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Design and Comparison of Hydrogen Fuel Cell and Solar Photovoltaic powered Base Transceiver Stations and ATMs

Vishal K. Mittal, Shivam Saxena, Shivani Abrol and Shweta Soam

Abstract – Energy being the very crucial issue in today's world is transforming its shape from the non-renewable sources to various renewable sources because of the two major repercussions using non-renewable sources – one is the deterioration of the environment due to combustion of the fossil fuels causing threats not only to abiotic components but to biotic components also of the ecosystem and the second is that these non-renewable resources are going to be consumed up soon. So, it demands to look for the clean and perennial energy source. There are many renewable sources such as solar, wind, tidal, wave etc., this paper discusses the application of hydrogen fuel cell and solar photovoltaic (PV) in powering the base transceiver stations (BTS) and ATMs. The paper presents the design analysis of the fuel cell and solar PV system in powering BTS and ATM. Finally the paper compares these two renewable methods of power generation in terms of cost, reliability and effectiveness.

Index terms – Automated Teller Machine (ATM), Base Transceiver Station (BTS), On-field generation, Polymer Electrolyte Membrane Fuel Cell (PEMFC), Solar photovoltaic (PV).

Nomenclature

T	Temperature (K)
R	Universal Gas constant (8.314 J/mol K)
P	Pressure of hydrogen gas (bar)
d_P	Density of hydrogen gas at pressure P (g/L)
n	No. of moles of hydrogen gas
M	Molar mass of hydrogen gas (g)
υ	Volume of hydrogen gas (m^3)
Γ_P	Volume Flow rate of hydrogen gas at pressure P (L/min)
q	Mass flow rate of hydrogen gas (g/h)
Q	Total consumption of hydrogen gas in a day (g)
m	Mass of hydrogen gas contained in a 7Nm^3 hydrogen cylinder (g)
ε	Electrical energy supplied by a 7Nm^3 hydrogen cylinder (kWh)
N_F	Number of fuel cells in a stack
t_H^x	Time for which 7Nm^3 hydrogen cylinder will power load x (h)
P_L^x	Load of x i.e. either BTS or ATM (kW)
E^x	Electrical Energy consumed by BTS or ATM in one day (kWh)
V	Operating voltage of PEMFC stack or battery
$\hbar$	Cost of one 7Nm^3 hydrogen gas cylinder (Rs)
$\Re$	Running cost of power generated by PEMFC (Rs/kWh)
N_B	Number of batteries required in the battery bank
c	Capacity of a battery (Ah)
C	Total capacity of battery bank (Ah)
DoD	Depth of discharge of battery (%)
t_b	Time the battery bank should give backup (h)
E_b	Backup energy provided by the battery (kWh)
t_c	Charging time of the battery bank using solar power (h)
S	Size of the extra solar panel required to charge the battery bank (kW)

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1. Introduction

ENERGY generation in today's electricity hungry world is a major issue to look upon as nearly 68.23% electricity is still generated from fossil fuels [1]. Fig.1 shows the percentage participation of various sources in generation of electric power in the world [1]. As the electric power demand is increasing very rapidly in this electric power conscious world, hence the more electric power is required to be generated. For this, in case of fossil fuels operated plants, the fuel intake will increase and hence the pollutants emission. Also it has been estimated as per the current consumption of fossil fuels that coal, natural gas and oil will last for 114, 52.8 and 50.7 years respectively [2]. Hence, it is required to go for a clean and perennial source of energy. Hydrogen energy and fuel cells are very prominent solutions regarding the above invoked issue. Hydrogen fuel cell has the efficiency between 40 – 60% which can be increased upto 85 – 90% utilizing the heat generated in fuel cell using combined heat and power systems which is the highest among other renewable sources [3]. The fuel cells can be categorized on the basis of their operating temperature, namely low temperature fuel cells which operate within 60^0C – 250^0C and high temperature fuel cells operating in the range 600^0C – 1000^0C. Proton exchange membrane fuel cell, alkaline fuel cell and phosphoric acid fuel cell are the examples of low temperature fuel cells where as molten carbonate and solid oxide fuel cells are high temperature fuel cells. The fuel cells can also be classified on the basis of the electrolyte being used, such as polymer electrolyte membrane fuel cell (PEMFC) in which electrolyte is a polymer, alkaline fuel cell in which electrolyte is an alkaline solution such as ethanol, phosphoric acid fuel cell in which electrolyte is phosphoric acid etc.

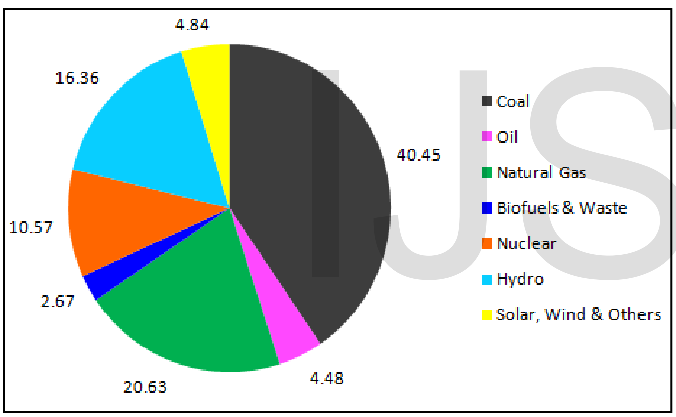

Fig.1: Percentage electric power generation capacity using different sources in the world.

Guaitolini *et al.* reviewed the current technologies of fuel cells and emphasized on the utilizing them along with combined cycles of heat and power [3]. Munch *et al.* presented solid oxide fuel cell generators to use to generate power and supplying heat for off-grid applications.[4]. Roy *et al.* presented an approach to mitigate the challenges face during the grid independent operation of fuel cell along with the study of hybrid system involving fuel cell and wind energy [5]. Kaya *et al.* presented a method of hydrogen production from the biomass. Conversion of methane to hydrogen was investigated at different methane to carbon dioxide ratios and temperatures. It was shown that hydrogen yields were increased by increasing temperature and decreasing CO_2 contents [6]. Zaika *et al.* discussed a new biogas reforming catalytic-processing system for the conversion of gaseous hydrocarbons gases to hydrogen to use in fuel cells [7]. Wibowo *et al.* proposed the use of integrated photovoltaic system to power BTSs in the remote areas [8].

This paper discusses the application of fuel cells and solar PV on-field energy generation systems in powering the BTSs and ATMs. BTSs are generally remotely situated, thus it is advantageous to use on-field generation. On-field supply has advantage over grid supply in terms of transmission losses which is absent in former. As power generation is equal to the load demand plus transmission losses, hence the power generation has to be more if power is supplied through grid than on-field power generation. In this paper the design analysis of fuel cell and solar PV systems to power BTSs and ATMs is presented along with the comparison of the two proposed power generation methods in terms of cost, reliability and effectiveness. The study has been done with PEMFC of Horizon Fuel Cell Technologies [9] and readily available solar PV panels.

The organization of the paper is as follows: Section I gives Introduction. Problem has been formulated in Section II. Section III provides the methodology of the proposed work. Results are presented in Section IV. Finally, the conclusion has been made in Section V.

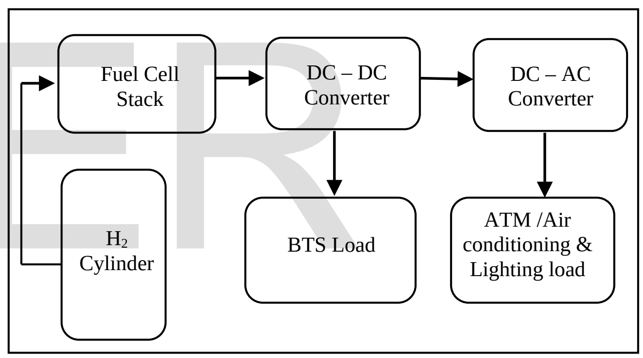

Fig.2: Fuel cell power supply system for BTS or ATM showing various loads and converters.

2. PROBLEM FORMULATION

2.1 Fuel Cell powered BTSs and ATMs

The chemical energy contained in the hydrogen is harnessed to generate the electrical energy. Thus, it is required to develop the energy conversion criterion based on the quantity of hydrogen required to participate in the chemical reaction. Since, the gases behave differently than the solids and liquids because the gaseous atoms are well separated than liquids and solids, thus temperature and pressure affects the volume of gases largely, which can be related by gas equation. The general gas equation is given by (1) which can be written as (2). The gas has different density at different pressures and is related as shown in (3). Since, the pressure of hydrogen gas (H_2) in the cylinder is different to the pressure required at the inlet valve of the fuel cell and hence the volume flow rate of H_2 from the cylinder and inlet to the fuel cell will be different.

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$$P\upsilon = nRT \quad (1)$$

$$P\upsilon = \frac{m}{M}RT \quad (2)$$

The density of H_2 is calculated in (3) and mass flow rate is given by (4). Since, the mass is always is conserved in a chemical reaction and also on the basis law of conservation of energy, the volume flow rate at different pressure *P2* can be calculated using (5) if volume flow rate at *P1* is known along with the knowledge of densities *d2* and *d1* at *P2* and *P1* respectively.

$$d_P = \frac{m}{\upsilon} = \frac{PM}{RT} \quad (3)$$

$$q = d_P \times \Gamma_P \quad (4)$$

$$\Gamma_{P2} = \frac{d_{P1}}{d_{P2}} \times \Gamma_{P1} \quad (5)$$

If q is the required mass flow rate of H_2 to the fuel cell to supply 1kW load continuously for one hour, then the total energy supplied to the load if m amount of H_2 is available is given by (6).

$$\varepsilon = \frac{m}{q} \quad (6)$$

If E^x is the total energy consumed by the load P_L^x during the whole day, then the amount of H_2 required to produce that much amount of energy is given by (7).

$$Q = q \times \mathrm{E}^x \quad (7)$$

1Nm^3 H_2 at 200 bar pressure weighs 89.88g. Thus, 7Nm^3 H_2 cylinder contains H_2 of mass m equal to 629.16g. Time for which the one cylinder will supply energy to load P_L^x is given by (8).

$$t_H^x = \frac{\varepsilon}{\mathrm{P}_L^x} \quad (8)$$

One direct H_2 PEMFC provides potential of 0.7 volts DC. Thus for an operating voltage of V, the number of fuel cells required in a stack is calculated in (9). The running cost of power generated from the PEMFC is given using (10).

$$N_F = \frac{\mathrm{V}}{0.7} \quad (9)$$

Rounded off to nearest integer.

$$\Re = \frac{\hbar}{\varepsilon} \quad (10)$$

2.2 Solar PV powered BTSs and ATMs

On the on-field generation of the solar energy it is required to use the battery bank to supply the continuous power when there is no generation in the absence of sunlight. As BTSs and ATMs are very crucial elements which cannot be shut down, so battery bank is one of the necessary components of the solar PV system. The energy that must be provided by the battery bank is given by (11).

$$E_b = \mathrm{P}_L^x \times t_b \quad (11)$$

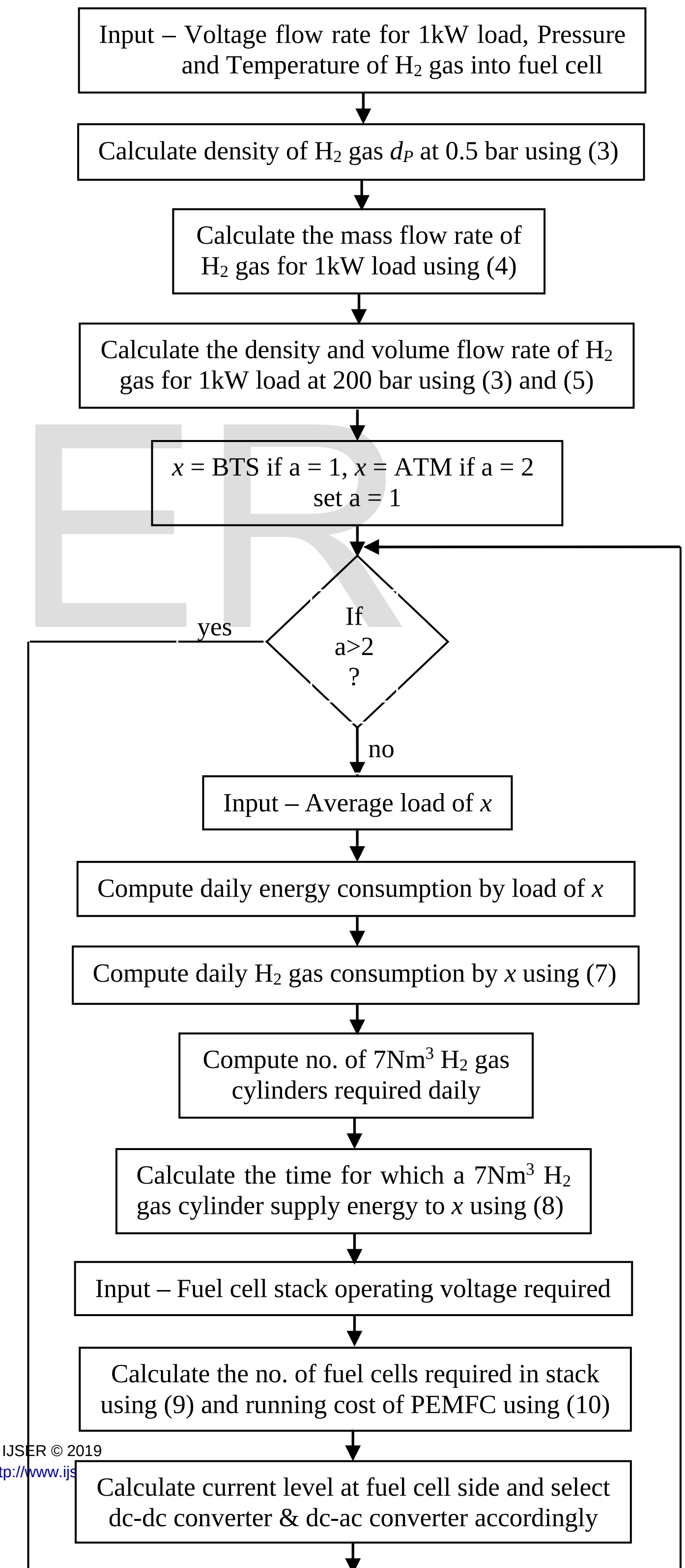

Fig.3: Flow chart for the design of fuel cell system for BTS and ATM.

Thus, the total capacity of the battery bank required is given by (12) and the number of batteries required in parallel to supply the backup power is given by (13).

$$C = \frac{E_b}{\mathrm{DoD} \times \mathrm{V}} \quad (12)$$

$$N_b = \frac{C}{c} \quad (13)$$

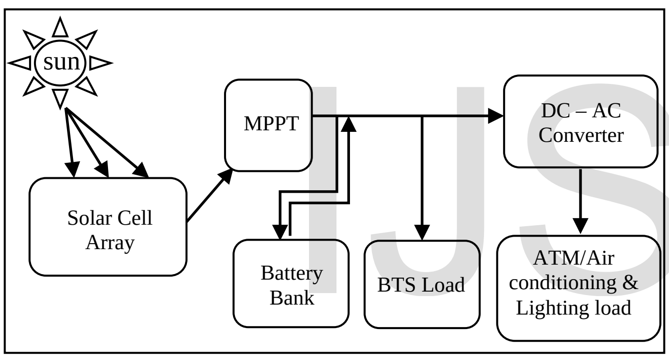

Fig.4: Solar PV system for BTS or ATM showing various loads and converters.

If t_c is the required charging time of the battery bank, then the size of the solar panel required is given by (14).

$$S = \frac{1}{\mathrm{t_c}} \times \mathrm{V} \times C \times \mathrm{DoD} \quad (14)$$

3. Methodology

Fig.2 presents the fuel cell powered system for BTS or ATM along with the various components required for the implementation. Since signal processing in the BTS required DC supply, thus it is fed with the DC through DC – DC converter. The other auxiliary loads which are shown require AC supply which can be obtained using DC – AC converter. The flow chart of the algorithm used to carry out the design analysis of the fuel cell power supply system is being presented in Fig.3.

TABLE 1
Hydrogen Gas Inflow Specifications at Fuel Cell

Pressure, *P*	Temperature, *T*	Γ_p for 1kW load
0.5 bar	298.15 K	15 L/min

Fig.4 presents the block diagram of the solar PV system for BTS and ATM. The various components needed for the implementation of the system are also presented. The flow chart for the system design utilizing solar energy to power BTS and ATM is being shown in Fig.5.

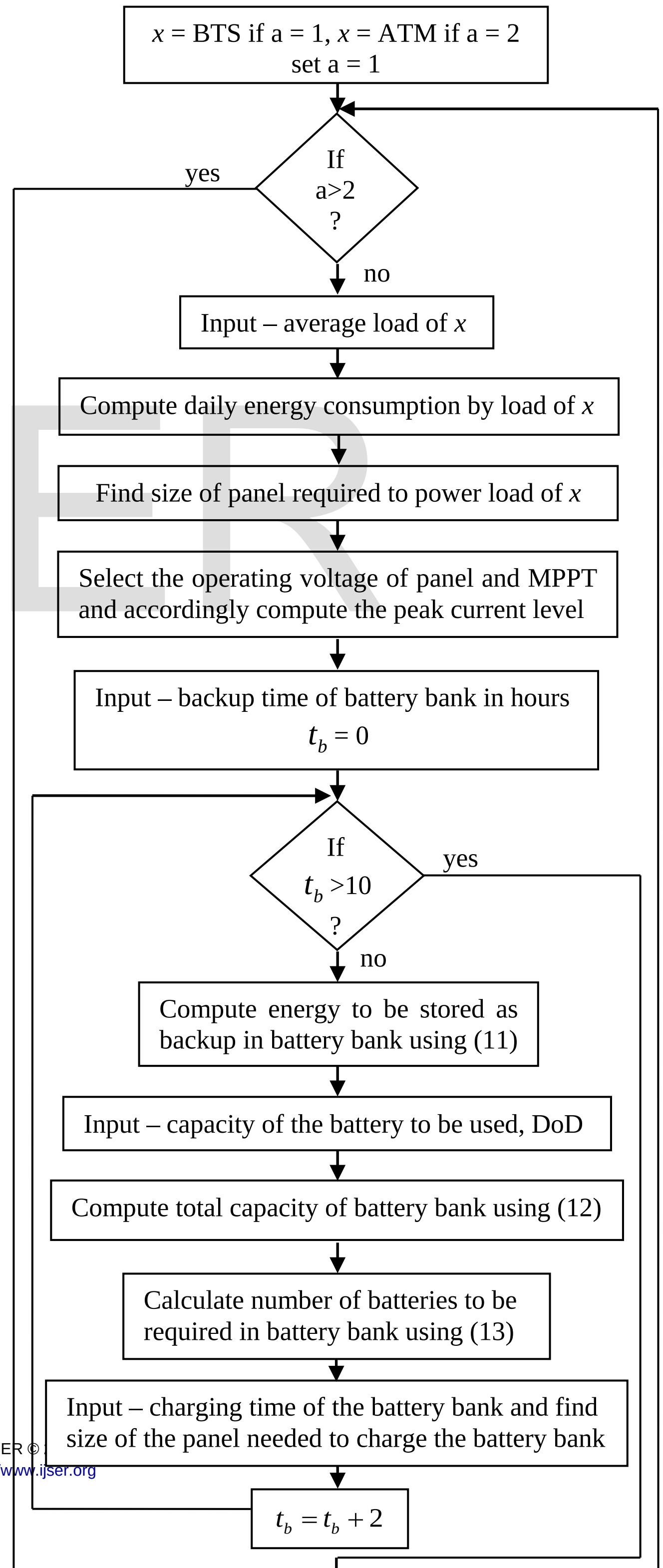

Fig.5: Flow chart for the design of solar PV system for BTS and ATM.

4. Result and Discussion

Table 1 presents the data specifications of H_2 which is required by the fuel cell to generate electricity to power 1kW load. The pressure of H_2 gas at the inlet to PEMFC is 0.5 bars which is different from the pressure of H_2 gas stored in the cylinder which is 200 bars. So, Table 2 presents the required mass and volume flow rates of H_2 gas which is obtained from the cylinder. Here, 7Nm^3 H_2 gas cylinder is used for the present analysis.

TABLE 2
Hydrogen Gas Specifications at Different Pressures

Pressure, *P* (bar)	**Mass flow rate, *q* (g/h)**	**Density, d_P (g/L)**	**Flow rate for 1kW load Γ_P (L/min)**
0.5	36.3070761115	0.04034179017	15
200	36.3070761115	16.136716067	0.0375

TABLE 3
Fuel Cell System Design Analysis to Power BTS

Parameter	**Value**
Rated operating voltage of stack, V	50V DC
Number of Fuel Cells in a stack required	72
Load	1.5 kW
Average Auxiliary load (Air conditioning and lighting)	1 kW
Total load, P_L^x	2.5 kW
Peak Current through fuel cell	60 A
Total energy consumed during one day, E^x	60 kWh
Total amount of H_2 required for one day, Q	2178.425 g
Amount of energy contained in one 7Nm^3 H_2 cylinder pressurized at 200 bar, $\mathcal{E}$	17.3286 kWh
Time duration for which the energy is supplied by one 7Nm^3 H_2 cylinder, t_H^x	6.9314 h
Number of 7Nm^3 H_2 cylinders consumed in a day	3.463
DC/DC Converter	48-52V/80A
DC/AC Converter	50V DC – 220V AC/ 1.5kW

Table 3 and 4 present the specifications of the fuel cell and solar PV system respectively required to power the BTS. Similarly, Table 5 and 6 present the specifications of the fuel cell and solar PV system respectively required to power the ATM. For the case of ATM, it is considered that the transaction time is around 10 seconds and the average number of transactions per day is 25.

As the sunlight is discontinuous in nature, thus it can be seen here that the battery bank is utmost important to implement the solar powered BTS or ATM. Table 7 and 8 present the capacity of the battery bank required for the mentioned backup times along with the number of batteries to be used. The size of the solar panel required to charge the battery bank is being determined for various battery banks size considering the charging time of 8h. The charging time value is being taken as the average time for which the sunlight is well available on a sunny day and the total size of the required solar panel for the whole system has been determined in terms of the readily available solar panel units – 350W, 500W and 1kW.

TABLE 4
Solar PV System Design Analysis to Power BTS

Parameter	**Value**
Rated operating voltage of MPPT, V	48V DC
Load	1.5 kW
Average Auxiliary load (Air conditioning and lighting)	1 kW
Total load, P_L^x	2.5 kW
Total energy consumed during one day, E^x	60 kWh
Size of solar panel required	3x1kW
Backup time, t_b	4 h
DoD of battery	50%
Battery bank capacity required	416.667 Ah
No. of batteries required†	3
Charging time of battery bank	8 h
Size of solar panel required to charge battery bank	1x1kW+1x350W
Peak current level through MPPT	90A
DC/AC Converter	48V DC – 220V AC/ 1.5kW

† Battery is considered of voltage 48V and capacity 150Ah.

TABLE 5
Fuel Cell System Design Analysis to Power ATM

Parameter	**Value**
Rated operating voltage of stack, V	50V DC
Number of Fuel Cells in a stack required	72
Load during no transaction	260 W
Load during transaction	410 W
Average Auxiliary load (Air conditioning and lighting)	1 kW
Total load, P_L^x during no transaction	1.26 kW
Total load, P_L^x during transaction	1.41 kW
Peak Current through fuel cell	38 A
Total energy consumed during one day, E^x	30.25 kWh

Total amount of H_2 required for one day, Q	1098.305 g
Amount of energy contained in one $7Nm^3$ H_2 cylinder pressurized at 200 bar, ε	17.3286 kWh
Time duration for which the energy is supplied by one $7Nm^3$ H_2 cylinder, t^x	13.7483 h
Number of $7Nm^3$ H_2 cylinders consumed in a day	1.746
DC/DC Converter	48-52V/80A
DC/AC Converter	50V DC – 220V AC/ 1.5kW

With this battery bank, the space requirement for the system will also increase Also the availability of sunlight is totally probabilistic in nature, so we cannot totally rely on the solar power. So it is mandate to have an option for the grid power in case of solar powered system. With this the advantage of curtailment of transmission losses by using on-field power generation will be lost. These ailments of the system can be overcome by using fuel cell powered system as this system does not require battery bank. Since, H_2 gas supply is continuous, thus no extra space is needed. Also, the power generation by harnessing the chemical energy of H_2 is weather independent, thus fuel cell system provides energy to the load whole day. Hence, the fuel cell system has greater reliability and effectiveness than solar PV system.

TABLE 6
Solar PV System Design Analysis to Power ATM

Parameter	**Value**
Rated operating voltage of MPPT, V	48V DC
Load during no transaction	260 W
Load during transaction	410 W
Average Auxiliary load (Air conditioning and lighting)	1 kW
Total load, P_L^x during no transaction	1.26 kW
Total load, P_L^x during transaction	1.41 kW
Total energy consumed during one day, E^x	30.25 kWh
Size of solar panel required	1x1kW+1x500W
Backup time, t_b	4 h
DoD of battery	50%
Battery bank capacity required	210.07 Ah
No. of batteries required†	2
Charging time of battery bank	8 h
Size of solar panel required to charge battery bank	1x500W+1x350W
Peak current level through MPPT	50A
DC/AC Converter	48V DC – 220V AC/ 1.5kW

TABLE 7
Size of Battery Bank and Solar Panel Requred by BTS for Different Backup Times

Backup time (h)	**Battery bank capacity* (Ah)**	**No. of batteries required†**	**Size of solar panel required**
2	208.33	2	3x350W
4	416.67	3	1x1kW + 1x350W
6	625	4	1x500W + 4x350W
8	833.33	6	2x1kW + 2x350W
10	1041.67	7	2x1kW + 1x500W + 2x350W

* Depth of Discharge of battery is taken to be 50%, † battery is considered to be of 48V and 150Ah capacity.

The size of the required solar panel for BTS and ATM having backup energy varying from 0h – 10h is being presented in Fig.6. Fig.7 shows the capital costs of the fuel cell and PV system for BTS. The capital cost of PV system having different backup time is shown here. It can be inferred that as the backup time increases the capital cost of solar PV system increases.

TABLE 8
Size of Battery Bank and Solar Panel Requred by ATM for Different Backup Times

Backup time (h)	**Battery bank capacity* (Ah)**	**No. of batteries required†**	**Size of solar panel required**
2	105.03	1	1x500W
4	210.07	2	1x500W + 1x350W
6	315.11	2	1x500W + 1x350W
8	420.14	3	1x1kW + 1x350W
10	525.18	4	5x350W

* Depth of Discharge of battery is taken to be 50%, † battery is considered to be of 48V and 150Ah capacity.

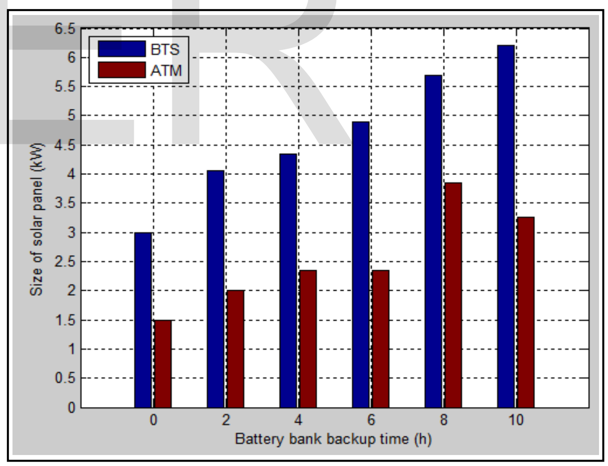

Fig.6: Variation in the size of the required solar panel for BTS and ATM loads with the variation in battery bank backup time.

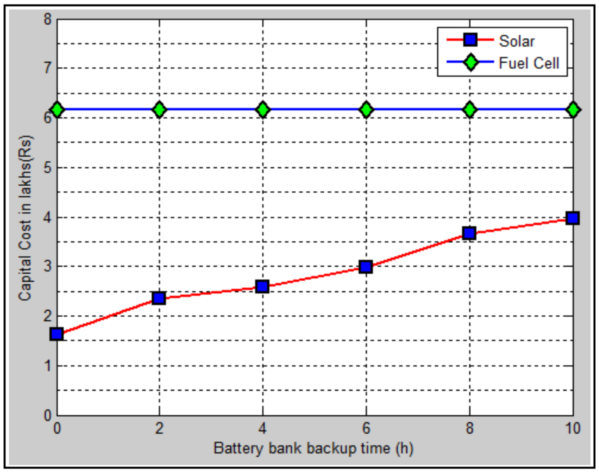

Fig.7: Comparison of the capital costs of the fuel cell system and solar PV system having different battery bank backup time for BTS.

Similarly, Fig.8 shows the capital cost of the two proposed systems for ATM. Although Fig.7 and Fig.8 show that the capital cost of fuel cell system is higher than the solar PV system but the power supplied by fuel cell system will be continuous and independent of the weather conditions without requiring the grid connection. Whereas for solar PV system, we are seeing that with increase in backup time, the capital cost is increasing. Thus, if the sun is not available for 2 to 3 days during bad weather conditions, then the backup for these days will add the capital cost of the solar PV system to surpass the capital cost of fuel cell system.

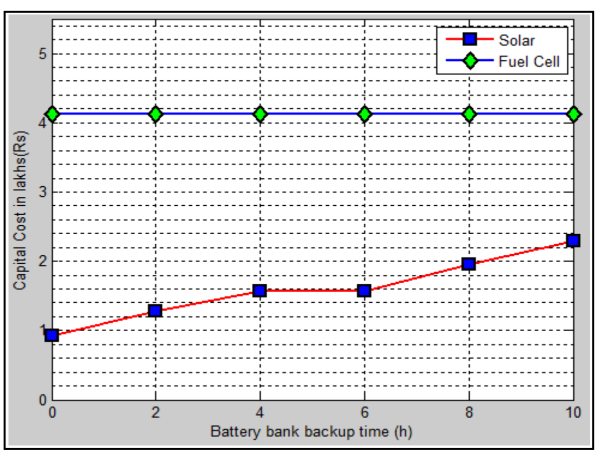

Fig.8: Comparison of the capital costs of the fuel cell system and solar PV system having different battery bank backup time for ATM.

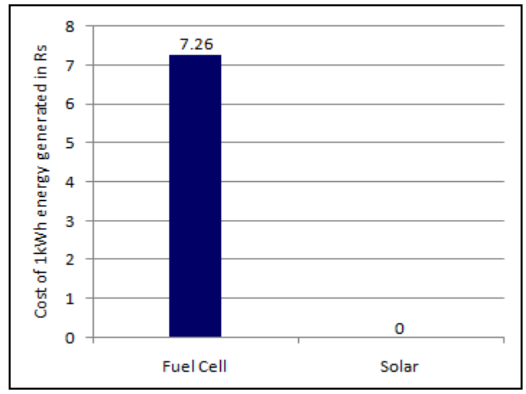

Fig.9: Comparison of the running cost of fuel cell and solar PV systems per kWh.

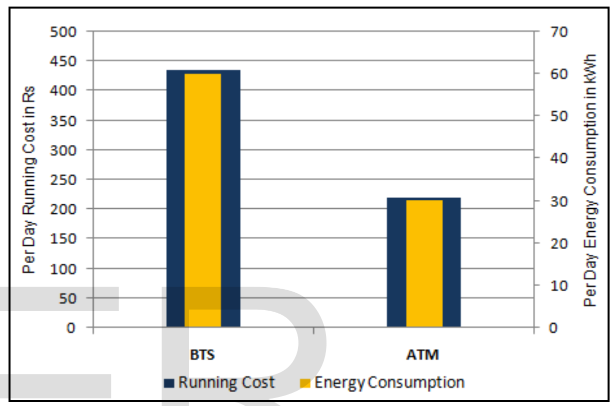

Fig.10: Comparison of per day energy consumption and running cost in BTS and ATM powered by fuel cell.

It can be seen from Fig. 9 that the running cost of solar PV system is negligible. In Fig. 10 the daily demand and the daily running cost of the fuel cell system are shown. The running cost of fuel cell system is dependent on the cost of H_2 gas production and transportation. On-site production of H_2 gas will cut down the transportation charges and the running cost can be decreased.

5. Conclusion and Future Scope

In this paper the two renewable systems of power generation fuel cell and solar PV systems are being compared to power the BTS and ATM. Both the systems discussed in this paper are on-field power generating systems and hence, there will be no transmission energy loss which would have been added in the generating energy if grid supply were used. As the BTS are remotely situated, so the transmission losses are of greater value to look upon. It has been seen that the capital cost and running cost of fuel cell system are higher than the solar PV system but the solar power is discontinuous in nature and highly weather dependent. To provide the sufficient backup, the capital cost of solar power system increases and thus it will be costly to implement the solar power system to power the BTS and ATM in a region which receives lesser solar insolation and experiences bad weather frequently. In such cases the fuel cell system will be very effective. Thus, we can say that the fuel cell system is more reliable and effective than the solar PV system. Further, the running cost of fuel cell can be reduced by generating hydrogen on site. Even the waste material can be used to generate the hydrogen gas which can be a very good solution to garbage problem. Thus, this work can be extended further by including the on-site hydrogen production for the fuel cell.

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