HYBRID-ELECTRIC PROPULSION FOR AUTOMOTIVE AND AVIATION APPLICATIONS

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Abstract

In parallel with the automotive industry, hybrid-electric propulsion is becoming a viable alternative propulsion technology for the aviation sector and reveals potential advantages including fuel savings, lower pollution, and reduced noise emission. Hybrid-electric propulsion systems (HEPS) can take advantage of the synergy between two technologies by utilizing both Internal Combustion Engines (ICEs) and Electric Motors (EMs) together, each operating at their respective optimum conditions. However, there can also be disadvantages to hybrid propulsion. We are conducting an analysis of hybrid-electric propulsion for aircraft, which is looking at modelling systems over a range of aircraft scale, from small UAVs to inter-city airliners. To support the theoretical models, a mid-scale hybrid-electric propulsion system for a single-seat manned aircraft is being designed, built and tested to generate data for validation and development of the simulation models. This paper draws parallels between the synergy of hybrid-electric propulsion for automotive and aviation applications and presents an innovative theoretical approach integrating several desktop PC software packages to analyse and optimize hybrid-electric technology for aircraft. Our findings to date indicate that hybrid-electric propulsion can have a significant impact in the small & mid-scale sectors, but only a minor impact in the large-scale sector assuming battery energy densities predicted for the next decade. Fuel savings of up to 50 % and 10 % have been calculated for a microlight aircraft and inter-city airliner respectively over the mission profiles considered.

1. INTRODUCTION

With the increasing GDPs of many countries and a significant drop in flight fares, air travel has become affordable to a large proportion of society. Due to this increase in demand over the last few decades, the aviation industry became a major consumer of primary energy and therefore, this industry is also exposed to a volatile oil price. In the United States for example, within the overall transportation sector, which accounted for 28 % of the primary energy consumption in 2010, the aviation fleet accounted for 9.4 % of this sector, as shown in Figure 1. Moreover, energy consumption by the aviation industry is expected to grow by about 10.0 % to 820.6 TWh from 2010 to 2035 [1]. However, light-duty vehicles consumed 60.2 % of the energy within the transportation sector in 2010, but due to the development of new technology concepts in this area, this sector expects a negative growth rate of about -3.0 % from 2010 to 2035 [1].

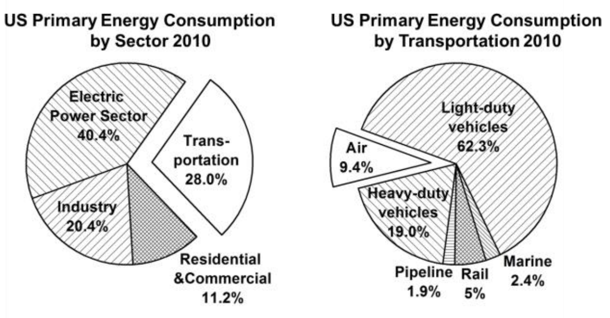

Figure 1. US Primary Energy Consumption by Sector (2.9×10^4 TWh) and by the Transportation Sector (7.9×10^3 TWh) in 2010.

Worldwide, about 19,000 aircraft (large, twin aisle, single aisle, and regional jets) were in service in 2011 and it is expected that this fleet will increase to about 36,000 aircraft by 2031 due to an annual increase in airline passengers of 4.0 % (~16,800 aircraft) and required replacement of current commercial aircraft (~12,600 aircraft) over this time period, caused by a growing world economy of 3.2 % per annum [2, 3]. As a result, about 30,000 new aircraft will be required by 2031.

Based on a forecast conducted by the Boeing Company [3], medium-range aircraft will be especially in demand in the future and so need to be considered in future concepts. Both facts, the increase in relative consumption of primary energy by the transportation sector, and the exposure to a volatile oil price, force the aviation industry to accelerate fleet renewal, improve non-fuel cost management, streamline fleet operations and encourage the development of alternative fuel sources [4]. However, the most challenging factors point toward the need for reduced energy consumption by airliners, thus mitigating both the impact of high fuel prices and environmental effects. Exploration of alternative fuel and forms of energy along with more efficient aircraft will reduce the volume of fossil fuel required and lower noise levels to address the NASA and ACARE goals [5-7]. Both institutions, the American NASA and the European ACARE, published a vision of the Air Transport System to meet society's needs and to encourage advanced technology uses in aviation. One of the technologies suggested, which can potentially meet the future requirements, is hybrid-electric propulsion systems (HEPS) for aircraft, to significantly reduce fuel consumption and emissions.

The development of HEPS is at its early stages in the aviation sector, but is already commercially available in the automotive sector. Indeed, in the past ten years hybrid-electric systems have been deployed by the major car manufacturers and as a result, sales of hybrid-electric cars increased significantly, especially at the beginning of this century. The technology leader is Toyota, selling almost 1.3 million hybrid cars in 2012, but the overall market share of hybrid-electric cars still remains very low, i.e. in 2012 only about 3 % of the 7.2 million new car sales in the USA [8, 9] and only about 1 % of the 12 million new car sales in EU-27 countries [10] respectively were hybrid-electric cars. However, due to the huge market potential, the car manufacturers are the major technology drivers in hybrid-electric propulsion and due to recent improvements, this technology is now gaining the interest of the aviation sector.

This paper reviews the current state-of-the-art of HEPS in the automotive and aviation sectors, and highlights their respective synergies. A detailed analysis for a single-seat aircraft is conducted to determine the hybridization effects in terms of fuel and energy saving, based on a defined mission profile. Subsequently, the feasibility of hybrid-electric propulsion for large-scale aircraft, and whether results can be scaled, are assessed. Finally, the paper draws conclusions from the hybridization effects for both industries and gives a future outlook on purely electric aviation and automotive sectors.

2. HYBRID-ELECTRIC PROPULSION

Hybrid-electric systems are defined as "A Hybrid-Electric Vehicle (HEV) is a vehicle in which propulsion energy is available from two or more kinds or types of energy stores, sources, or converters, and at least one of them can deliver electrical energy" [11]. In terms of this general definition many HEV configurations are possible, but this analysis focuses only on the utilization of Internal Combustion Engines (ICE) and Electric Motors (EM).

Due to the superior energy density of organic fuels for ICEs, this technology is favoured as the prime mover for automotive and aviation applications. However, ICEs can have drawbacks associated with lower efficiencies, especially away from their optimum operating point, a slow control response and variable performance characteristics compared to those of an EM, which has high efficiency and a robust, rapid control system.

The concept behind hybrid-electric propulsion is to take advantage of the synergy between the two technologies by utilizing both ICEs and EMs together [12], specifically the energy density of the ICE and the efficiency of the EM. Such a hybrid-electric propulsion system used in the automotive sector has potential advantages including: fuel savings and lower pollution, and additionally for the aviation sector, reduced take-off noise, and a reduced heat signature.

Small-scale hybrid-electric systems have been mainly applied in the automotive sector and represent a novel concept in the aviation sector. The architecture of HEPS can be classified into four main categories [13]:

- Series hybrid
- Parallel hybrid
- Series-parallel hybrid
- Complex hybrid

A graphical representation of these four different concepts is shown in Figure 2. Each concept has advantages and disadvantages, as discussed in the following section, but concepts such as micro- and mild hybrids including start-stop technologies are not considered in this analysis due to the insufficient motor size to drive the vehicle from purely electric power (EM-only mode).

Based on the investigation of Husain [14], inherent advantages of the series concept are the flexible location of the engine and the generator (GE) set, the simplicity of the drivetrain, and the suitability for short trips. Whereas inherent disadvantages are the need for three propulsion components (ICE, GE, and EM), the design of the EM for maximum power that the vehicle may require during acceleration / climb and that all three drivetrain components need to be sized for maximum power for long-distance, sustained, high speed driving (this is because the batteries will exhaust fairly quickly, leaving the ICE to supply all the power through the generator).

Conversely, the parallel configuration only requires two propulsion components (ICE and EM/GE), since the motor can also be used as the generator. Furthermore, a down-scaled ICE and a down-scaled motor can provide the same performance, until the batteries are depleted. For short trip missions, both can be rated at half of the maximum power to provide the total power, assuming that the batteries are never depleted. For long-distance trips, the engine may be rated for the maximum power, while the motor / generator may still be rated to half the maximum power or even smaller. Drawbacks considered with this configuration are the significantly increased control complexity, because power flow has to be regulated and blended from two parallel sources, and complex mechanical couplings may be required between the devices.

Series-parallel and complex hybrid configurations try to combine the advantages of both series and parallel hybrids, but are inherently heavier due to the extra motor and require a complex control strategy. Investigations of complex hybrid concepts are therefore still in the early stages. The control strategy for a hybrid-electric powertrain, managing the complex power transfer due to the two or more power sources of a hybrid system [15], represents an important parameter and can have a significant impact on the overall performance of the HEPS. Consequently, a high level controller is required to meet the respective requirements to determine torque, power demand and the throttle position [16, 17]. In principle, control strategies can be classified into two general categories [18]: (1) empirical data and (2) advanced control algorithms. Several advanced control algorithms such as fuzzy logic control, artificial neural networks [19], nonlinear control, etc. have been developed for the control of hybrid-electric powertrains, but also, a relatively simple rule-based strategy is commonly used. For example, the controller can be programmed to run the ICE in its most efficient operating areas (around its Ideal-Operating-Line) to achieve a high overall efficiency.

3. HEPS IN THE AUTOMOTIVE INDUSTRY

The history of hybrid-electric and purely electric cars has been tightly intertwined and started more than one hundred years ago. Indeed the first hybrid-electric car was developed by Ferdinand Porsche in 1902 [20]. However, this state-of-the-art review focuses on current applications of the powertrain types described, and considers only full-hybrid and plug-in hybrid vehicles. These two hybrid concepts differ only by the fact that the plug-in version provides the additional option to plug in a cable running from the vehicle to a mains-electricity socket to charge the vehicle's battery [21]. Only in these two configurations can the electric motor alone power the car, independent from the engine – which is the main difference when compared to current start-stop technologies.

The first major breakthrough from conventional engines to hybrid-electric cars was achieved by Toyota in 1997 with the commencement of the Toyota Prius [22]. This car has a series-parallel powertrain configuration consisting of an electric motor, an engine, a generator, a power split device, and a power control unit (inverter/converter). The power split device transfers part of the power produced by the engine to drive the wheels and the residual amount to the generator, depending on the driving conditions, to either provide electric power for the motor or to recharge the batteries. In general, this car advantageously runs the electric motor at low speeds, and calls on the engine when the car runs at higher speeds [23].

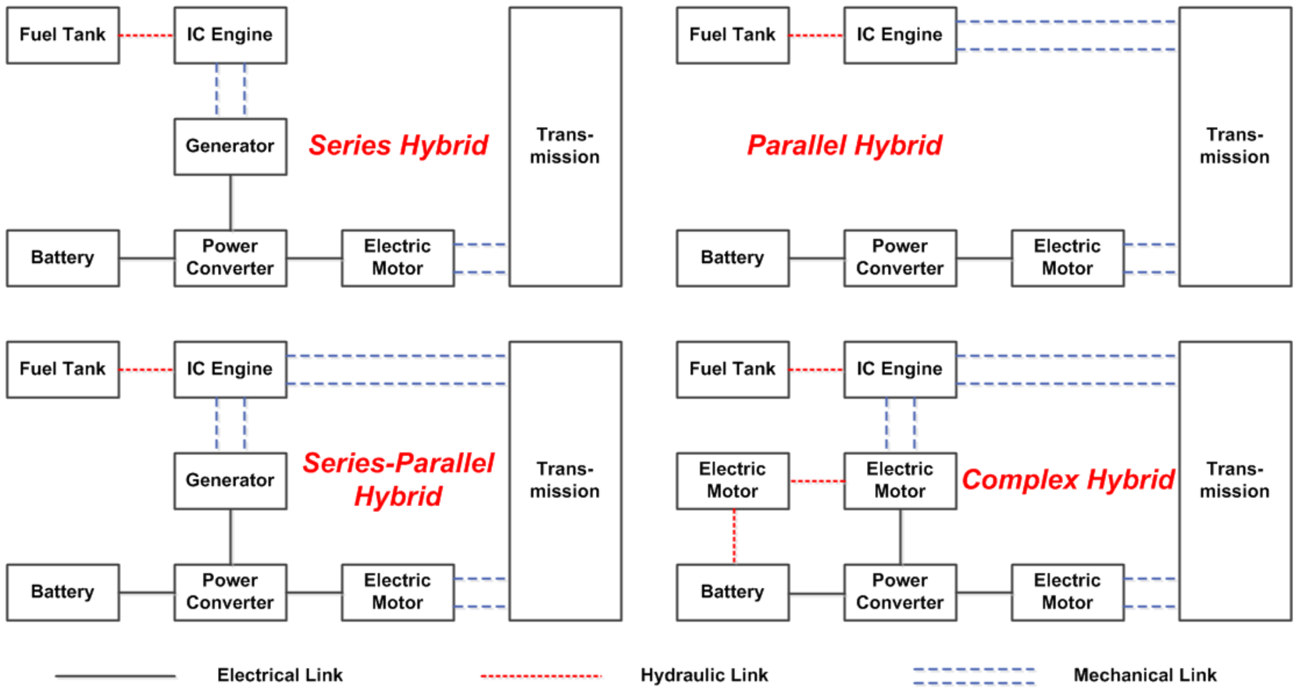

Figure 2. Hybrid-Electric Architectures (Full-Hybrid) [13].

Series powertrain configurations are usually used for heavy-duty vehicles, for example buses, such as the TEMSA – Avenue Hybrid bus, the Mercedes – Citaro bus and the MAN-Lion's City bus. Due to the start and stop characteristics of buses in urban driving, the ICE can be turned off when the battery supplies electrical energy to the motor. Along with the option to downsize the engine, a significant amount of energy is supplied from regenerative braking and down-slope driving, which is perfectly suited to a series powertrain configuration [24]. However, series hybrid powertrains are also used for cars such as the Chevrolet Volt, which was announced as the first series hybrid in mass production. Generally, series hybrid cars may reduce fuel consumption by 34 - 47 % but cost 5,000 – 12,000 Euros more than a standard vehicle [25].

Parallel powertrain configurations are usually used for light-duty vehicles. Cars such as the Honda Insight, Ford Escape Hybrid and the Lexus Hybrid implemented this type of powertrain, which includes a high control complexity but also promises an economic return, at high cost [24].

Due to the high potential of HEV, encouraged through various government policies [26], several types of HEV have been established and are nowadays manufactured by every major Original Equipment Manufacturer (OEM). Each configuration differs slightly from OEM to OEM but can still generally be fitted into the four main architectures presented. Furthermore, the size of the different components involved varies with the type of powertrain and degree of hybridisation, as well with the OEM. For example, in a series configuration and in a purely electric car, the motor has to be sized to meet the maximum power requirement whereas the engine can be downsized. On the other hand, in a parallel configuration, both power sources, EM and ICE, can be downsized, because both components can simultaneously provide torque to the powertrain. Considering a medium car such as the Toyota Prius or the Honda Insight, the motor size can vary from 30 kW - 100 kW and the battery capacity from 10 kWh - 16 kWh [27]. Batteries such as Lithium-ion and Lithium Polymer are commonly used, due to their relatively high energy density (≈ 150 Wh/kg) [28]. The battery charging time of HEVs is up to 10 hr, and can provide an electric range (motor only) of up to 100 km. In terms of miles per gallon (MPG)[1] [29], the best hybrid car, excluding plug-in hybrids, the Toyota Prius can achieve up to 50 MPG whereas purely electric cars such as the Chevrolet Spark EV can achieve up to 119 MPG_e[2]. A plug-in hybrid such as the Chevrolet Volt can perform up to 62 MPG_e [30].

Overall, HEVs have the ability to overcome the disadvantages of conventional engine and purely electric powered vehicles, including optimized fuel economy and reduced emissions, when compared to conventional vehicles, and increased range, reduced charging time, and reduced battery size when compared to pure EVs. Despite the commercial availability of hybrid cars, HEPS for automotive applications still face many challenges, including higher costs, when compared to conventional vehicles, electromagnetic interference caused by high-power components, and safety and reliability concerns due to increased component numbers and complexity, packaging of the system, vehicle control, and power management [21]. The design issues include:

- Power electronics and electrical machines
- Electromagnetic Interference
- Energy Storage Systems
- Regenerative Braking Control
- Power Management and Vehicle Control
- Thermal Management
- Modelling and Simulation, Vehicle Dynamics, Vehicle Design, and Optimization

Current research is focusing on parallel hybrids due to their acceptable cost-to-benefit relationship, but the electrical storage system remains the key element of HEVs, because its capacity, power and lifetime decisively define the costs of the overall system [31].

4. HEPS IN THE AVIATION SECTOR

Following the promising benefits of HEPS in the automotive sector, this alternative propulsion concept has started to gain interest in the aviation sector. HEPS present a significant change to aircraft propulsion and as yet no prototype airliner with a HEPS has been built. As a first step towards hybrid-electric powertrains, HEPS have been integrated in mid-scale (GA) demonstrators to evaluate their feasibility and future potential in aviation. Depending on the success of HEPS in the mid-scale sector, hybrid-electric demonstrators might also be extended into the large-scale sector.

This section provides an overview of existing HEPS mid-scale demonstrators, and presents a simulated performance assessment of our hybrid-electric aircraft – called the “SOUL”. Finally, the feasibility of HEPS is also investigated for the large-scale sector and the results

[1] Fuel Economy, i.e. MPG, is measured based on a combined city and highway fuel economy estimates – weighted by 55 % city and 45 % highway – accoridng to the standards of the United States Environmental Protection Agency (EPA) [26].

[2] Since electricity is not measured in gallons, a conversion factor is used to translate the fuel economy into miles per gallon of gasoline equivalent (MPG_e) based on 100% conversion of the fuel calorific value.

obtained are compared with those from the mid-scale sector.

4.1. HEPS Mid-Scale Demonstrators

Hybridization of powerplants in the mid-scale (manned flight GA) sector represents a recent concept which has not yet been fully exploited. Two different hybrid approaches are discussed to obtain a more fuel-efficient aircraft: (1) a combination of a fuel cell and an electric motor (EM) and (2) a combination of an ICE and an EM, shown in Table 1.

To date, for fixed wing aircraft, three demonstrators using a fuel cell with an EM in a hybrid powertrain have been built: one realized by Boeing (partners: UQM Technologies, Gore, Diamond Aircraft, SAFT France, Air Liquide, Regional Government of Madrid) in 2008, another by the European Community ("ENFICA-FC" project, partners: Turin Polytechnic University, SkyLeader, APL, Mavel Elettronica, University of Pisa) in 2009 [32, 33] and a third by DLR, based on a Lange Antares airframe in 2009 [34].

The first demonstration of a hybrid-electric (ICE and EM) manned aircraft was developed by Robertson from the Engineering Department at the University of Cambridge, UK in association with Flylight Airsports Ltd. This approach can be seen as a pre-step to our current research and utilized a 2.2 kW ICE and 11.2 kW EM in a parallel drive train. The EM was a custom-wound brushless DC outrunner motor which was assisted by a 76cc four stroke ICE, replacing the standard two stroke ICE on an Alatus motor-glider. The EM was driven by a custom-built controller, powered by 16 LiPo cells of 40 Ah capacity, giving an electrical energy storage capacity of 2.4 kWh [35, 36]. The first test flight of this experimental aircraft was in September 2010 at Sywell Aerodrome, UK.

A second hybrid-electric aircraft was built by the Embry-Riddle Eagle Flight Research Center, an official extension of the Embry-Riddle Aeronautical University, located near Daytona Beach, USA. The team of nearly 100 students and 10 professors used the hybrid propulsion system, based on a system developed by Flight Design, to compete in the NASA's Green Flight Challenge 2011. Their approach utilized a parallel hybrid power plant consisting of a four cylinder 75 kW Rotax 912 engine and a 30 kW electric motor powered by Lithium Polymer batteries. A poly-V belt system couples the electric motor to the Rotax engine and an overrunning clutch system was installed to allow the engine to operate without the electric motor for take-off and climb, with the electric motor operating without the Rotax engine during cruise flight. A driveshaft connects the engine to a belt reduction system and the propeller at the front of the aircraft, due to the engine location in the Eco-Eagle, which is mounted behind the occupants [37].

In 2011 a series hybrid-electric prototype aircraft was successfully demonstrated by Siemens AG, Diamond Aircraft, and EADS at the Le Bourget air show in Paris. The maiden flight was on June 8, 2011 at the Wiener Neustadt airfield in Vienna, Austria. This claims to have been the world's first aircraft with a series hybrid-electric drive system. The aircraft, DA36 E-Star, a motor glider based on a Diamond Aircraft HK 36 Super Dimona, featured a 70 kW EM made by Siemens and 30 kW Wankel ICE made by Austro Engine [38]. A converter from Siemens supplies the electric motor with power from the battery and generator so that the Wankel engine always runs at a constant power output of 30 kW. The battery system from EADS provides the required power

Table 1: State-of-the-Art: Hybrid-Electric Propulsion Systems for Mid-Scale Aircraft.

Research Institution	**Cambridge University, Flylight**	**Embry Riddle**	**Siemens, EADS, Diamond Aircraft**	**Siemens, EADS, Diamond Aircraft**	**Cambridge University**
Project	Hybrid Alatus	Eco Eagle	DA36 E-Star	DA36 E-Star 2	**HEPA**
Maiden Flight	2010	2011	2011	2013	**2014**
Airframe	Alatus-M	Stemme S10	HK 36 Dimona	HK 36 Dimona	**Gramex SOUL**
MTOW	235 kg	980 kg	770 kg	770 kg	**235 kg**
ICE-Type	4-stroke	4-stroke	Wankel	Wankel	**4-stroke**
ICE	2.8 kW	74.5 kW	30 kW	30 kW	**8 kW**
EM	12 kW	29.8 kW	70 kW	65 kW	**12 kW**
Battery	LiPo, 40 Ah	LiPo	Unknown	Unknown	**LiPo**
Architecture	Parallel	Parallel	Series	Series	**Parallel**
Recharge Battery	No	No	Yes	Yes	**Yes**
Take-Off	ICE + EM	ICE	ICE+GE+EM	ICE+GE+EM	**ICE + EM**
Cruise	ICE + EM	EM	ICE+GE+EM	ICE+GE+EM	**ICE + GE**
Climb	ICE + EM	ICE	ICE+GE+EM	ICE+GE+EM	**ICE + EM**
Landing	-	unknown	unknown	unknown	**-**

during take-off and climb and the cells are recharged during the cruise phase [39]. The technology concept developed is intended to be used for large-scale aircraft and it is predicted to cut fuel consumption and emissions by 25 % compared to today's most efficient aircraft drives [39].

A more advanced version of the DA36 E-Star, named DA36 E-Star 2, has recently been presented at the Paris "Le Bourget" air show in June 2013. The main difference to the previous version is the revised electrical drive system developed by Siemens. This drive system provides an output of 80 kW during take-off and a continuous power of 65 kW. The electric motor (5 kW/kg) of the integrated drivetrain weighs 13 kg and its specific continuous power is twice as that of the first prototype. Overall, this drivetrain reduces the empty weight of the motor-glider by around 100 kg when compared to its predecessor in 2011 and therefore, an increase in flight range / duration is expected [40].

Our current research project considers a microlight aircraft, SOUL, with a low airframe mass and high Lift-to-Drag-Ratio (L/D) ratio to mitigate the extra weight of the batteries. This 200 kg technology demonstrator will use a combination of off-the-shelf and custom modified components, including an 8 kW ICE and a 12 kW EM, in a parallel hybrid configuration. The hybrid-electric powerplant will be characterized on a ground-based test bed before being integrated into a suitable airframe, with flight testing due to commence in late 2014. We believe that this will be the first parallel hybrid, manned aircraft, with the capability of in-flight battery recharging, to be modeled and flown. The weight restrictions imposed by the UK air law [41] for deregulated aircraft mean that our powertrain needs to consider the lightest hybrid-electric configuration possible with low mechanical complexity. As mentioned previously, this rules out series, series-parallel and complex hybrid systems due to their inherently heavier designs when compared to the parallel hybrid configuration.

In the following section, the design process for the hybrid-electric SOUL is presented and a theoretical assessment is presented to predict its fuel and energy savings, based on a 1 hr mission profile, compared to a standard engine-only reference scenario.

4.2. HEPS Demonstrator SOUL

Before assessing the performance of the hybrid-electric SOUL aircraft, this section gives a short introduction to the simulation environment developed as well as the initial design processes utilised for the hybrid powerplant.

4.2.1. Simulation Environment

To determine the fuel and energy saving potential of a HEPS, an innovative simulation approach has been developed consisting of several linked software packages including X-Plane [42], Matlab Simulink [43] and JavaProp [44]. X-Plane provides a very realistic flight model, whereas JavaProp models the propeller performance and Matlab Simulink represents the core of the simulation including four main blocks: the "Navigation Module", the "HEPS", the "Weight Calculation" and "X-Plane Communication". The "X-Plane Communication" module is used to build a UDP connection from Matlab Simulink to X-Plane, where the propeller performance map obtained from JavaProp is implemented in Matlab Simulink through look-up tables. To obtain a real-time simulation environment, Matlab and X-Plane are synchronized through an additional toolbox, the Real-Time Windows Target [45].

Based on a defined mission profile, the Navigation Module, consisting of a Flight Planner Module (FPM) and an Aircraft Control Module (ACM), follows and calculates the heading adjustment according to the great-circle distance implemented in the FPM. The ACM determines the throttle setting, rudder, aileron and elevator deflection before the aerodynamic controls are passed to X-Plane, whereas the throttle setting is input to the HEPS block.

The HEPS Module, consisting of several sub-blocks i.e. the controller, engine, motor, battery, reduction drive, and propeller simulates the behaviour of the hybrid-electric propulsion system and the interaction of the components involved. The characteristics of the engine and the motor / generator are measured on a test rig; determining torque, fuel consumption, and current into or out of the batteries. The battery State-of-Charge (SoC) is also modelled according to its performance and subsequently, it is used by the controller to manage the power-flow. The standard advance ratio is then applied to determine propeller efficiency, power coefficients and thrust to convert the generated torque into thrust, before the thrust is passed to X-Plane. The calculation of the specific propeller coefficients and its performance characteristics is based on JavaProp, a separate software package.

In addition to the HEPS powerplant, an engine-only scenario has been designed to obtain the relative baseline fuel consumption for the same mission profile. This real-time simulation environment provides a realistic flight model and consequently, a useful conclusion about the performance of the HEPS compared to a conventional 4-stroke engine can be drawn.

A more detailed description of the simulation environment is published in [46],it has since been updated with a model for the reduction drive using experimental data, rather than a fixed efficiency.

4.2.2. HEPS Design for the SOUL

This design process starts with the selection of a lightweight airframe with a relatively high L/D to compensate the extra weight of the batteries. The single-seat prototype aircraft SOUL, manufactured by Gramex in the Czech Republic, is a composite ultra-light aircraft and is made from a carbon-fibre composite (epoxy, PVC foam sandwich structure) with a white gel coat finish and is usually equipped with a Bailey V5, 200cc, four-stroke internal combustion engine. This engine provides a maximum of 15 kW and therefore, the new HEPS has been designed to provide at least 15 kW as well.

With regard to the weight restriction under UK air law for the Single-Seat Deregulated Microlights (SSDR) category, the initial design is minimal weight, using a custom wound 12 kW JM1 Joby Motor and an 8 kW tuned Honda GX 160 engine, providing up to 20 kW in total to the propeller, as illustrated in Figure 3 [47].

This parallel powertrain can run in three different operating modes: (1) ICE-only, (2) EM-only, and, (3) ICE & GE. An EM-only mode is not considered due to the high inefficiencies associated with turning the engine against its compression. Overall, the engine represents a key element in the HEPS since it runs throughout the entire flight and therefore has a major impact on the overall energy consumption.

Based on this initial design, which predicts a fuel saving potential of up to 37 % [47], an optimization routine has been developed to determine which hybridization factor can achieve the highest energy saving compared to the reference scenario (standard four-stroke engine, 15 kW). Further to the initial design, the controller strategy has been replaced with an Ideal Operating Line (IOL) strategy to obtain the best possible performance of the HEPS. Consequently, the ICE runs only at its IOL during the entire flight, even during the charging process for the batteries. The peak power of the ICE is only available when the batteries are completely depleted and no

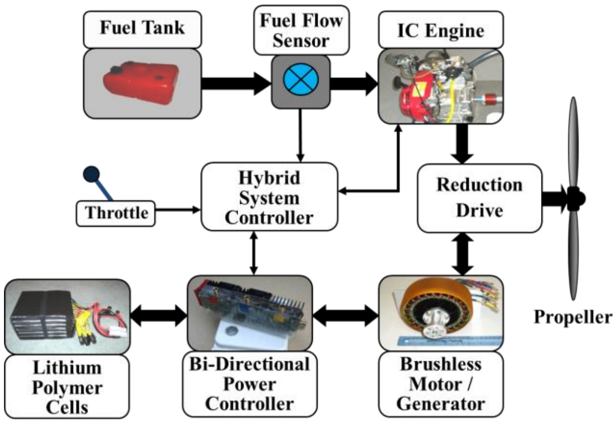

Figure 3. Initial HEPS Design for the SOUL.

additional power can be obtained from the motor. This could potentially lead to a scenario in which the powertrain considered cannot meet the mission profile, i.e. for long distance flights at high speeds.

Table 2 provides an overview of the powertrain configurations considered to determine the hybridization factor (HF) with the highest energy saving potential. Here, hybridization (or the hybridization factor) is defined as the electric motor fraction of the total powerplant rating. To determine the different component weights, a power density of 4 kW/kg and 0.667 kW/kg is used for the motor and internal combustion engine, respectively. Both numbers are based on actual measurements taken from the JM1 motor and the Honda GX160. The energy storage is determined linearly, based on the maximum fuel tank (20 kg ≈ 25 liter) of the SOUL, as shown in equation (1):

$$\text{Fuel Mass} = 20\left(\frac{100\text{-HF}}{100}\right)\ [\text{kg}] \qquad (1)$$

The residual weight (difference between current weight and MTOW) is then used to determine the amount of batteries carried on-board.

4.2.3. Performance Assessment

The HEPS prototype aircraft SOUL is now integrated in the simulation environment to determine its fuel consumption for a defined mission profile, in comparison to the same SOUL airframe fitted with a standard 20 HP (15 kW) 4-stroke engine.

The performance is simulated for five different flights over a 1 hr mission profile at a constant altitude of 700 m considering a take-off and a landing airspeed of 20 m/s and a cruise speed of (1) 22 m/s, (2) 25 m/s, (3) 30 m/s, (4) 35 m/s, and (5) 38 m/s.

Table 2 Various Sizing Configurations based on the Initial Design. *MTOW is 235 kg. *Aircraft weight includes the airframe, pilot, propeller, reduction drive, cables, instruments and engine mount. **Max fuel tank of SOUL is 25 liters corresponding to 20 kg of gasoline.*

	Hybridization [%]								
	0	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
EM [kW]	0	6	8	10	12	14	16	18	20
ICE [kW]	15	14	12	10	8	6	4	2	0
Total [kW]	15	20	20	20	20	20	20	20	20
	Component Weights [kg]								
Aircraft* [kg]	182.5	182.5	182.5	182.5	182.5	182.5	182.5	182.5	182.5
EM [kg]	0	1.5	2	2.5	3	3.5	4	4.5	5
ICE [kg]	22.5	21	18	15	12	9	6	3	0
Batteries [kg]	0	16	20.5	25	29.5	34	38.5	43	47.5
Fuel [kg]	20**	14	12	10	8	6	4	5	0
Total Weight [kg]	225	235	235	235	235	235	235	235	235

To measure the actual performance of the various HEPS powertrains compared to the reference scenario, two indicators, Fuel Saving (FS) and Energy Saving (ES), are defined, shown in equations (2) and (3) respectively. Based on the calorific conversion value of 43 MJ/kg[3], the fuel saving indicator is a very simple ratio and only takes the energy content of the fuel burned [kWh] into account but does not include the electrical energy [kWh] used. Consequently, equation (2) contains the fuel energy used by the hybrid-electric powertrain (F_U) divided by the fuel energy used by the engine (F_{REF}), over the mission considered.

$$FS = \left(1-\frac{F_U}{F_{REF}}\right)100\ [\%] \qquad (2)$$

In addition to the fuel saving indicator, the energy saving indicator defined in equation (3) also considers the electrical energy used, with different source grid efficiencies (η_{grid})[4]. Consequently, not only is the HEPS fuel energy used (F_U) compared to that of the reference scenario (F_{REF}), but so also is the electrical energy used during the flight; derived from the battery capacity (B_{cap}) multiplied by the reduction in its state-of-charge (SoC) over the flight.

$$ES = \left(1-\frac{F_U + \frac{(100\text{-}SoC)B_{cap}}{\eta_{grid}}}{F_{REF}}\right)100\ [\%] \qquad (3)$$

Both indicators, FS and ES, are calculated for each flight, from which an average for each hybridization factor is taken to express the entire speed range in one single factor.

Looking at the fuel saving indicator, shown in Figure 4, a powerplant hybridization of 60 % (such as the SOUL) can achieve a fuel saving of 50 % when compared to the reference scenario. Based on that definition, a scenario of 100 % saving in fuel is possible when using a purely electric powertrain (HF = 100 %) and freely available energy to charge the batteries such as from a solar panel or wind turbine (neglecting the energy input to manufacture these devices). Moreover, the analysis shows a linear relation between the HF from 40 % to 100 % and the fuel saving potential.

Both the grid efficiency and the controller strategy significantly impact the overall performance of a hybrid-electric aircraft, since the HEPS controller decides if the batteries should be recharged in-flight, if enough power is available, or on the ground. Considering the higher recharging efficiency available on the ground, it may not make sense to recharge the batteries in-flight, if the aircraft is about to land. The in-flight recharging efficiency of the HEPS is only about 20 % and therefore, it is probably less efficient than any recharging scenario on the ground (provided the equipment is available).

[3] SAE J1711 Standards Paper

[4] The grid efficiency (%) considers the energy conversion chain from primary sources right up to the aircraft, including a grid transmission efficiency and a charging efficiency.

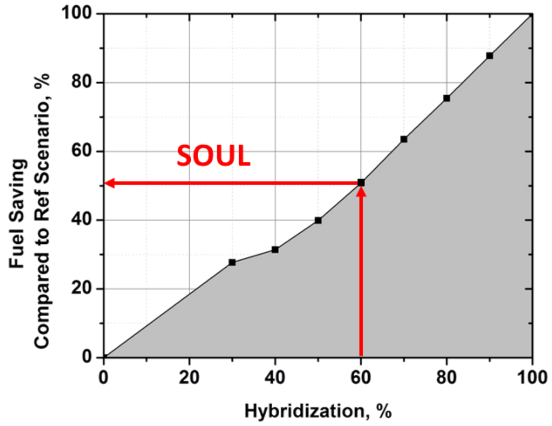

Figure 4. Fuel Saving Compared to Reference Scenario based on the defined 1hr Mission Profile.

However, the grid efficiency is very difficult to determine, since it depends on the actual energy mix used, and varies from country to country. In the western world, a grid efficiency of 35 % including a charging efficiency of 90 % is a reasonable assumption [48]. At this grid efficiency, the energy saving potential increases with the hybridization of the powerplant, up to a maximum saving of 61 % for a purely electric powertrain.

Considering the entire possible range of grid efficiencies, shown in Figure 5, it can be seen that the grid efficiency has a relatively low impact at low hybridization factor, due to the dominant contribution of the engine. In these scenarios, the motor including its electrical subsystem represents only an additional boost power during take-off and therefore, the grid efficiency doesn't have a significant impact on the overall performance.

However, the best-case scenario for this mission profile is obtained by using a purely electric powertrain

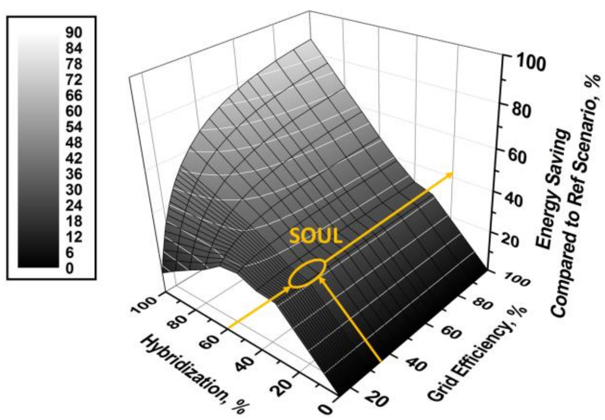

Figure 5. Energy Saving Compared to Reference Scenario based on the defined 1hr Mission Profile.

(HF = 100 %) and by assuming a perfectly efficient conversion process to recharge the batteries after the end of the flight. This means that the calorific value of the fuel can be fully (but unrealistically) converted to electrical energy.

To compare the energy used by hybrid-electric vehicles for different mission profiles and across sectors, NASA has suggested normalization of the results into an equivalent Miles per Gallon (MPG_e) indicator, defined as:

$$MPG_e = \left(\frac{\text{Distance Flown}}{\text{Fuel Energy} + \text{Electrical Energy}} \right) \quad (4)$$

wherein the fuel energy content is equivalent to electrical energy as given above [49]. Consequently, this definition corresponds to the ES in equation (3), with a grid efficiency of 100 %.

According to this definition, the SOUL is predicted to achieve 107 MPG_e at ~ 70 mph – better than two of the entrants, which achieved less than 100 MPG_e per person carried at similar speed, in the NASA Green Flight Challenge 2011 [50]. By considering a conversion efficiency of 100 %, a purely electric SOUL aircraft performs best and can achieve 368 MPG_e at ~ 70 mph.

Even though a purely electric powertrain seems to offer a significant improvement over a conventional internal combustion engine in terms of fuel and energy saving, this conclusion is only valid for a short mission profile (<1 hr) as conducted in this analysis. For example, the purely electric powertrain could not meet a high-speed mission profile over a long duration. To meet a various range of mission profiles (short and long duration), a trade-off between efficiency and energy density has to be accepted. This purely electric motor configuration is more efficient than the engine, but the usable energy density of fuel is much higher than that of batteries. Consequently, not only does a hybrid powertrain (HF ≈ 60%) provide a significant improvement in fuel saving, but it also provides the ability to cover long duration mission profiles.

To verify the HEPS being developed and to obtain in-flight data, test flights of the SOUL commenced in 2014. The flight data obtained will be used to confirm the simulation environment developed and to optimize the controller strategy for future flights.

4.3. HEPS for Large-Scale Aircraft

Following on from the fuel savings predicted with hybrid-electric propulsion in the mid-scale sector, this section analyses potential scaling effects for the large-scale sector i.e. airliners. Due to the high demand for medium range aircraft (~ 2 hr mission profiles), a B737-800 [51] using the CFM56-7 turbofan engine, is considered to investigate the feasibility of HEPS in the this sector. The mission profile is defined by a take-off / climb for 0.25 hr (v=175 m/s, RoC= 11.85 m/s), cruise for 1.5 hr (v=236.9 m/s, RoC= 0 m/s), and descent / landing for 0.25 hr (v=175 m/s, RoC= -11.85 m/s). Furthermore, for simplicity, zero thrust requirements are assumed for the landing phase and no safety regulations, i.e. no reserve fuel, have been taken into account.

A similar simulation environment has been set up to explore the scaling effects, but in contrast to the forward facing approach used for the SOUL, a backward facing Simulink model has been derived to calculate the respective performance, in which no communication between Matlab Simulink and X-Plane is required. Further changes mainly address the engine and the motor, as the properties of the hybrid-electric gas-turbine are simulated in a different software package i.e. GasTurb [52]. The output data from GasTurb, based on the CFM56-7 turbofan engine with an electric boost on the low pressure fan, is then implemented in Simulink. The Simulink code itself is simplified during take-off and landing; due to the relationship of the altitude and the performance of the turbofan engine, a new performance data set (from GasTurb) is required for every change in altitude. A subdivision of the altitude into ranges is an appropriate simplification and therefore, the simulation can still meet the goal of the analysis.

By using a Lithium-Polymer battery package of 7 MWh with a mass of 9,335 kg (~ 750 Wh/kg) and an electric motor of 4 MW, a maximum fuel saving of 10 % has been obtained for the mission profile considered. Since this research addresses the long-term future, an improvement in battery technology is a reasonable assumption i.e. an energy density improvement of 5.5 % per year until 2038, based on a current battery energy density of 200 Wh/kg.

A significant difference between the SOUL demonstrator considered and a typical airliner, such as the B737-800, is the ratio of the powers required during take-off and cruise. For both aircraft types analysed, maximum power is required during take-off, but during cruise a smaller aircraft requires only ~ 35 % of the maximum available power, whereas an airliner due to its high airspeed still requires ~ 60 % - 70 % of the maximum available power. Consequently, with the battery energy densities foreseeable in the near future, HEPS are better suited to small and medium scale aircraft rather than large aircraft due to:

- the thermal efficiency of small 4-stroke engines (~ 25 %) being inherently less than that of turbofan engines (~ 45 %)
- the weight saving from significant down-scaling potential of the engine in the smaller sectors
- the option to recharge the batteries in flight, even with a down-scaled engine, for medium-scale aircraft

However, without substantial improvement of the batteries in terms of energy density, hybrid-electric propulsion will not be viable in the large scale sector, and can not meet the goals defined by NASA and ACARE. With battery performance improvement, driven largely by automotive and consumer product requirements, HEPS can be an important contributor to future fuel savings in aviation, but also needs to be supported by advanced aerodynamics, structures and materials to maximize the L/D ratio and minimize weight. A recent study [53], conducted by Boeing Research & Technologies, General Electric, and Georgia Tech, considers these factors and concludes a future potential fuel saving of 70 %. Consequently, hybrid-electric propulsion along with advanced aircraft technologies may well meet the future requirements defined by NASA and ACARE.

5. CONCLUSIONS

Hybrid-electric propulsion systems present a viable alternative to conventional fuel-burning engines, with the potential to reduce fuel consumption and emissions in both automotive and aviation sectors.

In terms of the aviation sector, this analysis suggests that aircraft from small to large scale can benefit from HEPS, but the results obtained also indicate that the scaling effects are not directly transferable from one sector to another. In the medium-scale GA sector, the hybrid-electric prototype SOUL aircraft (HF = 60 %) suggests a fuel saving of up to 50 % for short mission profiles (< 1 hour). Increased hybridization of the powerplant leads to even higher fuel savings, but due to the relatively low energy density of batteries today, this increase in efficiency also results in a decrease of the aircraft range. For large-scale aircraft such as commercial airliners, a future fuel saving of up to 10 % has been calculated for HEPS relative to conventional turbofan engines in a current airframe. However, when combined with aerodynamic, materials and structural advancements hybrid-electric propulsion reveals a fuel saving potential of 70 %, together with significant benefits in emissions and noise reduction.

The automotive industry is the driver for this technology and has already started to commercialize hybrid cars. Typical concepts used are the series, parallel, and series-parallel powertrain configurations, but so far, it is still unknown which concept provides the most benefit to the customer considering the trade-off between fuel savings and the higher initial cost. The most promising concept is the series-parallel configuration, developed and patented by Toyota, but which also involves a complex control scheme. With regard to the aviation sector, only the series and parallel configurations have been implemented in prototype aircraft, and commercial hybrid-electric aircraft are still some way off. The aviation industry is currently in the early stages of adopting HEPS, and has to face similar challenges to the automotive industry in the development of power electronics, energy storage systems, power & thermal management etc. but with regard to a different set of criteria, in particular, minimum weight. The automotive sector is relatively more flexible in terms of weight and space and it can therefore utilize more complex powertrains including additional generators / motors, clutches, controllers & batteries to increase the efficiency of the powertrain.

A major difference between the HEPS for automotive and aviation applications is the recharging process for the batteries. In the automotive sector, regenerative braking and down-slope driving are used significantly to recharge the batteries, whereas for aircraft, the batteries are recharged through the spare power of the engine or from the grid, once landed. To use the propeller as a windmill during descent (analogous to recharging the batteries through regenerative braking in cars) is very inefficient due to the propeller's inappropriate shape for functioning effectively as a windmill. Even when the engine runs at its optimum conditions, it is still less efficient than ground based charging options. As with plug-in hybrid-electric cars, the performance and energy saving potential of hybrid-electric aircraft is very sensitive to the recharging process, and therefore, to the grid efficiency. The energy saving analysis conducted in this paper reveals that significant energy savings can be achieved by using a purely electric aircraft, recharged at high grid efficiency, but only for short mission profiles. Conversely, at low grid efficiencies, a HEPS with a hybridization factor from 60 % to 70 % can achieve a better overall performance than a purely electric aircraft, and can also undertake extended flight durations.

Considering a similar ratio of peak to cruise powers for light-duty vehicles as for mid-scale aircraft, hybrid cars are similarly more efficient than conventional engine cars for short mission profiles. Since most people mainly use their cars for short distances, a HEV seems to be an alternative propulsion concept with a significant benefit in fuel savings. Assuming current financial incentives, a recent study by McKinsey has shown that plug-in hybrid electric vehicles and battery-only vehicles could account for 16 % of new-car sales in New York, 9 % in Paris and 5 % in Shanghai by 2015 [54].

Looking to the very distant future and as an end note, it is our view that hybrid-electric propulsion is a stepping stone towards purely electric vehicles; while battery technology catches up with the energy density of liquid fuels. The intrinsic reliability and high efficiency of electric motors means that they will eventually supersede internal combustion engines in vehicles. High efficiency, static plant will be used to charge the batteries, so revolutionising the transportation industry – but with the associated challenges of generating and distributing the additional electrical energy required.

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