Energy and Green house gas payback time analysis of an Air Breathing Fuel Cell Stack

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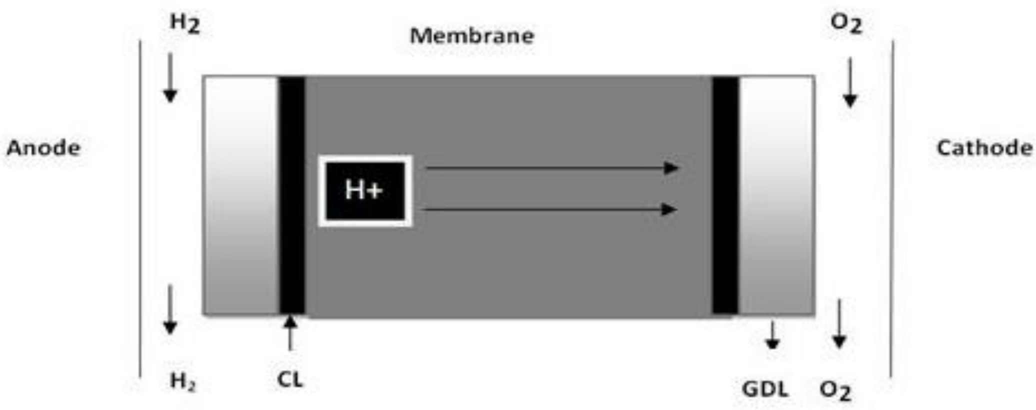
Abstract: Energy generation using fuel cells offers the possibility of high conversion efficiency and reduced pollution. An assessment of the environmental impact of fuel cells over the entire lifecycle is needed to determine the specific benefits in various application scenarios. Life cycle energy consumption and green house gas emission assessment must include a "cradle to grave" approach encompassing materials/manufacturing processes, fuel production, fuel compression and disposal/recycling. This paper deals with the analysis of Energy Payback Time (EPBT) and Green house gas Payback Time (GPBT) of anAir Breathing Fuel Cell (ABFC) stack, by estimating the embodied energy consumption and green house gas emissions within the whole lifecycle of the stack from the extraction of primary resources to the deployment including the manufacturing, usage and disposal phases. This analysis would be a useful tool for industry and government in estimating energy savings and environmental credits, and providing a holistic understanding on regulatory needs. In this paper, the life cycle energy consumption of a fabricated 100W ABFC Stack is found to be 313.7204 kWh, its Energy payback time (EPBT) is found to be 1.283 years (i.e., the time taken for the stack to generate the same amount of energy required for its life cycle which includes the energy requirement during its manufacturing, operation and disposal phases.) and the corresponding life cycle greenhouse gas emissions and Greenhouse gas payback time (GPBT) are found to be 103.14 kg CO_2eq and 0.52 years accordingly. Energy payback period and Carbon payback period of 100W ABFC stack have been compared with 25 kW Roof top solar PV and 1.65 MW wind turbine.

Key words: *Air Breathing Fuel Cell, life cycle analysis, energy payback ratio, Green house gas emissions*

1. Introduction

Renewable energy sources reduce our dependency on foreign fossil fuels and do not emit "climate-harmful" green house gases like CO_2 into the atmosphere when used to produce electrical energy [1]. According to the 'general circulation models' (GCMs) used by the IPCC the ongoing rise in atmospheric CO_2 concentration will lead to significant global warming [2]. Fuel cells are a future energy system with a high potential for environmentally-friendly energy conversion [3]. They can be considered as green power because they are environmentally clean, has low emission of oxides of nitrogen and sulphur and at the same time, they can operate with a very low level of noise. Polymer electrolyte membrane fuel cells (PEMFCs) may well be powering millions of cars by 2020 [4]. Fuel Cells that take up oxygen, for the cathode reaction, from ambient air by passive means are known as "air-breathing" fuel cells (ABFCs). The work process of the ABFC is shown in Fig. 1 and it is suitable to be used in portable power supply, vehicles, residential and distributed power plants [5, 6]. The ABFCs eliminate the use of compressor/blower and humidifier on the cathode side, thus making the system simple, light and compact. Since an air-breathing fuel cell take up oxygen by natural convection i.e., directly from the surrounding air, the ambient conditions play a very important role on the cell performance [7]. A basic diagram showing the structure of the ABFC is shown in Fig. 2. The main elements inside the cell are: end/supporting plates, conductor plates, flow field plates and membrane electrode assembly (MEA). The electrodes are composed of a Gas Diffusion Layer (GDL),) and a Catalyst Layer (CL), both layers have a porous, partially hydrophobic structure.



Anode side reaction : $2H_2 \rightarrow 4H^+ + 4e^-$ Cathode side reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall reaction : $H_2 + O_2 \rightarrow 2H_2O$ + Electricity + Heat

Fig 1.Work process and reaction principle of a Fuel cell

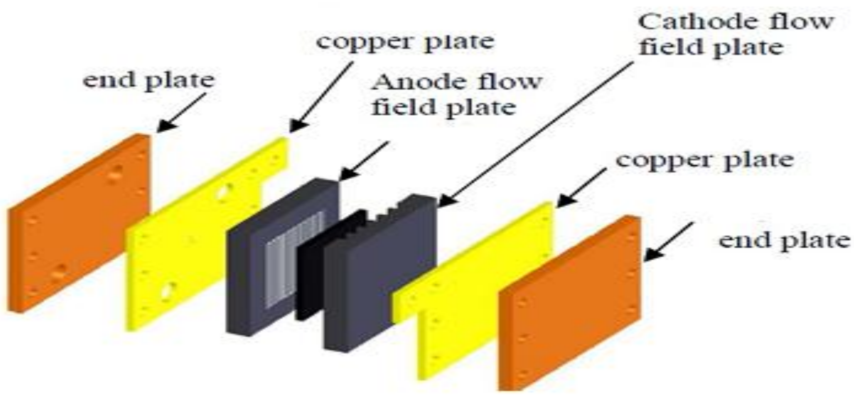


Fig 2.Structure of the ABFC.

Life cycle assessment (LCA) is most widely associated with estimating the energy consumption and greenhouse gas emissions of various consumer products [8]. The power of LCA technique lies in its ability to consider the entire life cycle of a product in great depth, considering all of the direct and 'behind the scenes' actions from cradle to grave, as summarised:

- The individual stages required to produce a fuel cell system are identified, either by observing and interviewing manufacturers or from reviewing literature on their design and fabrication;

- Each stage is broken down into sequentially smaller processes as shown in Fig. 3, giving a hierarchy that can extend from the manufacturing the components of stack to their disposal;

- An inventory is produced for each of these processes, giving the energy inputs. Data is acquired from peer-reviewed inventory databases or from further research.

- In this paper we review our data on the fabrication of the ABFC stack. Results are then presented for the estimated primary energy consumption and green house gas emissions that are caused by manufacturing the ABFC stack, and then calculation of two popular environmental indicators of LCA, the energy payback time (EPBT) and greenhouse gas payback time (GPBT) which can be used to measure the sustainability of fuel cell stacks.

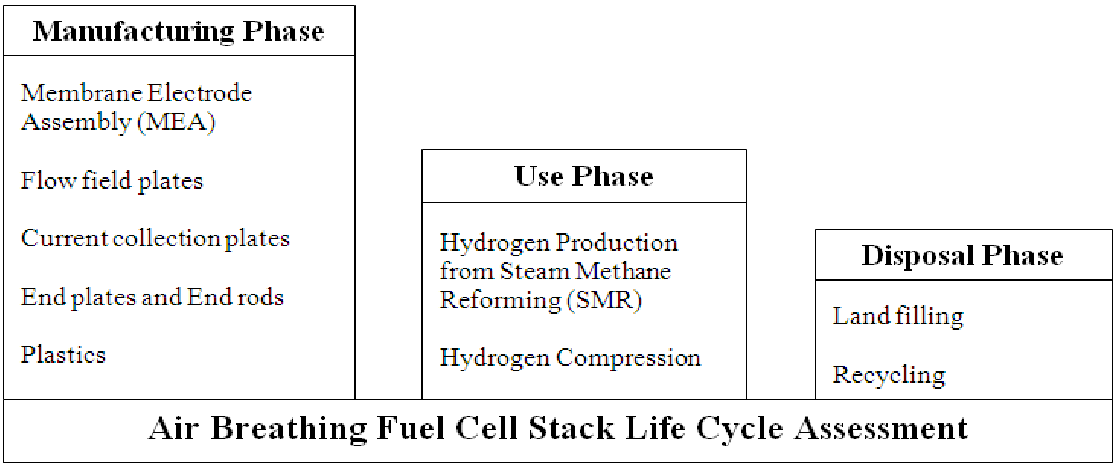


Fig 3.Hierarchy of the Life Cycle of ABFC Stack.

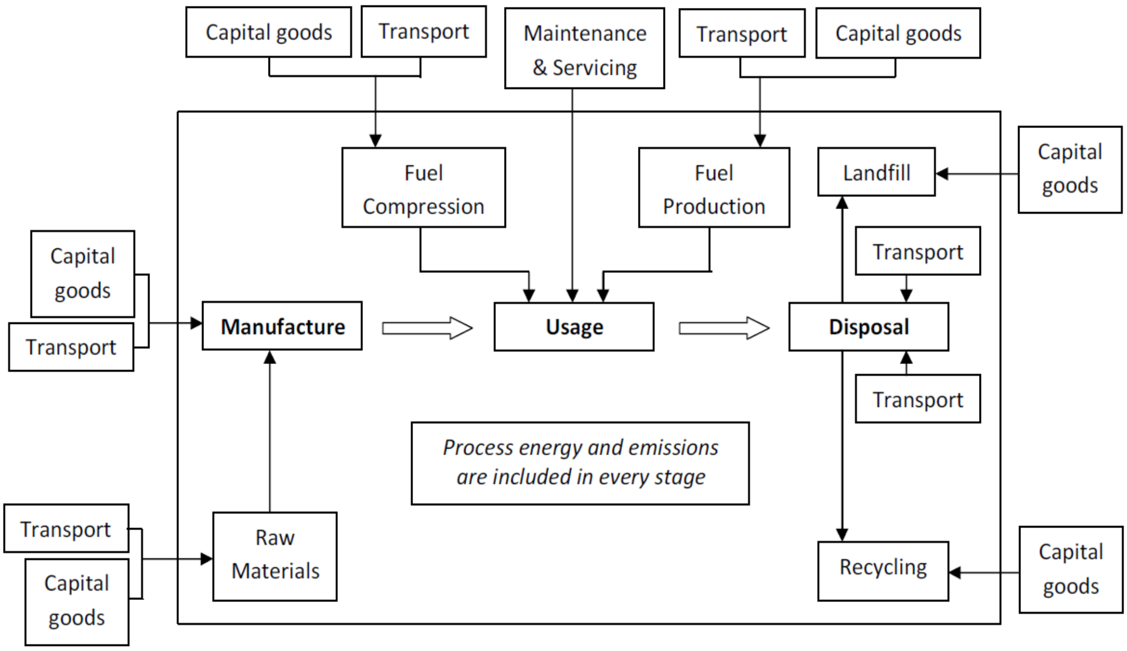


Fig 4. The boundary of LCA

The concept, Energy payback time (EPBT) communicate the environmental benefit of an energy saving product and have been used previously to justify the wind turbines, solar PV and CFL bulbs [9-15]. EPBT is defined as the embodied energy consumption of the ABFC stack divided by annual energy output of the stack. Embodied Energy refers to the energy used within the whole life cycle of the fuel cell, from the extraction of primary resources to deployment including energy used during manufacturing processes, transportation and installation. Therefore type of the fuel cell, system location (transportation issues), system design, system usage and system disposal should all be identified in the embodied energy analysis. It is also important to investigate the percentage of energy used in the same major processes and focus on the main sectors as they have great impacts on the results for calculating the embodied energy and hence the EPBT. However, it is impossible to gather all the data and understand each step in creating each single component in a fuel cell stack, and some simplified assumptions have been made. Greenhouse gas payback time (GPBT) is the study of payback period based on the greenhouse gas (GHG) emissions. Since fuel cell is one of the generation sources which do not generate CO_2 during its operation, the usage of fuel cell is always recommended. However, it generates CO_2 and other gases during its entire life cycle such as extraction, production, and disposal phases. The

GPBT is given by the embodied GHG emission of the ABFC stack divided by the GHG emissions produced by a local power plant. Estimating the embodied GHG emissions is also a great challenge and will have significant impact on the GPBT calculation. The most common way to express the GHG emissions is using the unit of kg CO_2 equivalent, kg CO_2 eq. Therefore the paper aims at evaluation of the EPBT and GPBT of the ABFC stack.

The paper is organized as follows. Section II describes the methodology for the LCA of ABFC stack. In Section III, Energy payback time (EPBT) analysis is presented. In Section IV, Greenhouse gas payback time (GPBT) analysis is discussed. Finally, Section V concludes the analysis.

Fig 5. The 100W ABFC Stack

2. Methodology

2.1 System Description

In this study the conventional LCA procedure viz. goal and scope definition, life cycle inventory, impact assessment is considered. The aim of this LCA Study is to quantify the non-renewable primary energy usage and GHG emissions from ABFC stack. All indicators of the study such as energy usage, emissions are indexed based on the functional unit which is defined as 1kWh of electricity. The ABFC stack and the balance of system (BOS) components are categorized into three phases viz. manufacturing, usage and disposal phases. The Fig.4 shows the LCA boundary. The system boundary defined by solid line, showing which life cycle stages and considerations are accounted for in this study. Those shown outside of the box are neglected.

The ABFC stack consists of eighteen single-fuel cells which are connected in series as demonstrated in the Fig.5. It requires only hydrogen cylinder in case of ABFC stack as it breaths oxygen from air by the process of forced convection with the help of two fans equipped with the stack. The characteristics of an ABFC stack are summarized in Tabel.1.

Table 1: Main characteristics of ABFC stack

Component	**Material**	**Weight**
MEA	Carbon fiber, platinum, Teflon, Nafion-117 membrane	0.1077 kg
End plates	Stainless steel	1.748 kg
End rods	Stainless steel	0.1676 kg
Coolant plates	Graphite	0.1609 kg
Flow field plates	Graphite	1.7293 kg
Fans	Plastic, copper, steel	0.16098 kg
Total Weight of ABPEMFC Stack		4.074 kg

2.2 Energy Payback Time (EPBT) Estimation

The energy payback time (EPBT) is given by the Eq. 1, Where $E_{in,M}$ is the embodied energy of the fuel cell in manufacturing phase, kWh; $E_{in,U}$ is the embodied energy of the fuel cell in usage phase, kWh; $E_{in,D}$ is the embodied energy of the fuel cell in usage phase, kWh; and E_{out} is the annual energy output of the fuel cell.

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$$EPBT = \frac{E_{in,M} + E_{in,U} + E_{in,D}}{E_{out}} \quad (1)$$

2.3 Embodied Energy Estimation

Embodied energy refers to the energy used within the whole lifecycle, from the extraction of primary resources to the deployment including the manufacturing, usage and disposal phases. Here the embodied energy is divided into three categories, i.e., embodied energy of the fuel cell in manufacturing phase, embodied energy of the fuel cell in the usage phase and embodied energy of the fuel cell in disposal phase. The embodied energy of the fuel cell in manufacturing phase is defined by Eq.2, Where E_{MEA} is the embodied energy of the membrane electrode assembly, kWh; E_{FFP} is the embodied energy of the flow field plates, kWh; E_{CCP} is the embodied energy of the current collection plates, kWh; E_{CP} is the embodied energy of the cooling plates, kWh; E_{EP} is the embodied energy of the end plates, kWh; E_{ER} is the embodied energy of the end rods, kWh; and E_P embodied energy of the plastic, kWh.

$$E_{in,M} = E_{MEA} + E_{FFP} + E_{CCP} + E_{CP} + E_{EP} + E_{ER} + E_P \qquad (2)$$

The embodied energy of the membrane electrode assembly is defined by Eq.3, Where $E_{Pt}$is the embodied energy of the platinum, kWh; E_M is the embodied energy of the membrane, kWh; and E_{GDL} is the embodied energy of the gas diffusion layer, kWh.

$$E_{MEA} = E_{Pt} + E_M + E_{GDL} \qquad (3)$$

The embodied energy of the fuel cell in usage phase is defined by Eq.4, Where E_{H2P} is the embodied energy of the hydrogen production, kWh; and E_{H2C} is the embodied energy of the hydrogen compression, kWh.

$$E_{in,U} = E_{H_2P} + E_{H_2C} \qquad (4)$$

The embodied energy of the fuel cell in disposal phase is defined by Eq.5, Where $E_{Lf}$is the embodied energy of the land filling, kWh; and E_R is the embodied energy of the Recycling, kWh.

$$E_{in,D} = E_{Lf} + E_R \qquad (5)$$

2.4 Green House Gas Payback Time (GPBT) Estimation

The greenhouse gas payback time (GPBT) is calculated by Eq.6, Where $G_{in,M}$ is the embodied GHG of the fuel cell in manufacturing phase Kg CO_2 eq; $G_{in,U}$ is the embodied energy of the fuel cell in usage phase Kg CO_2 eq; $G_{in,D}$ is the embodied energy of the fuel cell in disposal phase, Kg CO_2 eq; and G is the annual GHG output of the diesel power station, Kg CO_2 eq.

$$GPBT = \frac{G_{in,M} + G_{in,U} + G_{in,D}}{G} \qquad (6)$$

2.5 Embodied GHG Estimation

Embodied GHG refers to the GHG used within the whole lifecycle from the extraction of the primary resources to the deployment including the manufacturing, usage and disposal phases. Here the embodied GHG is divided into three categories, i.e., embodied GHG of the fuel cell in manufacturing phase, embodied GHG of the fuel cell in usage phase and embodied GHG of the fuel cell in disposal phase. The embodied GHG of the fuel cell in manufacturing phase is defined by Eq.7.

$$G_{in,M} = G_{MEA} + G_{FFP} + G_{CCP} + G_{CP} + G_{EP} + G_{ER} + G_P \qquad (7)$$

Where G_{MEA} is the embodied GHG of the membrane electrode assembly, Kg CO_2 eq; G_{FFP} is the embodied GHG of the flow field plates, Kg CO_2 eq; G_{CCP} is the embodied GHG of the current collection plates, MWh; G_{CP} is the embodied GHG of the cooling plates, Kg CO_2 eq; G_{EP} is the embodied GHG of the end plates, Kg CO_2 eq; G_{ER} is the embodied GHG of the end rods, Kg CO_2 eq; and G_P embodied GHG of the plastic, Kg CO_2 eq.

The embodied GHG of the fuel cell in usage phase is defined by Eq.8, Where G_{H2P} is the embodied GHG of the hydrogen production, Kg CO_2 eq; and G_{H2C} is the embodied GHG of the hydrogen compression, Kg CO_2 eq.

$$G_{in,U}=G_{H2P}+G_{H2C} \qquad (8)$$

The embodied GHG of the fuel cell in disposal phase is defined by Eq.9, Where $G_{Lf}$is the embodied GHG of the land filling, Kg CO_2 eq; and G_R is the embodied GHG of the Recycling, Kg CO_2 eq.

$$G_{in,D} = G_{Lf} + G_R \qquad (9)$$

3. Energy Payback Time Calculation

For evaluating the embodied energy of the ABFC stack, it was mainly referred to the previous studies. The primary energy consumption for producing one unit of each material is tabulated in Table 2 and the embodied energy of different components of the ABFC Stack are presented in Table 3. The embodied energy of the fuel cell in manufacturing phase is estimated to be about 359.598 kWh. The embodied energy of the fuel cell in usage phase is divided into two categories, i.e., embodied energy of the hydrogen production, and embodied energy of the hydrogen compression.

Table 2: Primary Energy Consumption of Material used in ABFC stack

Material	**Primary Energy**	**Embodied Energy (kWh)**	**Reference**
Platinum	0.2116MJ/mg	31.11	[16]
Carbon Fiber	0.00756 MJ/mg	165.84	[17]
Graphite	0.16 MJ/g	84.01	[18]
Stainless Steel	143 MJ/kg	76.09	[19]
Plastic	86 MJ/kg	2.538	[19]

The Ballard estimate of 20,000 hours is reported in penthet. al [3], but this may not be realistic within the time frame of this study. So, the life of ABFC Stack is taken as 10,000 hours. Working 8 hours per day, the stack will work for 4 years. The life time hydrogen consumption of the stack is 11.448 m^3.The primary energy consumption of hydrogen production from the natural gas using the process of steam - methane reformation is 0.27891 MJ/m^3 [20]. Therefore, the embodied energy of the hydrogen production from natural gas using steam methane reformer is 0.886 KWh. The specific energy consumption of hydrogen compression for different compression pressures is tabulated in Table 4 [21].

Table 3: Embodied Energy of ABFC stack Components

Component	**Embodied Energy (kWh)**
MEAs	196.963
End Plates	69.434
End Rods	6.657
Coolant Plates	7.154
Flow Field Plates	76.852
Fans	2.538

The regression equation fitted for the above mentioned data in Table 4 is given by Eq.10 and the coefficient of regression for the above fit is 0.995.

$$E=0.001*P+1.7105 \quad \text{kWh/kg} \quad (10)$$

Table 4: Specific energy consumption of hydrogen compression at various compression pressures

Compression Pressure (MPa)	**Specific Energy Consumption (kWh/kg)**
241.3	1.93
344.7	2.08
689.4	2.39

The pressure at which the hydrogen is stored in the cylinder in our laboratory is 20MPa (200bar). Therefore the specific energy consumption of the hydrogen compression is 1.7305 kWh/kg (0.1557 kWh/m^3).The embodied energy of the hydrogen compression is 1.7829 kWh. The embodied energy of the fuel cell, in usage phase is estimated to be about 2.668 kWh.

The embodied energy of the fuel cell in disposal phase is divided into two categories, i.e., embodied energy of the land filling and embodied energy of the

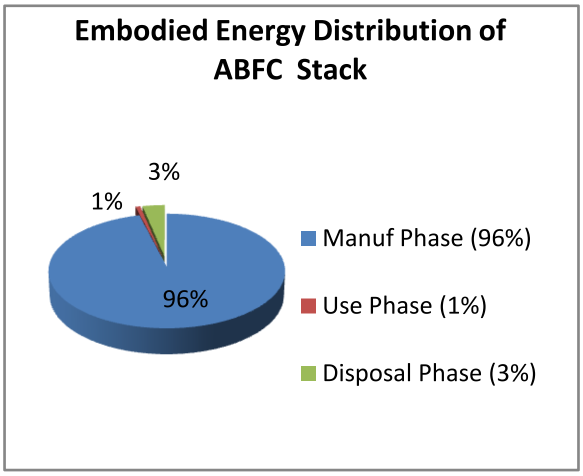

Fig 6. Total embodied energy distribution of the 100W ABFC Stack

recycling. Again the embodied energy of the land filling is divided into two categories, i.e., embodied energy of the road transport and embodied energy of the fuel (diesel) used in land filling equipments. Here, the Components Chosen for Land filling are graphite, plastics and MEAs. The specific energy consumption of transport is 0.5 MJ/Ton-Km [22].The land fill site is located at a distance of 100KM from the laboratory. The embodied energy of transport is 0.0278 kWh. The specific energy consumption of fuel for land fill equipment is 0.268MJ/kg [23].The embodied energy of the land filling equipment is 0.1495 KWh. The specific energy consumption of steel recycling (100%) is 23MJ/kg [24].The embodied energy of steel recycling is 12.23 KWh. Therefore the embodied energy of the fuel cell in disposal phase is estimated to be about 12.4073 KWh.

The pie chart of embodied distribution of the ABFC Stack is demonstrated in Fig 6. The total embodied energy of the 100W ABFC Stack is 374.6733 kWh, including 359.598 kWh (96%) from manufacturing phase, 2.668 kWh (1%) from usage phase, and 12.4073 kWh (3%) from disposal phase. The pie chart of embodied energy distribution for manufacturing phase is demonstrated in Fig 7.The percentage of embodied energy for MEAs is the highest, 55% and for flow field plates is 21%. In usage Phase, the percentage of embodied energy for hydrogen compression is highest, 66.83% and for hydrogen production is 33.17%. In disposal Phase, the percentage of embodied energy for recycling is highest, 98.57% and for land filling is 1.43%. The annual energy output (E_{OUT}) of the ABFC Stack is 292 KWh. The energy payback time (EPBT) of the ABFC Stack is estimated to be 1.23 years.

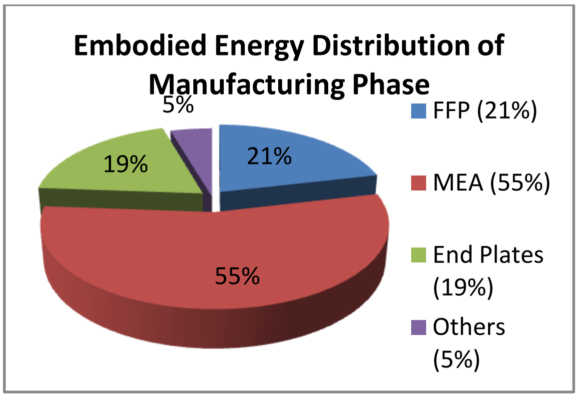

Fig 7. Embodied energy distribution for manufacturing phase

4. Green House Gas Payback Time Calculation

The GHGs produced for power generation depends greatly on fuel type. Based on the data provided by the local diesel power stations, the GHG emission rate is about 768.57 g CO_2 eq /KWh. The annual energy output of the ABFC Stack is estimated to be 292 KWh .The equivalent saved CO_2 emissions generated from the power is 292KWh × 0.76857 kg CO_2 eq /KWh = 224.422 kg CO_2 eq. The embodied GHG of different components of ABFC Stack is presented in Table 5 and the GHG emission rate of each material is tabulated in Table 6.

The embodied GHG emission of the fuel cell in manufacturing phase is estimated to be about 94.54 kg CO_2 eq. The embodied GHG of the fuel cell in usage phase is divided into two categories, i.e., embodied GHG of the hydrogen production, and embodied GHG of the hydrogen compression. The GHG emission rate of hydrogen production from natural gas using the process of steam - methane reformation is 89.82 g CO_2 eq /m^3 [20].Therefore, the embodied energy of hydrogen production from natural gas using steam methane reformer is 1.02836 kg CO_2 eq.The specific GHG emission rate of hydrogen compression is 7 g CO_2 eq /MJ [21]. The embodied energy of the hydrogen compression is 41.9302 g CO_2 eq. The embodied energy of the fuel cell in usage phase is estimated to be about 1.0702 kg CO_2 .

Table 5: GHG emission of Material used in ABFC stack

Material	GHG Emission Rate	Embodied GHG (kg CO_2 eq)	Reference
Platinum	1.642 kg CO_2 eq /g	0.5676	[16]
Carbon Fiber	0.0858 kg CO_2 eq /MJ	51.22	[17]
Graphite	0.0858 kg CO_2 eq /MJ	25.972	[18]
Stainless Steel	8.6 kg CO_2 eq /kg	16.474	[19]
Plastic	3.2 kg CO_2 eq / kg	0.34	[19]

The embodied GHG of the fuel cell in disposal phase is divided into two categories, i.e., embodied GHG of the land filling and embodied GHG of the recycling. Again the embodied GHG of the land filling is divided into two categories, i.e., embodied GHG of the road transport and embodied GHG of the fuel (diesel) used in land filling equipment. The Components Chosen for Land filling are graphite, plastics and MEAs. The IPCC emission factor for transport is 74.066 t CO_2/TJ [22].

Table 6: Embodied GHG of ABFC stack Components

Component	Embodied GHG (kg CO_2 eq)
MEAs	51.7876
End Plates	15.032
End Rods	1.4413
Coolant Plates	2.209
Flow Field Plates	23.74
Fans	0.34

The land fill site is located at a distance of 100KM from the laboratory. The embodied GHG of transport is 0.007414 kg CO_2 eq.. The embodied energy of the land filling equipment is 0.03986 kg CO_2 eq.. The specific emission of steel recycling (100%) is 3.9 kg CO_2 eq /kg [24].The embodied energy of steel recycling is 7.4708 kg CO_2 eq. Therefore the embodied energy of the fuel cell in disposal phase is estimated to be about 7.518 kg CO_2 eq. The pie chart of embodied GHG distribution of ABFC Stack is demonstrated in Fig 8.

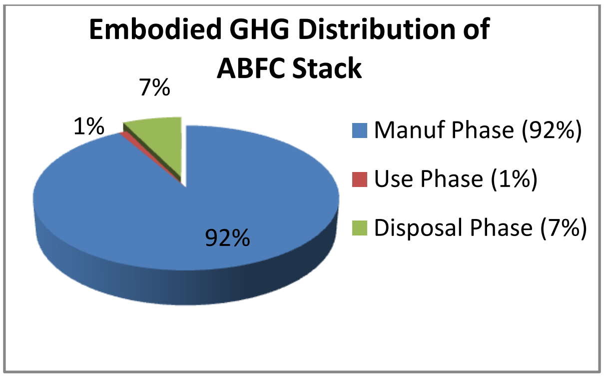

Fig 8. Embodied GHG distribution of ABFC Stack

The total embodied GHG of the 100W ABFC Stack is 103.14 kg CO_2 eq, including 94.5499 kg CO_2 eq(92%) from the manufacturing phase, 1.0702 kg CO_2 eq (1%) from the usage phase and 7.518 kg CO_2 eq (7%) from the disposal phase. The pie chart of embodied GHG emissions for the manufacturing phase is demonstrated in Fig 9.The percentage of embodied GHG emissions for MEAs is highest, 55% and for flow field plates is 25%. In usage Phase, the percentage of the embodied GHG emissions for hydrogen production is highest, 96.1% and for hydrogen compression is 3.9%. In disposal Phase, the percentage of embodied GHG emissions for recycling is highest, 60.21% and for land filling is 39.79%. The Greenhouse gas payback time (GPBT) of the ABFC Stack is estimated to be 0.52 years.

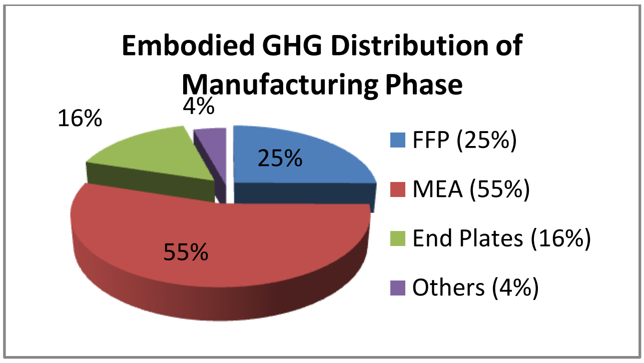

Fig 9. Embodied GHG distribution for manufacturing phase

Table 7: Comparison of 100W ABFC stack with1.65 MW wind turbine and 25 kW Grid connected roof top system.

Parameter	**Solar PV**	**Wind**	**Fuel Cell**
Embodied Energy	65,361 kWh/25KW	10,043 kWh/1.65KW	374.673 kWh/100W
EPBT	1.6	1.12	1.283
Embodied GHG Emissions	15,257.5 $kgCO_{2eq}$/25KW	3,93,842.59 $kgCO_{2eq}$/1.65KW	103.14 $kgCO_{2eq}$/100W
GPBT	0.39	0.136	0.52

Energy payback period and Carbon payback period analysis of a 100W Air breathing Fuel cell stack have been calculated and compared with 25 kW Roof top solar PV and 1.65 MW wind turbine [25 and is tabulated in Table.7. The Comparison of Embodied Energy of renewable energy systems is shown in Fig.10.The embodied energy of a 100W ABFC stack in the lifespan was estimated to be 313.7204 KWh, whereas for 25 kW solar PV and 1.6KW wind turbine, it is found to be 65,361 kWh and 10,043 kWh respectively.

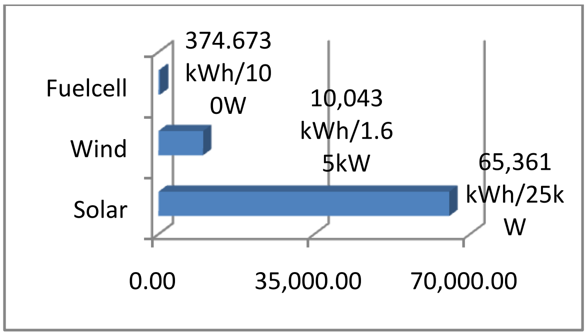

Fig 10. Comparison of Embodied Energy of Renewable energy systems.

The Comparison of Embodied GHG Emissions of renewable energy systems is shown in Fig.11.The embodied GHG emissions of a 100W ABFC stack in the lifespan was estimated to be 103.14 kg CO_2 eq, whereas for 25 kW solar PV and 1.6KW wind turbine, it is found to be 15,257.5 $kgCO_{2eq}$ and 3,93,842.59 $kgCO_{2eq}$ respectively.

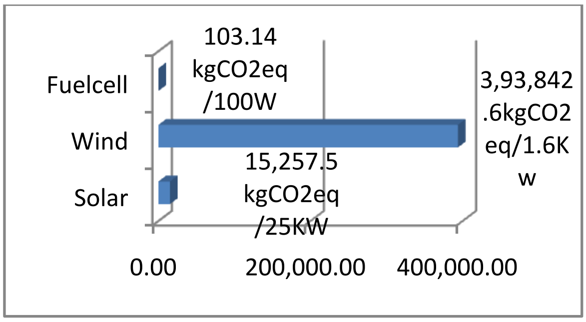

Fig 11. Comparison of Embodied GHG Emissions of Renewable energy systems.

The Comparison of Energy payback time of renewable energy systems is shown in Fig.12. The EPBT of the ABFC Stack is calculated to be 1.283 years, whereas for 25 kW solar PV and 1.6KW wind turbine, it is found to be 1.60 years and 1.12 years respectively.

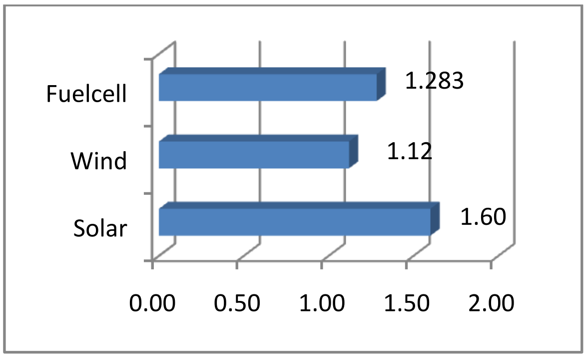

Fig 12. Comparison of EPBT of Renewable energy systems.

The Comparison of green house gas payback time of Renewable energy systems is shown in Fig.13. The GPBT of the ABFC Stack is calculated to be 0.52 years, whereas for 25 kW solar PV and 1.6KW wind turbine, it is found to be 0.39 years and 0.136 years respectively.

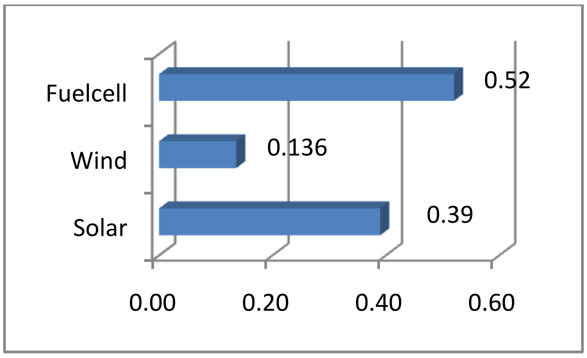

Fig 13. Comparison of GPBT of Renewable energy systems.

5. Conclusion

This paper investigated the EPBT and GPBT of the stack to study the sustainability of the 100W ABFC Stack. The embodied energy of the whole system in the lifespan was estimated to be 313.7204 KWh, with 298.6451 KWh (95.19%) from manufacturing phase, 2.668 KWh (0.85%) from usage phase, and 12.4073 KWh (3.95%) from disposal phase. The embodied GHG emissions of the whole system in the lifespan was estimated to be 103.14 kg CO_2 eq, with 94.5499 kg CO_2 eq (92%) from manufacturing phase, 1.0702 kg CO_2 eq (1%) from usage phase, and 7.518 kg CO_2 eq (7%) from disposal phase. Nearly half of the embodied energy and GHG emissions are form the fabrication of MEA. The EPBT of the Stack is calculated to be 1.283 years and GPBT is 0.52 years which are much shorter than the life time of the stack (8 years). The LCA of 100W ABFC stack is compared with 25 kW Roof top solar PV and 1.65 MW wind turbine. From the above study, environmental impacts are more for ABFC Stack compared solar PV and wind turbine. In conclusion, the stack is truly sustainable and green in its lifespan and there is a need for future timely updates of the LCA data as ABFC stack fabricating technologies continue to improve

6. References

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