Proton exchange membrane fuel cells for electrical power generation on-board commercial airplanes

Joseph W. Pratt, Leonard E. Klebanoff, Karina Munoz-Ramos, Abbas A. Akhil, Dita B. Curgus, Benjamin L. Schenkman

Sandia National Laboratories/California, P.O. Box 969, Livermore, CA 94551, USA

Sandia National Laboratories/New Mexico, P.O. Box 5800, Albuquerque, NM 87185, USA

A R T I C L E   I N F O
Article history:
Received 20 February 2012
Received in revised form 26 June 2012
Accepted 6 August 2012
Available online 13 September 2012

Keywords:
PEM fuel cell
More electric airplane
Heat recovery
System design
Airplane performance

A B S T R A C T
Deployed on a commercial airplane, proton exchange membrane (PEM) fuel cells may offer emissions reductions, thermal efficiency gains, and enable locating the power near the point of use. This work seeks to understand whether on-board fuel cell systems are technically feasible, and, if so, if they could offer a performance advantage for the airplane when using today's off-the-shelf technology. We also examine the effects of the fuel cell system on airplane performance with (1) different electrical loads, (2) different locations on the airplane, and (3) expected advances in fuel cell and hydrogen storage technologies.

Through hardware analysis and thermodynamic simulation, we found that an additional fuel cell system on a commercial airplane is technically feasible using current technology. Although applied to a Boeing 787-type airplane, the method presented is applicable to other airframes as well. Recovery and onboard use of the heat and water that is generated by the fuel cell is an important method to increase the benefit of such a system. The best performance is achieved when the fuel cell is coupled to a load that utilizes the full output of the fuel cell for the entire flight. The effects of location are small and location may be better determined by other considerations such as safety and modularity.

Although the PEM fuel cell generates power more efficiently than the gas turbine generators currently used, when considering the effect of the fuel cell system on the airplane's overall performance we found that an overall performance penalty (i.e., the airplane will burn more jet fuel) would result if using current technology for the fuel cell and hydrogen storage. However, we found that with expected developments in PEM fuel cell and hydrogen storage technology, PEM fuel cell systems can provide an overall benefit to airplane performance.

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1. Introduction

Fuel cells have become increasingly important as alternative sources of power, offering the potential for drastic reduction in emissions in particulate matter (PM), nitrogen oxides (NOx), and CO2. In addition, they offer exceptionally quiet operation, highly efficient use of the fuel energy, and for the larger values of stored energy, a higher energy storage density than batteries. For a number of years, the manufacturers of commercial aircraft, most notably Boeing and Airbus, have realized that fuel cells may offer advantages for commercial aircraft operation. Apart from emissions reductions and thermal efficiency referenced above, they can constitute distributed power systems, enabling locating the...
power near the point of use (reducing wiring) and also reducing the power draw from the engines.

A primary question is if fuel cells offer operational advantages over traditional power in systems that are used routinely in flight, for example galley power, in-flight entertainment, and to provide additional power to the aircraft electrical grid when “peaker” power is needed. This interest in the use of fuel cells is timely, as the electrical needs on-board are going up considerably as systems that were formerly hydraulic in operation are being converted to electric operation [1]. For the new Boeing 787, the aircraft-wide electrical generation capacity is 1.5 MW – almost an order of magnitude larger than for previous designs.

Recently the German Aerospace Center (DLR) has conducted successful flight tests of a fuel cell power system for hydraulic backup power [2], and a fuel cell-powered nose wheel drive motor [3], and has examined design of a fuel cell system providing power, water, and inert gas [4], although the latter study does not consider the impact on airplane performance. In addition, Boeing has been examining the use of fuel cells for on-board electrical power generation for at least the past 10 years, including for distributed power systems [5–8]. A few years ago, Boeing sponsored a study which examined the use of a PEM fuel cell for a ram air turbine (RAT) emergency power backup system [9]. The results of that study indicated that the fuel cell could successfully replace a conventional RAT, but offered little performance advantages. Fuel cells have also been explored for auxiliary power units (APU) and other high-altitude applications [10–15].

In this study, we examine the system design options and overall feasibility of deploying a PEM fuel cell on-board a commercial aircraft through a comprehensive consideration of the entire airplane’s performance with and without the fuel cell system. Although we have chosen to apply this concept to a particular airplane and mission to provide specific results, the method we use has been described in detail so that other workers are able to apply it to other platforms and/or flights given the appropriate data.

We begin by applying the fuel cell to power a single electrical load, the 20 kW in-flight entertainment (IFE) system, to understand the feasibility, advantages, and disadvantages of various system configurations. Following that, we examine the effect of several design and implementation changes on airplane performance. These changes are: (1) different types of electrical loads, (2) different physical locations of the PEM fuel cell system on the airplane, and (3) expected technology improvements for PEM fuel cells and hydrogen storage systems. In a companion paper we examine the electrical characteristics for a variety of on-board applications such as galley power and peaker power [16].

This study is unique compared to other work in this field in that (1) the system we are considering is intended to be used throughout a normal flight, (2) the electrical output could be tied-in to the existing electrical system, and (3) we consider the entire airplane when assessing the net effect on performance.

2. Analysis

The purpose of this study is to find how deployment of a fuel cell on a commercial airplane would affect the overall performance of the airplane. To accomplish this, two basic airplane designs were considered: one airplane without a fuel cell (the base airplane), and one airplane designed to perform the same mission as the first airplane, only carrying a fuel cell and associated hardware to fulfill a specific electrical need. While the fuel cell in this study will supply some of the electricity and heat needed by the airplane, it will not eliminate the need for either the main engine generators or auxiliary power unit. The difference in the performance of these two airplanes is made quantitative by calculating the fuel required to fly the identical mission in the two cases, which requires understanding the influence of drag. Calculating the required fuel also allows us to assess fuel use as it directly relates to power generation on the airplane. As the focus of this study is on the airplane, no attempt to assess the energy needed to produce, store, and dispense the hydrogen for the fuel cell has been made.

The airplane selected as the basis for this study is a derivative of a Boeing 787-8. “Derivative” means that while the specifications would be similar to a 787-8, the airplane on which a fuel cell is deployed would be a different model not currently planned by Boeing. This platform was selected primarily because it represents the state-of-the-art in “more electric airplane” (MEA) designs. The MEA differs from traditional airplanes in that many of its systems that were previously powered by pressurized air extracted from the main engines (bleed air) or by hydraulic power are now powered by electricity. These additional electrical loads include engine start, wing de-ice, cabin environmental control and pressurization, brakes, and flight controls [17]. This totally re-designed, much larger electrical system could potentially be more readily adapted to incorporate an on-board fuel cell. In addition, the larger electrical load means that the potential benefit to using fuel cells to replace current generators might be higher than for current, less-electric airplanes.

The mission we model is a transcontinental flight between San Francisco International Airport (SFO) and John F. Kennedy International Airport (JFK) in New York City, a distance of 4139 km (2235 nm). This choice was made as being a typical intermediate-length flight for a 787-8.

It is important to review the system specifications for the “base aircraft” of the model, indicated in Table 1.

2.1. Models

2.1.1. Airplane performance model

Many individual factors can be used to measure the performance of an airplane depending on the particular emphasis. These factors include fuel consumption, ratio of lift over drag, velocity (or Mach number), weight, and fuel capacity. Each of these may be more important than the others for a particular application. However, all of these factors can be combined together to give an expression for airplane range. The Breguet range equation is a classic method combining these factors, and can be expressed as [19]:

\[ R = \frac{aM}{c_f} \ln \frac{W_1}{W_2} \]

(1)

where \( R \) is the range, \( a \) the local speed of sound, \( M \) the Mach number, \( c_f \) the thrust specific fuel consumption, \( C_l \) the coefficient of lift, \( C_D \) the coefficient of drag, \( W_1 \) starting weight, and \( W_2 \) the final weight. The equation can be used to determine range between any two points (1–2) on a flight.

2.1.1.1. Base airplane, base mission. A special case is where the Breguet equation is solved for the range of an entire mission. In this case, \( W_1 \) is the weight of the aircraft at takeoff and \( W_2 \) is the weight of the aircraft at landing. \( W_1 \) can be expressed as the sum of its parts:

\[ W_1 = W_{OBW} + W_p + W_{F, unused} + W_{F, reserve} \]

(2)

\( W_{OBW} \) is the operating empty weight, which is the weight of the structure, engines, furnishings, unusable fuel, other integral parts of the airplane configuration, and standard supplies, personnel, equipment necessary for full operations. \( W_p \) is the payload, including passengers, their baggage, and cargo. \( W_{F, unused} \) is the fuel burned during the mission, and \( W_{F, reserve} \) is the extra fuel that must be carried but is not used in normal missions.
For this special case the airplane has used all of its fuel ($W_{F_{used}}$) upon landing, so that $W_2$ is:

$$W_2 = W_{GW} + W_P + W_{F_{reserve}} \quad (3)$$

The minimum amount of reserve fuel is regulated by the FAA and depends on the mission length and destination. Airlines may add to this amount in accordance with their own policies. In general, the reserve fuel can be expressed as a fraction of the used fuel:

$$W_{F_{reserve}} = x W_{F_{used}} \quad (4)$$

Airplane drag ($C_D$) can be separated into two components, induced drag ($C_{Dl}$) due to the creation of lift, and zero-lift drag ($C_{D0}$) due to all other effects including the shape, friction, etc. (more information on the types of drag can be found in Ref. [19]). Thus:

$$C_D = C_{Dl} + C_{D0} \quad (5)$$

Combining Eqs. (1)–(5) results in a range equation for the base airplane on the base mission:

$$R = \frac{aM}{c_T} \frac{C_l}{C_{Dl} + C_{D0}} \ln \left( 1 + \frac{W_{F_{used}}}{W_{GW} + W_P + xW_{F_{used}}} \right) \quad (6)$$

### 2.1.1.2. Effect of weight and drag changes.

The effect of adding a fuel cell system to the airplane is quantified by comparing the performance of the base airplane to the performance of the airplane with the fuel cell. Since this study assumes a derivative of the existing 787 airplane, we assume there is no change to the overall shape or airplane performance capabilities if fuel cells are utilized. This means that, for purposes of this study, all variables in the range equation are assumed constant between the base case and the case with the fuel cell system, with two exceptions. The first is the change in airplane weights $W_1$ and $W_2$ due to the additional fuel cell system weight, and the second is the change in the zero-lift drag coefficient $C_{D0}$ due to additional airplane cooling requirements. In either case, the effect of using fuel cells can be quantified by the amount of extra fuel needed (or fuel saved) for the airplane to accomplish the same mission as the base airplane.

The first step in this analysis is to rearrange Eq. (6):

$$R \frac{aM}{c_T} \frac{1}{C_l} = \frac{1}{C_{Dl} + C_{D0}} \ln \left( 1 + \frac{W_{F_{used}}}{W_{GW} + W_P + xW_{F_{used}}} \right) \quad (7)$$

Since all the terms on the left-hand side are assumed to be the same for the base airplane and the airplane with the fuel cell, they can be combined to a single constant ($K$):

$$R \frac{aM}{c_T} = K \quad (8)$$

Combining Eqs. (7) and (8) shows that:

$$K = \frac{1}{C_{Dl} + C_{D0}} \ln \left( 1 + \frac{W_{F_{used}}}{W_{GW} + W_P + xW_{F_{used}}} \right) \quad (9)$$

Eq. (9) is then solved for the base airplane to determine the constant $K$.

We want to quantify the effect on the fuel used, so Eq. (9) can be rearranged to solve for $W_{F_{used}}$:

$$W_{F_{used}} = \frac{(W_{GW} + W_P)(e^{K(C_{D0} + C_{Dl})} - 1)}{1 + x(1 - e^{K(C_{D0} + C_{Dl})})} \quad (10)$$

A change (from the base airplane) in operating empty weight $\Delta W_{GW}$ and/or zero-lift drag $\Delta C_{D0}$ will correspond to a change in the fuel used, $\Delta W_{F_{used}}$. Eq. (10) can then be written as:

$$W_{F_{used}} + \Delta W_{F_{used}} = \frac{W_{GW} + \Delta W_{GW} + W_P(e^{K(C_{D0} + C_{Dl})} - 1)}{1 + x(1 - e^{K(C_{D0} + C_{Dl})})} \quad (11)$$

Solving for $\Delta W_{F_{used}}$ and combining the drag terms using Eq. (5) gives:

$$\Delta W_{F_{used}} = \frac{W_{GW} + \Delta W_{GW} + W_P(e^{K(C_{D0} + C_{Dl})} - 1) - W_{F_{used}}}{1 + x(1 - e^{K(C_{D0} + C_{Dl})})} \quad (12)$$

This gives the additional fuel that must be carried for the airplane with the fuel cell system to achieve the same mission performance as the base airplane. By including the effect of both additional weight and drag, it automatically takes into account the interaction between the two. However, the disadvantage is only the combined effect can be seen. To better understand the individual effects of the weight and drag, the results shown in this paper solve Eq. (12) twice: once for a change in weight assuming no change in drag, and once for a change in drag assuming no change in weight. The fuel changes are then added. The slight error of using this method (less than 0.2% for values typical in this work) is considered acceptable so that the different effects can be seen.

The assumption that the induced drag ($C_{Dl}$) remains constant introduces another small error into the results. In reality, the increased weight of the airplane due to the fuel cell system will slightly increase the induced drag. In addition, the thrust specific fuel consumption will slightly decrease when the fuel is preheated, so the actual effect when utilizing fuel preheating will slightly more advantageous than the results indicate.

### 2.1.1.2.1. Determining the weight and change in weight.

Although the 787-8 is currently being delivered to customers, the operating empty weight ($W_{GW}$) of the airplane is changing as production progresses and no official figures for this or other parameters are publicly available from Boeing. Maximum takeoff weight, maximum fuel, and maximum payload figures are available [18], but because of the trade-off between payload and fuel, simply adding or subtracting these numbers will not give $W_{GW}$. Unpublished reports, projections, and anecdotes estimate $W_{GW}$ will be near to 250,000 lb (113,399 kg), which is what is used for the base airplane in this study.

Payload weight ($W_P$) is estimated by considering a fully-loaded passenger flight with no revenue cargo. As mentioned in Table 1, the base airplane is assumed to be configured for 291 passengers. Assuming an average of 104 kg (230 lb) per passenger (including baggage), the payload will weigh 30,359 kg (66,930 lb).

The fuel used for the base airplane and mission ($W_{F_{used}}$) is not known. However, current 787-8 data shows that the maximum range is 15,740 km (8500 nm) [20] and the maximum usable fuel is 101,894 kg (224,638 lb) [18]. Assuming that maximum fuel is
used to achieve maximum range, this gives an average fuel burn of 6.47 kg km\(^{-1}\) (26.43 lb nm\(^{-1}\)). Multiplying by the distance of the base mission, 4139 km (2235 nm), gives a base mission fuel consumption of 26,794 kg (59,070 lb). This method will surely give a high number, since as the Breguet equation shows, on a maximum range flight proportionally more fuel is needed to carry the fuel than on the base mission. For another estimate of fuel consumption, Boeing claims the 787 to be 20\% more efficient than a 767 [5,21]. This efficiency gain can be combined with a Boeing report that shows that the fleet-wide average fuel burn for all 767s to be 1.45 kg s\(^{-1}\) (11.537 lb h\(^{-1}\)) [22], resulting in a predicted 787 average fuel burn of 1.16 kg s\(^{-1}\) (9.229 lb h\(^{-1}\)). For the base mission of 5 h, this comes to a fuel consumption of 20,933 kg (46,150 lb). Combining the 26,794 kg fuel consumption estimate above with the 20,933 kg estimate here, a reasonable assumption is that the base mission will have a fuel consumption of about 50,000 lb (22,680 kg).

Ninety minutes of reserve fuel is used in this study (based on [23]), which for a 5-h mission gives a value of $x = 1/3$ in Eq. (4) and a reserve fuel amount ($W_{F,\text{Reserve}}$) of 7560 kg (16,667 lb).

Adding all these components together gives a total airplane weight of 173,998 kg (383,598 lb) at takeoff ($W_1$), and 151,318 kg (333,597 lb) at landing ($W_2$). The change in operating empty weight ($\Delta W_{\text{OEW}}$) is simply the weight of the entire fuel cell system minus any weight savings. The weight of the fuel cell system includes the fuel cell, hydrogen storage, heat exchangers, pumps, blowers, piping, and accessories. It also includes additional Jet-A needed to provide the increased demand for pressurized air required by the fuel cell. Weight savings that are considered in this study are reductions in engine generator size, reduction in the amount of water carried (due to production of water from the fuel cell), and reductions in Jet-A carried that is no longer needed for generating the heat and/or electricity that the fuel cell provides.

Using the above numbers, Eq. (12) shows that every 1 kg (or lb) increase in operating empty weight will require an additional 0.16 kg (or 0.35 lb) of Jet-A fuel to accomplish the same mission as the base airplane.

2.1.1.2.2. Determining the drag and change in drag. Eq. (5) revealed that drag is made up of two major components: drag induced by the lift force, and zero-lift drag. Zero-lift drag is made up of many components: Roskam and Lan [19] have an 11-component equation of which the last term is “miscellaneous” and accounts for at least eight more components. It is beyond the scope of this paper to detail all these different drag components. However, because the airplane with the fuel cell system is assumed to have the same shape and structure as the base airplane, all of these components are considered constant with one exception: the drag due to cooling air.

The need for cooling air can be summarized as:

- Any heat generated within the airplane, including the fuel cell waste heat, must be rejected to the outside environment or the cabin will become intolerably hot.
- Heat transfer through the skin of the airplane is small due to the low density of air at flight altitudes and the composite structure of the 787 which has a poor thermal conductivity.
- Except for the small amount of heat lost through the skin, all heat must eventually be rejected to the atmosphere by ram air cooling.
- Any increase in ram air cooling requires that more air be scooped up into the airplane, which increases parasitic drag.

The key idea is that every watt of heat generated on the airplane requires some ram air cooling, which adds to the zero-lift drag of the airplane.

Cooling drag is not a major part of overall drag and accordingly estimates of its magnitude are not available in the literature, even airplane designers may not be sure of this number. In light of this, we must estimate the cooling drag from what is known (using publicly available data) by the following procedure:

1. Assume the zero-lift drag coefficient ($C_{D0}$) for the 787-8 is 0.022. This is in the range for jet transport airplanes. It is less than the older Airbus A-300B (0.024 according to Roskam and Lan [19]) and at the limit of current technology according to Fillipone [24].

2. Assume parasitic drag accounts for 60% of zero-lift drag. This gives a parasitic drag component of 0.0132. This is reasonable when compared to other transport airplanes: 0.0131 for a Boeing 707-320, 0.0165 for an Airbus A-340, and 0.0135 for a Boeing 767 [19]. Being lower than the similarly-sized 767 is expected since the 787 is claimed to have utilized several drag reduction strategies [25].

3. Assume miscellaneous drag accounts for 7\% of parasitic drag. This is an average of the estimates from Roskam and Lan (9\%, Ref. [19]) and Fillipone (5\%, Ref. [24]).

4. Assume cooling air drag accounts for 5\% of the total miscellaneous drag. This is an engineering estimate based on consideration and knowledge of the other components of the miscellaneous drag category. This results in a drag coefficient of 0.0000462 due to ram air cooling for the base airplane.

To relate the drag number to an amount of heat rejection, we need to estimate how much heat is rejected in the base airplane. Again, this number is not known but must be estimated. The generated heat that must be rejected by the ram air cooling system is divided into three categories:

1. Heat generated by passengers, absorbed by the cabin air and rejected through the air conditioning units (37.5 kW).
2. Heat generated by electronics and galley equipment in the cabin, that is absorbed by cabin air and rejected through the air conditioning units (121 kW).
3. Heat generated by electronics and galley equipment that is absorbed by the liquid cooling system (power electronics cooling loop, PECS) (199 kW).

These heat loads were estimated based on knowledge about electronic equipment efficiencies and power consumption and assuming each passenger contributes 100 W of heat while onboard. In total, approximately 360 kW of heat must be rejected through the current ram air cooling system. To relate this to the drag coefficient, it is assumed that there is a linear relationship between the drag coefficient and the heat rejection. This results in a drag coefficient of 0.000000129 per kW. Therefore, given a change in cooling demand, we can calculate the change in zero lift drag ($\Delta C_{D0}$) by this relationship and solve Eq. (12) to find the corresponding change in fuel requirements. This reveals that every 1 kW of additional heat to be rejected will require an additional 0.15 kg (0.33 lb) of Jet-A to overcome the additional parasitic drag as a result of fuel cell deployment and achieve the same performance as the base airplane.

The airplane design and performance numbers used above are naturally estimates. In light of this, we find with 90% confidence that the overall uncertainty of the effect of cooling drag on fuel consumption is less than 25\%, or a drag coefficient change due to cooling uncertainty of ±0.000000032 per kW. At worst case (where cooling drag is a significant contributor to performance changes) this results in approximately 6\% uncertainty in the overall fuel consumption numbers given in Section 3.
2.1.2. System component models

2.1.2.1. Fuel cell. It is the job of the PEM fuel cell component model to predict the fuel cell’s performance based on the operating conditions. The model consists of electrochemical, heat transfer, and mass transfer calculations. The electrochemical calculations follow the typical engineering equations as found in common references on fuel cells [26,27]. As a summary, on the single cell level the system of equations is:

\[ V_{\text{Operating}} = E - V_{\text{Activation}} - V_{\text{Ohmic}} - V_{\text{MT}} \]  

(13)

where the Nernst voltage \(E\) is:

\[ E = E^0 + \frac{RT}{nF} \ln \left( \frac{p_{o_2}}{p_{i_2}} \right)^{1/2} \]  

(14)

where \(p_X\) is the partial pressure of species \(X\), \(n\) is the number of electrons transferred per mole of reactant (2 in the case of hydrogen oxidation), and \(F\) is the Faraday constant.

The activation loss is (assuming a charge transfer coefficient of 0.5):

\[ V_{\text{Activation}} = \frac{2RT}{nF} \sinh \left( \frac{i}{2i_0} \right) \]  

(15)

The ohmic loss is:

\[ V_{\text{Ohmic}} = r_{\text{cell}} \cdot i \]  

(16)

And the mass transfer loss is:

\[ V_{\text{MT}} = -\frac{RT}{nF} \ln \left[ 1 - \frac{i}{i_0} \right] \]  

(17)

The stack chosen to model for this study is the Hydrogenics HyPM module. Relevant manufacturer’s data for the 12 kW Hydrogenics HyPM HD 12 Power Module, used as the scalable fuel cell unit for this study, is shown in Table 2. Voltage-current performance and efficiency at the stack level as given by the manufacturer were obtained from Ref. [28]. Combining this with knowledge about the typical engineering equations as found in common references on fuel cells [26,27]. As a summary, on the single cell level the system of equations is:

\[ V_{\text{Operating}} = E - V_{\text{Activation}} - V_{\text{Ohmic}} - V_{\text{MT}} \]  

(13)

where the Nernst voltage \(E\) is:

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### Table 2

Data for the modeled PEM fuel cell. Manufacturer’s data from [28,29].

<table>
<thead>
<tr>
<th>Manufacturer’s data</th>
<th>HyPM HD 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td></td>
</tr>
<tr>
<td>Maximum continuous power</td>
<td>12.5 kW</td>
</tr>
<tr>
<td>Voltage range</td>
<td>30–60 VDC</td>
</tr>
<tr>
<td>Maximum operating current</td>
<td>350 A</td>
</tr>
<tr>
<td>Volume</td>
<td>124 L (4.38 ft(^3))</td>
</tr>
<tr>
<td>Mass</td>
<td>86 kg (190 lb)</td>
</tr>
<tr>
<td>Cooling</td>
<td>Water-cooled, includes pump, requires external heat exchanger</td>
</tr>
<tr>
<td>Air</td>
<td>Includes blower</td>
</tr>
<tr>
<td>Number of cells</td>
<td>60</td>
</tr>
<tr>
<td>Cell active area (approximate)</td>
<td>500 cm(^2) (77.5 in(^2))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modeled data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen utilization</td>
<td>95%</td>
</tr>
<tr>
<td>Oxygen utilization</td>
<td>50%</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>70 °C (158 °F)</td>
</tr>
<tr>
<td>Anode, cathode, and coolant exhaust temps</td>
<td>70 °C (158 °F)</td>
</tr>
<tr>
<td>Anode and cathode operating pressure</td>
<td>1 atm (0.17 atm above ambient inside airplane)</td>
</tr>
<tr>
<td>Cathode blower efficiency</td>
<td>60%</td>
</tr>
<tr>
<td>Exchange current density (i_0)</td>
<td>0.00045 mA cm(^{-2})</td>
</tr>
<tr>
<td>Cell resistance (r)</td>
<td>0.00015 kΩ cm(^{2})</td>
</tr>
<tr>
<td>Limiting current density (i_0)</td>
<td>740 mA cm(^{-2})</td>
</tr>
</tbody>
</table>

It should not be inferred that this is the only product or manufacturer that will work for this application but is taken as the representative technology and serves well the function of this engineering analysis. Other PEMFC manufacturers have similar-performing units, so our analysis should well-represent the capabilities of the technology in general. As we have limited our feasibility study to commercially available, off-the-shelf units, the performance of the stack may lag behind that of research units. However, in the latter part of this study we attempt to account for advanced PEM technology by considering fuel cells that meet DOE target technology. See the Section 2.2.4 for further information.

To determine the physical sizes of the fuel cells required to meet the loads in this study, first the operating point of the fuel cell that minimizes system (fuel cell and hydrogen storage) mass and volume was determined. While for a fuel cell alone this would surely be the maximum operating power, when considering the hydrogen storage this is not necessarily true because of the lower fuel cell efficiency at maximum power. This sizing exercise produced an optimal fuel cell operating point of 670 mA cm\(^{-2}\) at 0.66 V, shown by the arrow in Fig. 1. This operating point corre-
sponds to values of 149 W kg\(^{-1}\) (67.6 W lb\(^{-1}\)) for specific power and 103 W L\(^{-1}\) (2920 W ft\(^{-3}\)) for power density, which were used in subsequent analysis for system sizing via linear scaling.

These specific power and power density values may appear low when compared to values stated by manufacturers for other products on the market. This is because not only is the modeled module a “high power” unit and contains the necessary accessories in addition to the stack but also the fuel cell is not operating at its maximum rated power. Therefore, we believe they represent realistic values for the kind of system required for near-term implementation on a commercial airliner.

### 2.1.2.2. Hydrogen storage.

For hydrogen storage options we considered metal hydride, liquid, and gas. Figs. 2 and 3 provide comparisons between these options in terms of storage mass and volume, respectively, for given amounts of hydrogen stored. Each of these options is described below in this context.

#### 2.1.2.2.1. Compressed gas.

Compressed gas hydrogen is the highest energy density option and the most straightforward method to store hydrogen. The mass of the tank and the amount of hydrogen stored can be readily calculated using Eq. (2)

\[
\text{Tank mass} = \frac{m_{HV}}{\text{HHV}} + \text{Liquid Mass}
\]

\[
\text{Volume of Tank} = \frac{m_{HV}}{\text{HHV}} + \text{Liquid Volume}
\]

For 6 kg (13.2 lb) of hydrogen, this leads to a tank mass of 98 kg (216 lb), or about 6.1% gravimetric density. Similarly for volume, the linear fit to manufacturers’ data shows that the relationship between hydrogen mass and volume for the 350 bar (5000 psi) compressed gas tanks is 17.0 g\(\text{H}_2\) L\(^{-1}\) (1.06 lb ft\(^{-3}\)).

The hydrogen storage vessel model integrates the hydrogen flow rate over the mission to find the total amount used for the mission and adds additional unused hydrogen to ensure that the tank pressure will be at a specified minimum value (in this case, 100 psi) when the fuel needed is used up. It models the hydrogen as a real gas and finds the required storage volume for the specified pressure.

#### 2.1.2.2.2. Metal hydride.

Because there is ample space on the airplane, but any increase in weight affects performance, storage system weight is used as the primary metric to evaluate suitability. The secondary metric is commercial availability. Therefore, while the liquid hydrogen options offer the most promise for high gravimetric energy density, compressed gas tanks are chosen because of their widespread availability.

The compressed gas storage tanks analyzed for this study are composite tanks with polymer liners, also known as Type IV tanks. They are the highest pressure, lightest weight tanks available on the market. The data for the 350 bar (5000 psi) and 700 bar (10,000 psi) tanks shown in Figs. 2 and 3 come from two commercial vendors, Lincoln Composites and Quantum Technologies. Compressed gas at 700 bar (10,000 psi) was eliminated during preliminary screening because although it has a smaller volume than 350 bar (5000 psi) tanks, the weight is more and it has additional safety and fuel logistics concerns.

For use in this study, 350 bar compressed gas hydrogen tanks were selected and sized according to the linear trend observed in Figs. 2 and 3. It is assumed that a custom-designed tank would be used for the airplane application and it would have similar characteristics to the off-the-shelf models that are depicted in the figures. Therefore the equation used to size the tank mass is the one used to linearly fit the manufacturers’ data:

\[
\text{Tank mass} = 16.19 \times \text{H}_2 \text{Mass} + 0.3862
\]

For 6 kg (13.2 lb) of hydrogen, this leads to a tank mass of 98 kg (216 lb), or about 6.1% gravimetric density. Similarly for volume, the linear fit to manufacturers’ data shows that the relationship between hydrogen mass and volume for the 350 bar (5000 psi) compressed gas tanks is 17.0 g\(\text{H}_2\) L\(^{-1}\) (1.06 lb ft\(^{-3}\)).

The hydrogen storage vessel model integrates the hydrogen flow rate over the mission to find the total amount used for the mission and adds additional unused hydrogen to ensure that the tank pressure will be at a specified minimum value (in this case, 100 psi) when the fuel needed is used up. It models the hydrogen as a real gas and finds the required storage volume for the specified pressure.

#### 2.1.2.3. Efficiency.

Because of the different definitions of efficiency in the literature, we explicitly define the efficiency we calculate as the thermal efficiency (\(\eta\)):

\[
\eta = \frac{P}{(m\text{HV})_{\text{fuel}}}
\]

Here, \(P\) is the electrical and/or thermal power delivered by the entire fuel cell based system. That is, it includes both the electricity supplied by the fuel cell and any heat generated by the fuel cell that is utilized for a useful purpose. \(m\) is the mass flow rate of hydrogen going into the fuel cell, and \(\text{HV}\) is the heating value of hydrogen. Because the product of a PEM fuel cell comes out at less than 100 °C, the higher heating value (HHV) of the fuel is traditionally used and that convention is followed here.

#### 2.1.2.4. Other components.

A fuel cell system requires a number of components for operation, including pumps, blowers, fans, and heat exchangers. These are all modeled thermodynamically based on energy conservation and reasonable 1st law efficiencies. The primary method to determine the fuel cell system component sizes (weight and volume) was to use the thermodynamic analysis of the system to find the performance requirements, and then consult with manufacturers for the appropriate available or planned product that will satisfy those requirements.
2.2. Design options

2.2.1. System options

Arrangement of the major components of a fuel cell system into a practical working system depends primarily on the method of fuel cell cooling and waste heat recovery. Many possible configurations were attempted on paper and of these, eleven “Cases” warranted additional investigation. These were considered as they all represent possible deployment configurations, with different interfaces to the aircraft cooling systems and a variety of uses of the waste heat. In all of them, it is assumed that any air needed by the fuel cell system, whether for cooling or for oxygen supply, comes from the cabin. It is also assumed that all hot air coming out of the fuel cell module, whether exhaust from the fuel cell or air used for cooling, is routed to the cabin exhaust system and eventually rejected to the atmosphere.

Brief descriptions of the cases as seen in Fig. 4 are:

- Cases 1a and 1b: The fuel cell’s internal liquid cooling system is air cooled. In Case 1b (dashed lines) hot cooling air is combined with the fuel cell exhaust and used to heat water. Although often associated with low power applications, air-cooled systems are commercially available in packages up to 30 kW.
- Cases 2a and 2b: The fuel cell’s internal liquid cooling system is cooled by the airplane’s liquid cooling loop. In Case 2b (dashed lines) exhaust air from the fuel cell is used to heat hot water.
- Cases 3a and 3b are similar to 2a and 2b but limit the amount of generated potable hot water to a reasonable level and as a

![Fig. 4. Schematics for the 11 cases studied in detail. Descriptions are in the text.](image-url)
consequence, require more cooling from the airplane’s cooling system to fully dissipate the waste heat from the fuel cell. Case 3b also shows the case for maximum potable water generation, as the warm, moist, oxygen-depleted air stream from the fuel cell is cooled to condense the water, which is then sent to the potable water system.

- Cases 4a and 4b: The fuel cell’s internal liquid cooling loop is used to heat a quantity of water not intentionally limited. Exhaust air from the fuel cell is used to pre-heat the water, and some water is condensed in the process. In Case 4b (dashed lines) exhaust air is further cooled by the airplane’s liquid cooling loop to further condense and recover water.
- Case 5: The fuel cell’s internal liquid cooling loop is used to preheat a quantity of water not intentionally limited. The excess hydrogen from the fuel cell is kept separate from the air and instead combusted in a hydrogen furnace to produce high-temperature waste heat which is used to heat the galley ovens. The oven exhaust further heats the water. This design does not require any cooling by the airplane’s systems.
- Cases 6a and 6b: The fuel cell’s internal liquid cooling loop is used to heat the airplane’s fuel. Enhancing the energy content of the Jet-A by adding the fuel cell waste heat improves the efficiency of the airplane’s main engines. In Case 6b (dashed lines) exhaust heat from the fuel cell is also used to heat the airplane’s fuel, producing condensed water in the process. A secondary coolant loop is used to prevent mixing of the airplane’s fuel with air or water. In either Case none of the airplane’s cooling systems are needed.

2.2.2. Electrical load options

In an earlier study, one of the authors (L.E.K.) examined using a PEM fuel cell as a replacement for a Ram Air Turbine (RAT) emergency power system [9]. Beyond the seldom-used RAT application, there are several loads on the airplane that are routinely used and are amenable to near-term deployment of a PEM fuel cell. These routine loads include IFE, galley power, and peaker power (to be described), which were chosen as being likely first deployment options due to their non-critical nature and modest sizes. Currently, IFE and galley electrical needs are served by electrical generators on the main (thrust) engines. The three selected systems were simulated to meet each of the nine load scenarios summarized in Table 3. In this way it can be seen how different loads impact the overall performance of the systems, thus enabling recommendations not only for the best-performing system configurations but also for the on-board load(s) most advantageously powered by fuel cell technology.

2.2.2.1. In-flight entertainment load. The in-flight entertainment (IFE) system includes all electronics for providing movies, TV shows, and audio programming for the passengers, but excludes any electrical receptacles that may be provided for powering or charging laptops and other devices. We estimate that the IFE system consumes a maximum of 20 kW and is active for all phases of flight.

2.2.2.2. Galley load. Galley loads are needed.

2.2.2.2.1. In-flight entertainment load. The in-flight entertainment (IFE) system includes all electronics for providing movies, TV shows, and audio programming for the passengers, but excludes any electrical receptacles that may be provided for powering or charging laptops and other devices. We estimate that the IFE system consumes a maximum of 20 kW and is active for all phases of flight.

2.2.2.3. Peaker load. Because on the 787-8 the main engines generate so much electrical power compared to other airplanes, during periods of low engine load the amount of power needed to generate electricity is a large fraction of total engine output. This occurs

Table 3
The nine different load scenarios considered in this study.

<table>
<thead>
<tr>
<th>ID</th>
<th>Load description</th>
<th>Maximum electrical demand (kW)</th>
<th>Phases of flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>In-flight entertainment (IFE)</td>
<td>20</td>
<td>All</td>
</tr>
<tr>
<td>2</td>
<td>Mid-Galley</td>
<td>20</td>
<td>Initial taxi, takeoff/climb, and cruise</td>
</tr>
<tr>
<td>3</td>
<td>Forward Galley</td>
<td>40</td>
<td>Initial taxi, takeoff/climb, and cruise</td>
</tr>
<tr>
<td>4</td>
<td>Aft Galley</td>
<td>60</td>
<td>Initial taxi, takeoff/climb, and cruise</td>
</tr>
<tr>
<td>5</td>
<td>All Galley combined</td>
<td>120</td>
<td>Initial taxi, takeoff/climb, and cruise</td>
</tr>
<tr>
<td>6</td>
<td>Single Peaker</td>
<td>75</td>
<td>Descent and landing</td>
</tr>
<tr>
<td>7</td>
<td>Both Peakers</td>
<td>150</td>
<td>Descent and landing</td>
</tr>
<tr>
<td>8</td>
<td>All Galleys (5) and Both Peakers (7)</td>
<td>150</td>
<td>120 kW during initial taxi, takeoff/climb, and cruise; 150 kW during descent and landing</td>
</tr>
<tr>
<td>9</td>
<td>All Loads (1, 5, and 7)</td>
<td>170</td>
<td>140 kW during initial taxi, takeoff/climb, and cruise; 170 kW during descent and landing, 20 kW during final taxi</td>
</tr>
</tbody>
</table>
primarily during descent and landing, when engines are often throttled back to idle. At these times, the engine is spinning slowly enough that if the power demand (either thrust or electrical generation) was to suddenly increase, the engine’s compressor may cease to function properly, or stall, and the engine would shut down. The difference between the stall condition and the operating condition is referred to as the stall margin. It would be advantageous to remove some of the electrical burden on the engines during times of low engine power output. This would allow either a larger stall margin or a reduced engine size for the same stall margin.

An additional concern is that the engine efficiency decreases with decreasing power. This reduced efficiency extends to the generators on the engines. As the engine slows during descent and landing, its thermal efficiency decreases, making the overall electrical energy generation less efficient.

An alternative source of power that is only used for peak electrical loads (a “peaker”) during descent and landing would provide dual benefit, increasing both stall margin and efficiency. In this study, two 75 kW peaker fuel cells (one per main engine) operating during descent and landing is also considered. However, we do not assess the impact on stall margin or efficiency.

### 2.2.3. Location options

There are five main location categories that were considered:

1. Fuel cell and hydrogen near load (base case).
2. Fuel cell and hydrogen in fairing or “pack bay”.
3. Fuel cell and hydrogen in tail.
4. Hydrogen in the fairing, fuel cell at the loads.
5. Hydrogen in the tail, fuel cell at the loads.

A dimensioned outline of the 787-8 is given in Fig. 5 showing each of these locations.

The issues influencing the choice of the optimal location of a fuel cell are:

1. Available space on the airplane.
2. Safety of the installed systems.
3. Tubing, ducting, and wiring mass and volume.
5. Rejection of waste (warm and moist air from the cathode, condensed water, hot coolant, and/or excess hydrogen).

These factors are described below.

#### 2.2.3.1. Available space on the airplane

There are two locations on the airplane where there is a significant amount of empty space due to the aerodynamic requirements of the airplane shape: the fairing (where the wing joins the body) and the tail cone. These two locations have the advantage of being able to host excess equipment volume without compromising interior space or changing the external shape of the aircraft.

![Diagram of airplane](image-url)

If instead the fuel cell and/or hydrogen is located near the load, it must displace an existing or planned piece of equipment such as part of a galley, overhead storage, under-floor cargo space, or passenger seat space. The inconvenience to an airline customer may make this option less attractive. For example, a typical galley cart occupies approximately 240 L (8.5 ft³). The 40 kW system sized for the Forward Galley would occupy approximately 1150 L (40 ft³), meaning it would displace an equivalent of nearly five galley carts. By comparison, the available volume in the tail cone area is estimated to be over 2800 L (100 ft³), and possibly more in the fairing area.

#### 2.2.3.2. Safety considerations of the installed fuel cell systems

While fuel cells and hydrogen storage systems have in many respects an exemplary safety record, the aviation application exposes the travelling public to this technology in a very proximate way. The relative locations of people and hydrogen technology hardware strongly influences where such technology would likely be deployed on the airplane. From a safety perspective, the fire-rated section of the tail has a significant advantage in that it is behind a firewall and the space is rated for fire hazards, such as might be a concern for a hydrogen fuel–fuel cell system. A firewall does not currently exist in the fairing area, although such an upgrade is certainly possible and reasonable. These safety issues will be important considerations for early adoption onto an aircraft from both regulatory and customer acceptance points of view.

One of the location options has the hydrogen storage and fuel cell separated from each other. Such a separation requires that the hydrogen to be piped through the airplane to the point of use. While all-welded tubing and fail–safe shutoff valves at the hydrogen storage end should mitigate the safety issues, the perceived increase in risk due to the H₂ piping may make this option less attractive.

Fueling the system might be more difficult if the tank was located in the tail, which is approximately 20 ft (6 m) above the ground, especially if liquid hydrogen is used.

#### 2.2.3.3. Electrical equipment and wiring

Utilizing on-board fuel cells as a source of electrical power may enable distributed electrical systems by putting the fuel cell at the point of load [6]. Besides providing possible redundancy benefits, one hypothesis is that this would substantially decrease the amount of electrical hardware and wiring, resulting in better overall airplane performance. To test this hypothesis, we must estimate the wire mass and volume for each location strategy.

The choice of distribution voltage and type (AC or DC) can impact the number and size of the wires required, so this must be determined before wire mass and volume can be estimated. Three possible electrical distribution architectures were considered:

1. Low voltage (50 V) DC. A DC system has the advantage of directly taking the DC output of the fuel cell without the need for a DC–AC inverter. In addition, the 50 VDC needs only two wires compared to a three-phase (three wire) AC system. A voltage lower than 50 V also provides safety and maintenance advantages. However, wire diameters will be the largest of all options. The 787 does not currently have a 50 VDC distribution system, so this option is mainly considered for stand-alone configuration (a dedicated fuel cell and load circuit independent of the existing electrical system).
2. High voltage (±270 V) DC. This system has the advantage of being DC, but requires more attention to safety during maintenance than the 50 VDC system. The 787 already has a ±270 V distribution bus so this will not add any additional requirements and will allow the fuel cell system to tie directly into the existing electrical system.
3. 230 V AC. This is the main electrical distribution bus on the existing 787. While this system requires a DC–AC inverter to convert the output DC fuel cell power, the electricity from the fuel cell sent to this bus can be used in all airplane loads.

Table 4 shows the amperage requirements for the three electrical architecture options and the different possible fuel cell output levels. The AC current calculations assume a 0.95 power factor. Note that 3-phase AC power inherently requires less current per wire than equivalent DC power. The 50 VDC option has very large currents, and high-current DC may not allow application of proper
switching and protection equipment. Therefore, 50 VDC is eliminated from further consideration.

Table 5 shows the appropriate wire sizes based on the design current. It is assumed that an AC distribution system will utilize the existing grounding bus running throughout the 787, so only three conductors are needed. Note that there would be two 75 kW units for the Both Peakers load, resulting in a total of four conductors for the DC case and six conductors for the AC case.

Because of the difference between the two system types (DC versus AC), it is necessary to also consider the difference in equipment. For example, it is important to compare/contrast the size of the DC–DC converter (that regulates the DC output of the fuel cell to 270 VDC) for the DC system with the size of the DC–AC inverter (required to convert the low voltage DC output of the fuel cell to 230 VAC power) for the AC system. Commercially available equipment was used to estimate these sizes. For the DC–DC converter, we used an aviation-optimized 60 kW unit manufactured by Aero-Vironment with a specific power of 3.8 kW kg\(^{-1}\) [39]. For the DC–AC inverter, we used a 30 kW transportation unit manufactured by US Hybrid that has a specific power of 1.07 kW kg\(^{-1}\) [40]. These values were linearly scaled by the power of each load to find the sizes for approximately 446 kPa (50 psig) by stainless steel (type 316L or 304L) needed for fuel cell system deployment. Therefore, we also realized that in this paper we are focusing on the electrical system of the airplane’s existing electrical system. Those findings were used. This provides a minimum design pressure of 13,890 kPa (2000 psi g). Although this is well above the intended distribution pressure (446 kPa/50 psi g), it provides a safety margin in case of regulator failure, and mitigates the effect of possible tubing wear in the high-vibration environment of an airplane. As customers and passengers feel more comfortable with hydrogen safety, it may be reasonable to reduce the wall thicknesses or possibly switch to a non-metallic tubing to minimize the plumbing weight.

Supply and exhaust air streams are assumed distributed by 4-in. (nominal diameter) PVC ducts, and water by ½-in. (nominal diameter) nylon-reinforced silicone tubing. Either medium could be used to transfer heat from the fuel cell to the heat load, but preliminary analysis revealed that conveying heat via hot water greatly reduced the weight and volume of the piping compared to using hot air. Furthermore, heat exchangers and fans/pumps are more efficient when handling water. For these reasons, conveying heat via hot air was rejected and not considered in any further analysis.

The weight of the regulator is taken to be 2.3 kg (5 lb). Each hydrogen tank is assumed to have one regulator, and to find the number of regulators required, it is assumed that the maximum hydrogen capacity per tank is 7 kg (15.4 lb) (a size consistent with today’s larger mass-produced tanks).

2.2.3.5. Waste heat recovery. In addition to the electricity it generates, the fuel cell also discharges two streams of waste heat: the exhaust of oxygen-depleted air after it passes through the cathode, and the hot liquid in the cooling loop that is used to maintain stack temperature. In this study, the stack was assumed to operate at 70 °C (158 °F) meaning that both the air and hot cooling water are expected to come out at this temperature. The cooling water carries a significantly higher proportion of the heat load: in our simulations we found that over 90% of the total heat rejected is through the cooling water.

The fuel cell also releases a small amount of hydrogen. One additional concept that was considered is taking this small amount of hydrogen and, instead of combining it with the air exhaust, burning it in a combustor to create a high-temperature waste heat stream. Because the combustor would realistically need to be located in the fire-rated tail section, the application of this concept is limited to the heat loads in the rear of the aircraft.

There are few places on the airplane that require heat. Some, like wing de-icing, would require a significant re-design of the base airplane and are not considered. In the cabin, there are three uses of heat: (1) hot water for washing in lavatories and galleys, (2) hot water for beverages, and (3) food service ovens. The high temperature waste heat concept (burning the hydrogen, described above) could be constructed using a hydrogen-fueled furnace arrangement, with the resulting hot air stream used to fully heat the galley ovens, completely replacing their electrical needs.

Table 4

<table>
<thead>
<tr>
<th>Load (kW)</th>
<th>Design current (150% rated amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 VDC</td>
</tr>
<tr>
<td>75</td>
<td>2250</td>
</tr>
<tr>
<td>60</td>
<td>1800</td>
</tr>
<tr>
<td>40</td>
<td>1200</td>
</tr>
<tr>
<td>20</td>
<td>600</td>
</tr>
</tbody>
</table>

Wire sizes for the 270 VDC and ±270 VAC distribution systems.

<table>
<thead>
<tr>
<th>Load (kW)</th>
<th>AWG</th>
<th>Number of conductors</th>
<th>Dia. (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>±270 VDC wire selection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>4/o</td>
<td>2</td>
<td>486.8</td>
</tr>
<tr>
<td>60</td>
<td>3/o</td>
<td>2</td>
<td>404.0</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>2</td>
<td>216.7</td>
</tr>
<tr>
<td>20</td>
<td>6</td>
<td>2</td>
<td>79.4</td>
</tr>
<tr>
<td>230 VAC wire selection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>2/o</td>
<td>3</td>
<td>321.4</td>
</tr>
<tr>
<td>60</td>
<td>1/o</td>
<td>3</td>
<td>258.4</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>3</td>
<td>171.5</td>
</tr>
<tr>
<td>20</td>
<td>6</td>
<td>3</td>
<td>79.4</td>
</tr>
</tbody>
</table>
add to the system weight and volume. Thus, this potential use is ignored.

A remaining use of heat is to heat the airplane's propulsive fuel (Jet-A). Any addition of heat to the fuel will decrease the amount of fuel burned by the engines, resulting in an efficiency gain. Military aircraft commonly use this strategy with a variety of on-board heat sources, while on commercial airplanes the practice is common within the engines themselves, where the fuel is pre-heated by the engine oil. Simulation results in this work reveal that for a 20 kW fuel cell system and the flight-averaged Jet-A consumption of 1.26 kg s\(^{-1}\) (24.9 gpm), the fuel temperature increase would be about 7 °C (13 °F). For a 170 kW fuel cell, the fuel temperature would increase would be about 54 °C (97 °F) (Jet-A begins to boil at approximately 200 °C (392 °F) [42]). While these temperatures seem to indicate that Jet-A volatilization may not be a concern, it may be an issue for very large fuel cell systems and/or if the airplane is operated in hot climates on many short-duration missions, where the fuel in the tank does not have a chance to cool down during flights.

2.2.3.6. Rejection of waste streams from the fuel cell. The fuel cell has between one and four waste streams (depending on the design), the heat recovery aspects of which were described in the previous section:

1. Warm, moist, oxygen-depleted air from cathode.
2. Water condensed from the cathode stream (only if the cathode stream is subsequently cooled below the dewpoint).
3. Hot cooling water (some fuel cells are cooled in other ways).
4. Small amount of excess hydrogen exhaust from anode (most PEM fuel cells do not exhaust any hydrogen, or mix it with the large quantity of excess air from the cathode to present no fire hazard).

There will always be oxygen-depleted exhaust air at above-ambient temperature that needs to be discharged. The amount of oxygen in this stream is typically 10% or lower for modern stack designs, meaning it is not breathable and could not be exhausted into the cabin. Furthermore, exhausting it into the cabin would add to the heat load on the cabin air conditioning system. So the oxygen-depleted cathode exhaust stream must be sent overboard and should be ducted to the same line which exhausts cabin air.

If the cathode exhaust is cooled before discharging, some water will condense. This water should be “pure” although any contaminants in the air stream may also enter the water. However, a simple in-line filtration system and, if needed, ultraviolet purification (as currently used for the potable water supply on commercial airplanes) could be applied before sending this water stream to the potable water storage tank on board. The advantage of capturing this water instead of sending it to the waste tank is that it enables the airplane to carry less water at takeoff, lowering its takeoff weight. As shown in the discussion of the impact of weight on range and fuel consumption, for every 1 L of water (≈ 1 kg) less on takeoff, the airplane could carry 0.16 kg L less of jet fuel and achieve the same mission.

Over 90% of the heat generated by the fuel cell is carried away by its internal cooling water system. For a typical PEM fuel cell operating condition, this amount can be approximated by the net electrical power of the stack (e.g., for a 10 kW stack, approximately 10 kW of heat will be exhausted through the cooling water). Because we assume the internal cooling system is closed-loop, this heat must be rejected to one of the airplane’s cooling systems and/or to a waste heat recovery option.

The amount of hydrogen exhausted from the stack is small compared to the cathode exhaust containing oxygen-depleted air and water vapor. Commercial fuel cells will simply combine this with the cathode exhaust and send to the atmosphere. The resulting mixture will not be flammable due to the small amount of hydrogen and the reduced oxygen concentration in the cathode exhaust.

2.2.4. Technology options

The earlier section on the fuel cell and hydrogen models described the “Current Technology” PEM fuel cell and hydrogen storage vessel used as the basis for this study. The fuel cell has a specific power of 149 W kg\(^{-1}\) (67.6 W lb\(^{-1}\)) and the 350 bar (5000 psi) gaseous hydrogen storage tanks were estimated to have 6.1% gravimetric density.

In this study we also examine the effect of PEM fuel cell and hydrogen storage technology developments on overall airplane performance. This is done by repeating the entire analysis with the only difference being to change the sizes of the fuel cell and hydrogen storage vessel to match those in Department of Energy technical targets, referred to as “DOE Target Technology.”

The 2015 targets for 80 kW integrated transportation fuel cell power systems operating on direct hydrogen are 650 W kg\(^{-1}\) (295 W lb\(^{-1}\)) gravimetric density [43], and these numbers are used for the PEM fuel cell in the “DOE Target Technology” analysis. The corresponding numbers for hydrogen storage are taken from the “ultimate” targets of on-board hydrogen storage systems for light-duty vehicles: 7.5% gravimetric density [44].

3. Results

3.1. Location evaluation

This section shows the quantifiable results that relate the effect of component location on the mass of tubing, ducting, and wiring needed for a fuel cell system. This part of the study considers a fuel cell system supplying electricity to the in-flight entertainment (IFE) load, a 20 kW load constant for the entire flight. Considering just the IFE load for this part of the study is acceptable because the conclusions related to location are applicable to all load cases. Combining these results with the qualitative reasoning discussed earlier, a recommended location is determined.

3.1.1. Tubing and ducting

The tubing and ducting is used to distribute the fuel, air, water, and waste heat streams associated with the fuel cell system. Depending on the location of the various system components, the required length of each tube or duct was determined from the airplane dimensions (see Fig. 5). A factor of 1.5 was multiplied by this length to account for changes in plumbing elevation, bends and turns, fittings, and valves. The resulting “effective length” was multiplied by the weight per length and volume per length to find the size of each required tube or duct.

The details are omitted here, because even for the worst (heaviest) cases, the magnitude of the piping masses (<50 kg (110 lb)) is not a very large addition to the mass of the aircraft. Recall that the estimated takeoff weight of the base airplane is 173,998 kg (383,598 lb). So, for each fuel cell system, the plumbing mass is minor. Placing each fuel cell and hydrogen storage system near the load it serves is the lightest option. However, the added mass of locating both the fuel cell and hydrogen system either in the fairing or in the tail is small and may be worth the convenience of utilizing existing empty space. Separating the fuel cell from the hydrogen storage leads to a large increase in mass due to the long runs of stainless steel tubing that are required to distribute the hydrogen to the fuel cell. It may be possible to reduce the wall thickness of this tubing and/or change to a non-metallic material which would decrease, but not eliminate the penalty of separating the fuel cell from the hydrogen.
The results assume the use of waste heat recovery such as that shown in Case 3b. When there is no waste heat recovery, the mass will decrease by about 2 kg (4.4 lb) for the cases where the fuel cell is close to the load, up to 10 kg (22 lb) when the fuel cell is furthest from the load. The results also assume that heat is distributed to the loads via hot water, not hot air.

The overall result from the piping and tubing analysis is that the piping system mass can be minimized by keeping the hydrogen and fuel cell as close to each other as possible, either together near the load, or together away from the load. The location of the fuel cell relative to the load will impact the results but the overall change is small and other location factors should be considered first.

### 3.1.2. Wiring

The combined masses of the wiring and DC–DC converter or DC–AC inverter for the different loads and their locations around the airplane are shown in Fig. 6, assuming the fuel cell is located in the fairing. The distances between locations were estimated to be the same as in the piping and tubing analysis (previous section), including a factor of 1.5 to account for bends, connectors, etc. This assumes that the output of the fuel cell is converted to the distribution system voltage right at the fuel cell module – there is no wiring allowance for the part between the fuel cell and the conversion device.

From the figure it is clear that the ±270 VDC system has a lower overall mass than the 230 VAC system in every case. This is mainly due to the difference between the size of the DC–DC converter and the DC–AC inverter. While these results assume that the fuel cell is located in the fairing area, the trend is the same for any fuel cell location.

### 3.1.3. Summary of system location findings

A combination of the piping and wiring size analysis results is shown in Fig. 7. The sum of all the galley loads for the fairing and tail are 158 kg (348 lb) and 148 kg (326 lb), respectively, showing that the total difference is small between these two options if all the galley loads are being considered. It can also be seen that locating the fuel cell system next to all the loads can save nearly 150 kg (331 lb) compared to locating it in either the fairing or tail sections. This figure does not include the IFE or Peaker, because it is assumed that the location of those loads is flexible and will be near the fuel cell no matter where it is located.

Co-locating the fuel cell and hydrogen storage in either the fairing or tail section provides logistical advantages to the deployment and maintenance of the fuel cell system. The fire-rated sub-section of the tail offers an added safety, and possibly regulatory, benefit, but the space in this sub-section is limited. The fairing may be safer for refueling activities since it is lower to the ground.

For these reasons, and the small difference in mass between locating the system in the fairing or tail, the fairing section is chosen as the location for the remainder of this study. Since the differences between the fairing and tail locations are small, performing the analysis assuming the system is located in the tail area would lead to very similar results.

### 3.2. System design evaluation

In this section we examine the 11 system design options (Fig. 4) and determine the design trade-offs, advantages, and disadvantages of each option. Similarly to the evaluation of location, here we consider just the 20 kW IFE load to simplify the analysis, and assume that the fuel cell and hydrogen are located together in the fairing. While the choice of load will affect the quantitative results, the conclusions regarding system design will be the same regardless of the load selected for analysis. Thus the goal of this section, determination of recommended system configurations, is not affected by this choice. The section begins with an overview of the results and then discusses each system design option in detail.

#### 3.2.1. Overview

Fig. 8 plots the fuel cell system thermal efficiencies, as defined in Eq. (19), for It can be seen that the highest efficiency cases are
the ones that utilize the most waste heat, either through heating water (Cases 4a and 4b), heating galley ovens (Case 5), or heating the airplane’s fuel (Cases 6a and 6b).

Fig. 9 summarizes the mass analysis including a component-by-component breakdown. The blue outline bars show the net system mass. For comparison, the “standard passenger” used by the airplane industry has a mass of 104 kg (230 lb) including luggage. The mass analysis includes physical hardware requirements and operating requirements. The physical hardware includes the fuel cell, hydrogen, hydrogen storage, piping and accessories, heat exchangers, pumps, and blowers, and electrical hardware and wiring. The increases in mass due to operating requirements includes increases in Jet-A due to additional system mass, cooling drag, and electrical power required by the ECS system to supply the necessary air for the fuel cell. The decrease in mass due to operating requirements includes a decrease in Jet-A due to reduced electrical generation of the main engines (for supplying both electrical and thermal loads), decreased Jet-A due to fuel pre-heating, and water production by the fuel cell system. A reduction in mass due to smaller required engine generators is also calculated.

The figure reveals that, except for Cases 1a and 1b, all the systems have very little difference in the hardware portion (the fuel cell (blue), hydrogen storage (red), hydrogen (green), piping and accessories (light purple), heat exchangers, pumps, and blowers (orange), and electrical (pink)). The largest differences come from the additional Jet-A requirements and savings, and water recovery savings. For this reason, a system that requires little or no heat rejection to the airplane’s cooling system and recovers potable water, such as Case 4b, has a net mass advantage compared to others. The reason Cases 1a and 1b are so different is the penalties associated with large air-to-air heat exchangers and the supply of the necessary amount of cooling air.

Fig. 10 summarizes the volume analysis. For comparison, a typical galley beverage cart has a volume of 240 L (8.5 ft³), with the available volume in the tail cone area estimated to be over 2800 L (100 ft³), and possibly more in the fairing area. This analysis only considers the physical hardware required for the system, as it is assumed that the volume of the fuel or water tanks will not be changed and any more or less Jet-A or water carried will have no effect on the volume. From this figure it is apparent that all cases except for Cases 1a and 1b have similar system volumes, which are determined largely by the volume associated with hydrogen storage. The reason for Case 5’s difference in volume is the hydrogen combustor/furnace, which has a large volume.
estimated actual hot water usage for both consumption and LPM (0.225 gpm). This was chosen as a reasonable amount based on the limited water, but hot water production is limited to a maximum of 0.85 gpm. This complexity and Case 2b should be discarded. Case 2a may be of added heat recovery system has no real benefit to offset the added difference between the two cases is negligible. This means that the systems' feature a reasonable amount of heat recovery leading to a performance improvement over the case without any heat recovery (Case 2a). Case 3b is slightly better performing than Case 3a. Cases 4a and 4b are nearly identical to 3a and 3b except the amount of hot water generated is not constrained. This also enables Cases 4a and 4b to utilize the fuel cell's exhaust heat to further heat the water. Like 3b, Case 4b further cools the fuel cell's exhaust (rejecting heat to the PECS) to capture 37.9 L of water. Both Cases 4a and 4b have the same overall efficiency of 86.6%. Compared to Case 4a, the water capture of Case 4b requires extra equipment and Jet-A to overcome the cooling load. As in Case 3b, the water credit more than makes up for this extra burden. The highly efficient capture of waste heat allows the use of fuel cells for IFE in this configuration to provide a performance benefit to the aircraft, as shown in Fig. 11.

In spite of being among the best performing systems, Cases 4a and 4b were rejected for further analysis because of the impracticality of actually using so much hot water on board the airplane. However, because they are so similar to Cases 3a and 3b except for the amount of hot water generated, it is useful to compare the sets of cases to reveal the large benefit associated with fully utilizing the waste heat and displacing electrical heating loads, should another option for utilizing the waste heat on-board become available.

These cases also illustrate the potential of a heat sink that could be cooled or regenerated while the airplane is on the ground. If all the heat from the fuel cell could be captured by a sink during flight, the benefit to the airplane could outweigh the size of the sink.

A potential solution to the problem of low-grade waste heat is to heat the exhaust stream by burning the small amount of hydrogen that is wasted by the fuel cell. Case 5 examines this arrangement by keeping the hydrogen and oxygen-depleted air exhausts separate when they exit the fuel cell. The hydrogen is combusted with a portion of the air in a hydrogen furnace and the products are mixed with the remaining air. This stream exits the furnace at 882 °C (1620 °F) and is sent directly to the galley ovens. The ovens are heated to 450 °F (232 °C), utilizing 1.7 kW of the heat energy from this stream. The oven exhaust stream is used to heat water at an unconstrained rate of 11.4 LPM (2.5 gpm). Prior to being heated by the oven exhaust stream, the water is heated by the fuel cell's heat.

Case 5 exhibits the highest system efficiency (88.62%) and its performance is only behind Cases 4a and 4b. Furthermore, the highly efficient capture of waste heat allows the use of a fuel cell for IFE in the configuration of Case 5 to provide a performance benefit to the aircraft, as shown in Fig. 11. However, Case 5 it suffers the same drawback as Cases 4a and 4b in that it produces an unreasonable amount of hot water. Additionally, the overall performance is worse than Cases 4 and 4b because of the added equipment (hydrogen furnace) and less water recovery.

One way to make Case 5 more practical in terms of hot water generation is to limit the amount of hot water, similarly to Cases 3a and 3b. The effect of this will be nearly equivalent to the differ-
ence between Cases 3a and 4a. That is, the performance will be
close to but higher than Case 3a. The added complexity compared
to Case 3a combined with the worse performance makes this an
option not worth pursuing.

Cases 6a and 6b reject all of the fuel cell’s heat to the airplane’s
fuel (Jet-A). This arrangement does not require any cooling from
the airplane’s environmental systems (and thus does not add any
cooling drag) and has the added benefit of increasing the enthalpy
of the fuel so that less fuel needs to be burned to generate the same
amount of thrust.

Case 6b additionally utilizes the fuel to cool the fuel cell exhaust
stream and extract water. The efficiency (84.4%) is slightly higher
than Case 6a (81.9%) because of the extra heat recovered in this
process. However, the amount of water recovered is small (6.9 L)
and the added equipment results in a system with nearly the same
overall performance benefit as Case 6a. In addition, there are po-
tential hazards associated with a leak developing in the heat
exchangers and the mixing of fuel, air, and/or water in either the
fuel system or the potable water system.

These cases are the best performing practical cases. However,
Case 6b should not be considered because of the increased com-
plexity and hazard potential without any performance benefit.

In light of the preceding discussion, the following are the pre-
ferred systems:

- For easiest implementation with minimal impact, the water-
cooled, no waste heat recovery system (Case 2a) is
recommended.
- For best performance, the Jet-fuel cooled system (Case 6a) is
recommended.
- For most use of heat within the cabin, the water-cooled, hot
water heating, and water recovery system (Case 3b) is
recommended.

The results of analyzing these three systems with respect to
various loads and advanced fuel cell and hydrogen storage tech-
nologies is presented in the two sections that follow.

### 3.3. System performance with current technology for various loads

In this section we find the effects of various other electrical
loads on the overall PEM fuel cell system mass, in order to
determine to what extent the load will affect overall airplane per-
formance and therefore a preferred implementation strategy. For
all results that follow, we assume the fuel cell and hydrogen are lo-
cated together in the fairing area.

#### 3.3.1. Mass

The overall masses of the three preferred system configurations,
Cases 2a, 3b, and 6a, applied to the various loads are shown in
Figs. 12, 13 and 14, respectively. For reference, the definition of
each load scenario is given in Table 3. For all cases, the overall
trends are the same, and the dominant trend is that the fuel cell
and hydrogen storage vessel are responsible for a large fraction of
the overall system mass. The next largest component is the elec-
trical hardware, primarily the DC–DC converter.

A visible feature is that, in general, the system mass increases
with the size of the load. However, an exception to this can be seen
when comparing the “All Galleys” load scenario, which is 120 kW,
to the “Both Peakers” scenario, which is 150 kW. The reason the
higher-power Both Peakers has a lower net mass is because the
peakers only operate for the descent and landing phases of flight
(25 min total) compared to the All Galleys which operate for initial
taxi, takeoff and climb, and cruise (4 h and 28 min). Thus, the mass
of hydrogen and the mass of the hydrogen storage system required
for the Peakers case is much smaller.

Another feature of the different load scenarios that becomes
evident through this analysis is the complementary nature of the
galley loads with the peaker load. For Case 2a, the All Galleys sce-
nario has a net mass of 1506 kg (3320 lb) and the Both Peakers has a
net mass of 1244 kg (2743 lb). However, combining these two
loads in the Both Peakers and All Galleys scenario has a net mass of
1858 kg (4096 lb), or just 68% of the mass if these two systems
were considered separately. The reason for this is that the two sys-
tems operate at different phases of flight so they can share the
same fuel cell.

#### 3.3.2. Performance

All of the effects of the fuel cell system can be consolidated to
find the overall impact on Jet-A requirements for the airplane,
using the method described in Section 2. Fig. 15 shows the change
in jet fuel that results from each of the three system configurations
(Cases 2a, 3b, and 6a) and all of the possible load scenarios. It is
evident that, when considering current technology for the fuel cell

![Fig. 12. Mass distribution for Case 2a (water cooled, no heat recovery) for the different loads, using current technology for the fuel cell and hydrogen storage. The different colors in the narrow bars represent different components. Quantities above the zero-line are for mass added to the system, and quantities below the zero-line are for mass credits. The net change (the sum of the added mass and mass credits) is shown by the wide hollow bar. For comparison, the “standard passenger” has a mass of 104 kg (230 lb) including luggage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
and hydrogen storage system, every possibility will require the airplane with the fuel cell to use more jet fuel than the base airplane without the fuel cell.

Other, more subtle effects are also discernible from this figure. While Figs. 12–14 showed that the Both Peakers scenario has a lower net mass than the All Galleys scenario, from this figure it can be seen that the All Galleys scenario performs better. In fact, the Both Peakers scenario (150 kW) has a worse performance than the All Loads scenario (170 kW), which includes the peakers! The reason for this goes back to the fact that the peakers only operate for a short duration of the flight. While this saves hydrogen storage mass, it does not allow the system to get any significant amount of “credits” for generating electricity, water, or heat. In essence, the airplane has to spend fuel to carry the peaker system without getting much benefit. On the other hand, the systems that operate for longer periods generate large amounts of usable water and/or heat, offsetting the extra fuel that must be carried to transport these systems. This observation can be generalized by saying that if a fuel cell system is going to be carried on-board, the best overall performance will result from operating it as much as possible. The same observation was made by MacKay et al. [13]. However, there may be other reasons to operate a fuel cell sparingly, such as in a peaker application, that outweigh the performance penalty. For a fuel cell used all the time, fuel cell degradation would force the user to either replace the fuel cell more often, or to oversize it to achieve a length of service comparable to a gas turbine (Roth and Giffin [45] estimate that fuel cell degradation would require over-sizing the fuel cell by about 4% to achieve the same length-of-service (20,000 h) typical for a gas turbine). Both options would add cost to the system and the latter would also increase the mass penalty.

Another effect that can be partially found by examining Fig. 15 is the difference between saving mass through water recovery and heat recovery to the potable water system, versus saving fuel through heat recovery to the jet fuel. This can be seen by comparing Case 3b with Case 6a for any of the load scenarios, looking at this figure and both Figs. 13 and 14. As an example, the All Loads scenario is considered, and the relevant information is summarized in Table 6. While Case 3b has 203 kg larger Total Mass Savings than Case 6a, Case 6a has 17 kg more in Total Jet Fuel Savings. The reason for this non-intuitive result is that the type of savings matters. One kilogram of jet fuel saved through fuel heating is a Total Jet Fuel Savings. But one kilogram of fuel cell system mass saved only...
3.3.3. Summary

The analysis performed in the previous section was repeated, with the only change being a reduction in the sizes of the fuel cell and hydrogen storage vessel, in order to see what the effect of future technology improvements that reduce both mass and volume of the hydrogen storage and fuel cell might have on the feasibility and performance of an on-board aviation fuel cell system. Like the last section, we consider just the three preferred system configurations and assume the fuel cell and hydrogen storage are located together in the fairing area.

3.4. System performance with DOE target technology

The trends are nearly identical to those in the results for the current technology (Figs. 12–14). The only exception is that the fraction of total mass due to the fuel cell and hydrogen storage has decreased, as expected. In fact, the electrical equipment mass now surpasses that of the fuel cell.

Upon comparison to the analogous current technology graphs, it can be seen that the total mass has decreased by nearly a factor of two. Thus, achieving the DOE targets for fuel cells and hydrogen storage for light-duty vehicles will result in lighter systems for fuel cell electricity generation on board commercial airplanes.

3.4.1. Mass

Mass distributions are shown for completeness in Figs. 16–18. The trends are nearly identical to those in the results for the current technology (Figs. 12–14). The only exception is that the fraction of total mass due to the fuel cell and hydrogen storage has decreased, as expected. In fact, the electrical equipment mass now surpasses that of the fuel cell.

Upon comparison to the analogous current technology graphs, it can be seen that the total mass has decreased by nearly a factor of two. Thus, achieving the DOE targets for fuel cells and hydrogen storage for light-duty vehicles will result in lighter systems for fuel cell electricity generation on board commercial airplanes.

3.4.2. Performance

Like the current technology analysis, the impact of the system on overall airplane performance, as defined by the amount of jet fuel (Jet-A) added or subtracted from the base airplane to the airplane with the fuel cell, was determined. Fig. 19 is the result for all of the load scenarios and the three system configurations, assuming DOE target technology for the fuel cell and hydrogen storage vessel.

From here it is evident that the fuel cell system is able to provide a performance benefit to the airplane when the fuel cooled system (Case 6a) is implemented, and to a lesser degree when the water cooled/water recovery/limited hot water system (Case 3b) is chosen. The simple water cooled system without any heat or water recovery (Case 2a) still does not provide a benefit.

The amount of the benefit is also shown to depend on the load scenario. The trends are a little different than the current technology analysis, and not so straightforward. For example, the benefit of Case 3b increases with decreased system size, similar to the current technology results, but the All Galleys scenario shows the opposite trend – a better benefit with a larger system. And comparing the IFE and Mid-Galley scenarios shows a difference in the benefit in spite of the fact that both systems are 20 kW. The reason for...
Fig. 16. Mass distribution for Case 2a (water cooled, no heat recovery) for the different loads, using DOE target technology for the fuel cell and hydrogen storage. The different colors in the narrow bars represent different components. Quantities above the zero-line are for mass added to the system, and quantities below the zero-line are for mass credits. The net change (the sum of the added mass and mass credits) is shown by the wide hollow bar. For comparison, the "standard passenger" has a mass of 104 kg (230 lb) including luggage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 17. Mass distribution for Case 3b (water cooled, water recovery, limited hot water) for the different loads, using DOE target technology for the fuel cell and hydrogen storage. The different colors in the narrow bars represent different components. Quantities above the zero-line are for mass added to the system, and quantities below the zero-line are for mass credits. The net change (the sum of the added mass and mass credits) is shown by the wide hollow bar. For comparison, the "standard passenger" has a mass of 104 kg (230 lb) including luggage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 18. Mass distribution for Case 6a (fuel cooled) for the different loads, using DOE target technology for the fuel cell and hydrogen storage. The different colors in the narrow bars represent different components. Quantities above the zero-line are for mass added to the system, and quantities below the zero-line are for mass credits. The net change (the sum of the added mass and mass credits) is shown by the wide hollow bar. For comparison, the "standard passenger" has a mass of 104 kg (230 lb) including luggage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
this is that the effects of load location become more important, as piping and wiring masses become a larger fraction of the total mass (because the fuel cell and hydrogen mass has decreased so much).

There are two ways to illustrate the benefit (or penalty) a fuel cell system provides to the airplane. One way is to compare the total fuel required by the base airplane to the total fuel required by the airplane with a fuel cell to accomplish the mission. In some ways this method is appropriate because this is what may be most useful to an airplane customer as it reflects a "bottom line" effect. For example, looking at the fuel cooled system configuration supplying electricity to All Galleys, the fuel savings is 46 kg. That means that while the base airplane requires 22,680 kg of fuel, the airplane with the fuel cell requires 22,634 kg, a decrease of about 0.2%. A customer could project a 0.2% fuel savings over their expected usage and decide if it makes economic sense considering all the factors that affect their business.

Another way to illustrate the benefit (or penalty) is to compare the fuel cell system impact not to the entire airplane, but just to the portion of the airplane that is directly impacted by the fuel cell system. This can be done by comparing only the portion of jet fuel it takes the base airplane to supply the electrical and heat loads to the amount of jet fuel required by the fuel cell system to do the same. (Note that while the fuel cell system must necessarily provide electric power to the airplane because of things like added weight, drag, and the electricity required by the pressurization system to supply the fuel cell's air.) This method is also appropriate because it is a direct comparison of the two competing technologies (fuel cell versus engine generator) as opposed to comparing the effect of a fuel cell system to the entire airplane. It has already been noted that the base airplane weighs 173,998 kg at takeoff and carries 22,680 kg of fuel, while the fuel cell system weighs about 2000 kg and adds about 150 kg of fuel, or about 0.1% of the respective totals (for the worst case: largest system with current technology). So while the "bottom line" method is appropriate in some case, changes to the fuel cell system become nearly lost in the small overall numbers, whereas comparing the fuel cell system to the current electrical system allows for more insight into the effectiveness of the systems themselves.

To that end, Fig. 20 compares the amount of fuel required by the base airplane to generate electricity to the amount required by the fuel cell to do the same. This chart is for the fuel cooled system using DOE target technology. The efficiency of the airplane to generate electricity from the main engines is taken as 34%. This is possibly lower in practice, down to 25% depending on the electrical system, and if the auxiliary power unit is used, the efficiency will be about half that of the main engines. Using lower efficiency numbers would have the effect of increasing the amount of fuel needed by the base airplane to generate electricity (the blue bars) while not affecting the fuel cell's requirements (the orange bars). Table 7 summarizes the numbers and also shows the differences in terms of percentages. In the case of the galleys, the fuel cell system saves around 25% of the jet fuel that is dedicated to electric power generation for the base airplane. For the peakers, the fuel cell system results in a large penalty (nearly 5-times the fuel required), because the fuel cell peakers are only used for a small portion of the flight. Therefore, only a small percentage of the fuel cell benefits accrue for the peaker application.

The results can be cast in another way, and that is by putting the fuel savings in terms of CO₂ emissions. This is shown in Fig. 21, where "avoided CO₂" refers to the CO₂ emissions saved by comparing the fuel cell airplane to the base airplane, using the fuel requirements given in Table 7. Here, it shown for yearly emissions of a fleet of 1000 airplanes each flying 150 base missions, and assuming there is no contribution from hydrogen production to CO₂ emissions (i.e., renewable energy is used to generate the hydrogen used in the fuel cells). Boeing currently has over 800 orders for the 787 [46], and predicts that the market for 787-class airplanes ("small twin aisle") will be 4430 by 2029 [47], so 1000 787-type airplanes is reasonable. 150 base missions is equivalent to 750 h of flight time per year, which is what was used in Ref. [22]. CO₂ is calculated by assuming complete combustion of C₁₂H₂₃, used to represent the average hydrocarbon content of jet fuel, yielding 3.16 kg of CO₂ generated for every 1 kg of jet fuel burned. The figure does not include either of the peaker load scenarios since those do not provide any avoided emissions. To put these avoided CO₂ results in context, US EPA calculations estimate that avoiding 10,000 metric tons of CO₂ per year is equivalent to taking nearly 2000 passenger cars off the road [48].
3.4.3. Summary

The DOE target technology analysis showed:

Overall airplane performance benefits can result from improved fuel cell and hydrogen technologies in accordance with DOE targets.

While the performance as measured by fuel savings is small when compared to the entire airplane’s fuel consumption, the fuel cell system can save over 30% of the fuel that is devoted to electricity generation (Case 6a with the IFE load).

4. Conclusions

Our analysis has shown that it is feasible for PEM fuel cell systems to be used on commercial aircraft, and has revealed how the on-board PEM fuel cell system’s location, electrical loads, and future technology developments impact the overall performance of the airplane. As a result of our analysis, the following observations can be made:

- The fuel cell and hydrogen storage should be located together in either the fairing area or the tail cone area. Locating the fuel cell near the hydrogen supply saves hydrogen supply tubing, and locating the fuel cell near the electrical load saves wiring. Doing both can save 50–100 kg in system mass. However, the fuel cell systems are not small, so locating them near the load may cause existing equipment to be displaced or require the use of cargo space.
- Air cooled systems are not preferred: they require a large increase in current air handling units’ capacities, have large weight and volumes, and have large performance penalties.
- The uses of low-grade waste heat within the cabin are limited. The amount of hot water that could be generated by the fuel cell’s exhaust heat is approximately 5–10-times that which could be reasonably used on the airplane.
- Adding a heat exchanger to cool the fuel cell’s exhaust and recovering the water results in an overall benefit despite the added equipment and cooling drag.
- The most weight-impactful non-hardware factors on the airplane’s performance are the amounts of water and waste heat that can be recovered. However, waste heat recovery is limited by available on-board uses while water recovery depends on the effectiveness of the heat exchanger cooling the exhaust stream.
- The fuel cell and hydrogen storage are the most important (heaviest) hardware components.
- For maximum performance benefit, the fuel cell should be used at full load for the entire flight; loads such as the in-flight entertainment and galley are attractive because of this. For partially operating systems, the benefit of heat and water recovery is limited to only the portion of flight that it is operating, but the mass penalty takes effect for the entire flight.
- A future fuel cell system, comprised of DOE-target technology for the fuel cell and hydrogen storage, will provide an overall performance benefit to the airplane. The fuel cell and hydrogen vessel are responsible for the majority of the system mass and volume, so reducing the sizes of these has a large impact on the overall system.
- A future fuel cell system would provide an electrical generation efficiency gain of over 30% in some cases, even when considering the added mass and drag effects on the airplane. This could result in a savings of over 20,000 metric tons of CO₂ emissions per year if implemented on a fleet of 1000 airplanes such as the 787.

It should be noted that when considering the use of a PEM fuel cell system on-board a commercial airplane, there may be other factors not considered in this study that outweigh the performance benefit or penalty, such as distributed power generation, system redundancy, capital cost and hydrogen availability. In addition, we have only considered a fuel cell system add-on to an existing

<table>
<thead>
<tr>
<th>Load scenario</th>
<th>Fuel required by base airplane (main engine generator, 34% efficiency) (kg)</th>
<th>Fuel required by fuel cell airplane (fuel cooled system with DOE target technology) (kg)</th>
<th>Percentage (fuel cell airplane/base airplane) (%)</th>
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<td>IFE</td>
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Fig. 21. Yearly avoided CO₂ emissions for a fleet of 1000 fuel cell-equipped airplanes operating 750 h/yr, using a fuel cooled fuel cell system (Case 6a) and renewable hydrogen, and comparing to the base airplane generating electricity via the main engines at 34% efficiency.
airplane platform. If an airplane were designed from the ground-up integrating a fuel cell for power generation, it is believed that the fuel cell-equipped airplane would achieve a higher performance benefit than is illustrated in this work.

Acknowledgements

Special thanks to the Boeing Commercial Airplanes staff: Joe Breit, Andy Bayliss, Trevor Laib, Farhad Nozari, and Casey Roberts for their assistance with understanding airplane configuration, electrical systems, and performance. This work was sponsored by Department of Energy (DOE) – Energy Efficiency & Renewable Energy (EERE) – Fuel Cell Technologies (FCT) – Market Transformation group – thanks to Pete Devlin for his support.

Sandia National Laboratories is a multi-program laboratory managed and operated by SANDIA CORPORATION, a wholly owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy’s National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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