Abstract

Fuel cells are increasingly touted as the dominant automotive propulsion technology of the future. Although, the high initial cost of fuel cells preclude their introduction to the mass market for sometime, this was led to a new approach for niche markets so-called auxiliary power units (APUs) [1]. Several fuel cell technologies have been appropriated for use in APU systems such as proton exchange membrane fuel cell (PEMFC) which is the main goal in this project. The PEM fuel cell powered APUs is particularly attractive in saving energy and economic point of views. This project is mainly concentrated on the PEMFC stack APUs technology running on hydrogen-fed fuel for two promising market applications: luxury passenger vehicle and line-haul heavy-duty truck. On the basis of the available data, the electric power density (P/V) obtained by the PEMFC stack APUs for both selected applications were identical. It is a fact that there are several technical considerations involved and are essential to be taken into account to assess the potential of this technology for both selected applications.

Introduction

Over the last five years, the interest to use the fuel cells powered auxiliary power units (APUs) in vehicles has risen due to their potential to reduce emissions, noise, vibration, fuel consumption and size relative to conventional internal combustion engine (ICE) APUs. APU is a device designed to provide additional on-board power in vehicles. The key factors influence on the selection of fuel cell APUs technology is: cost, weight (i.e. power density), efficiency, and system volume. Several fuel cell technologies have been appropriated for use in APU systems such as proton exchange membrane fuel cell (PEMFC). Today the PEM fuel cell is seriously considered for vehicle applications. The PEM fuel cells deliver high power density and offer the advantages of low weight and volume compared to the other fuel cells. The operating temperature in the PEM fuel cells is relatively low and this allows starting quickly and leads to have less wear on system components and better durability. The PEM fuel cells are particularly suitable for use in passenger vehicles and this is due to their fast startup time, low sensitivity to orientation, and favorable power-to-weight ratio. The PEM fuel cells like other fuel cells have a unique set of requirements and characteristics for each particular APUs application. Power requirement is one of the key parameters to determine how fuel cell APUs might be attractive for a set of promising market applications [1]. The main goal is to design low operating temperature PEMFC stack APUs running on hydrogen-fed fuel to estimate its potential for the two selected applications: luxury passenger vehicles and line-haul heavy-duty trucks. Several considerations such as: power size, energy, weight, and space target are thus needed to take into account to assess the potential of this technology for the two selected applications.
Problem Statement

Although the low operating temperature of the PEM fuel cells makes them very suitable for APU applications, problems of hydrogen storage and lack of infrastructure limits its commercialization in transportation applications. One of the biggest problems related to hydrogen use in the PEM fuel cell for passenger vehicles is hydrogen on-board storage [2].

There are of course several electric accessories and other key parameters which have to be considered and thus added to determine where and how the PEM fuel cell APUs might be attractive. There are also several components and subsystems which have to be added to the fuel cell system since the PEM fuel cell stack APUs is just one component of the overall system. Therefore, the fuel cell system requires the integration of several components or subsystems besides the fuel cell stack itself as the fuel cell will generate only dc power and utilize only certain processes fuel. In addition, each application, besides power output, has its own specific requirements, such as efficiency, water balance, heat utilization, quick startup, size, weight, fuel supply, etc [1].

The design is built upon a review of a few literatures, and available data, however, the data were not sufficient to estimate the potential of the PEM fuel cell stack APUs as a heart component of the overall fuel cell system for the selected applications and thus more analysis is needed even at this step.

Literature Survey

The PEM fuel cells deliver high power density and offer the advantages of low weight and volume compared to the other fuel cells. The efficiency in PEM fuel cells is approximately between 40-50 percent. The cells power outputs generally range from 50-250 kW [6]. The PEM fuel cells are used primarily for transportation applications and some stationary applications. Because of their fast startup time, low sensitivity to orientation, and favorable power-to-weight ratio, PEM fuel cells are particularly suitable for use in passenger vehicles, such as cars and buses.

Several international automotive companies have launched major fuel cell vehicle development programs and the Bush Administration has designated fuel cells vehicles as central to federal automotive R&D efforts. The high initial costs of fuel cells preclude the introduction of fuel cells as automotive propulsion technology to the mass market and this leads to a new approach so-called APUs [1]. APU is a device on a vehicle whose purpose is to provide energy for functions other than propulsion. It provides auxiliary power for vehicle comfort features and added functionality and eliminates the high fuel consumption, wear and tear, and emissions associated with the long idle operation when on-board electricity is being generated by running the main drive engine [5].

Fuel cells as APUs offer potential advantages in overall energy efficiency, emissions and costs. There are of course several key parameters to determine where and how fuel cell APUs might be attractive including operational characteristics of auxiliary power (total power requirement, time of use, etc) and market variables (total vehicle cost, sales, and trends).

For each particular APU application, fuel cells have a unique set of requirements and characteristics. Fuel cell and fuel cell system design are not necessarily the same for each of these applications. Each application, besides power output, has its own specific requirements, such as efficiency, water balance, heat utilization, quick startup, size, weight, fuel supply, etc [1].

The increasing in electric power demands has prompted the auto industry to explore a transition from 12/14-V systems to 36/42-V systems. To determine the most appropriate APU size for near-term electrification of passenger cars, the power demands was calculated for all accessories and amenities that might be required while the vehicle is at rest. In this respect, the power requirements, volume and weight targets, costs, market sizes, and potential benefits for several fuel cell technologies and fuels were analyzed though as
it was mentioned their assessment is limited by
data availability. In their research, the total
maximum power requirement for an APU in a
luxury passenger vehicle excluding the whole
electric accessories was calculated between 5-7
kW in summer and winter conditions. The total
maximum power requirement for an APU
(stack and auxiliary components) for line-haul
heavy-duty trucks was 3-kW [1].
A fuel cell stack is the heart of a fuel cell
system; however, without the supporting
equipment the stack itself would not be very
useful. The fuel cell system typically involves
the following subsystems: oxidant supply,
hydrogen fuel supply, heat management, water
management, power conditioning and
instrumentation and controls [2].
One of the barriers to use PEM fuel cells as
APUs particularly for transportation is non-
existence of hydrogen fuel infrastructure, and
difficulties related to hydrogen storage.
Hydrogen can be stored as compressed gas, as a
cryogenic liquid or in metal hydrides. Tanks for
compressed gaseous hydrogen are bulky, even
if hydrogen is compressed to 450 bars. It takes
about 40-50 liters of space to store 1 kg of
hydrogen. The amount of fuel to be stored on-
board depends on the vehicle fuel efficiency
and required range.
From the previous research it was found that
there would be important research step to
conduct a cost-benefit analysis of fuel cell
APUs and competing alternatives. A
comprehensive analysis of material and energy
flows on-board the vehicle is needed to quantify
potential emissions and energy benefits. More
data collection of existing prototype systems
and on-going fuel cell demonstrations is
recommended, along with vehicle system
modeling of APU-enhanced systems. More
analyses is needed of auxiliary (i.e. non-
propulsion) power cost, weight, and volume
targets [1].

Project Description

Introduction

The design of the PEM fuel cell stack
APUs for this project is built upon several
assumptions and also some previous findings
from the literature review for two potential
market applications: luxury passenger vehicle
and line-haul heavy-duty truck. The maximum
total power demand for APUs in a luxury
passenger vehicle in winter and summer
conditions could be as high as 5-7 kW.
Therefore, the basis of the calculations for the
design of this technology for luxury passenger
vehicle was upon the maximum total power
demand, 6690 W, in winter condition. In this
respect, the total maximum APU power
requirement (stack and auxiliary components)
in line-haul heavy-duty truck was considered
3000 W[1].

Design

The methodology used for the design was
mainly built upon PEM fuel cell load and also
APU loads in two selected voltage systems: 12
V-DC and 36V-DC and then connect them
together in order to estimate the potential of this
technology for both selected applications
respectively. The main concept behind the two
selected voltage systems could be to reduce the
electric losses due to the increase in electric
power demands and thus a transition from
12/14 V-DC to 36/42 V-DC systems.

PEM Fuel Cell Specification

Assumptions

2. The average voltage of each cell in each
stack (Vc) is 0.65 V[Appendix].
3. The current density of the fuel cell is
0.65 A cm² which is corresponding to
the Vc [Appendix].
4. The active cell area is 120 cm².
5. Individual fuel cells in series are
arranged in parallel stacks.
6. The overall thickness of each cell
including anode, cathode, electrolyte and
interconnect is 0.4 cm.
7. The thickness of the end plate is 1
cm[3].
**Calculations**

Power density and power generated through each fuel cell stack will be calculated respectively:

\[
P = I \times V
\]

\[
P/A = (0.65 \text{ A cm}^{-2}) \times (0.65 \text{ V}) = 0.423 \text{ W cm}^{-2}
\]

\[
P_{\text{cell}} = (0.423 \text{ W cm}^{-2}) \times (120 \text{ cm}^2) = 50.8 \text{ W}
\]

Thereby, the total number of PEM fuel cells required, voltage and current generated for the APU of luxury passenger vehicle and line-haul heavy-duty truck will be calculated respectively:

**Luxury passenger vehicle**

Total number of the cells required:
\[
n_{\text{cell}} = 6690/50.8 = 132
\]

Total voltage: \( V = (0.65) \times (132) = 86 \text{ v} \)

Total current: \( I = (0.65) \times (120) = 78 \text{ A} \)

**Line-haul heavy-duty truck**

Total number of the cells required:
\[
n_{\text{cell}} = 3000/50.8 = 59
\]

Total voltage: \( V = (0.65) \times (59) = 38.4 \text{ v} \)

Total current: \( I = (0.65) \times (120) = 78 \text{ A} \)

**APU Applications Specification**

The following tables illustrate the total number of the required PEM stacks and cells in each stack as APUs for luxury passenger vehicle and line-haul heavy-duty truck respectively. Thereby total fuel cell stack power output will be calculated such that it is well high enough to fulfil the whole power demand for each selected applications.

**Calculations**

**Table 1 PEMFC APUs for Luxury Passenger Vehicle**

<table>
<thead>
<tr>
<th>Total Numbers</th>
<th>12 V-DC System</th>
<th>36 V-DC System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stacks (N)</td>
<td>( V_{\text{total}/12}=86/12 = 7.17 )</td>
<td>( V_{\text{total}/36}=86/36 = 2.39 )</td>
</tr>
<tr>
<td>Cells in each stack (n')</td>
<td>( 12/ V_{c} = 12/0.65=18.5 )</td>
<td>( 36/ V_{c} = 36/0.65=55.4 )</td>
</tr>
<tr>
<td>Cells (n)</td>
<td>8*18 = 144</td>
<td>3*55 = 165</td>
</tr>
<tr>
<td>Total fuel cell stack power Pe (W)</td>
<td>( P= (N<em>I)</em> V )</td>
<td>( P= (N<em>I)</em> V )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>12 V-DC System</th>
<th>36 V-DC System</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 stacks &amp; 18 cells for each stack</td>
<td>3 stacks &amp; 55 cells for each stack</td>
</tr>
<tr>
<td>Total fuel cell stack power Pe (W)</td>
<td>( P= (N<em>I)</em> V )</td>
</tr>
</tbody>
</table>

**Table 2 PEMFC APUs for Line-haul heavy-duty Truck**

<table>
<thead>
<tr>
<th>Total Numbers</th>
<th>12 V-DC System</th>
<th>36 V-DC System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stacks (N)</td>
<td>( V_{\text{total}/12}=38.4 /12 = 3.2 )</td>
<td>( V_{\text{total}/36}=38.4 /36 = 1.07 )</td>
</tr>
<tr>
<td>Cells in each stack (n')</td>
<td>( 12/ V_{c} = 12/0.65=18.5 )</td>
<td>( 36/ V_{c} = 36/0.65=55.4 )</td>
</tr>
<tr>
<td>Cells (n)</td>
<td>4*18 = 72</td>
<td>2*55 = 110</td>
</tr>
<tr>
<td>Total fuel cell stack power Pe (W)</td>
<td>( P= (N<em>I)</em> V )</td>
<td>( P= (N<em>I)</em> V )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>12 V-DC System</th>
<th>36 V-DC System</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 stacks &amp; 18 cells for each stack</td>
<td>2 stacks &amp; 55 cells for each stack</td>
</tr>
<tr>
<td>Total fuel cell stack power Pe (W)</td>
<td>( P= (N<em>I)</em> V )</td>
</tr>
</tbody>
</table>
**PEM Fuel Cell Usage & Production**

The following tables demonstrate the rate of the oxygen usage and hydrogen-fed fuel consumption in PEMFC stack APUs for the two selected applications respectively. The inlet air flow rate to remove the product water flows through the cell and subsequently the exit air flow rate were calculated. The air is always fed through the cell well above the stoichiometric rate ($\lambda$), typically twice as much, otherwise the exit air would be totally depleted of oxygen.

The actual efficiency of the cell is calculated by the ratio of actual cell voltage and the output voltage with reference to the HHV as the PEM fuel cell is operating at low temperature ($80^\circ$C). The heat and also the electrical power generated during the operational of the PEMFC stack as APUs for the each selected applications were calculated respectively [Appendix].

<table>
<thead>
<tr>
<th>Table 3 PEMFCs APU for Luxury Passenger Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$12\ V-DC\ System$</td>
</tr>
<tr>
<td>Pe(W)</td>
</tr>
<tr>
<td>Vc (v)</td>
</tr>
<tr>
<td>$F = 96485\ C$</td>
</tr>
<tr>
<td>$m_{O_2} = (0.0032/4<em>F)</em>(Pe/Vc)$</td>
</tr>
<tr>
<td>$m_{O_2}$ (kg/s)</td>
</tr>
<tr>
<td>$m_{\text{(air inlet)}} = (3.57 \times 10^{-7})*\lambda \times (Pe/Vc)$</td>
</tr>
<tr>
<td>$m_{\text{(air inlet)}}$ (kg/s)</td>
</tr>
<tr>
<td>$m_{\text{(air outlet)}} = m_{\text{(air inlet)}} - m_{O_2}$</td>
</tr>
<tr>
<td>$m_{\text{(air outlet)}}$ (kg/s)</td>
</tr>
<tr>
<td>$m_{H_2} = (1.05 \times 10^{-8})*(Pe/Vc)$</td>
</tr>
<tr>
<td>$m_{H_2}$ (kg/s)</td>
</tr>
<tr>
<td>$m_{H_2O} = (9.34 \times 10^{-8})*Pe/Vc$</td>
</tr>
<tr>
<td>$m_{H_2O}$ (kg/s)</td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
<tr>
<td>Heat Generation</td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>I (A)</td>
</tr>
<tr>
<td>Heat Generation (W)</td>
</tr>
<tr>
<td>Electricity Generation= $Pe *((1.48/Vc)-1))$</td>
</tr>
<tr>
<td>Electricity Generation (W)</td>
</tr>
</tbody>
</table>
Table 4 PEMFCs APU for Line-haul heavy-duty truck

<table>
<thead>
<tr>
<th></th>
<th>12 V-DC System</th>
<th>36 V-DC System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pe(W)</td>
<td>3744</td>
<td>5616</td>
</tr>
<tr>
<td>Vc (v)</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>m_O2 (kg/s)</td>
<td>0.000477</td>
<td>0.000716</td>
</tr>
<tr>
<td>m_air inlet (kg/s)</td>
<td>0.00413</td>
<td>0.00617</td>
</tr>
<tr>
<td>m_air outlet (kg/s)</td>
<td>0.00365</td>
<td>0.00545</td>
</tr>
<tr>
<td>m_H2 (kg/s)</td>
<td>0.0000605</td>
<td>0.0000907</td>
</tr>
<tr>
<td>m_H2O (kg/s)</td>
<td>0.000538</td>
<td>0.000807</td>
</tr>
<tr>
<td>efficiency</td>
<td>44%</td>
<td></td>
</tr>
<tr>
<td>Heat Generation</td>
<td>n<em>I</em>(1.48-Vc)</td>
<td></td>
</tr>
<tr>
<td>n (total no of cells)</td>
<td>72</td>
<td>110</td>
</tr>
<tr>
<td>I (A)</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>Heat Generation (W)</td>
<td>4662</td>
<td>7122</td>
</tr>
<tr>
<td>Electricity Generation (W)</td>
<td>4781</td>
<td>7171</td>
</tr>
</tbody>
</table>

PEMFC Stack Size

The following tables illustrate the power density (kW/L), one of the key parameters in automotive industry, to compare the electricity generation by the PEMFC stack APUs for each selected applications. The height and the volume of each Fuel Cell for the selected applications will be calculated by the following equations [3]:

\[
\begin{align*}
    h_{\text{stack}} &= (h_{\text{interconnect}} + h_{\text{anode}} + h_{\text{electrolyte}} + h_{\text{cathode}} + 2*h_{\text{endplates}}) * n_{\text{cell}} \\
    V_{\text{stack}} &= A_{\text{cell}} * h_{\text{stack}} * N
\end{align*}
\]

Table 5 PEMFCs APU for Luxury Passenger Vehicle

<table>
<thead>
<tr>
<th></th>
<th>12 V-DC System</th>
<th>36 V-DC System</th>
</tr>
</thead>
<tbody>
<tr>
<td>n'</td>
<td>18</td>
<td>55</td>
</tr>
<tr>
<td>N</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>h_stack (cm)</td>
<td>73.6</td>
<td>72</td>
</tr>
<tr>
<td>A_{cell} (cm^2)</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>V_{stack} (L)</td>
<td>8.83</td>
<td>8.64</td>
</tr>
<tr>
<td>Power output (W)</td>
<td>7488</td>
<td>8424</td>
</tr>
<tr>
<td>Power density (kW/L)</td>
<td>0.848</td>
<td>0.975</td>
</tr>
</tbody>
</table>
Table 6 PEMFCs APU for Line-haul heavy-duty truck

<table>
<thead>
<tr>
<th></th>
<th>12 V-DC System</th>
<th>36 V-DC System</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n' )</td>
<td>18</td>
<td>55</td>
</tr>
<tr>
<td>( N )</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>( h_{\text{stack}} ) (cm)</td>
<td>36.8</td>
<td>48</td>
</tr>
<tr>
<td>( A_{\text{cell}} ) (cm(^2))</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>( V_{\text{stack}} ) (L)</td>
<td>4.42</td>
<td>5.76</td>
</tr>
<tr>
<td>Power output (W)</td>
<td>3744</td>
<td>5616</td>
</tr>
<tr>
<td>Power density (kW/L)</td>
<td><strong>0.847</strong></td>
<td><strong>0.975</strong></td>
</tr>
</tbody>
</table>

**Discussion**

Although the PEMFC stack is the heart of the fuel cell system, it is just one component of the overall system. While the fuel cell system requires the integration of several components and subsystems apart from the fuel cell stack itself as the fuel cell will generate only dc power and utilize only certain processes fuel. The fuel cell system has three subsystems: the fuel processor, the fuel cell stack, and power conditioner. "Balance of plant" components include pumps, compressors, heat exchangers, electric motors, controllers and batteries. The fuel cell system configuration also greatly depends on the application such that in some cases more components or subsystems are needed to be added. Each application, besides power output, has its own specific requirements, such as efficiency, water balance, heat utilization, quick start-up, size, weight, fuel supply, etc. Although low operating temperature of the PEM fuel cells make them very suitable for APU applications, problems of hydrogen storage and lack of infrastructure limits its commercialization in transportation applications. One of the biggest problems related to hydrogen use in the PEM fuel cell for passenger vehicles is hydrogen on-board storage. Hydrogen can be stored as compressed gas as cryogenic liquid or contained with metal or chemical hydrides which empty chemical reactions to store and release hydrogen. Tanks for compressed gaseous hydrogen are bulky even if hydrogen is compressed to 450 bars and thus it takes 40-50 liters of space to store 1 kg of hydrogen [1,2].

It was found that the PEM fuel cell as APUs technology has the potential to reduce emissions, noise, fuel consumption and size relative to conventional, ICE as APUs. The efficiency of the PEMFCs as APUs is, however, more than a comparable ICE as APUs, this can not be compared at their most favorable operating point. These two technologies are intrinsically different and have great difference in efficiency in terms of power characteristics. While an ICE has its maximum efficiency at or near its maximum power, a fuel cell system has its maximum efficiency at partial load. Therefore, the efficiency of the PEM fuel cell propulsion system in a typical driving schedule where an automobile engine operates most of the time at partial load can be about twice that of an ICE [2].

**Conclusions**

This project dealt with the design of the PEMFC stack APUs to estimate its potential for the two promising market applications: luxury passenger vehicles and line-haul heavy-duty truck. The following table compares the several parameters calculated for both selected applications in this project:
In this project, it was deduced that:

- The configuration of the PEMFC stacks APUs for both selected applications may lead to have variations in number of stacks but equal number of cells for each stack.
- The total voltage of the PEMFC stack depends on the number of stacks.
- Identical electric power generated per volume (P/V) by PEMFC stack APUs for both selected applications. In this respect, however, each application, besides power output, has its own specific requirements, such as efficiency, water balance, heat utilization, quick startup, size, weight, fuel supply, etc. In addition, the fuel cell system besides the fuel cell stack itself requires the integration of several components and subsystems. This is eventually followed by the integration of the fuel cell system into the vehicles. Thus, there are several considerations influenced on the system volume and subsequently power generated per volume for each selected application [1].

This design is built upon a review of the literature, and available data, however, the data were not sufficient to estimate the potential of the PEM fuel cell stack APUs as a heart component of the overall fuel cell system for the selected applications and thus more analysis is needed even in this step. In overall, future efforts are expected to focus on the development of fuel cell balance of plant technologies related to fuel storage, fuel processing, and infrastructure, scale up of advanced fuel cell systems and integration into vehicles for demonstration and technology improvements in fuel cell power density, system efficiency, systems integration, and cost reduction[4].
References


[4] [www.usfcc.com](http://www.usfcc.com), spring 2001


Appendix

The mean voltage of each (Vc) PEM fuel cell at about 70 \(^\circ\)C at normal air pressure is obtained from the figure 2.4. V-I performance for a typical PEMFC and this also gives the current density correspondingly [2].

**PEMFC Stack Size:**

The stack volume and height are obtained from the following equations [3]:

\[
h_{\text{stack}} = (h_{\text{interconnect}} + h_{\text{anode}} + h_{\text{electrolyte}} + h_{\text{cathode}}) \times n_{\text{cell}} + 2 \times h_{\text{endplates}}
\]

\[
V_{\text{stack}} = A_{\text{cell}} \times h_{\text{stack}} \times N
\]

Where:

- \(N\) is the number of stacks
- \(n_{\text{cell}}\) is the number of cells in each stack

**Fuel Cell Equations:**

**O\(_2\) & H\(_2\) Usage Mass Flow Rates:**

The mass flow rate of the oxygen and hydrogen fuel consumed to produce water will be obtained by the following equations:

\[
m_{O_2} = \frac{1}{4 \times F} \times (Pe/Vc) \text{ mol/s}
\]

\[
m_{O_2} = \frac{0.0032}{4 \times F} \times (Pe/Vc) \text{ kg/s}
\]

Where:

- \(F = 96485 \text{ C}\)

The mass flow rate of hydrogen is derived in a way similar to oxygen, except that there are two electrons from each mole of hydrogen:

\[
m_{H_2} = \frac{Pe}{2 \times F \times Vc} \text{ mol/s}
\]

The molar mass of hydrogen is 2.02 \(\times 10^{-3}\) kg/mol so this becomes at stoichiometric operation [2]:

\[
m_{H_2} = (1.05 \times 10^{-8}) \times (Pe/Vc) \text{ kg/s}
\]

This equation only applies to a hydrogen-fed fuel cell.

**Air Inlet & Outlet Mass Flow Rates:**

The mass flow rate of air fed to the cathode will be obtained by the following equation [2]:

\[
m_{\text{air inlet}} = \frac{(28.97 \times 10^{-3})}{(0.21 \times 4 \times F)} \times (Pe/Vc) \text{ kg/s}
\]
In the above equation:
- The molar proportion of air that is oxygen = 0.21.
- The entry air is assumed to be dry at 20 °C, total pressure at 1 bar, and 70% relative humidity. The molar mass of air is 28.97*10^{-3} kg/mol

However, the above equation is impractical since in practice the air is always fed through the cell well above the stoichiometric rate (\( \lambda \)), typically twice as much, otherwise the exit air would be totally depleted of oxygen [2].

\[
m_{\text{air inlet}} = (3.57 \times 10^{-7}) \times \lambda \times (P_e/V_c) \text{ kg/s}
\]

Where: \( \lambda = 2 \)

The temperature of the exit air is assumed above about 60 °C. Thereby mass flow rate of the exit air will be derived by the difference of the mass flow rate of inlet air and mass flow rate of oxygen consumed.

\[
m_{\text{air outlet}} = m_{\text{air inlet}} - m_{O2} \text{ kg/s}
\]

**H₂O Production Mass Flow Rates:**

It is a hydrogen-fed fuel cell, and thus water is produced at the rate of one mole for every two electrons [2].

\[
m_{H₂O} = (1/2*F) \times (P_e/V_c) \text{ mol/s}
\]

The molecular mass of water is 18.02*10^{-3} kg/mol, therefore:

\[
m_{H₂O} = (9.34 \times 10^{-8}) \times P_e/V_c \text{ kg/s}
\]

**Efficiency:**

It is assumed that the PEMFC as APUs is operating at low temperature about 80 °C. Therefore, the actual efficiency of the cell is calculated by the ratio of actual cell voltage and the output voltage with reference to the HHV as the PEM fuel cell is operating at low temperature (80 °C) and thus the water product is in liquid form [2].

\[
\text{efficiency} = V_c/1.48
\]
Where:
Output voltage = 1.48 (water is in liquid form)

**HG & EG Production:**
The heat and also the electrical power generated during the operational of the PEMFC stack as APUs for the each selected applications were obtained respectively [2].

\[
\text{Heat Generation} = n*I*(1.48 - Vc) \\
\text{Electricity Generation} = Pe *((1.48/Vc)-1))
\]

Where:
n is the total number of cells
Pe is total fuel cell stack power output