

Projecting the Impact of Aircraft Design Decisions on the Performance of a Fuel Cell Power and Energy System in Unmanned Aircraft Systems

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ABSTRACT

Fuel Cells provide an attractive alternative to battery powered Unmanned Aircraft Systems (UAS) as they maintain the simplicity of an all-electric vehicle architecture while taking advantage of highly energy-dense fuels. Unfortunately, the overall energy and power density of the power and energy (P&E) system cannot be determined from the fuel and fuel cell technology without also including the context of the associated aircraft and mission. These outside requirements play a particularly important role in the design of Small UAS (SUAS) P&E systems where the fixed weight of the fuel cell plant may approach or exceed the weight of the fuel utilized. Over the past seven years Protonex has developed fuel cell power systems for a number of different SUAS, creating an empirical database and methodology suitable for future SUAS design efforts.

This methodology centers on estimating the weight fractions of the power conversion and energy storage systems in comparison to the overall vehicle weight. The author's previous work focused on presenting this methodology on a macro scale for the initial phases of a conceptual design. As the UAS design concept matures additional dependencies emerge, particularly due to the impact of mission requirements such as the required environmental operating envelope.

In this paper the authors expand the design methodology to include the impact of aircraft level requirements and design decisions. The expanded methodology is presented conceptually and in practice via application to specific UAS design examples.

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INTRODUCTION

Fuel Cell Power and Energy (P&E) systems have the potential to dramatically increase the endurance of Unmanned Aircraft Systems, particularly in the smaller size classes where electric powertrains are the norm. Typical design practice in this class of UAS uses the specific energy of different fueling solutions as a basis for initial analysis. This approach is poorly suited to analyzing a Fuel Cell P&E system, as the specific energy of such a system depends on the power requirements of the aircraft in question, the weight percentage of that vehicle devoted to propulsion, as well as the fuel chemistry and fuel cell technology selected. This dependence has historically made it difficult for aircraft designers to quickly estimate the feasibility or attractiveness of utilizing a fuel cell P&E system in their application, as a simple literature review of previous fuel cell UAS programs can provide seemingly contradictory values. Additionally, the relative complexity of a fuel cell P&E system requires careful

integration between the airframer and P&E system manufacturer starting early in the design process, making it relatively expensive to attempt and discouraging a simple "build & test" approach to evaluating the feasibility of a fuel cell UAS.

In a previous work [1] the authors presented a method to estimate the weight fraction required to be devoted to the P&E system based on common conceptual design inputs, thereby allowing aircraft designers to determine the suitability of utilizing a Fuel Cell earlier in the design process. This paper expands on the previous description of the method by presenting two examples of its application to small unmanned aircraft systems (SUAS) designs, thereby demonstrating the impact of differing mission requirements on overall system metrics.

METHOD

Equations 1, 2, and 3 form the basis of the method, defining the weight fractions devoted to Power (W_{Power}) and

Energy (W_{fuel}) in terms of a few simple input variables. Endurance is typically a design input, Peak and Average power can be easily approximated from design inputs, as shown in [equations 4 & 5](#). The remaining three values (PSP, FSE_{stored} , η) are relatively constant across fuel cell power systems, with typical values for PEM based systems shown in [table 1](#).

$$\frac{W_{\text{plant}}}{GTOW} = \frac{1}{PSP} \frac{\text{PeakPower}}{GTOW} \quad (1)$$

$$\frac{W_{\text{fuel}}}{GTOW} = \frac{1}{FSE_{\text{stored}}} \frac{\text{AvgPower}}{GTOW} \text{Endurance} \frac{1}{\eta} \quad (2)$$

$$\frac{W_{\text{ps}}}{GTOW} = \frac{W_{\text{plant}}}{GTOW} + \frac{W_{\text{fuel}}}{GTOW} \quad (3)$$

$$\frac{\text{AvgPower}}{GTOW} = \frac{V_{\text{average}}}{L/D} (\text{Aux}_{\text{ratio}}) \frac{1}{\eta_{\text{propulsion}}} \quad (4)$$

$$\frac{\text{PeakPower}}{GTOW} = \text{Peak}_{\text{ratio}} \frac{\text{AvgPower}}{GTOW} \quad (5)$$

After calculation the designer can compare the power system weight fraction to the overall weight of a competitive system (for example battery weight) or against historical data, [Figure 1](#), to assess the appeal and feasibility of incorporating a fuel cell based P&E system.

Table 1. Typical SUAS Fuel Cell P&E System Values

Input	Typical Value ²
PSP	20-30 W/N
FSE_{stored}	150-200 Wh/N
η	45-55%
$\eta_{\text{propulsion}}$	60-90%

This method can be adapted to predict the performance of a hybridized P&E system in which the PEM fuel cell system is combined with a rechargeable battery to handle short duration peaks in the power demand. In such an application [Equation 1](#) is recast in the following form:

$$\frac{W_{\text{plant}}}{GTOW} = \frac{1}{PSP} \frac{\text{MaxPower}}{GTOW} + \frac{t_{\text{peak}}}{BSE} \left(\frac{\text{PeakPower}}{GTOW} - \frac{\text{MaxPower}}{GTOW} \right) \quad (6)$$

In this modification the PeakPower term remains the peak in the power demanded by the aircraft, and MaxPower now represents the maximum output of the fuel cell plant itself. Whereas previously these two values had been assumed to be

equal, the new form allows for aircraft power in excess of MaxPower, with the deficit made up by the battery. The relative attractiveness of hybridization can be quickly determined by comparing the mass of batteries required to cover this deficit over the predicted peak duration to the mass of simply increasing plant size and output. This relationship can be expressed in terms of the maximum peak duration for which hybridization is attractive, as shown in [Equation 7](#).

$$t_{\text{peak}} < \frac{BSE}{PSP} \quad (7)$$

EXAMPLE A - NRL ION TIGER

An example of an SUAS that has been outfitted with a fuel cell power system is the Navy Research Laboratory (NRL) Ion Tiger [\[4\]](#). The Ion Tiger was designed to carry a 5 lb payload for up to 24 hrs at cruise velocity, and the aircraft design reflected a desire to maximize aerodynamic efficiency. The vehicle is launched via a cable winch, minimizing take-off power, and has a relatively slow rate of climb. Design values for the Ion Tiger are shown in [Table 2](#) below. Note that high values for PSP and FSE_{stored} have been used as both benefit from the larger scale of the Ion Tiger, one of the larger SUAS (defined as Tier I & Tier II). A larger fuselage volume allows a more mass efficient storage design (surface area to volume), while a larger plant size allows more freedom in component selection and less compromises for packaging.

Table 2. Ion Tiger SUAS Characteristics [\[4\]](#)

Cruise Power	300 W
Peak Power	550 W
L/D	17
Cruise Velocity	14 m/s (~27 kts)
Auxiliary Power Ratio	1.3
PSP	28 W/N (~280 W/kg)
FSE_{stored}	200 Wh/N (2000 Wh/kg)
Peak _{ratio}	1.7
BSE	190 Wh/kg
η	50%
$\eta_{\text{propulsion}}$	70%

Using [Equation 7](#) and the values above with a notional 190 Wh/kg BSE, it can be seen that hybridizing the Ion Tiger power system is only weight-attractive when peaks in power are sustained for under ~ 35 minutes. The Ion Tiger does not require a high-power takeoff, but it does require continuous peak power to fly into a headwind for extended periods of time (>35 minutes). Therefore, it was decided that the fuel

¹This equation is modified from [\[1\]](#) to include propulsive efficiency and to redefine Power_{auxiliary} as a ratio (Aux_{ratio})

²Note that these are "per weight (force)" to agree with the use of Gross Take-off Weight in the equations