Department of Mechanical and Aerospace Engineering

A sizing tool for domestic scale autonomous PEM fuel cell for electricity production

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Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: *Muhammad Zulfiqar Ali* Date:

I am thankful to almighty Allah, the most gracious and the most merciful, for blessing me more than I wished.

This work is especially dedicated to my loving Parents, brothers and sister for giving me the opportunity to fulfill my dreams and support to achieve my ambitions.

And to my wife Barira and children Liaba and Abdullah who were always there for me, supporting and enduring me.

"It is good to have an end to journey toward; but it is the journey that matters, in the end."

— Ernest Hemingway

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Abstract

Nowadays renewable energy is becoming main source of energy and the challenge is the storage of produced energy. One of the ways of storing this energy is to use this renewable energy to produce hydrogen from water and store it for further usage.

This thesis presents a sizing tool for autonomous working of PEMFC for electricity production. This tool can be used to calculate the size of each component, which is used in this autonomous system. This tool is in the form of a excel sheet.

This tool took into account the practical electrical load and these load values are applied to 5kW polymer electrolyte membrane fuel cell [PEMFC] through a 10kW load bank. The practical values of hydrogen consumption are taken from data files and used as a base to calculate the capacity of each component to facilitate the proper production of electricity from this PEMFC system. This research tool can be used to determine the ideal availability of hydrogen in storage tank, electrolyser capacity, water tank capacity and energy demand for production of that much hydrogen from electrolyser.

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Project objectives

- Development of a practical sizing tool based on experimentation
- Collection of hydrogen consumption data from the fuel cell under observation
- Development of a equation for hydrogen consumption which matches the manufacturer hydrogen consumption.
- Implementation of domestic summer and winter electrical loads for their respective hydrogen consumptions.
- Conversion of machine units into standard hydrogen units.
- Analysis of energy consumption for PEM electrolyser.
- Analysis of electrolyser water requirements.
- Analysis of solar panel area for electrolyser energy requirements.

1. Introduction

Global fossil fuel based power industry is becoming unsustainable for an environmental friendly supply of energy so it is suggested that alternative sources of energy must be developed [1]. Also the present power industry is a mixture of conventional and renewable energy technologies. Renewable energy contribution is increasing day by day in the power system. In a power system supply and demand matching is of most important. As consumer around the globe is increasing and also their energy demands are increasing.

For any power system, matching a demand is most importance but this demand side is not a fixed one. It varies from hour to hour, day to day and seasons to seasons. So whenever a power system is to be designed, it should take into account the variation in demand sides. These load demands depend upon the covered areas of a house, kind of appliances being used, also on the types of energy being used. Presently electricity and gas are two major sources of energy for domestic loads. Some houses have both forms and some are only electricity dependents [23].

To design a proper power system, which fulfils all the demands of the area, it must have sufficient resources to meet that demand. For this purpose sizing tools are required which can give us an idea of required resources well before the start of a project. These sizing tools take into account all the possible needs of any autonomous system. In this project an autonomous system-sizing tool is derived which will give us the requirements of all its components upon which it depends. These tools takes into account the electric load of that area and gives us the system requirements.

In any power system energy transmission is also of most importance. In some cases it is not cost efficient to make a whole transmission networks. At remote areas, it is considered best to establish some autonomous system, which has the capability to meet all the demands of that area. And to start any project of this nature we should have some sizing tools to estimate the cost as well as the size of the system well before in time to avoid any inconvenience at later stages.

2. Literature review

This section gives us the details of the components of the autonomous PEM fuel cell system. This section gives us an overview of the sub-systems, which join together to make it a practical system. It consists of a PEM fuel cell, storage tanks for hydrogen and oxygen, electrolyser, power supply connection in this case only renewable energy are considered and water storage tank. It also briefly explains the processes involved and the available technologies to make such a system a reality.

2.1. System description

System consisting of electrolysers and fuel cells are becoming promising renewable energy storage substitutes for batteries. Figure 1 below, shows a PEM fuel cell, storage tanks for hydrogen and oxygen, electrolyser, power source connection and water storage tank. This system is expected to provide eco-friendly and reliable energy to remote areas where no grid connection is available. This system can also be used as back-up power source for communication and medical appliances.

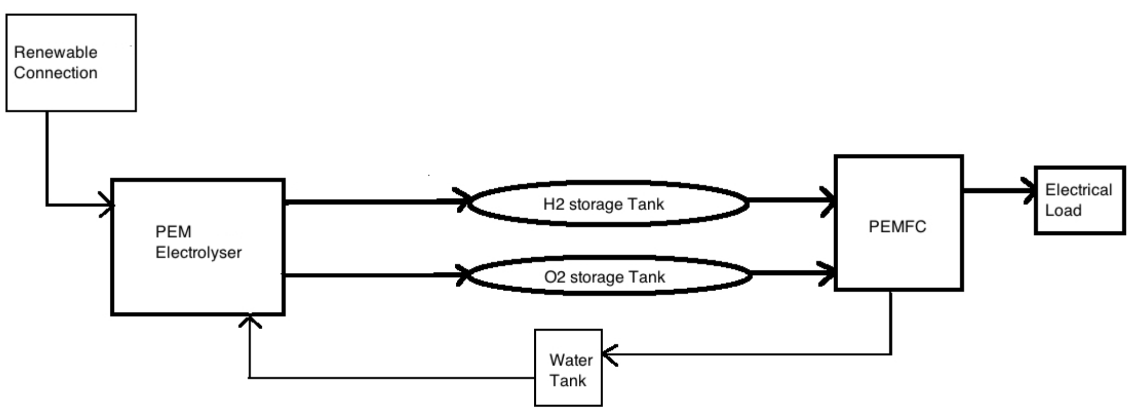


Figure 1. Schematic for autonomous PEMFC

The systems comprising of fuel cells and electrolysers are not a new concept [2]. These systems are similar to large-scale re-chargeable batteries. In this scheme fuel cell acts as energy conversion device and remaining component of this system makes it a true storage device. The renewable connection initially provides power to system for storage and this stored energy can be reused by converting it back to electricity with the help of fuel cell. When the stored hydrogen is exhausted with in the cylinders, this system can generates its own hydrogen by using the renewable energy for future use [3].

2.2. Polymer electrolyte membrane fuel cell

Fuel Cells are energy converter of electro-chemical type in which chemical fuels such as hydrogen and oxygen are directly converted into electrical and heat energy. Fuel cells differ from batteries in a sense that in batteries energy is stored in the form of chemicals while in fuel cells it is converted from reactants and the product is in transient state with in the fuel cell [4]. They can There are various types of fuel cell such as polymer electrolyte membrane fuel cell, direct methanol fuel cell, alkaline fuel cell, phosphoric acid fuel cell, molten carbonate fuel cell, solid oxide fuel cell and regenerative fuel cell. These all use different electrolytes.

Polymer electrolyte membrane fuel cells are used for low power outputs typically between 1kW to 50kW. They are rapidly start-up and have quick response to load change. This fuel cell is also named as proton exchange membrane fuel cells. PEMFC are zero emission high efficiency power generators.

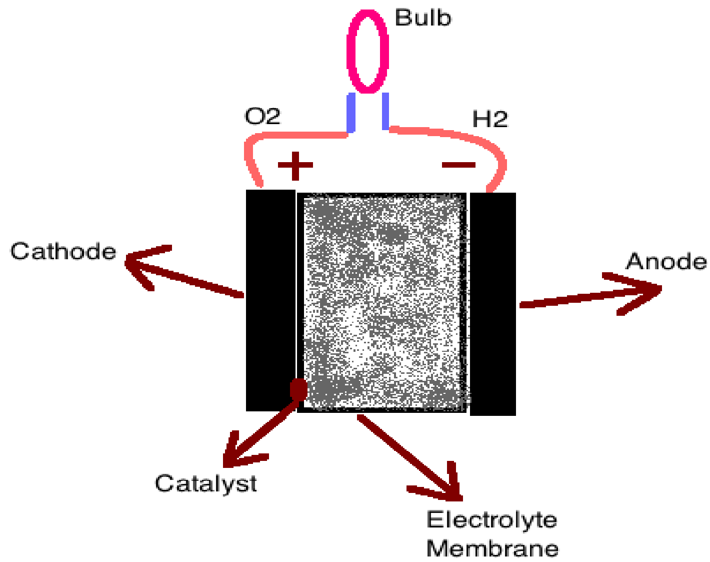


FIGURE 2. Inside view of PEM fuel cell.

PEM fuel consists of four basic elements including the anode, cathode, the electrolyte and the catalyst as shown in figure 2. In this anode is porous and negative through which fuel (hydrogen) enters while the cathode is also porous and positive which distributes the oxygen. The electrolyte is membrane, which is in contact with both the electrodes. An electrolyte or membrane is considered as the most important part of the fuel cell. It is the part where the chemical reaction occurs. And catalyst is a material, which encourages the reaction between hydrogen and oxygen.

At anode, hydrogen diffuses through anode and diffusion layer to the catalyst. This causes the proton and electron to split.

At Anode: $H_2 \rightarrow 2H^+ + 2e^-$

The hydrogen ions produced passes through membrane while electron flows through the outer current circuit.

At cathode, oxygen is forced through the catalyst, where it forms oxygen atoms and each having negative charge. The negative charge attracts the hydrogen positive ions through the membrane where they combine to form a water molecule.

At Cathode: $2H^{+} + \frac{1}{2}O_2 + 2e^{-} \rightarrow H_2O$

This resulting water is extracted from the system.

Overall: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$+ electricity

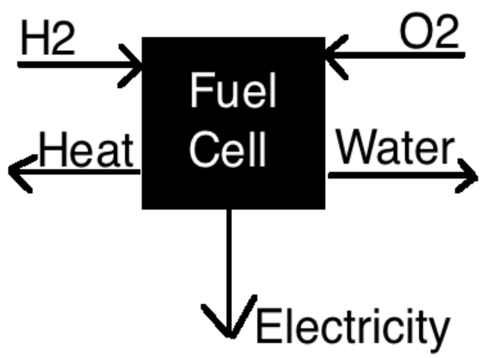


Figure 3. Overall working of PEM fuel cell

Approximately 0.7V is produced by single fuel cell reaction and to increase the voltage fuel cells are stacked and the voltage is simply added [5]. As for this thesis hydrogen consumption is of major concern the standard hydrogen consumption for GenCore 5B48 Fuel Cell System is shown in graph below [9]. In the graph below slm stands for standard litres per minutes. Left side Y- axis shows the standard usage of hydrogen with respect to load and usage time variation. On the X-axis power in kW and on right side Y-axis is the run time. This standard graph of machine shows that its response is a linear with the load. With increasing load its hydrogen consumption also increases linearly.

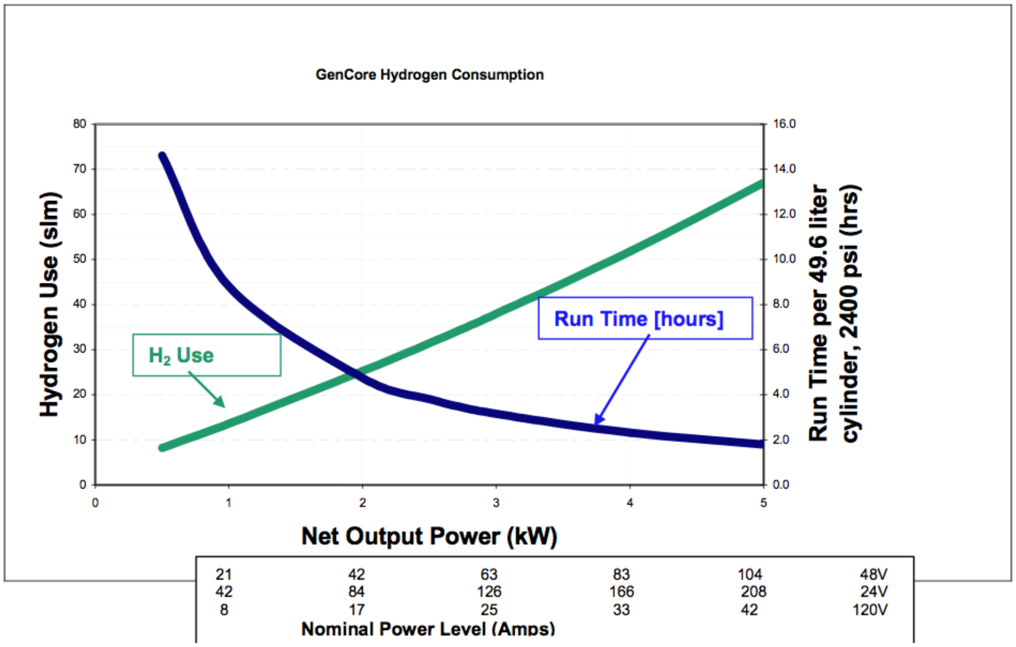


Figure 4. Hydrogen consumption for standard GenCore 5B48 fuel cell

The PEM fuel cell used for this experiment was GenCore 5B48 Fuel Cell System. This fuel cell was connected to a Crestchic 10.75 kW load bank and a computer with liaison software was also attached to the fuel cell. The fuel cell, load bank and the software used are shown the figures below.

Figure 5. Computer system and PEMFC

Figure 6. GenCore 5B48 fuel cell

Figure 7. Hydrogen storage tanks

Above figures shows the PEMFC along with attached computer and the hydrogen storage tanks.

The PEMFC interface software is shown in the figure below. This interface software gives all the information about PEMFC system. It shows the voltage, current and temperature for all the components at any time and shows the proper working of each component.

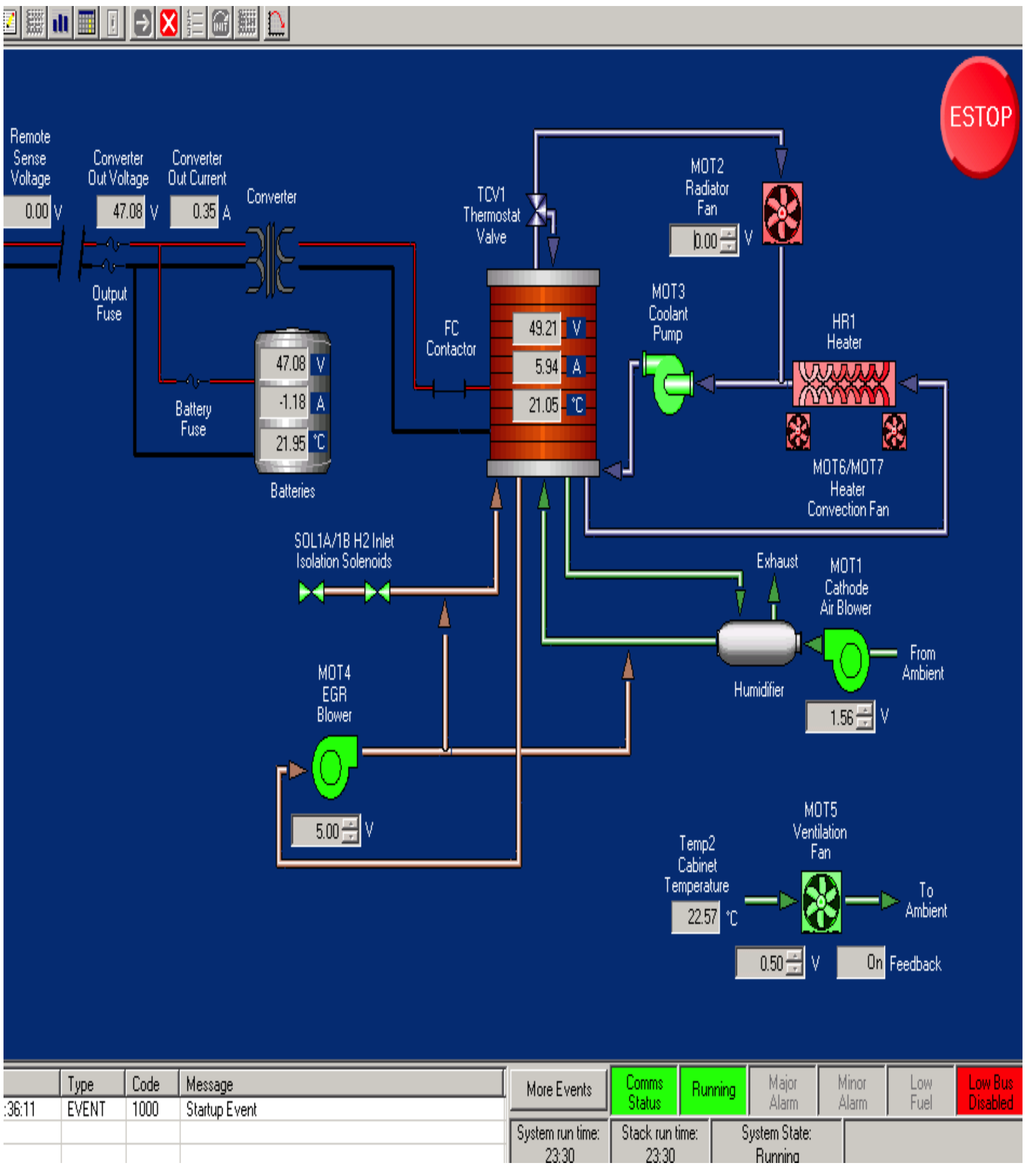


Figure 8. GenCore software interface

Load bank is using corona control system, which is software to provide connection of load bank with the computer and rest of system. It has a high performance microprocessor that helps in getting real time data from the load band. The load bank with its associated software is shown in the figures below.

Figure 9. 10.75 kW load bank

The working specifications for the above said load bank are

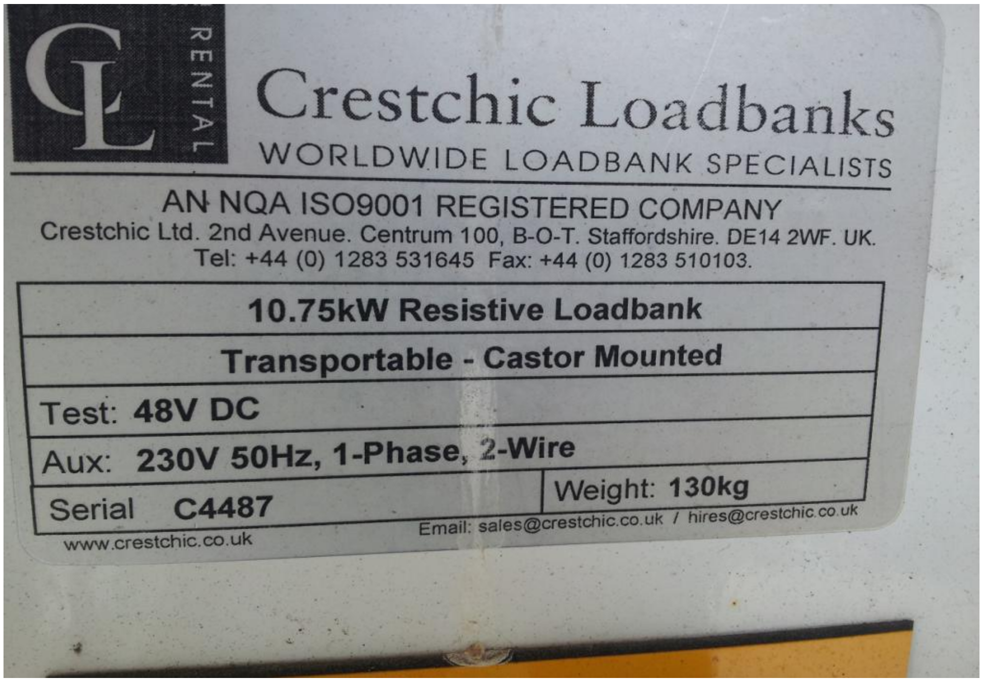


Figure 10. Load bank specifications

The load bank controller gives information on machine running time, about load on machine at that instant of time, voltage, current, power and percentage of full load which is being used at that instant of time. The controller is shown below

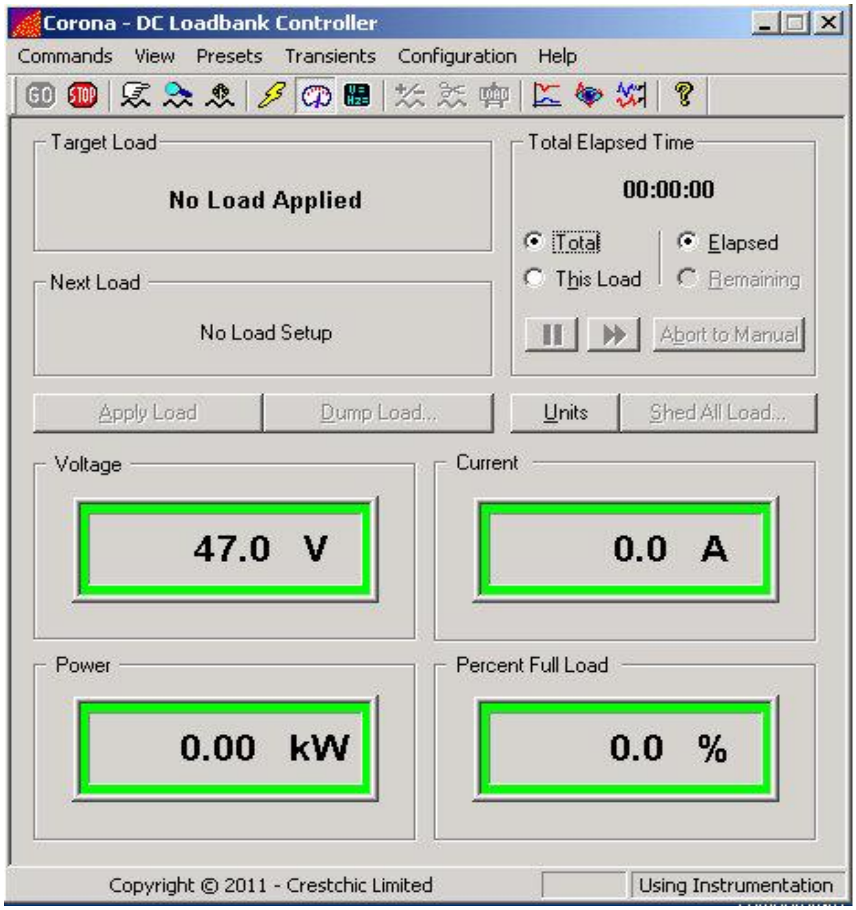


Figure 11. Load bank controller

2.3. Types of hydrogen productions

Hydrogen is one of the occurring elements in the world but it is in the form of chemical compounds. So hydrogen extraction sources are water, natural gas, and coal or plant matter. It cannot be extracted from a well or a mine. As its extraction needs lot of energy so it can be best considered as energy carrier rather than a source of energy. The energy given by hydrogen as a source is just the stored energy during its manufacturing. There are many means of hydrogen production such as [12].

1. Steam Reforming
2. Off-gas clean-up
3. Electrolysis

4. Photo process
5. Thermo chemical process
6. Radiolysis
7. Solar hydrogen
8. Partial oxidation of hydrocarbons

Out of these production means electrolysis and Off-gas clean up are the current and shot terms used technologies. In this project electrolysis is adopted because it is well proven technology and it is best suitable for small scale hydrogen productions.

2.4. Electrolyser

Electrolysers are equipment's used to split water into its constituent elements hydrogen and oxygen and electrolysis is the process of splitting water into its base elements i.e. hydrogen and oxygen. It can be shown with thermodynamic equation as

$$H_2O + \text{electrical energy} \rightarrow H_2 + 1/2\ O_2$$

2.4.1. Types of electrolysers

There are many types of electrolysers depending upon the type of electrolysis being used some of the types are [6]

Alkaline electrolysis

Acidic electrolysis

Low-temperature PEM electrolysis

Thermo-chemical electrolysis

Photochemical electrolysis

Biochemical electrolysis

Out of the above, the mostly used types are alkaline electrolysis and PEM electrolysis. Due to high conductivity alkaline electrolysis is generally preferred. There are also some disadvantages associated with these alkaline electrolysers such as non-uniform charge distribution, handling problem, high-energy consumption due to high cell resistance. But PEM based electrolyser has overcome some of these problems.

2.4.2. PEM electrolysis

Hydrogen can be produced from many methods but the most suitable practical method compatible with renewable energy sources is water electrolysis. One of the methods of electrolysis is PEM electrolysis. It is the process reverse of PEM fuel cell process. In this process, water splits into proton, oxygen and electron by applying a direct voltage. Proton produced passes through the electrolyte membrane and on cathode gives hydrogen by combining with electron [7].

PEM electrolyser is similar in construction to PEM fuel cell. Just like PEMFC it has porous electrodes, polymer membrane, current flow fields, collectors for current and separators in the form of plates. The difference is in principal operation that both are reverse of each other. Another difference is that both electrolyser and fuel cell have different materials i.e fuel cell use carbon material while electrolyser use metallic materials for components. Besides cell stack, electrolyser must have a power supply, water supply, water pump for circulation and gas-water separators [8].

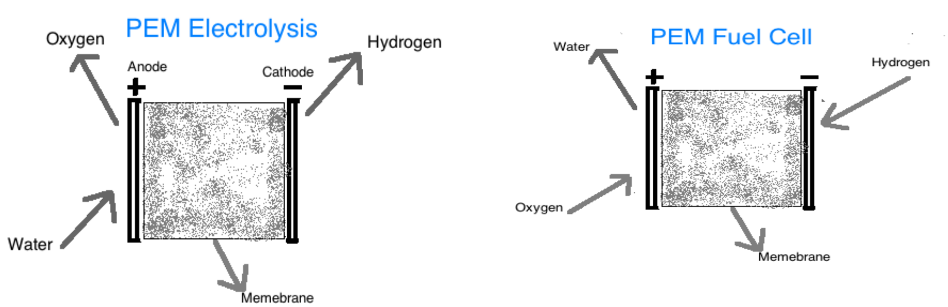


Figure 13. Schematic representation of PEM electrolysis and fuel cell processes

2.5. Hydrogen storage

Hydrogen storage is one of the most important components of autonomous PEMFC system. It's the first element in the periodic table. It's the lightest element and its mass density is 0.08245 kg m^{-3} at atmospheric temperature. It has a very low boiling point that enables it to remain only in gaseous form when temperature and pressure are kept at standard conditions. Another property of hydrogen is that it can be stored as a gas, liquid and in some solid forms [10].

Hydrogen storage in the form of gas and liquid are well-developed technologies. These are stored in cryogenic tanks. There is a need of some parasitic energy for both these forms to get stored in tanks or to be used from the tanks. This technology of cryogenic tank storage requires quarter of stored hydrogen, as a parasitic energy because of this it is quite intensive energy process. Solid-state hydrogen storage technology is becoming a good alternative to the gas and liquid storages because of its improved safety and volumetric energy density [11] [13].

Usually hydrogen is stored in the form of gas at high pressure and cylinders are thick walled and are made of high strength materials. Hydrogen storage vessels can be categorised into four types [12] [14]

1. Cylinder are of metals
2. Load-bearing metal liner, hoop wrapped with resin-impregnated continuous filament
3. Non-load bearing metal liner, axially and hoop wrapped with resin-impregnated continuous filament
4. Non-load bearing non-metal linear, axially and hoop wrapped with resin-impregnated continuous filament.

First three categories are usually made of stainless steels while fourth category is made of advanced composite material and are the most modernised compressed air hydrogen storage. Figure below shows the compressed hydrogen gas cylinder

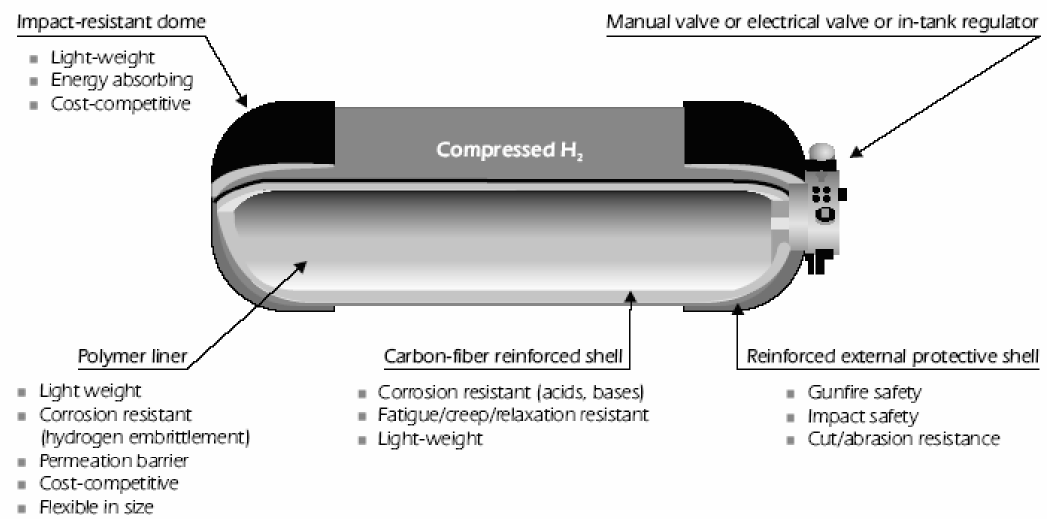


Figure 14. Compressed hydrogen gas cylinder [11].

2.6. Power supply

For supplying power to electrolyser for autonomous PEM fuel cell system renewable energy is the best available option. Among the renewable many options can be implemented but solar and wind energies are of most importance. For Autonomous PEMFC electrical system solar-hydrogen or wind-hydrogen systems are most widely used. These systems are completely independent of grid connections and can support such autonomous PEMFC systems. Also they are environmentally friendly and more reliable than conventional power systems.

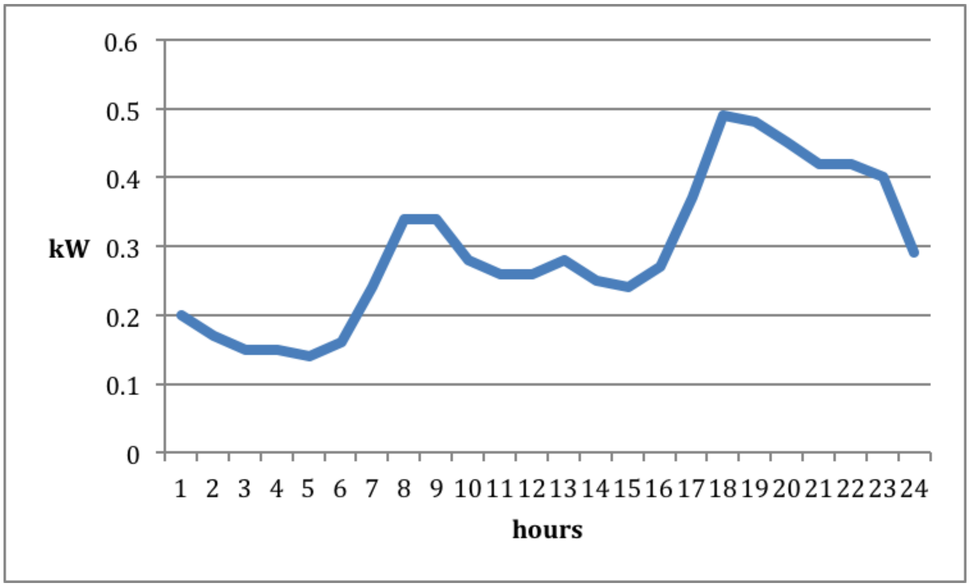
3. Hydrogen consumption consideration

3.1. Load profile

For practical calculations, practical domestic household load demand profile is implemented on the load bank attached to the PEM fuel cell. Sources for electric loads are "Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use" by Yigzaw G et all and documents referenced under numbers [20] [21]. In present days electricity demands remain the same but gas consumptions are decreasing this is either because of improved electronics or improved building structures [23].

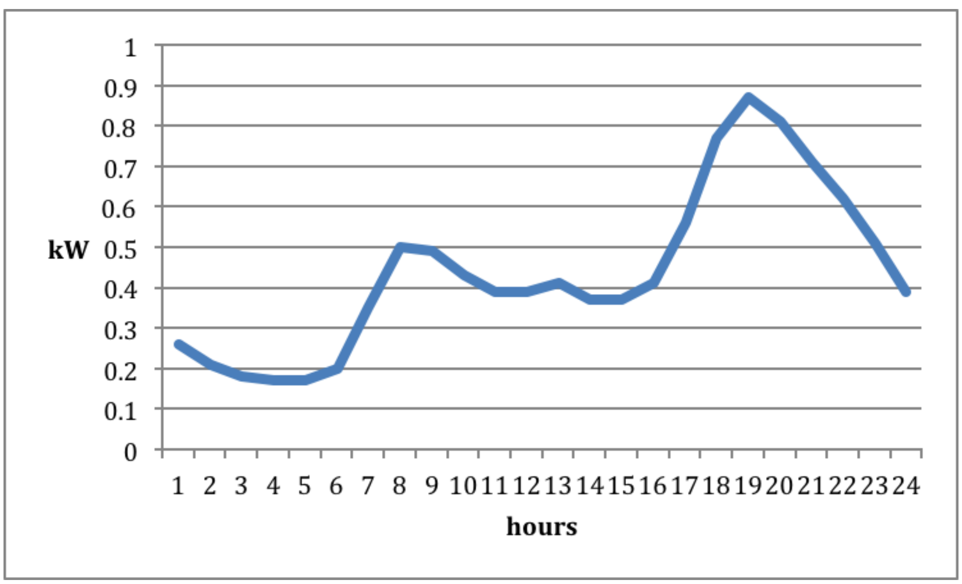
In these it calculated that energy consumptions varies for different types of houses which are divided into detached , semi detached, terraced and bungalows types. The energy consumption varies from 200 kWh to 800kWh per month. For our consideration it is assumed that typical household consumes 3300kWh annually and the profile are selected accordingly depending upon the electricity usage. In this gas consumption is not taken into account.

The load profiles are in averaged half hourly values. The available half hourly values are converted into averaged hourly values to easily implement the values on load bank. The typical daily ordinary house load profile for summer and winter seasons are shown below in the forms of graphs. The values on the Y-axis are in kW and the time is taken on the x-axis.



Graph 1. Averaged hourly summer day values

Graph 1 clearly shows a uneven load throughout a day. There is a sudden increase at the night times. The load values are very small because of the reasons that one it is neglecting the gas usage and secondly it is hourly consumption.



Graph 2. Averaged hourly winter day values

In graph 2 it is clearly indicated that there is a significant rise in demand much earlier than the summer profile this is because of the reason that lights are switched on earlier and switched off later in time because the days are of shorter duration.

3.2. Laboratory work

To create a load profile a command window prompts in which we can either adjust load according to percentage load with respect to machine load capacity or current required for that load. For every load, secondary add push button on the command prompt was used to create a load and a time for running the machine for that load is also to be included in that profile. The load profile defining editor is shown in the figure below

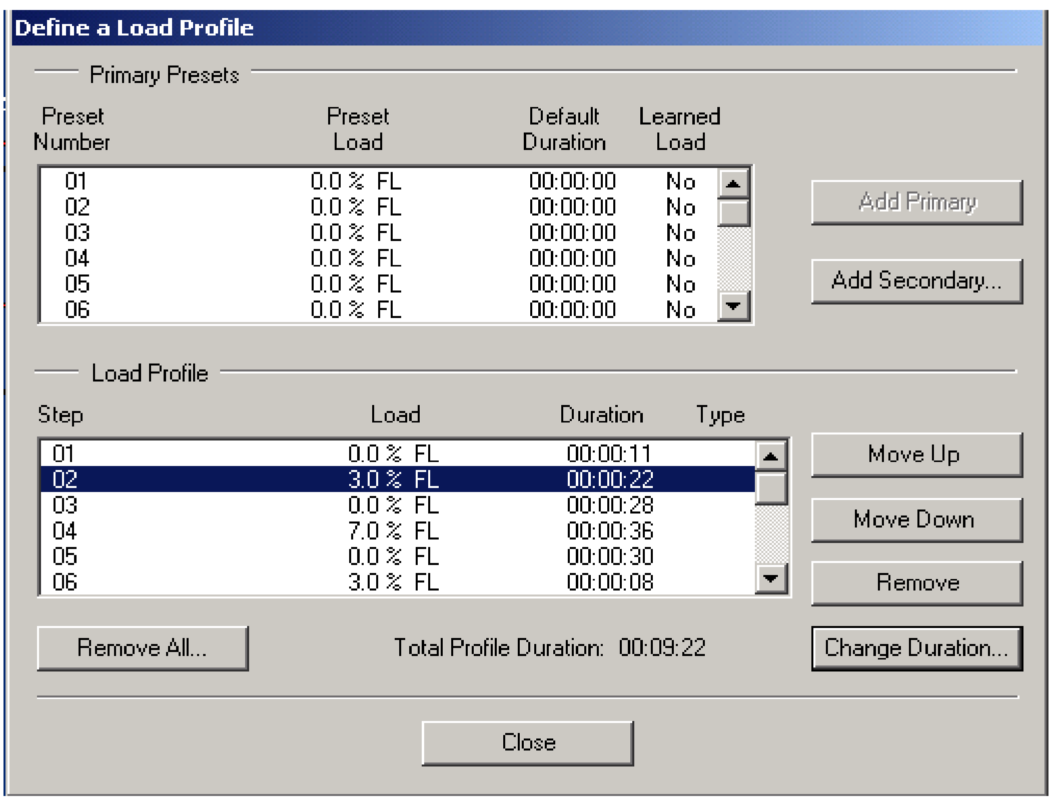


Figure 15. Load profile editor

The profile for the above mentioned hourly load was created on the load profile editor and each load was run on the PEMFC for one minute. When the load profile is created the editor generates a load bank pre-sets report of that profile showing the percentage load profile along with its timing and all system specification. The figures below shows different information in load bank pre-set report.

```
// -------------------------------------------------------------
//                      LOADBANK PRESETS REPORT
//
//          Printout of Preset Load Details and Load Profile
//    Information for Createchic Loadbank - Contract Number 4487
//
//             Corona D.C. Load Control System Software
//                Copyright (C) 2011 - Createchic Ltd
//
//             Date of Report : June 21, 2013 - 10:30
//
// -------------------------------------------------------------


//    Generator Parameters
//
Nominal Voltage          =      48.000000 Volts
Full Load Output         =       5.000000 kW
Full Load Tolerance      =     110.000000 %
Use of Measured Values   =        Enabled
```

Figure 16. Machine Information in pre-set report

The above figure shows that report contains the information of the manufacturer along with software information, the date of the experiment along with starting time. This report also states information of voltage, full load output of system, tolerance percentage and the status of measured values.

The figure below shows the profile created and it was also the part of the report. It clearly shows the percentage of full load and the duration of each load. For each load with its run time was created in the form of steps. It clearly shows that there are twenty-four values each corresponding to average hourly value of a day. Two set of experiments were performed with random values, one without a break and in other after every load value a buffer value of 0.0 kW for 15 sec was applied. Rest of the information is same only the load profile part of the pre-set documents are different. Both the load profiles are shown below.

```
//      Details of Load Profile
//
.
.                          % Full Load   Duration
.                          -----------   --------
Step 001 :                   8.400000    00:01:00
Step 002 :                   6.400000    00:01:00
Step 003 :                   5.000000    00:01:00
Step 004 :                   4.200000    00:01:00
Step 005 :                   3.800000    00:01:00
Step 006 :                   4.200000    00:01:00
Step 007 :                   7.200000    00:01:00
Step 008 :                  10.800000    00:01:00
Step 009 :                  11.600000    00:01:00
Step 010 :                  13.000000    00:01:00
Step 011 :                  13.000000    00:01:00
Step 012 :                  13.200000    00:01:00
Step 013 :                  13.800000    00:01:00
Step 014 :                  13.000000    00:01:00
Step 015 :                  12.200000    00:01:00
Step 016 :                  12.800000    00:01:00
Step 017 :                  17.200000    00:01:00
Step 018 :                  20.200000    00:01:00
Step 019 :                  19.400000    00:01:00
Step 020 :                  17.800000    00:01:00
Step 021 :                  15.800000    00:01:00
Step 022 :                  13.800000    00:01:00
Step 023 :                  11.600000    00:01:00
Step 024 :                   8.800000    00:01:00
```

```
//      Details of Load Profile
//
.
.                          % Full Load   Duration
.                          -----------   --------
Step 001 :                   8.400000    00:00:30
Step 002 :                   0.000000    00:00:15
Step 003 :                   6.400000    00:00:30
Step 004 :                   0.000000    00:00:15
Step 005 :                   5.000000    00:00:30
Step 006 :                   0.000000    00:00:15
Step 007 :                   4.200000    00:00:30
Step 008 :                   0.000000    00:00:15
Step 009 :                   3.800000    00:00:30
Step 010 :                   0.000000    00:00:15
Step 011 :                   4.200000    00:00:30
Step 012 :                   0.000000    00:00:15
Step 013 :                   7.200000    00:00:30
Step 014 :                   0.000000    00:00:15
Step 015 :                  10.800000    00:00:30
Step 016 :                   0.000000    00:00:15
Step 017 :                  11.600000    00:00:30
Step 018 :                   0.000000    00:00:15
Step 019 :                  13.000000    00:00:30
Step 020 :                   0.000000    00:00:15
Step 021 :                  13.000000    00:00:30
Step 022 :                   0.000000    00:00:15
Step 023 :                  13.200000    00:00:30
Step 024 :                   0.000000    00:00:15
Step 025 :                  13.800000    00:00:30
Step 026 :                   0.000000    00:00:15
Step 027 :                  13.000000    00:00:30
Step 028 :                   0.000000    00:00:15
Step 029 :                  12.200000    00:00:30
Step 030 :                   0.000000    00:00:15
Step 031 :                  12.800000    00:00:30
Step 032 :                   0.000000    00:00:15
Step 033 :                  17.200000    00:00:30
```

Figure 17. Load profile implemented on load bank

The other information included in the report are shown in the figure below.

```
//      Results Report Parameters
//
Results Output Period     =  5 Seconds
Results Load Units        =  kW
Time-of-Day Time Stamp    =  Disabled
Results Title Line        =  'TEST RESULTS'
Results Signature Line    =  'Engineers Signature: ________________'


//      Transient Capture Parameters
//
Capture Duration       =  12 Seconds
Load-Change Units      =  kW


//      Chart Recorder Parameters
//
Recorded Parameter 1   =  'DC Voltage'
Recorded Parameter 2   =  'DC Current'
Recorded Parameter 3   =  'Power'
Chart Period            =  60 Seconds


//      End of Preset Report
```

Figure 18. Pre-set report other information

3.3. Results

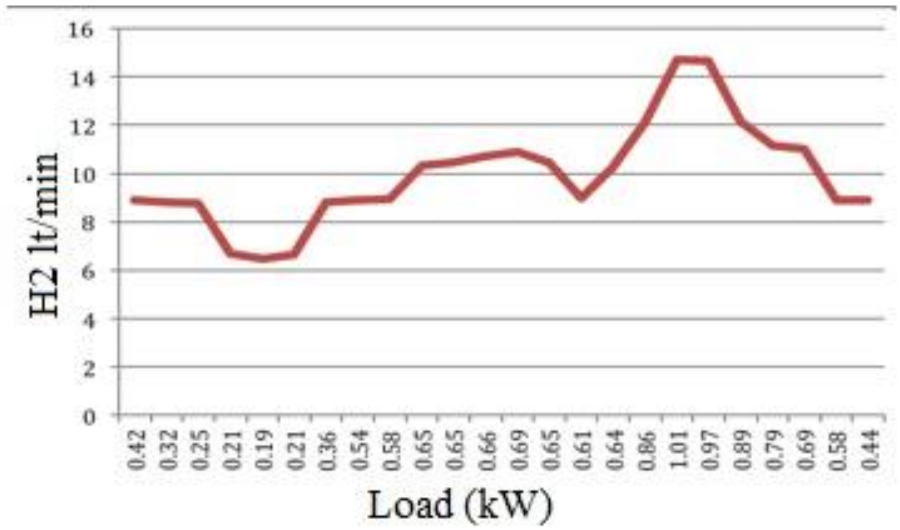
System creates a log file after every five minutes in which it states all the working conditions of the PEMFC. The file created by the system is named as GC5BB000000300_Sys_HSD_2013_06_21_10_35_10.csv. This excel file contains all the system working information. In this file column BD gives us the H2 consumption, which is main interest of this experiment. The hydrogen consumption always calculated by the system is in liters/min. The figure below shows the layout of the excel sheet showing the BD column with the heading of that column as H2 usage. For plotting of results we have arranged the values in the ascending order. In experiment the values were applied randomly. The graph for the fuel consumption w.r.t to values load values is shown below.

BD12 fx 0

	A	B	C	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN
1	System: GC5BB000000300 GCC Software Version: GC_VER_1.9.2													
2	integer Date	GMT	Local Time	H2 Usage	Converter Po	Current Slave	Slave Unit St	Slave Unit Po	Slave Unit St	Number of C	This Unit Des	Slave Unit Bu	This Unit Add	Total Bus Pow
3	1371808512	06/21/2013 08:55:12 AM	06/21/2013 09:55:12 AM	0	0	0	0	0	0	0	3	0	1	0
4	1371808514	06/21/2013 08:55:14 AM	06/21/2013 09:55:14 AM	0	0	0	0	0	0	0	3	0	1	0
5	1371808516	06/21/2013 08:55:16 AM	06/21/2013 09:55:16 AM	0	0	0	0	0	0	0	3	0	1	0
6	1371808518	06/21/2013 08:55:18 AM	06/21/2013 09:55:18 AM	0	0	0	0	0	0	0	3	0	1	0
7	1371808520	06/21/2013 08:55:20 AM	06/21/2013 09:55:20 AM	0	0	0	0	0	0	0	3	0	1	0
8	1371808522	06/21/2013 08:55:22 AM	06/21/2013 09:55:22 AM	0	0	0	0	0	0	0	3	0	1	0
9	1371808524	06/21/2013 08:55:24 AM	06/21/2013 09:55:24 AM	0	0	0	0	0	0	0	3	0	1	0
10	1371808526	06/21/2013 08:55:26 AM	06/21/2013 09:55:26 AM	0	0	0	0	0	0	0	3	0	1	0
11	1371808528	06/21/2013 08:55:28 AM	06/21/2013 09:55:28 AM	0	0	0	0	0	0	0	3	0	1	0
12	1371808530	06/21/2013 08:55:30 AM	06/21/2013 09:55:30 AM	0	0	0	0	0	0	0	3	0	1	0
13	1371808532	06/21/2013 08:55:32 AM	06/21/2013 09:55:32 AM	0	0	0	0	0	0	0	3	0	1	0
14	1371808534	06/21/2013 08:55:34 AM	06/21/2013 09:55:34 AM	0	0	0	0	0	0	0	3	0	1	0
15	1371808536	06/21/2013 08:55:36 AM	06/21/2013 09:55:36 AM	0	0	0	0	0	0	0	3	0	1	0
16	1371808538	06/21/2013 08:55:38 AM	06/21/2013 09:55:38 AM	0	0	0	0	0	0	0	3	0	1	0
17	1371808540	06/21/2013 08:55:40 AM	06/21/2013 09:55:40 AM	0	0	0	0	0	0	0	3	0	1	0
18	1371808543	06/21/2013 08:55:43 AM	06/21/2013 09:55:43 AM	0	0	0	0	0	0	0	3	0	1	0
19	1371808545	06/21/2013 08:55:45 AM	06/21/2013 09:55:45 AM	0	0	0	0	0	0	0	3	0	1	0
20	1371808547	06/21/2013 08:55:47 AM	06/21/2013 09:55:47 AM	0	0	0	0	0	0	0	3	0	1	0
21	1371808549	06/21/2013 08:55:49 AM	06/21/2013 09:55:49 AM	0	0	0	0	0	0	0	3	0	1	0
22	1371808551	06/21/2013 08:55:51 AM	06/21/2013 09:55:51 AM	0	0	0	0	0	0	0	3	0	1	0
23	1371808553	06/21/2013 08:55:53 AM	06/21/2013 09:55:53 AM	0	0	0	0	0	0	0	3	0	1	0
24	1371808555	06/21/2013 08:55:55 AM	06/21/2013 09:55:55 AM	0	0	0	0	0	0	0	3	0	1	0
25	1371808557	06/21/2013 08:55:57 AM	06/21/2013 09:55:57 AM	0	0	0	0	0	0	0	3	0	1	0
26	1371808559	06/21/2013 08:55:59 AM	06/21/2013 09:55:59 AM	0	0	0	0	0	0	0	3	0	1	0
27	1371808561	06/21/2013 08:56:01 AM	06/21/2013 09:56:01 AM	0	0	0	0	0	0	0	3	0	1	0
28	1371808563	06/21/2013 08:56:03 AM	06/21/2013 09:56:03 AM	0	0	0	0	0	0	0	3	0	1	0
29	1371808565	06/21/2013 08:56:05 AM	06/21/2013 09:56:05 AM	0	0	0	0	0	0	0	3	0	1	0
30	1371808567	06/21/2013 08:56:07 AM	06/21/2013 09:56:07 AM	0.315	0	0	0	0	0	0	3	0	1	0
31	1371808569	06/21/2013 08:56:09 AM	06/21/2013 09:56:09 AM	0.315	0	0	0	0	0	0	3	0	1	0
32	1371808571	06/21/2013 08:56:11 AM	06/21/2013 09:56:11 AM	0.315	0	0	0	0	0	0	3	0	1	0

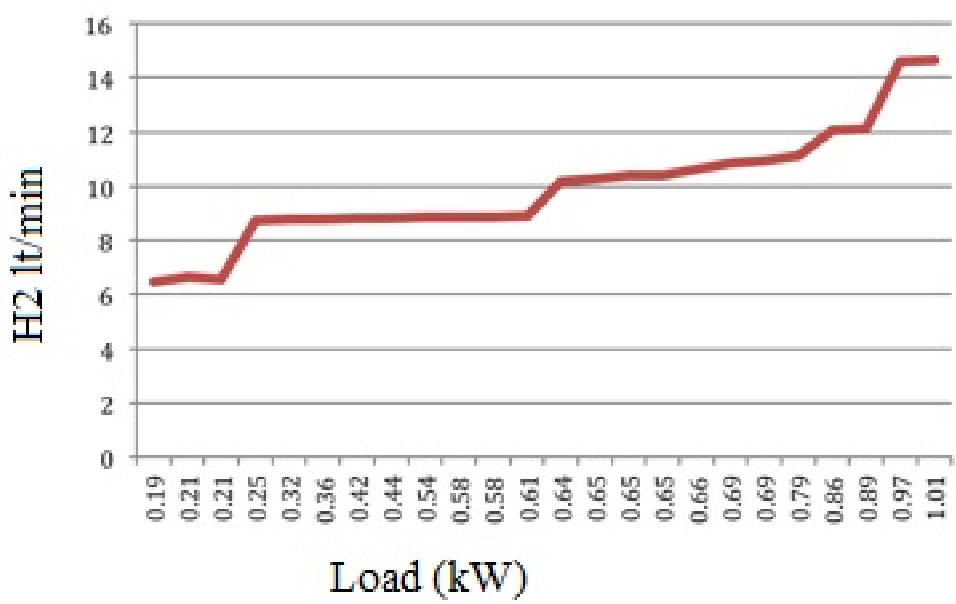
Figure 19. System file showing H2 usage

The graph showing the load and consumption are shown below. In graph 3. the load values are shown in the random but in the graph 4. the values are in ascending order but the hydrogen consumption remains the same for each values.



Graph 3. Random values of load along X-axis

It is noted during the experiment results from PEM fuel cell that the hydrogen consumption values remains the same as long the load remains the same. To get a generalised value which can be used for all values of load the x-axis load values are sorted in the ascending order and the corresponding load values also got arranged in the same manner.



Graph 4. Arranged values of load along X-axis

In these graphs values on the Y-axis are hydrogen consumption and on the x-axis are the electrical loads.

The graph above after being arranged in the ascending shows slightly a different behaviour from the original manufacturer hydrogen consumption graph. Manufacturer graph is a linear one while the experimental graph is slightly slow in change. This might be due to small timing for which the load was applied on the PEM fuel cell.

The arranged graph shows approximately a linear relationship but to form an equation of line Least Square Fitting (LSF) principle is applied in matlab. It gives a actual value graph and the approximate linear equation to generalise it for further uses. Using Curve Fitting Toolbox, LSF was performed in matlab and the command for this tool is **cftool** in matlab. The results for the above mentioned matlab process is shown in the figures below. In this tool we can select different model and for our calculation linear model is selected to match with the manufacturer hydrogen consumption.

Figure below shows the actual above graph and the proposed Linear Fitting derived for the applied load and consumption values. In this X-axis is showing the load values and hydrogen consumption values are shown on the Y-axis.

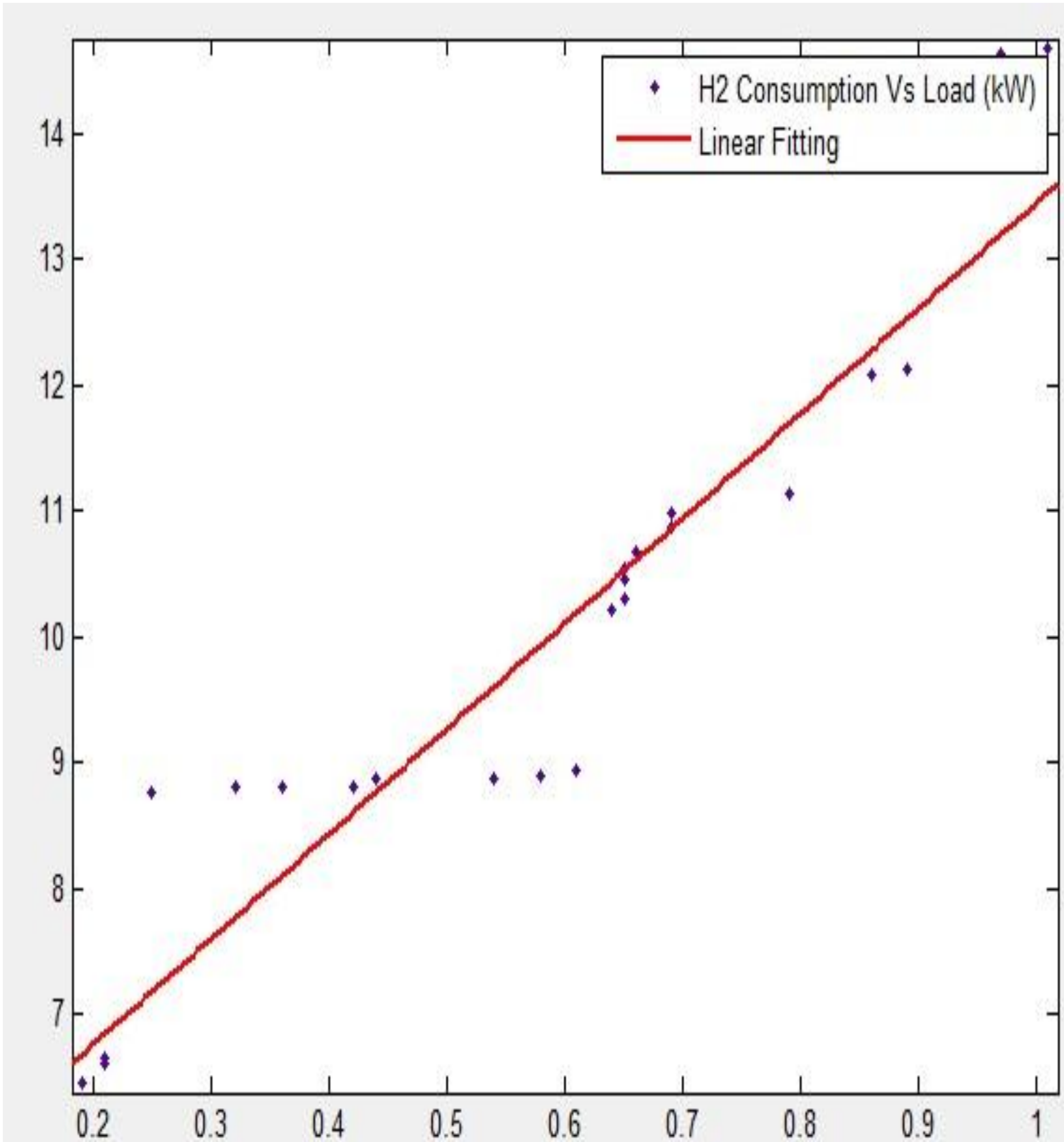


Figure 20. Actual Values and proposed straight line by LSF

Figure below shows the proposed equation of linear fitting along with the constant values. It also shows the range of the constants and best possible constant values are also shown.

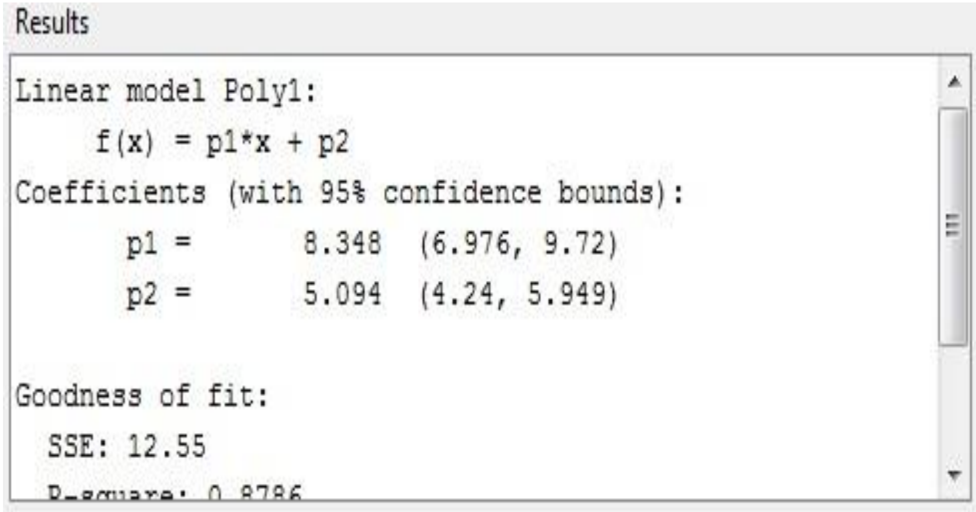


Figure 21. Proposed equation of straight line by LSF

This tool also gives the analysed results of the proposed linear fitted equation. These results are very much nearer to the actual standard hydrogen consumption values. The standard hydrogen consumption value for the PEMFC used is 13 slm for 1kW load which is very much nearer to the proposed results shown below.

Xi	f(Xi)
0.19	6.68048
0.272	7.365
0.354	8.04953
0.436	8.73406
0.518	9.41859
0.6	10.1031
0.682	10.7876
0.764	11.4722
0.846	12.1567
0.928	12.8412
1.01	13.5258

Figure 22. Analysed results by proposed equation of line

The above Proposed equation is applied in the excel sheet to form a tool which will calculate the hydrogen consumption for electric load profiles.

4. Sizing tool

As described above in the figure 1, the system consists of PEM fuel cell, electrolyser, water storage tank and the solar panel. At the base of this tool calculations is the hydrogen consumption of the under experiment fuel cell and from that we have derived a equation of line by using the least square fitting rule in matlab and implemented it for all values of load and hydrogen consumption for different loads values are calculated. These values are in the units of litres/min units, which were first converted for hourly values by multiplying these with 60 minutes to make them hourly values.

These values are further converted into standard hydrogen units, which are Nm^3 because the electrolyser produces hydrogen in gaseous form instead of liquid state. After having hydrogen consumption for each load from experimental values, in the next step energy requirements of electrolyser is calculated. In this per hour energy requirements are considered to produce that much amount of hydrogen needed for full working of PEM fuel cell during that specific hours. In this standard values in Nm^3 are taken into account.

After calculating the energy requirements of electrolyser the next step is the supply of water. In this step water is taken litres/min units, as standard conversion values are used so both values are equal in amount but in different units. The values assumed below are used to calculate the amount of water needed by electrolysers to produce hydrogen for that hourly load. The maximum amount of water against the maximum load will be the selected capacity of the water storage tank.

Finally as the system is autonomous in its working and its only power supply is from solar panel. Value for W/area for a solar panel is assumed below and used to calculate the covered area of total solar panel. Units for this part of calculations are square meters. The maximum power demand corresponding to the maximum load will demand maximum power supply which will be the selected area of solar panel in square meters.

4.1. Tool sheet assumptions

For excel tool sheet hydrogen consumption is calculated by the above defined procedure and the linear fitting equation is used. This equation gives the hydrogen consumption in liters per minute but this is converted into hourly consumption. There is assumption used in the hydrogen consumption but it totally depends on the experimental results obtained from the PEMFC under observation.

For hydrogen production it is assumed from literature review that PEM electrolyser produce **0.42-m3 h^{-1}** of hydrogen [15]. This

$$\mathbf{1Nm^3 = 1000\ litres}$$

$$\mathbf{0.42\ m^3 = 420\ litres}$$

For Electrical Consumption of PEM Electrolyser it is assumed that it will take **3kWh per Nm^3** of hydrogen produced [15] [19].

For water tank storage it is assumed that it requires approximately **9 litres of water to produce 1 kg of hydrogen** [16].

For conversion of hydrogen units from liquid to kg it is taken as [17], [18]

$$\mathbf{1kg = 11.126\ Nm^3}$$

or

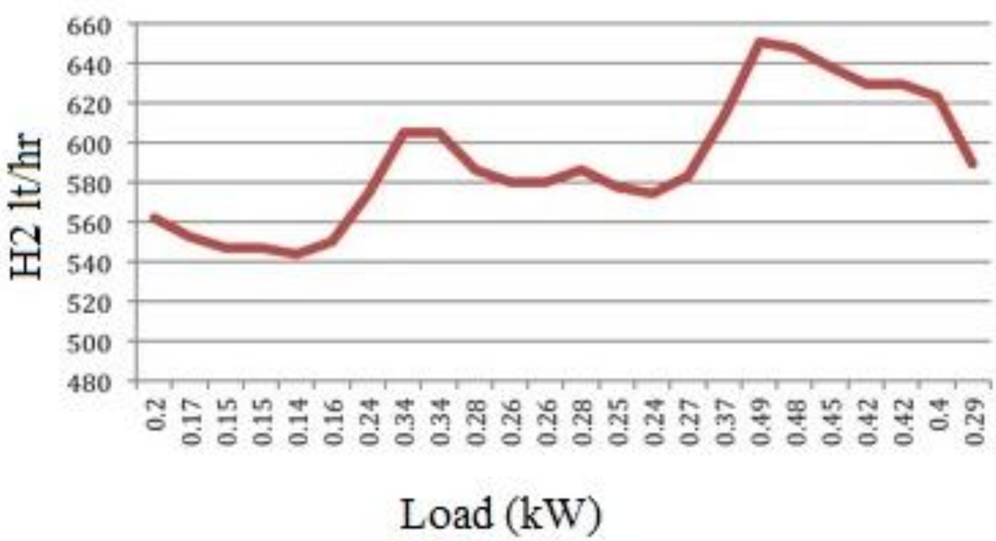
$$\mathbf{1kg = 14.128\ litres}$$

Actually solar panels produce 100-200 W per square meter and for my calculation it is assumed that **100 Watts/ 1 sq. meters** [21] [22] [23]**.**

For Nm^3 (Normal cubic meter) temperature is considered as 0^o C and pressure at 1 atm. All the above values are rounded to nearest significant numbers.

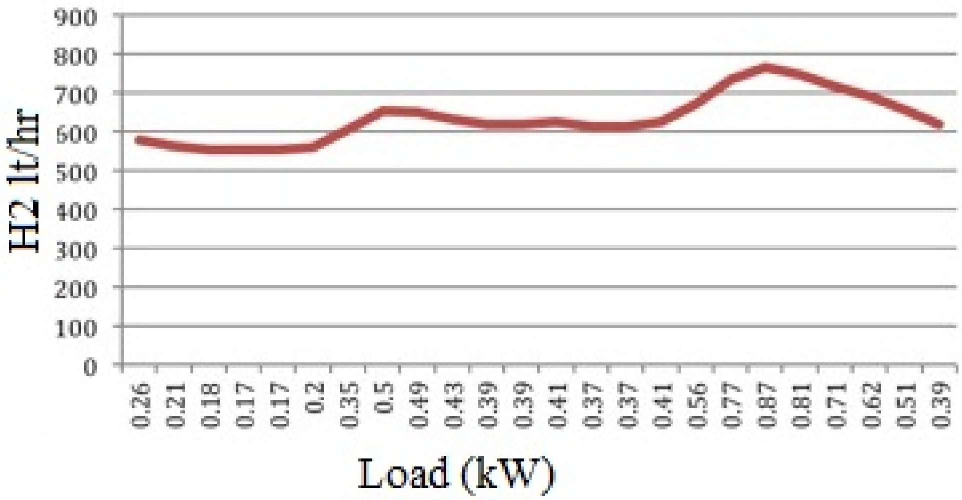
4.2. Tool testing

The above-mentioned winter and summer load profiles are tested in the tool sheet and the corresponding hydrogen consumptions were converted into hours instead of minutes. The corresponding graph showing the winter and summer daily per hourly consumptions are shown below.



Graph 5. Summer hydrogen consumption

In graph 5. x-axis shows the load in kW and the y-axis shows the hydrogen consumption in litres/hour. And corresponding winter consumption is shown in graph 6.



Graph 6. Winter hydrogen consumption

Similarly in graph 6. x-axis shows the load in kW and the y-axis shows the hydrogen consumption in litres/hour.

These two graphs clearly shows that as the load during the summer and winter seasons varies so as the hydrogen consumption. Similarly as during the winter season energy consumption increases it will need more hydrogen during the winters than the summer. So for designing a system, results, which are consuming or demanding grater hydrogen should be given priority and these values should be implemented in the system configuration.

This tool not only gives the hydrogen consumption but also suggests the capacities of other components of the system by using the above-mentioned values taken from literature review. For the above selected summer profile the corresponding energy requirement of electrolyser for each load is given in table 1.

Load	Required kWh
0.2	1.69
0.17	1.66
0.15	1.64
0.15	1.64
0.14	1.63
0.16	1.65
0.24	1.72
0.34	1.81
0.34	1.81
0.28	1.76
0.26	1.74
0.26	1.74
0.28	1.76
0.25	1.73
0.24	1.72
0.27	1.75
0.37	1.84
0.49	1.95
0.48	1.94
0.45	1.92
0.42	1.89
0.42	1.89
0.4	1.87
0.29	1.77

Table 1. Summer kWh power requirement w.r.t load

This above table is for summer profile and it shows the per hourly power requirement for electrolysis and it is assumed that for that hour, power from the renewable energy should remain constant around these values. This tool also suggests that 1.95 kWh is the maximum values against that daily electric load which should be selected so that it can fulfil the energy requirements of all the loads.

Similarly for winter load profile per hourly power requirements are shown in the table below.

Load	Required kWh
0.26	1.74
0.21	1.70
0.18	1.67
0.17	1.66
0.17	1.66
0.2	1.69
0.35	1.82
0.5	1.96
0.49	1.95
0.43	1.90
0.39	1.86
0.39	1.86
0.41	1.88
0.37	1.84
0.37	1.84
0.41	1.88
0.56	2.02
0.77	2.21
0.87	2.30
0.81	2.25
0.71	2.15
0.62	2.07
0.51	1.97
0.39	1.86

Table 2. Winter kWh power requirement w.r.t load

The table 3.2.2 suggests that if the system is designed for winter then the maximum energy requirement is around 2.30 kW for a day, which must be required in maximum to compensates all the energy requirements of the day.

The corresponding required area in per square meter for the above-mentioned loads i.e. summer and winter seasons for solar panel are given in the tables below.

Load	Panel area per sq. m
0.2	16.86
0.17	16.59
0.15	16.40
0.15	16.40
0.14	16.31
0.16	16.49
0.24	17.23
0.34	18.14
0.34	18.14
0.28	17.59
0.26	17.41
0.26	17.41
0.28	17.59
0.25	17.32
0.24	17.23
0.27	17.50
0.37	18.42
0.49	19.52
0.48	19.43
0.45	19.15
0.42	18.88
0.42	18.88
0.4	18.69
0.29	17.69

Table 3. Summer required panel area in square meters w.r.t load

As we know that solar panel area is a fixed quantity so it cannot be changed for alternating load values. So the maximum panel area will be considered so that it can fulfil all the load requirements. In case of above load 19.52 sq. meters will be the panel area which can meet the energy demand of the electrolyser.

Similarly for winter season as the energy requirements increases so as the panel area will also increases. Table 3.2.4 below gives the panel area against each load.

Load	Panel area per sq. m
0.26	17.41
0.21	16.95
0.18	16.68
0.17	16.59
0.17	16.59
0.2	16.86
0.35	18.24
0.5	19.61
0.49	19.52
0.43	18.97
0.39	18.60
0.39	18.60
0.41	18.79
0.37	18.42
0.37	18.42
0.41	18.79
0.56	20.16
0.77	22.09
0.87	23.00
0.81	22.45
0.71	21.54
0.62	20.71
0.51	19.70
0.39	18.60

Table 4. Winter required panel area in square meters w.r.t load

The surface area in square meter for panel should match the maximum load value of the year so that all energy needs for the system can be fulfilled. For this specific load profile 23.00 sq. meters of panel area is required which is sufficient for the whole energy demands of the electrolyser.

5. Discussion

In this tool, calculations are made on the practical results obtained from the PEMFC experiment. It is quite interesting to note that I this case when the load remains the constant the PEMFC hydrogen consumption also remain the constant. It should be worth mentioning here that all these calculations are for 3kW load profiles because the hydrogen consumption for load greater than 3 kW changes. In official manual of this PEMFC it is mentioned that this PEMFC will consume 40 slm at 3kW load and this consumption will increase to 75 slm at 5kW. The conversion values for capacity calculation of each component are based on the literature studies. In tool sheet, solar panel covered area is also calculated which also changes with the load profile. But it we consider the load variation during summer and winter as used above than the surface area for solar panel does not changes too much. In the tool sheet, 24 hourly loads are entered and the sheet will give the rest of the values on the basis of assumed values for each component.

PEMFC actually gives the values in litre/min but these values are first converted into litre/hour and then to Nm^3/hour. The reason for conversion is that we are using hydrogen in gaseous state and gases are always takes in cubic meters instead of litres. Then after the conversion they are converted to kilograms as our electrolyser conversion values are in kilograms. Then for each kilogram power requirements are calculated by using the assumed. Firstly the power values are calculated per hourly and then accumulative power per day is also calculated. This accumulative power is used further to calculate surface area of the solar panel which will provide the power to electrolyser.

From panel sizing it is clearly shown that if the maximum load panel size will be used we will have surplus energy from the panel for major period of the year.

6. Conclusion and future improvements

This thesis illustrates the capacity requirements of each component of autonomous PEMFC for electricity production. The results obtained through this tool shows changes in different results for different loads. This explains that in every season load demand changes and different resources are needed to coup these demand.

Nevertheless, in order to form a any tool for such systems each component should be tested experimentally and the practical data should be used to form such tool. Also different load should be tested on PEMFC varying from domestic to industrial to evaluate the working of PEMFC for such tools. Also the results from this GenCore 5B48 fuel cell cannot be taken as standard for all types of fuel cells.

Also to support this tool further, proper modelling is required which is not considered in this tool also proper simulation tools should be employed to further support this tool. This tool is just a analytical explanation depending upon simple calculations. To explore it further a proper simulation tool is required which will take into account PEM fuel model equations instead experimental results along with all the components mathematical models so that the system performance can further be evaluated and analysed. For such purpose software like matlab, Simulink and ESP-r can be utilised to further improve this area of research.

As this type of autonomous systems are emerging technologies so there are many other options of utilizing these PEM fuel cells systems. Instead of continuously producing electricity from fuel cell we can utilize solar and wind energies as main source and the fuel cell be used as backup power supply. As solar panel will provide the power during the day so this power will be used for domestic purpose as well as by electrolyser. During the night time the stored hydrogen will be used by fuel cell for electricity production. Also the surplus power will be used to perform electrolysis to produce hydrogen. In this way components capacities can be reduced. Also the cost of such systems is very important which takes into account the working cost as well as equipment cost.

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