Electrical Systems Analysis at NASA Glenn Research Center: Status and Prospects

Joshua E. Freeh, Anita D. Liang, Jeffrey J. Berton, and Timothy J. Wickenheiser
Glenn Research Center, Cleveland, Ohio

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Joshua E. Freeh[*]
Anita Liang[†]
Jeffrey J. Berton[*]
Timothy J. Wickenheiser[‡]
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

An analysis of an electrical power and propulsion system for a 2-place general aviation aircraft is presented to provide a status of such modeling at NASA Glenn Research Center. The thermodynamic/electrical model and mass prediction tools are described and the resulting system power and mass are shown. Three technology levels are used to predict the effect of advancements in component technology. Methods of fuel storage are compared by mass and volume. Prospects for future model development and validation at NASA as well as possible applications are also summarized.

Introduction

NASA aeronautics goals include reducing emissions and noise, and pioneering new technology innovation. Advancements in electrical power sources including fuel cells and electromechanical systems such as electric motors have shown promise in meeting these goals. The automobile and stationary power industries have embraced these technologies as a means to more efficient vehicles and power plants, as well as revolutionary new concepts. The resulting research and development effort has created lighter-weight, more compact and powerful fuel cells and electric motors. These improvements allow fuel cells and electric motors to begin to be considered for aeronautical applications.

The appeal of the fuel cell begins with the potential of producing nearly emission-less electrical power. This idea is exciting and the effect far-reaching, but it must be portrayed with the caveat of a 'cradle-to-grave' viewpoint for the fuel. Any claims for emissions reductions should include data for the lifespan of the fuel – from production and reformation to reaction within the fuel cell. With this statement in mind, the outlook is still very promising. Total emissions will likely be reduced and emissions from the fuel cell itself may be near-zero. A more practical advantage, compared to other electrical power sources, is that the fuel is contained external to the cell itself, unlike batteries and capacitors. Therefore, the total energy available is not directly limited by the cell or stack size, but by the ability to store fuel. Fuel cells are also modular and theoretically any voltage or power can be produced by a series and/or parallel configuration of stacks of cells. Furthermore, fuel cell energy conversion is electrochemical and not limited by the thermodynamic Carnot cycle. All thermodynamic power cycles, including gas turbines and intermittent combustion engines, are limited by this corollary restriction, where

$$\eta_{max} = 1 - \frac{T_1}{T_2}$$

The lack of the Carnot limitation alone makes fuel cells and other electrochemical power sources appealing as a possible revolutionary change in power production.

In addition, an electrically based power system may reduce noise by lowering internal powerplant noise and possibly further optimizing the propulsor and its performance. While this is of less concern for the automobile industry, the aviation industry is strongly regulated to established noise levels, especially near airports. While the propulsor and its noise would remain, the possible powerplant reductions make another argument for the technology.

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[*] Aerospace Engineer, Airbreathing Systems Analysis Office
[†] Chief, Aeropropulsion Projects Office
[‡] Chief, Airbreathing Systems Analysis Office

NASA has used fuel cells for every manned space flight. While a form of polymer electrolyte membrane (PEM) fuel cells was used for many of the Gemini missions, alkaline fuel cells have been used in the Apollo missions as well as the Space Shuttle. The fuel cells are supplied with pure H_2 and O_2 and power much of the vehicle electrical system. For the Apollo and Shuttle systems, the resulting water is potable and is an innovative way of producing the necessary drinking water for the crew. Interestingly, the specific power (power/mass) of Gemini and Apollo remained nearly constant, but the Shuttle specific power increased dramatically [1,2,3]. Currently, many transportation applications of fuel cells have returned to PEM designs because of new materials and other improvements. Compared to the space fuel cells, they are more compact with even more dramatic specific power and power density (power/volume) improvements in the last decade.

The improvements in specific power and power density have enabled more than just space applications. Possible aeronautical applications include general aviation (GA) and unmanned aerial vehicle (UAV) propulsion and power production units for larger airplanes (replacing the current auxiliary power unit). Aside from reducing noise and emissions and improving efficiency, entirely new vehicles may become possible because of the change in power system. For example, a regenerative system based on a combined fuel cell/electrolyzer/solar array cycle may enable extremely long-range or -duration air vehicles for scientific, communication or other purposes [4].

This potential has caused NASA Glenn Research Center (NASA GRC) to begin investigating the technology at many levels including basic research in materials and chemical reformation, systems analysis, and CFD and other high-fidelity analyses. While the primary NASA goals are in aerospace, efforts have been made to coordinate with NASA counterparts in the Department of Energy, industry and universities to ensure the most beneficial outcomes for the research. The following is a description of current system analysis results for a GA propulsion system. It provides a detailed introduction into the modeling techniques as well as an idea of the state of fuel cell propulsion for aircraft. Another paper presents the overall results of this study for a specific GA airframe, the MCR01 [5].

NASA GRC has been involved in similar electrical systems studies in the past. For example, a 1994 analysis examined the effects of various power system technology and mission requirements on the sizing of a solar/regenerative fuel cell-powered long endurance aircraft [6]. Another example is an exploration of Mars aircraft propulsion systems with an emphasis on the constraints of the Martian atmosphere [7]. NASA GRC was also involved in the development of the International Space Station (ISS) power system and the resulting experience has produced relevant work including a study to replace the ISS battery system with a group of flywheels [8]. The study includes detailed electrical models of a multi-component flywheel system.

Current electrical systems modeling at NASA GRC includes analyses such as the electrical power production unit for larger aircraft and GA/UAV propulsion. Larger aircraft propulsion is being examined in less detail for critical technology identification. Work is continuing on flywheel applications and resurging in the long-duration aircraft missions because of new and improved technologies and different mission designs. There are also ongoing investigations into future manned space flight fuel cell power systems.

Approach

The propulsion system is simulated primarily through steady-state thermodynamic and physical models. The major components of the system, shown in Figure 1, include the PEM fuel cell, electric motor, compressor, fuel cell heat exchanger, and propeller. In addition, mass is estimated for each of the above components as well as other electric components and the electrical power distribution system. Various fuels, their distribution and storage are compared primarily by mass and volume and are included in the final airplane model.

System Design

The system is designed to provide shaft power to a propeller. The electric motor converts the energy from electrical to mechanical power and the PEM fuel cell converts the energy from chemical to electrical power. The apparent 'backwards' description is meant to emphasize the simulation process that is used. The input shaft power therefore determines the fuel flow rate and air flow rate required. When modeled over a flight mission, these data establish the fuel required and therefore analytically size the airplane.

Due to the altitude changes and resulting ambient pressure reduction, a radial compressor is used to maintain constant pressure at the inlet of the fuel cell. While the pressure change is relatively small at GA cruise altitudes, most fuel cells are currently designed for at least ambient pressure and may see a slight performance improvement at higher pressures [9]. For this study, a fuel cell inlet pressure of 2 atm is used to improve fuel cell performance and to be conservative in the compressor design. The final compressor design requirements, including flow rates and pressure ratio, are remarkably similar to that of a supercharger for a car.

The fuel cell requires some form of heat removal such that it remains at the optimal temperature. Depending on the fuel cell type, different techniques can be used. For a PEM fuel cell, which operates at low temperatures (~80°C), the heat is low-grade and difficult to remove efficiently. While a detailed heat exchanger design is out of the scope of this study, the data based on simplified models are recorded.

As noted in Figure 1, batteries are used in series with the fuel cell in the hybrid configuration. The hybrid motive is that by augmenting the fuel cell power during takeoff, a smaller fuel cell may be used, therefore reducing the mass and also requiring less fuel for the mission. During cruise, the fuel cell would recharge the battery in case of a missed approach or other emergency power surge requirement.

Thermodynamic Model

A common issue in electrical and electrochemical systems modeling is that there is no complete model package currently available. Chemical process codes typically lack fidelity in the mechanical and electro-chemical subjects and similarly, electromechanical analysis codes lack a solid chemical and electrochemical background. When requiring propulsion codes such as a propeller performance model, the challenge of a universal tool becomes even more difficult. The software used in this analysis is the Numerical Propulsion Systems Simulation (NPSS), a NASA and U.S. aerospace industry-developed tool for gas turbine and rocket engine models [10].

NPSS is primarily a steady-state and transient nodal thermodynamic analysis code that was created so that the various organizations involved would have a similar tool for aerospace propulsion analysis. The code is object-oriented and therefore modular in that the code can be organized into portions analogous to gas turbine components, for example. The modularity also allows for higher-fidelity codes to be inserted into their respective section of the system model. A past example used a 1-dimensional mean-line compressor code external to NPSS, but accessed real-time by means of the CORBA software [11]. Higher fidelity examples such as CFD have also been demonstrated. NPSS also includes useful thermodynamic data and codes as built-in packages for the user. These include temperature and pressure data as a function of altitude, a form of the JANNAF data, and the CEA chemical equilibrium code [12].

NPSS has several advantages that enabled its use for aerospace electrical systems analysis. Some of the most important include the built-in CEA code, the modularity, the design/off-design capabilities, and the aerospace industry familiarity. The CEA code provides a well-known basis for calculating equilibrium chemical mixtures that is valuable when analyzing fuel reformation as well as the fuel cell. The modularity allows for different users to supply their own fuel cell models or configurations without modifying the source code or the internal models. The design and off-design capabilities allow the user to set design point conditions and then evaluate that component at other, off-design conditions. An example is setting the compressor design pressure ratio and speed at sea-level static conditions and then evaluating the same compressor at cruise via an experimentally-correlated compressor map. This capability has proven to be useful in the fuel cell model. Finally, NASA is not the only interested party in analyzing possible aerospace electrical systems and a common tool among aerospace organizations may prove as valuable in this field as it has in the gas turbine and rocket industries.

The thermodynamic PEM fuel cell model is a 0-dimensional model based on an ideal cell voltage and its losses. The losses are correlated using a multi-function curve-fit of a polarization curve of cell voltage vs. current density [13]. A small, conservative pressure effect is included based on data found in the DOE Fuel Cell Handbook [9]. This introduces a slight performance reduction for pressures below the design inlet pressure, a condition only seen at the extreme combinations of altitudes and flight speeds. Pressure increases are not seen in this study but are of interest. A more theoretical approach could be taken in which the Nernst equation would be used to evaluate partial pressure effects on the voltage, but experimental validation was lacking at the time of the analysis. The fuel cell characteristics, including design cell voltage, number of cells, stacks and their configuration, are set at the design point and then evaluated at off-design conditions using the polarization curve as the constant throughout the mission. An example is the difference between takeoff and cruise. If the fuel cell is designed at cruise, a relatively low power condition, then at takeoff, or higher power, the analysis would require a different current density and voltage based on the polarization curve. A similar approach was used in a thesis that designed a fuel cell scooter [14]. If designed correctly, the fuel cell can be more efficient at cruise and more current dense and therefore more powerful at takeoff. A related item to note is the difference between intermittent and continuous power. Because of the limits of heat removal, there is a power level above which the fuel cell will produce more heat than can be removed. This power level is known as the continuous power. Intermittent, or peak, power is typically the maximum allowable power produced for a short amount of time. For this application, cruise is limited to continuous power and the takeoff portion is able to use up to the peak power level.

The electric motor model is simply a conversion of electrical to mechanical power via an experimentally-correlated efficiency. The correlation is through a performance 'map' of shaft power vs. shaft rpm, with efficiency contours included. A map similar to that used in this analysis is shown in Figure 2. Two lines are shown: continuous and intermittent power, based on the same reasoning as described in the fuel cell section above. The motor continuous-power-to-peak-power ratio is found to be typically smaller than that of the fuel cell, and therefore more important in the final sizing and design. These maps are sometimes found in a technical specifications document for the motor. For this study, data for comparable motors are collected from four companies that currently design and manufacture electric motors for electric vehicles. All of the motors were designed to be compact and lightweight and therefore with the same design goals as with this study. Similar industrial motors are much heavier and larger in size. The four companies that are used are UQM Technologies, Solectria, AC Propulsion, and Ecostar [15-18]. The final performance map that was selected is the UQM Technologies data due to the quality and quantity of the data and its near-average performance (compared to the other three companies' motors). The map is moderately scaled to the actual power required but the applicable speeds are nearly that of the optimum propeller, thus eliminating the need for a gearbox. The motor portrayed by the map is a liquid-cooled brushless DC permanent magnet machine. In addition, a lower-power motor is required to drive the compressor. Similar performance maps are used, with a lower efficiency due to the smaller size and possible gearbox because of the high compressor speed.

The compressor model is the built-in NPSS 0-dimensional model again based on a performance map relating pressure ratio, air flow, speed and efficiency. As stated above, its primary design requirement is to deliver a constant fuel cell inlet pressure of 2 atm. The value is chosen to be a substantial requirement at some altitudes but also realistic for most PEM fuel cells. In addition, the required variation in pressure ratio is monitored to keep within a typical compressor performance regime. Based on the design specifications, single-stage, radial superchargers are found to be in the same range of values. Figure 3 shows an example of a performance map from Turbonetics, Inc., a manufacturer of high-performance car superchargers [19].

The primary heat exchanger is used to maintain optimum average fuel cell temperature. It is modeled using the default NPSS gas-to-gas heat exchanger with an input effectiveness. Other heat exchangers are required for the system, including the motor heat regulation and the compressor aftercooler. The aftercooler is required to reduce the compressor exhaust heat to a manageable temperature for the fuel cell. The motor coolant loop is not modeled because it is a closed-loop system based on a liquid flow rate. The aftercooler is modeled to monitor the system requirements.

Even though NPSS has propeller analysis capabilities, a more applicable model is used that is included in the airframe code, the NASA-developed Flight Optimization System (FLOPS) code [20]. For this analysis, the FLOPS propeller model is accessed real-time during the NPSS calculations to maximize thrust by varying propeller conditions. A detailed version of this method and its merits is described in [5].

Mass model

The mass model is a spreadsheet-based tool. Each component is scaled based on best available data with conservative assumptions. The fuel cell system accounts for the balance-of-plant as well as the fuel cell stack. The components included are the stack itself, its control electronics, air and hydrogen humidifiers, water separator and the heat exchangers. The fuel cell stack is scaled based on the best-available industry data. At the time of analysis, a General Motors press release was announced that included a significant amount of data near the power levels required for this analysis [21]. Continuous and intermittent power levels were provided, as well as mass and volume. Because of the modular nature, the final mass is scaled linearly from the intermittent specific power, the most conservative method in this case. It is important to note that this power level is not the mechanical shaft power but the electrical power that is calculated to include the parasitic loss from the compressor as well as a smaller percentage for other electronic needs from the airframe and power system electronics. Fuel cell electronics are accounted for as a percentage of the fuel cell system mass due to the lack of tools available for such a calculation. The percentage is about 60% for most systems, but is increased for higher-power systems. General guidance was received from the NASA GRC Electrical Systems Development Branch and the inverter/controller data below. The other balance-of-plant correlations are based on data from the NASA GRC Electrochemistry Branch [22].

Electric motor mass is calculated based on the specific power scaling of the UQM product line of motors. It was found that the most accurate linear scaling was based on the continuous specific power and this is the method that is used. One of the benefits of all four motor manufacturers listed above is that a separate inverter/controller was included for each motor. The electronics were similarly designed for compact and lightweight power, as well as for the specific motors that are the baselines for this analysis. Likewise, a motor controller mass is scaled linearly based on continuous specific power. The values for the smaller compressor motor are scaled the same way, but with lower specific power values due to the smaller size.

Another area that is difficult to assess at this level is the power distribution system, consisting of such hardware as the conductors and electrical connectors. While it is valuable to include some value as a place-holder and for conservatism, an accurate value is not known until a detailed design is complete. Therefore, a percentage of the fuel cell system mass is used, typically around 12%.

Fuel system modeling

The choice of fuel and its storage depends on many factors, both internal and external to the airplane. Internal examples include the type of fuel cell, mass and volume available and aircraft range desired. PEM fuel cells are extremely sensitive to impurities such as carbon monoxide and sulfur and therefore fuels other than pure hydrogen require extensive reformation. Mass and volume are two recurring design drivers in aircraft design and both severely limit the amount of fuel onboard, directly limiting the range of the aircraft. External factors for fuel selection include available fuel infrastructure and availability of the fuel itself. The lack of a pure hydrogen distribution infrastructure is a problem being actively addressed by the automobile industry and government research, though airport-specific issues may also be a factor.

For this study, due to the mass, volume, and purity constraints listed above, only non-hydrocarbon hydrogen storage methods are analyzed. Ten different methods, including compressed and liquid hydrogen, metal hydrides, and carbon nanotubes, are compared by mass and volume using the best available industry and/or physical data. Storage methods that require heating, catalysis or other subsystems are penalized accordingly. The comparison is shown in Figure 4. Estimated error bars are included to show the uncertainty and the MCR01 takeoff gross weight (TOGW) is shown for a sense of scale for the mass axis. In addition, gasoline data is shown as an equivalent energy source, not as a possible fuel to reform into hydrogen.

Fuel distribution is also considered in the overall mass estimate, but it has a high uncertainty in this early design stage, as is the power distribution. A constant value of 10% of the fuel cell system mass is used for conservatism.

Model Validation

An electrical system designed for GA propulsion has never been assembled, so there is little available validation data. In addition, most electrical system and even component data for automobile-based systems have not been published due to the proprietary concerns. Therefore, component validation is the most realistic method for current and near-future studies. Most of the performance and mass data is empirical and based on current industry data and is hence validated to some extent. However, a true systems-level validation has not occurred and is a recognized weakness of such a model. Current efforts at NASA GRC include development of an electrical systems test-bed and also external partnerships with similar research-oriented organizations.

Model Assumptions

The primary assumptions that are used for the study are mainly due to NASA being a technology-driven government organization and not a business entity. The question asked for this study is not whether an electrically-driven airplane is financially justified, but whether the airplane is technically possible. Therefore the first assumption is to ignore cost. Though the costs are decreasing, fuel cells are still made in the laboratory, not on an assembly line and are therefore still very expensive per kilowatt. The other major assumption is that the required fuel infrastructure is also ignored as it is out of the scope of this systems study. It is a major issue that needs to be addressed for all possible applications of fuel cells.

Three 'technology levels' are used to analyze the value of current research efforts and help direct future research: off-the-shelf, intermediate, and advanced technology. The assumptions that are used for each level are shown in Figure 5. As shown in the figure, the technology levels directly affect the component masses. More mature technology, such as compressors and power electronics are shown to improve slower than other, more actively-developed technologies such as the fuel cell. Not shown are the effects of efficiency improvement. These effects on the system will be addressed through a sensitivity analysis.

Results and Discussion

The powerplants are sized for two different GA airframes, the 2-place MCR01 [23] and the 4-place Cirrus SR-20 [24]. Both are composite airframes with the most current technology for their size classes. The MCR01 is powered by an 81 peak bhp Rotax 912 intermittent combustion (IC) engine [25] and the Cirrus is powered by a 200 peak bhp Teledyne Continental Motors IO360 IC engine [26]. In addition, propulsion systems for two larger commercial aircraft, the 50-passenger Embraer ERJ145 and the 100-passenger Boeing 717, are analyzed at a less detailed level to assess the effects of scaling to much higher power levels. The following focuses on the MCR01 sizing to simplify this summary. Further information on the other analyses is available from the first author, if interested. Also, as stated in the introduction, a second paper focuses on the detailed results of the complete MCR01 analysis [5].

The initial modeling approach is to match the peak shaft power of the electric motor to the peak power of the Rotax engine, 81 hp. This does not imply that the continuous power of the motor and the engine are the same. In fact, the values are very different due to the nature of each system. The IC engine barely loses power, going from the peak 81 hp to a continuous value of 79 hp. For the electrical power system, the motor, rather than the fuel cell stack, is found to be the limiting component. Its continuous power is typically 40% – 50% lower than the peak power, estimated at 40 hp for this case.

The power and mass results are shown in Figures 6 and 7. The power charts show several interesting results. While producing 81 shaft hp, the electrical power requirement of the fuel cell is calculated to be about 15% higher due to the compression system and other auxiliary loads. Secondly, the cruise power percentages are different from the takeoff values because of the compressor operation. To deliver constant fuel cell inlet pressure at altitude, a higher percentage of compressor power is required. It should also be noted that based on the continuous power requirements, the actual cruise power levels drop from 98 hp to 61 hp.

The mass charts also provide insight into the system. The fuel cell stack, for example, is typically considered to be the primary component in terms of mass. While it is calculated to be about 64% of the fuel cell system mass, it is only about 24% of the entire system mass. The electric motors and power management mass are both calculated to be larger portions of the total, at 28% and 31%, respectively.

Matching the peak shaft power of the IC engine is successful in that the airplane model is able to analytically takeoff and cruise for a very short time [5]. However, a more realistic approach is to match a lower power level that is determined through minimum flight requirements such as takeoff field length and cruise speed. While this version of the MCR01 analytically flies slower and lower, it does fly longer and more appreciable distances. This concept was presented to NASA from Advanced Technology Products, a Massachusetts company attempting to actually build such an aircraft [27]. The lower power level is determined to be 49 peak shaft hp. This reduction in power dramatically lowers the system mass and volume such that more fuel and its storage can be included, enabling longer aircraft range. The actual mass is reduced from 487 lbm for the 81 hp case to 342 lbm for the 49 hp case, about a 30% improvement. The relative power percentages are similar to that of the 81 hp case.

Much of the research for transportation applications of fuel cells is in mass reduction. Some of the possible advancements are listed in Figure 5 for the three technology levels and system mass totals are estimated for each level and compared in Figure 8. While the improvements are substantial, even the advanced technology case is heavier than a comparable IC engine. In order for the electrical system to earn its way onto the airplane, the remainder of the mass savings must come from improvement in efficiency.

Conclusions

A systems analysis of an electrical power system for a 2-place general aviation airplane is reviewed to provide a status of such efforts at NASA Glenn Research Center. While basic lessons can be learned from such analysis, there is a need for more accurate models and validation of those models, especially at the systems level. Specific improvements include design of the power management system and its mass prediction, more detailed fuel cell and electric motor thermodynamic and mass modeling, and heat exchanger modeling. Most of these tools exist in some form, but the integration into a single, coherent systems model is not trivial. A dynamic model that investigates startup, takeoff, and other mission transients would also be valuable for such a system. Finally, further investigation into various hybrid configurations may be beneficial based on both the technical and financial success of battery/IC engine automobile hybrids currently in the market.

Further analyses and model development are already underway at NASA GRC along with its partners. Equilibrium and kinetic hydrocarbon reformer models are being developed. The PEM fuel cell model is being improved and a solid oxide fuel cell model is being created. An electrical systems test-bed is being assembled that will be able to do much of the necessary validation of the models.

While the potential for ultra-low emissions and very efficient flight is appealing, one must realistically assess such claims through all forms of modeling and hardware testing. There have been many predictions about fuel cell technology in the past [28] and it remains the authors' goal to produce the most accurate results possible.

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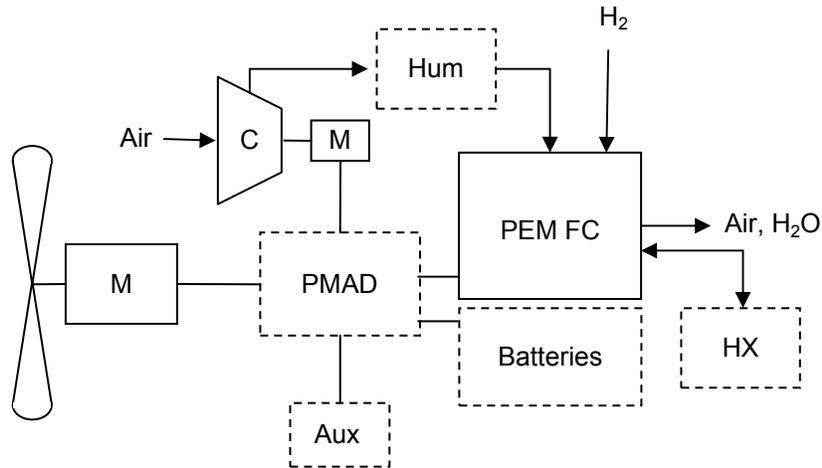33. Sodium Borohydride data, courtesy Millennium Cell, Inc., Eatontown, NJ.

Figure 1. A schematic of the propulsion and power system. Solid lines indicate a thermodynamic and a mass model while dashed lines indicate a mass model only. Batteries are present in the hybrid design.
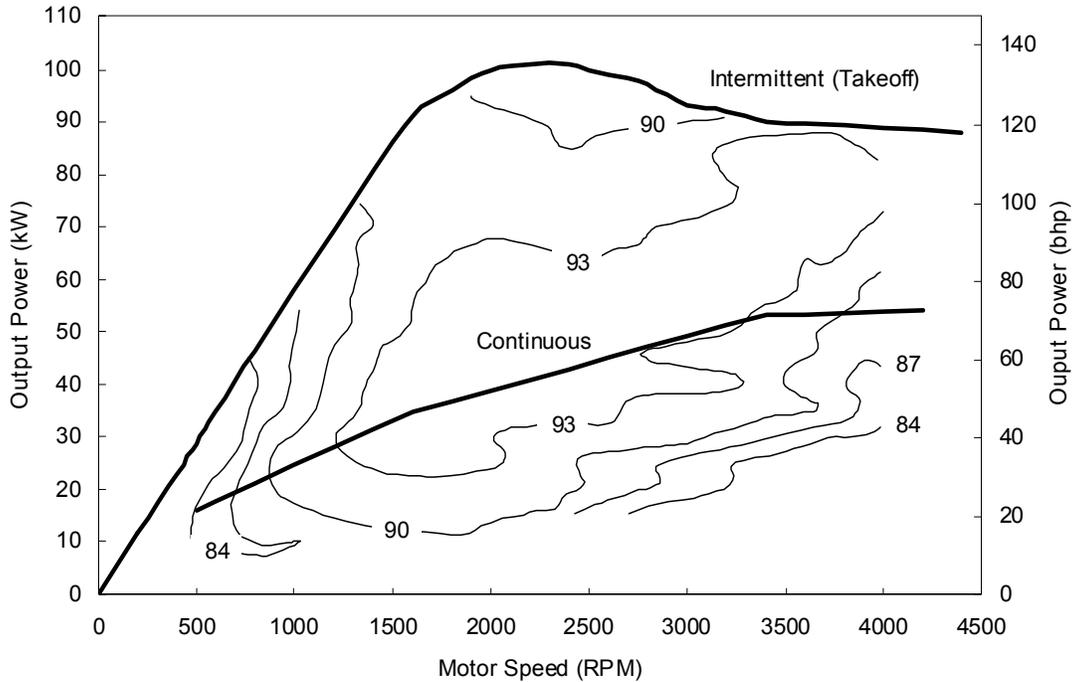

Figure 2. A motor performance map based on the UQM Technologies SR286. Efficiency contours are shown as percentages within the plot.
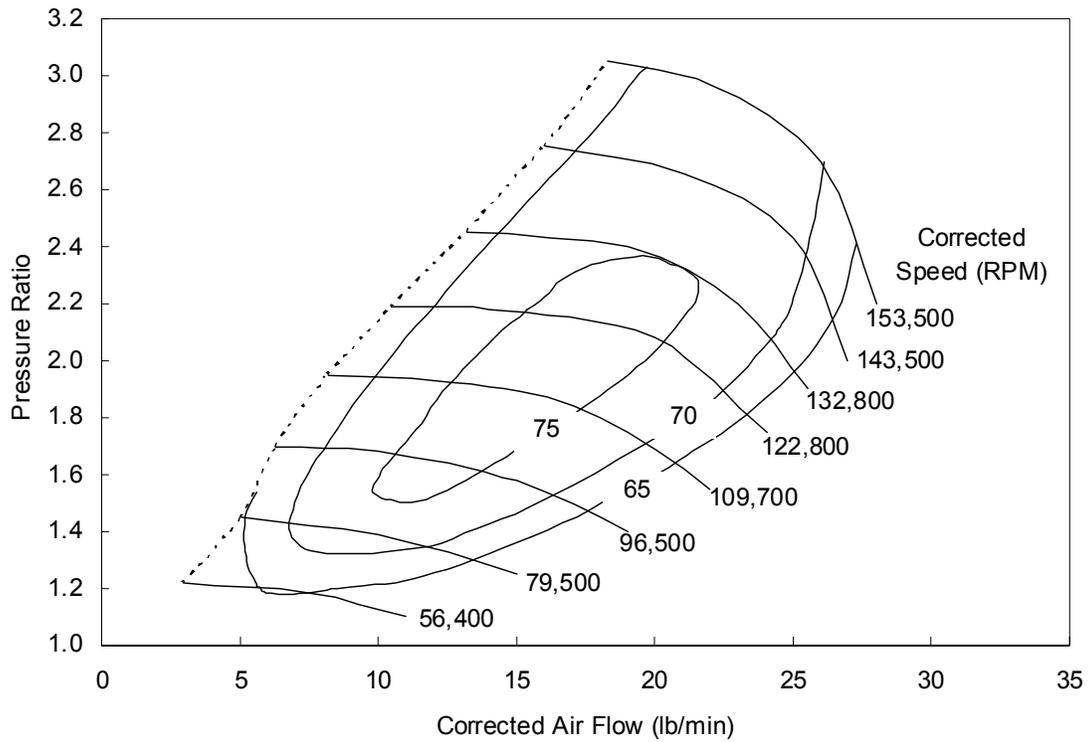
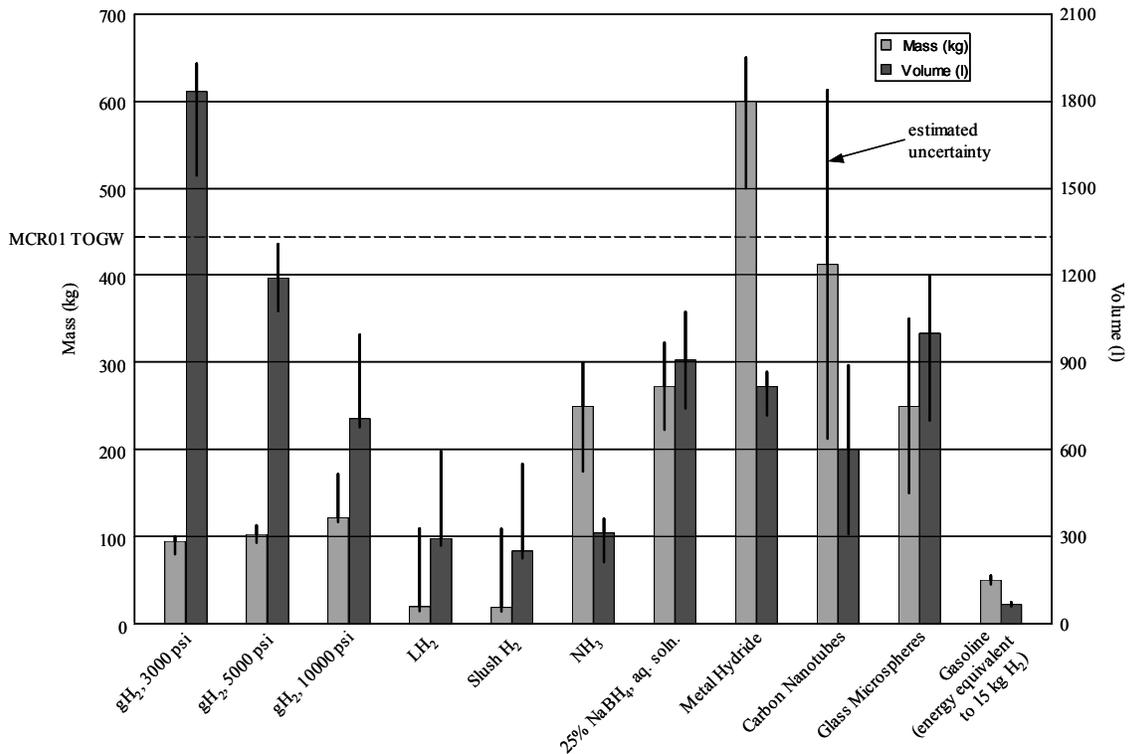Figure 3. A typical supercharger performance map from Turbonetics, Inc.

Figure 4. Comparison by mass and volume of various hydrogen storage technologies and their estimated uncertainty. 15 kg of H_2 is stored in each case. The takeoff gross weight of the MCR01 is included for scale for the mass axis. Also, gasoline is included not as a possible hydrocarbon source of hydrogen but as a comparison by energy (LHV). [29-33]

	Off-the-Shelf Technology	Intermediate Technology	Advanced Technology
	Based on commercially-available products	*Based on current government and industry research and development*	*Based on government and university laboratory demonstrations*
Fuel Cell Stack	Automotive-derivative PEM fuel cell stack (~1.0 hp/lb)	Higher operating temperature PEM fuel cell stack; higher power densities (~2.0 hp/lb)	New type of fuel cell with different chemistry, higher power densities, more efficient operation (~3.0 hp/lb)
Fuel Cell System	Automotive-derivative compressor, heat exchangers, humidifiers, separator (~0.6 hp/lb)	Integrated heat exchangers, humidifiers, separator into fuel cell; lightweight, more efficient compressor (~1.1 hp/lb)	Humidification, separation, extensive cooling not required (~1.6 hp/lb)
Electric Motor	Automotive-derivative permanent magnet electric motor (~0.7 hp/lb)	Electric motor with advanced cooling and more efficient design (~1.5 hp/lb)	Superconducting electric motor with very efficient and lightweight design (~5.0 hp/lb)
Power Electronics	Automotive-derivative power management and distribution (~0.5 hp/lb)	Higher temperature materials (SiC) and components; advanced cooling; more efficient design (~0.6 hp/lb)	Superconducting electronics for a very efficient and lightweight design (~0.9 hp/lb)
H2 Storage	Mid-pressure (5000 psi) compressed gas; liquid storage for long-duration missions	Improved high pressure composite tanks; lightweight metal hydrides; lightweight, low-temperature chemical reformation	Liquid system design with low boiloff, high safety; or fuel cell able to use common liquid fuels directly
Batteries	Currently available Li-Ion batteries	Advanced Li-Ion or similar chemistry batteries with higher power density	New battery chemistry with longer life and higher energy density

Figure 5. Technology level assumptions with some estimated specific power values.
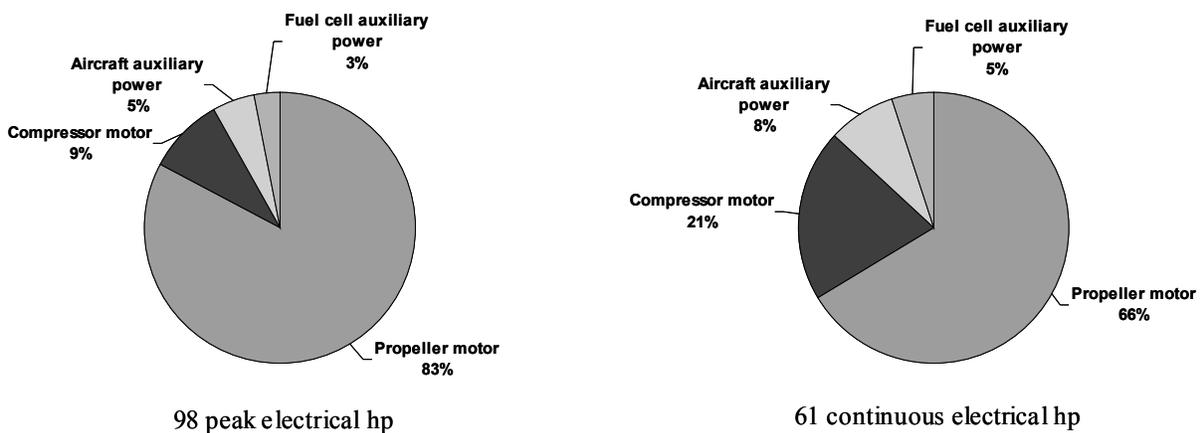

98 peak electrical hp

61 continuous electrical hp

Figure 6. Electrical power distribution for the 81 peak shaft hp case. The chart on the left is for takeoff conditions (0 ft. altitude and 0 knots) and the chart on the right is for typical cruise conditions (8,000 ft. altitude and 130 knots).

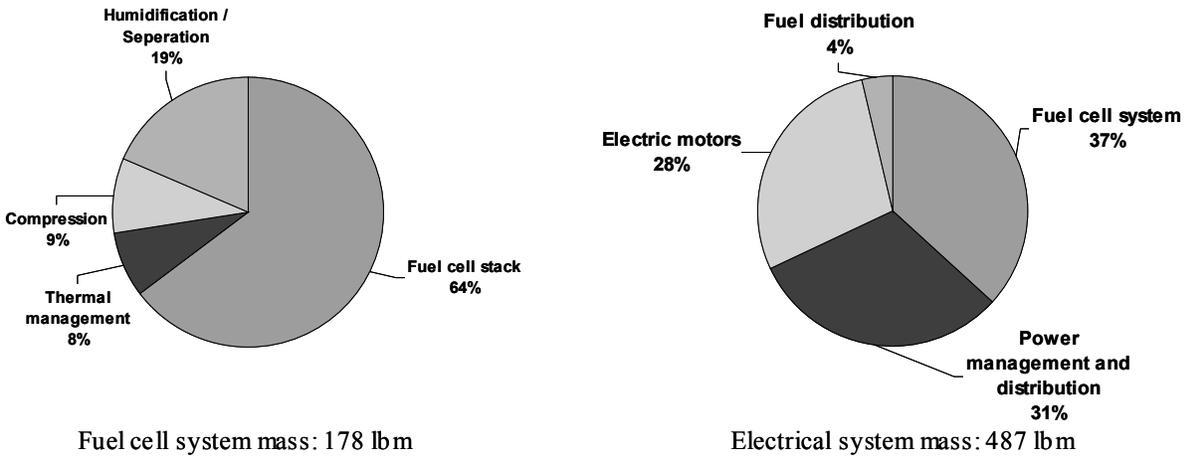Fuel cell system mass: 178 lbm   Electrical system mass: 487 lbm

Figure 7. Mass distribution for the 81 peak shaft hp case. The chart on the left is the distribution for the fuel cell system and the chart on the right is the distribution for the entire electrical system.
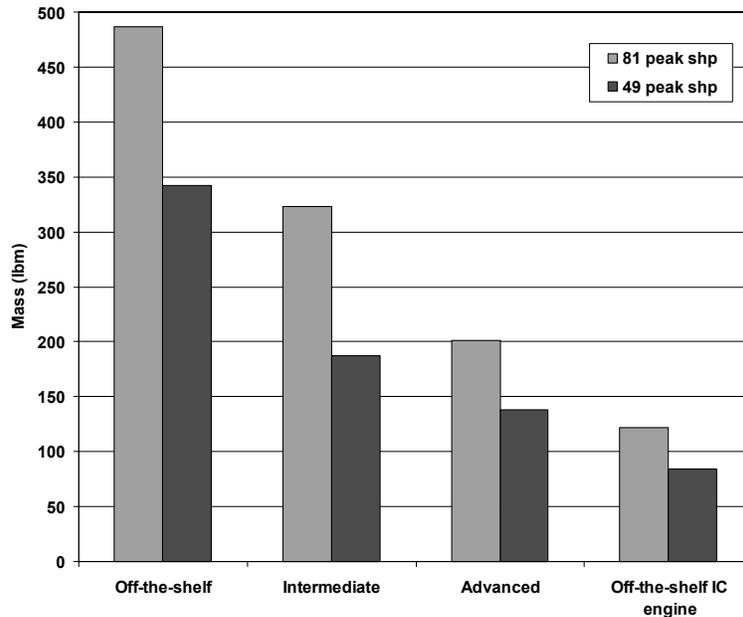

Figure 8. A representative chart of the effect of improved technology on electrical system mass. The data are for the 81 and 49 peak hp systems and the technology assumptions are based on Figure 5. The Rotax 912A IC engine mass is included for scale.

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Joshua E. Freeh, Anita D. Liang, Jeffrey J. Berton, and Timothy J. Wickenheiser

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13. ABSTRACT (Maximum 200 words)

An analysis of an electrical power and propulsion system for a 2-place general aviation aircraft is presented to provide a status of such modeling at NASA Glenn Research Center. The thermodynamic/electrical model and mass prediction tools are described and the resulting system power and mass are shown. Three technology levels are used to predict the effect of advancements in component technology. Methods of fuel storage are compared by mass and volume. Prospects for future model development and validation at NASA as well as possible applications are also summarized.

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