaction slowly comes down. Thus, the heat production gradually decreases due to the heat dissipation by the cooling system. Now the bed temperature reduces and reaches the cooling water temperature 20°C (293K) as shown in *Figure 8*.

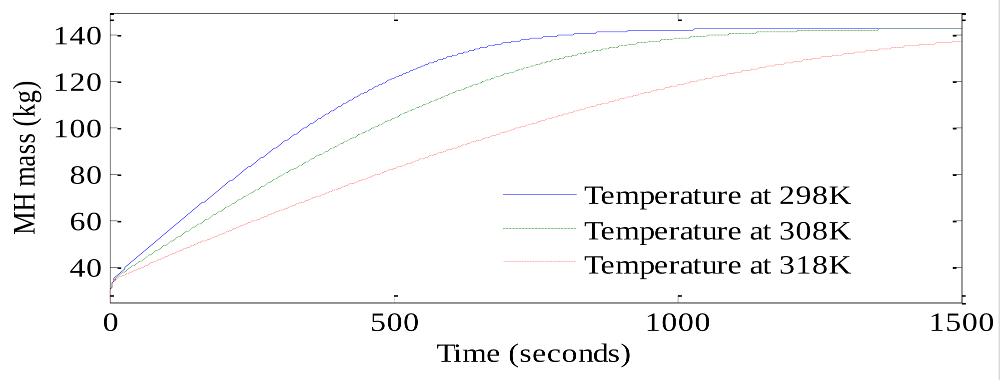

Figure 7 Mass of metal hydride stored with respect to time at various temperature

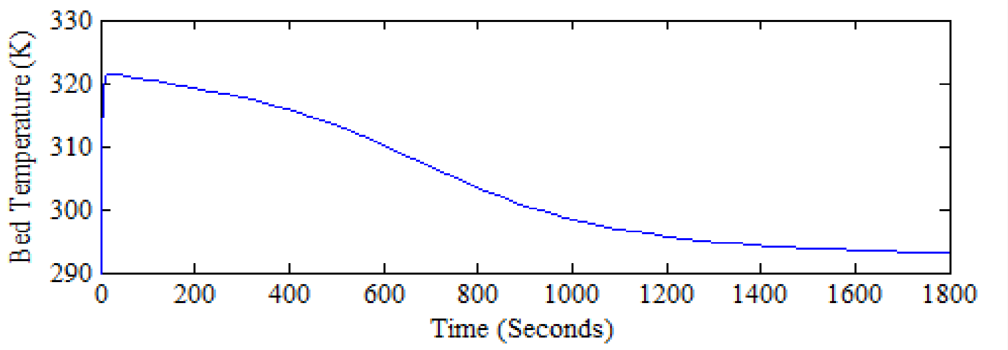

Figure 8 Variation of bed temperature during absorption process

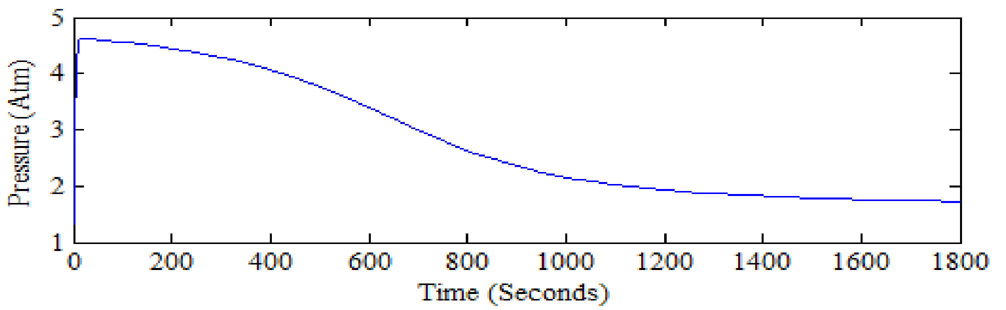

Figure 9 Variation of equilibrium pressure during absorption process

4.2.2 Simulation of desorption process

The discharge of hydrogen gas depends on the temperature of circulating water. The Simulink diagram for desorption process is shown in *Figure 10*. For a temperature of 353K, the discharge of hydrogen from metal hydride tank takes nearly 20 minutes. On increasing the temperature, the discharging time is reduced and is shown in *Figure 11*. An endothermic reaction is carried out in desorption process. By circulating heating water, the stored metal hydride is converted into hydrogen gas. This reaction slowly rises the bed temperature when all the stored hydrogen is discharged and is shown in *Figure 12*. It leads to increase in equilibrium pressure in the tank and is presented in *Figure 13*.

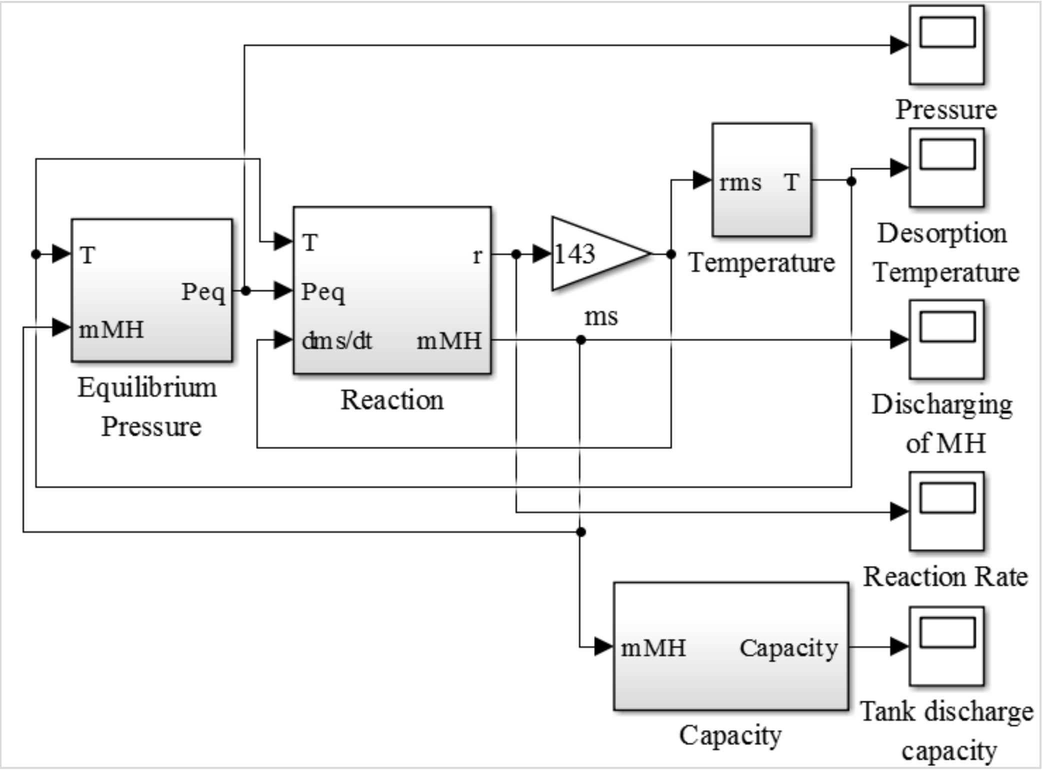

Figure 10 Simulink diagram of Metal Hydride hydrogen storage tank during desorption process

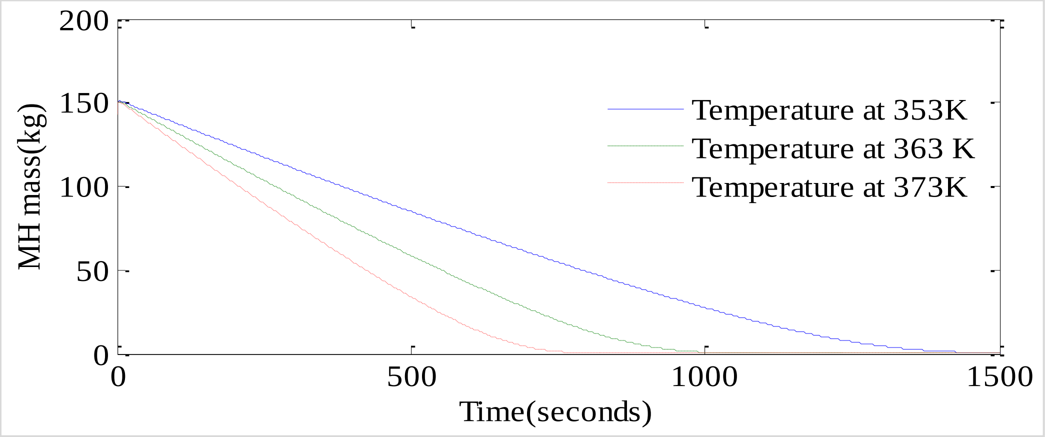

Figure 11 Discharge of metal hydride mass at different operating temperature

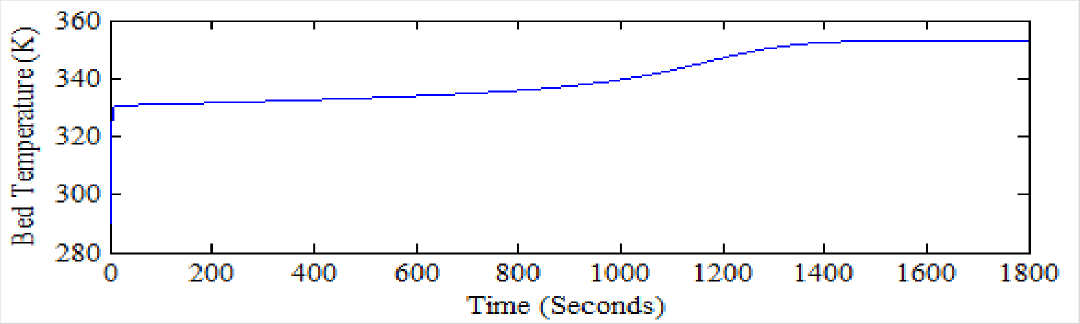

Figure 12 Variation of bed temperature during desorption process

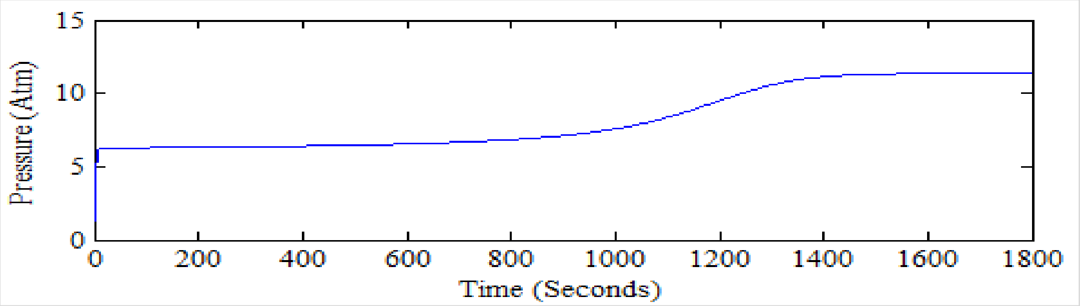

Figure 13 Variation of equilibrium pressure during desorption process

4.3 Simulation of fuel cell

The Simulink diagram of PEM Fuel cell is shown in *Figure 14*. The V-J characteristics of PEM fuel cell for different atmospheric pressures of hydrogen is shown in *Figure 15*.

The simulation is carried out at 80°C temperature. The limiting current for the stack is taken as 1.7A/cm2. The result shows that the increase in partial pressure leads to rise in cell voltage and power. This increase in output voltage decreases the voltage losses in the cell. Thus, on increasing the pressure value, the losses are reduced. The maximum power density curve for fuel cell is shown in *Figure 16.*

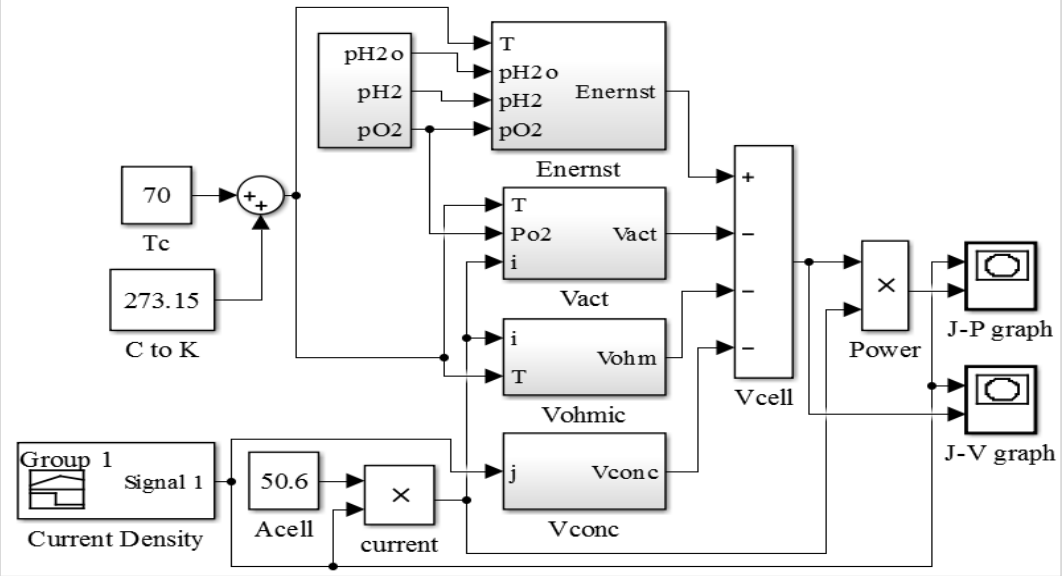

Figure 14 Simulink diagram of PEM fuel cell

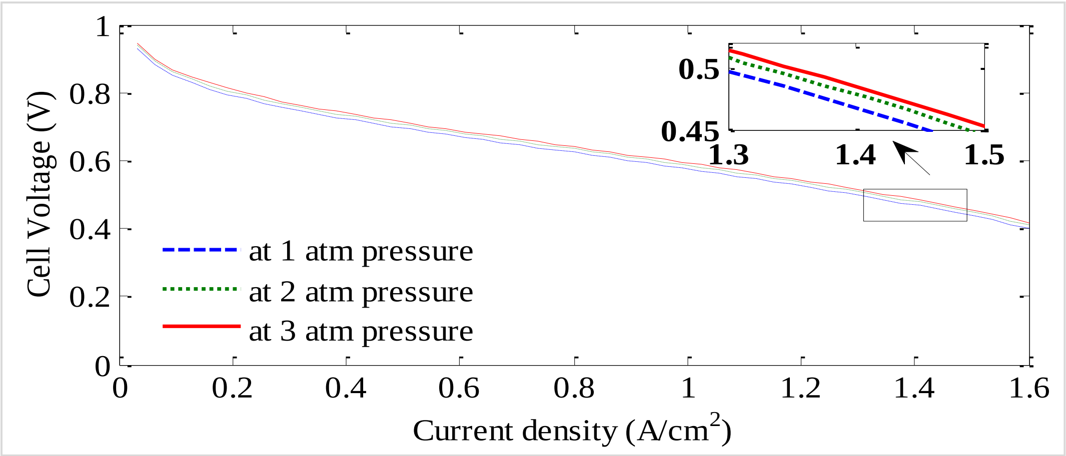

Figure 15 The V-J characteristics of Fuel cell at different operating pressures

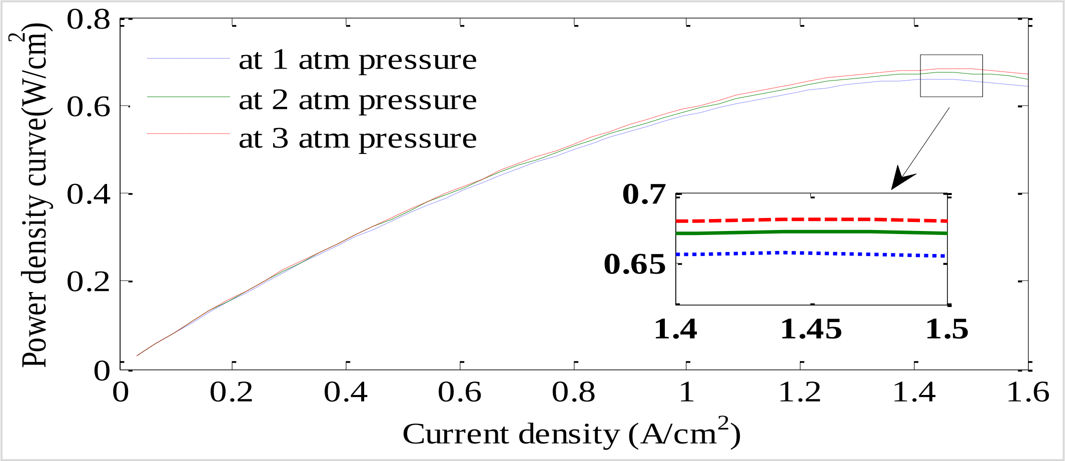

Figure 16 The Power density curve of Fuel cell at different operating pressures

4.4 Sizing calculation of PEM fuel cell

Average energy consumption during nighttime per day for a typical residential load is given in table 2. From table 2, the total energy required during night time is 6.888kWh per day. Taking into account, the maximum demand at nighttime which is 677 W, thus the fuel cell is designed to meet the load during night time.

For 3 atmospheric pressure and 80°C operating temperature, the maximum power density is 1.42 A/cm^2 and the output cell voltage is 0.48V from figure 15. The number of stacks required is given in Equation 33.

$$N = \frac{P_{el}}{V_{el} I_{el}} \approx 20 cells \quad (33)$$

The hydrogen flow rate for a single fuel cell is represented in Equation 34.

$$\dot{N}_{H_2} = \frac{I}{2qN_o} \quad (34)$$

$$= 3.74\times10^{-7} kmoles/sec = 500 ml/min$$

Where N_o is 6.022 ×10^{26}(Avogadro's number) and q is charge of electron is 1.602 ×10^{-19}. Therefore, for 20 cells of fuel cell stack, the required amount of hydrogen is 10 L/min.

4.5 Sizing calculation of PEM electrolyzer

Electrolyzer is used to convert the unused remaining energy E_{RE} into hydrogen gas so as to meet the demand during night time. The hydrogen production calculation is carried out by considering PEM single cell electrolyzer, with a cell voltage of 2V, current 40A and operating temperature 80°C. The production rate of hydrogen is depending only on the current value. To produce 1 kilomole of H_2, the electrolyzer consumes 1 kilomole of H_2O (contain N_0 molecules, the amount of hydrogen produced [40] is given by Equation 35,

$$\dot{N}_{H_2} = \frac{I}{2qN_o} \quad (35)$$

$$\dot{N}_{H_2} = \frac{40}{2 \times 1.602 \times 10^{-19} \times 6.022 \times 10^{26}} = 2.08 \times 10^{-7} kmoles(H_2)/sec$$

The hydrogen production from electrolyzer is 277ml/min. Mass of water molecules is 9 times that of hydrogen molecule; hence the water consumption rate is 2.493L/min. Similarly, the molecular mass of oxygen is 16 times that of hydrogen, i.e the gas is produced at the ratio 8:1 and the oxygen production is given as 2.216 L/min. The amount of heat exchanged with the surroundings are given by Equation 36.

$$\dot{Q} = (V - 1.48)I = 20.8W \qquad (36)$$

Energy required for the electrolyzer to produce one kilomole of H_2 at 85% efficiency (η) is given as in Equation 37.

$$W_{Electrolyzer} = \frac{\Delta H}{\eta} \qquad (37)$$

Where, ΔH is enthalpy for the reaction is given as 285.9 MJ/kmole. Hence the required energy is 385.3×10^6J/kmole (H_2). Therefore, for the production of 2.08×10^{-7} kmoles(H_2)/sec of hydrogen, the energy required is 80 joules/sec for a single cell electrolyzer. From the Equation (35), a single cell of electrolyzer produces 277mL/min of hydrogen gas. Hence to meet 10 L/min of hydrogen for fuel cell, the required number of cells in electrolyzer is 32.

4.6 Rating of solar PV power plant

The energy required for 32 cells of electrolyzer stack is 2.5 kWh. As a result, the remaining energy unused from solar PV is 2.5 kWh which is used by the electrolyzer. Hence the 1.5kW rooftop solar PV system is sufficient for this standalone solar PV based hydrogen energy storage system with fuel cell.

4.7Sizing calculation of metal hydride storage tank

Storage capacity of metal hydride storage tank is calculated from the above analysis, it is found that to store 7200 liters per day, and nearly 4 numbers of metal hydride storage tanks with a capacity of 2000 liters are required.

The average solar irradiance level in Madurai city for each month and the resultant hydrogen gas production from the electrolyzer are presented in *Figure 17*. In *Figure 17*, the bar chart represents the solar irradiance level in Madurai city [5] and the continuous line shows the corresponding hydrogen production during the month. The solar irradiance level decreases during the months of January, February, November and December. But the solar radiation reaches a maximum level of 6 kWh/m2/day during the months of April, May, June and July. During the months of higher solar irradiance level, the level of hydrogen production also increases. By storing the excess energy in the form of hydride in a storage tank, it can be used later during the months of January, February, November and December to meet out the demand.

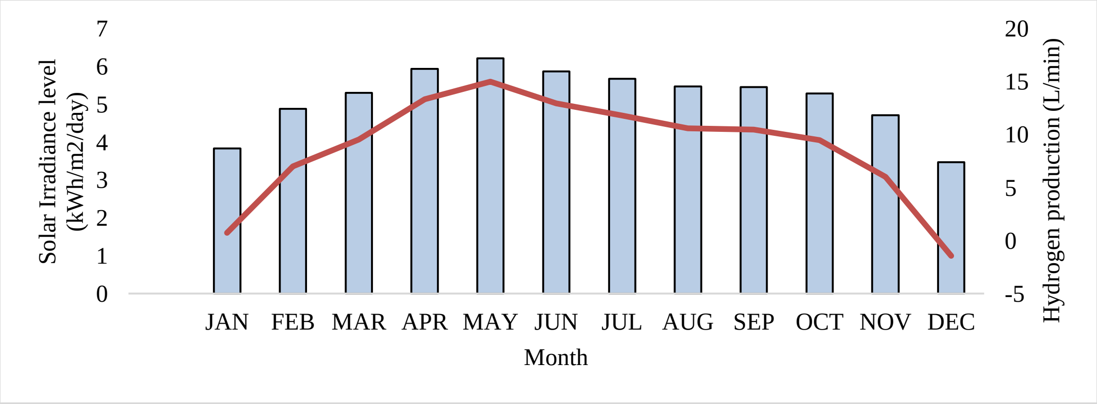

Figure 17 The production of hydrogen gas for different season

4.8 Model for hydrogen generation and storage

The PEM electrolyzer and metal hydride storage tank are connected together for hydrogen generation and storage process. The Simulink model is shown in *Figure 18.* From Equation 35, the hydrogen production from a single cell PEM electrolyzer is 1.6×10^{-3} kg/hour (18 liters/hour). Thus, the storage capacity of metal hydride tank needed is 300 liters(21*kg*). For storing hydrogen, cooling water is circulated at a temperature of 20°C. The bed temperature and equilibrium pressure are shown in *Figures 19* and *20* respectively.

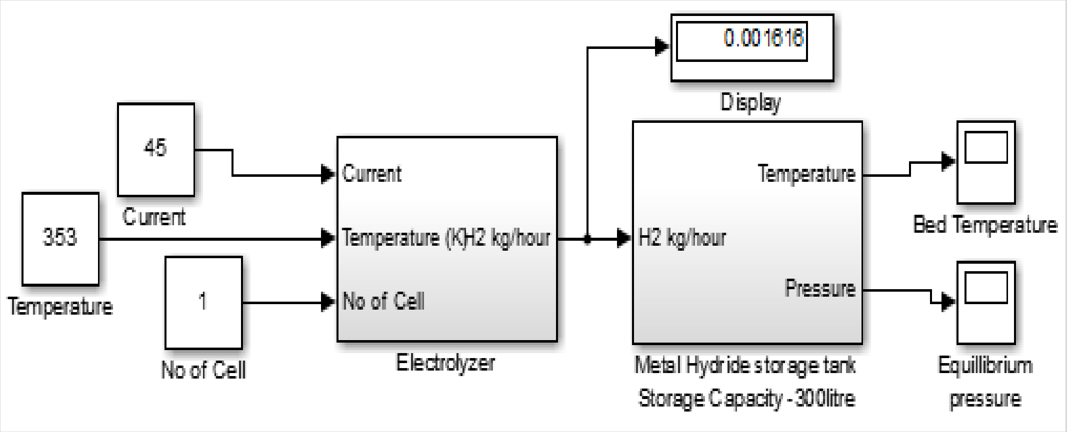

Figure 18 Simulink diagram of hydrogen generation from electrolyzer and storage in metal hydride tank

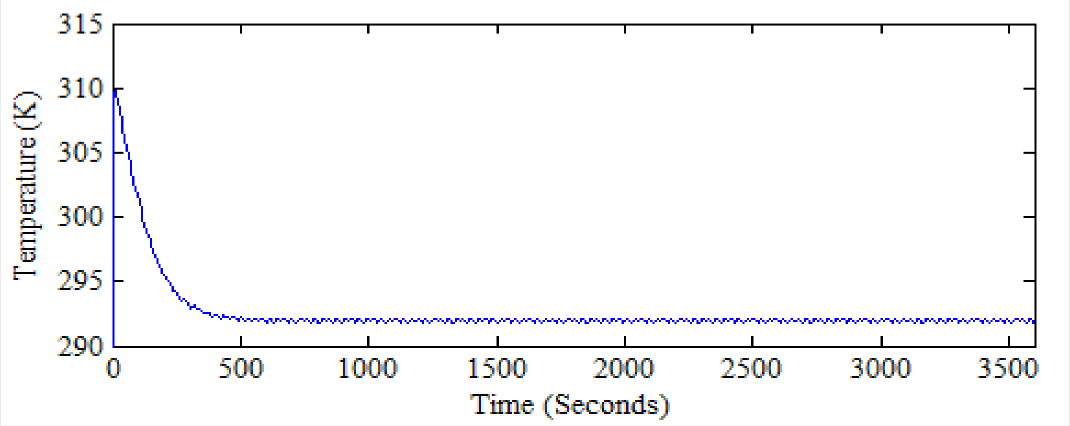

Figure 19 Bed temperatures during absorption process

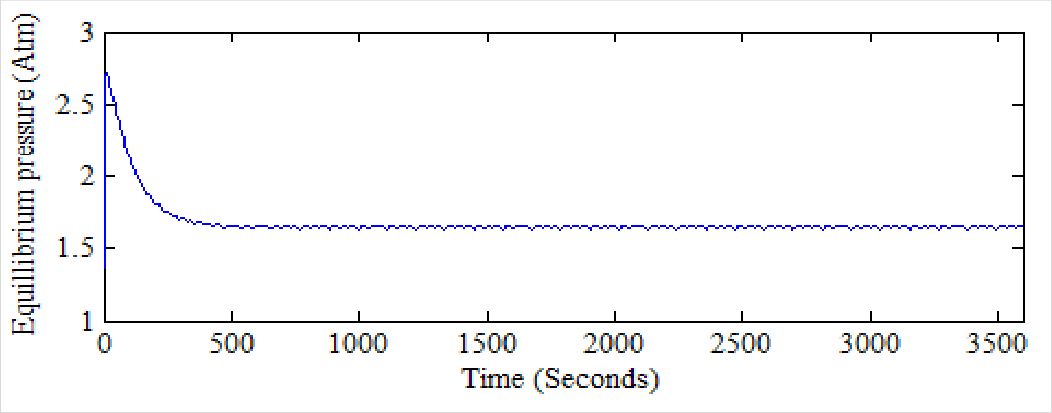

Figure 20 Equilibrium pressure during absorption process

4.9 Model for consumption of stored hydrogen

The metal hydride tank is interconnected with the fuel cell to utilize the stored hydrogen and the Simulink diagram is shown in *Figure 21*.

During the desorption process, the pressure difference among interior and exit of the tank acts as driving force to release hydrogen from the tank. The rate of hydrogen flow [32] is expressed as in Equation 38 and 39.

$$H_{2out} = \frac{P}{V_g\sqrt{RT}} A\sqrt{\gamma} M_e \left(1+(\gamma-1)M_e^2/2\right)^{(\gamma+1)(2-2\gamma)} \quad (38)$$

$$M_e^2 = min\left\{1, \left(2/(\gamma-1)\right)\left[\left(\frac{P}{P_e}\right)^{(\gamma-1)/\gamma} - 1\right]\right\} \quad (39)$$

where, P and T are inside pressure and temperature of the tank respectively. P_e is the exit tank pressure and M_e is Mach number at the tank exit. For an initial pressure of 6 atm and an operating temperature of 100°C, the resulting hydrogen discharge flow rate from metal hydride storage tank is shown in *Figure 22*. Based on the hydrogen flow rate, the output of fuel cell is shown in *Figure 23* for an operating temperature of 80°C.

The capacity of metal hydride storage tank is calculated for storing the hydrogen gas produced from electrolyzer. For a minute, the hydrogen production from 32 cell electrolyzer is 10 liters, therefore during day time is approximately 7200 liters i.e., 510*kg* of hydrogen gas. From this it is found that 4 numbers of metal hydride storage tanks with a capacity of 2000 liters are required.

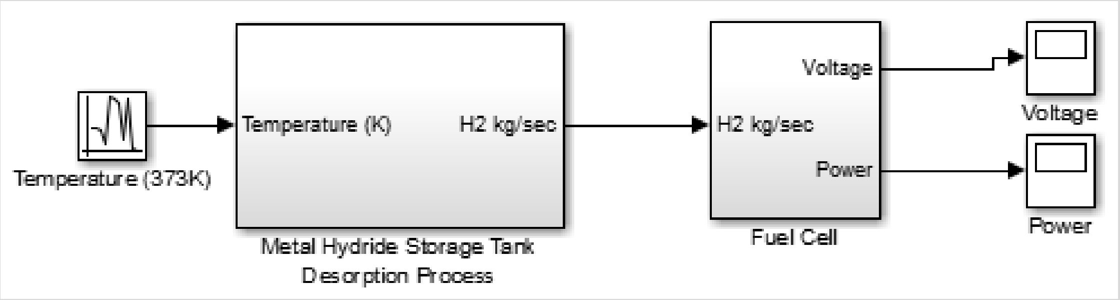

Figure 21 Simulink model for consumption of stored hydrogen from metal hydride storage tank to fuel cell

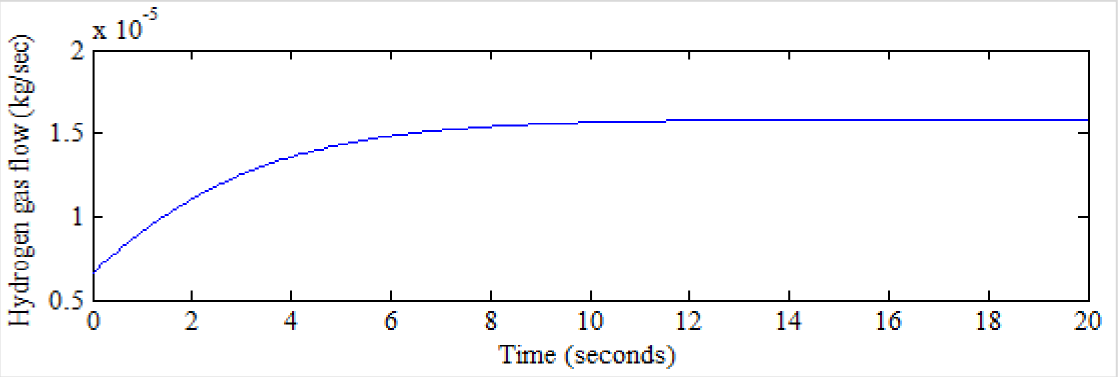

Figure 22 Hydrogen flow rate from storage tank during desorption process

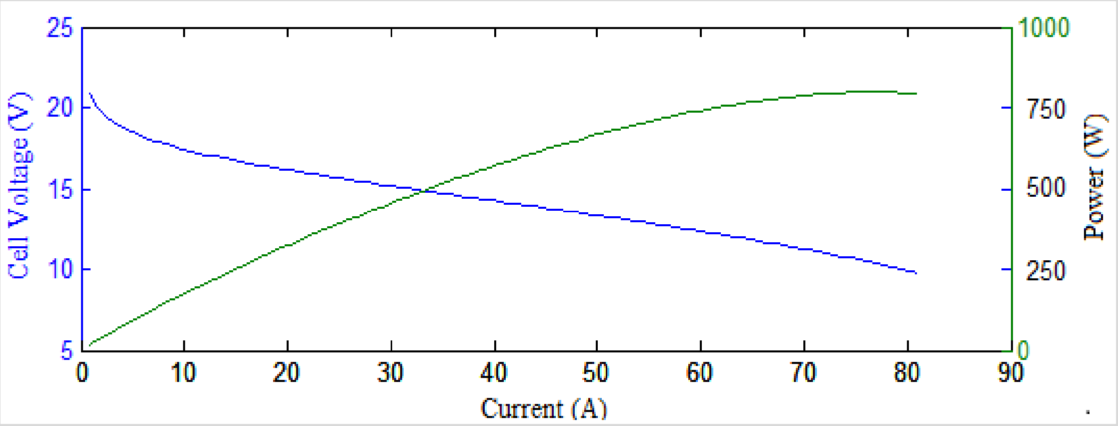

Figure 23 Output voltage and power of fuel cell

5. Discussion

Based on the mathematical models of PEM electrolyzer, metal hydride storage tank and PEM fuel cell, a standalone solar PV based hydrogen storage system is designed for residential applications, considering the average annual solar irradiance in Madurai city located in southern part of India. The day time energy requirement for residential application is taken as 5.57kWh and the night time energy requirement is taken as 6.88 kWh. Based on the average solar irradiance level, the total energy produced by 1.5kW solar PV system is obtained as 8.07kWh/day. After utilizing it for day time, the remaining unused energy is 2.5kWh. Considering the maximum load demand as 677W during night time, the required sizing of fuel cell is identified as 20 cells of fuel cell stack. For the 20 cells of fuel cell stack, the required hydrogen is 10L/min. To meet out the hydrogen requirement of fuel cell, the number of cells needed in the PEM electrolyzer is found as 32 with a rated capacity of single cell as 90W. The energy required by electrolyzer to produce the required amount of hydrogen gas is identified as 2.5kWh. Thus, the overall rating of rooftop solar power plant needed is 1.5kW. The generated hydrogen gas is stored in the metal hydride storage tank and the required capacity is identified as 7200L/day and therefore, 4 numbers of 2000L capacities of tank are required. This detailed design of standalone solar PV panel-based hydrogen energy storage system will be beneficial for practical implementation of the system.

The proposed standalone solar PV based hydrogen energy storage system with fuel cell eliminates the drawbacks of batteries such as short-term energy storage, uncertain lifetime, quick degradation, sensitivity to environmental conditions and limited storage capacity. The usage of metal hydride as storage medium is safer, portable and has long term storage capacity. Furthermore, the by-products, water and oxygen produced from fuel cell and electrolyzer can be recycled. The main limitation of this system is the huge cost involved as it is a barrier to the extensive use of hydrogen even though it is more efficient. The cost for a unit of power from hydrogen fuel cells is greater than other energy sources. This situation may change in the future as technology advances and if government subsidies are provided for implementing such systems.

A complete list of abbreviations is shown in *Appendix I.*

6. Conclusions and future work

In this paper, the mathematical models of PEM electrolyzer, metal hydride storage tank and fuel cell are developed and are simulated for different operating conditions using matrix laboratory (MATLAB) Simulink toolbox. A standalone solar PV based hydrogen storage system with fuel cell is designed for residential applications, considering the average annual solar irradiance in Madurai city located in southern part of India. For meeting the given load consumption pattern, the number of cells needed in the PEM electrolyzer is 32 and for PEM fuel cell, it is found to be 20. The capacity of Metal hydride storage tank is obtained as 7200 L and 1.5kW of rooftop solar power plant is needed. In addition, the interconnection of various models helps to obtain a solution for control and automation of hydrogen energy storage plant. By using standalone solar PV based hydrogen storage system with fuel cell, the problem of intermittent availability of renewable energy sources is overcome and can also be used for a long term. The periodic maintenance and replacement of batteries are resolved. In future, automatic energy management system can be designed for better utilization of solar energy. Thus, the hydrogen storage system with metal hydride forms a safe and an efficient energy storage system.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

R. Aruna: Conceptualization, data collection, analysis and interpretation of results, writing – original draft, writing – review and editing. **S. T. Jaya Christa:** Conceptualization, interpretation of results, writing – original draft, writing – review and editing. **Praveen Paul Jeyapaul:** Conceptualization, design, supervision, investigation on challenges and draft manuscript preparation.

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Appendix I

S. No.	Abbreviation	Description
1	AI	Artificial Intelligence
2	MATLAB	Matrix Laboratory
3	PV	Photo Voltaic
4	PEM	Polymer Electrode Membrane
5	PID	Proportional, Integral and Derivative
6	SC	Stoichiometric Coefficient