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Feasibility study and techno-economic analysis of an SOFC/battery hybrid system for vehicle applications

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Abstract

A feasibility study and techno-economic analysis for a hybrid power system intended for vehicular traction applications has been performed. The hybrid consists of an intermediate temperature solid oxide fuel cell (IT-SOFC) operating at 500–800 °C and a sodium–nickel chloride (ZEBRA) battery operating at 300 °C. Such a hybrid system has the benefits of extended range and fuel flexibility (due to the IT-SOFC), high power output and rapid response time (due to the battery). The above hybrid has been compared to a fuel cell-only, a battery-only and an ICE vehicle. It is shown that the capital cost associated with a fuel cell-only vehicle is still much higher than that of any other power source option and that a battery-only option would potentially encounter weight and volume limitations, particularly for long drive times. It is concluded that increasing drive time per day decreases substantially the payback time in relation to an ICE vehicle running on gasoline and thus that the hybrid vehicle is an economically attractive option for commercial vehicles with long drive times. In the case where the battery has reached volume production prices at £70 kWh^{-1} and current fuel duty values remain unchanged then a payback time <2 years is obtained. For a light delivery van operating with 6 h drive time per day, a fuel cell system model predicted a gasoline equivalent fuel economy of 25.1 $km\,L^{-1}$, almost twice that of a gasoline fuelled ICE vehicle of the same size, and CO_2 emissions of 71.6 $g\,km^{-1}$, well below any new technology target set so far. It is therefore recommended that a SOFC/ZEBRA demonstration be built to further explore its viability.

Keywords: Intermediate temperature SOFC; ZEBRA battery; Hybrid vehicle; Techno-economic analysis

1. Introduction

The drive to reduce emissions and improve vehicle efficiency has stimulated interest in alternatives to the internal combustion engine (ICE). The most promising and best-developed alternative uses electrical traction motors powered by electrochemical devices. Electrical drive systems can be found in pure electric, hybrid electric and fuel cell vehicles. Their advantages include: zero emissions at point of use (if battery powered or if a fuel cell operating on hydrogen is used), quiet operation, fast acceleration, recuperation of regenerative energy from braking and high efficiency drive trains and energy conversion. However, battery-only vehicles have a reputation for limited range, slow recharging and lack of a recharging infrastructure and hydrogen fuelled fuel cell vehicles suffer from range and refuelling infrastructure limitations as well as the necessity for the fuel cell system to be made large enough to accommodate the maximum power requirement, which may only constitute a small fraction of the drive cycle.

The work presented in this paper is part of project ABSOLUTE (advanced battery solid oxide fuel cell linked unit to maximise efficiency), a program that aims to combine a sodium–nickel chloride ZEBRA battery and an intermediate temperature solid oxide fuel cell (IT-SOFC) to form an all-electric hybrid power source for vehicle applications. Previous studies have looked at the design process of sizing the battery and fuel cell system for different applications and considered the fuel economy and range of different vehicles operated on different fuels [1–3]; in addition, modelling of the battery and fuel cell system [4] with a view to assessing the feasibility of thermal integration has been performed. This study considers the feasibility of developing such a hybrid system based on factors

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Nomenclature

cons	consumption
CC	capital cost (£)
CNG	compressed natural gas
E	energy (kWh)
FC	fuel cell
ICE	internal combustion engine
N_{days}	number of days
peak	peak power
P	power (kW)
PE	power to energy ratio (W Wh^{-1})
t	time (h)
UC	unit cost (£ kW^{-1}, £ kWh^{-1}, £ kg^{-1}, £ L^{-1})
UE	unit energy (kWh m^{-3})
$\upsilon_{\mathrm{average}}$	average speed (km h^{-1})

such as system size, emissions and techno-economics, by comparing it to a fuel cell-only, a battery-only and an ICE vehicle. This analysis is based on the operation of a light delivery van on methane fuel, assuming operation on the NEDC drive cycle [7] over different drive times per day and charge neutrality for the battery over a 24 h period.

1.1. Absolute project

The ABSOLUTE vehicle concept brings together a ZEBRA battery operating at ca. 300 °C and an IT-SOFC working in the temperature range of 500–800 °C. The use of solid oxide fuel cell technology is employed to gain broader fuel flexibility and simplified fuel processing requirements compared to polymer electrolyte fuel cells (PEFCs). In addition, the high specific energy of the ZEBRA battery allows for significant energy buffering and, by employing a 'battery dominant' hybrid system, the size of the fuel cell system and dc/dc converter (situated between the fuel cell and battery) can be minimised. Since IT-SOFC technology is less mature than that of the battery, minimising the size of the IT-SOFC makes the system less expensive and more feasible in the short to medium term. Therefore, the battery is sized to accommodate the peak power requirement and act as an 'energy buffer', while the fuel cell is designed to satisfy the overall energy demand of the vehicle such that under typical operation the range is limited by the size of the fuel tank rather than the energy capacity of the battery.

1.2. Fuel cells for transport applications

SOFCs can readily operate on a range of available fuels. Delphi have demonstrated SOFC prototype systems of up to 5 $\mathrm{kW_e}$ running on externally reformed gasoline [5,6]. More recently, SOFCs as potential power sources for automotive traction have started to attract interest. The main benefits of using SOFCs for automotive applications include:

- SOFCs have greater fuel flexibility than low temperature fuel cells. Their high operating temperature means that CO produced in the reforming process of hydrocarbon fuels does not act as a catalyst poison and can be used as a fuel source. This means that the fuel-processing unit can be simplified and logistical fuels, such as gasoline and diesel, become a realistic and cost effective option. Hydrogen can, of course, still be used.
- The high-grade excess heat produced by SOFCs can be used to service the endothermic steam reforming process and supply cabin heating (alleviating a portion of the hotel load, i.e., the auxiliary power required to service the comfort and safety of the driver and passengers of the vehicle).
- The cost of materials for SOFCs is potentially lower than for PEFCs.

However, many challenges still need to be overcome to use SOFCs for automotive applications. These include:

- SOFC stacks typically have lower power densities than PEFC stacks.
- High temperature SOFCs have poor thermal shock properties and their anodes do not appreciate redox cycling; thus these are not suited for repetitive start-up/shut-down cycles.
- Long start-up times compared to PEFCs (high temperature SOFCs typically have a start-up time of several hours).

Many of the disadvantages just referred to can be avoided by careful design of the vehicle operation; hybridisation with another power source; or by lowering the SOFC temperature.

1.3. Absolute hybrid vehicle concept

Fig. 1 shows the ABSOLUTE hybrid concept diagram, including the connections for mechanical, chemical, electrical and thermal energy transfer and the data communications and control interface.

The system follows a series hybrid architecture commonly found on all-electric hybrids. The use of an electric motor allows for traction power and regenerative braking. A power controller unit handles the voltage conversion between fuel cell, battery and motor. A fuel cell management interface (FCMI) controls the operation of the fuel cell and balance-of-plant and a battery management interface (BMI) controls the operation of the battery. Overarching these two control units and interfacing with the remaining hardware is the vehicle management unit (VMU). All control is performed using an industry standard CAN interface protocol. Connection for receiving and delivering external ac power is also included to provide options for mains battery charging and using the system as a generator for utility and recreational purposes.

To assess the feasibility of the hybrid fuel cell/battery vehicle a modelling methodology has been adopted. This is briefly explained in Section 2. The paper subsequently presents a techno-economic analysis that aims to assess the economic feasibility of the hybrid system under study. This analysis is used as

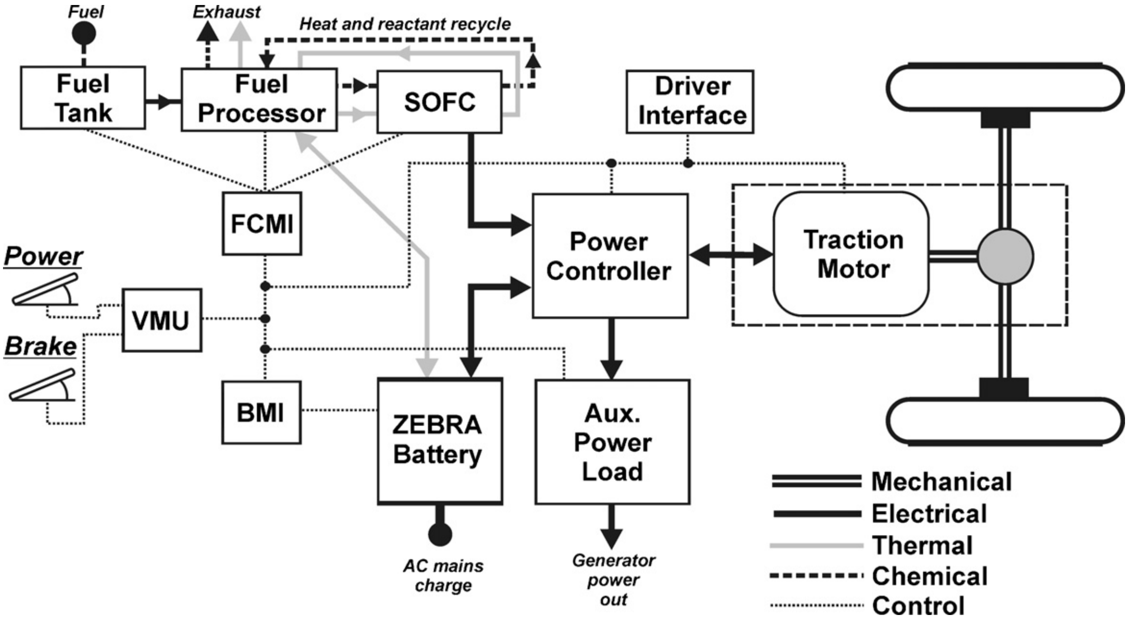

Fig. 1. Illustration of the conceptual system architecture of the ABSOLUTE hybrid.

the basis to discuss other important issues, such as fuel economy, CO_2 emissions reduction, volume and weight, etc.

2. Absolute hybrid vehicle modelling methodology

Fig. 2 shows a diagram that illustrates the modelling methodology followed to examine the viability of the ABSOLUTE hybrid vehicle. The first step in this methodology is to define the vehicle type (by setting all the vehicle parameters, such as the drag coefficient, rolling resistance, efficiency of the electric motor, controller and gearing, payload weight, etc.) and its specific application (delivery van, commuter car, taxi, etc.). The application establishes the nature of the drive cycle, the length of time that the drive cycle is exercised and the non-driving time over which the battery can be recharged. To avoid problems of stop/start operation and dynamic load changes on the fuel cell, a nominally ‘always on’ strategy was taken for the IT-SOFC such that, during non-drive time, the fuel cell power is used to recharge the battery and where the battery is assumed to accommodate the peak power requirement and act as an ‘energy buffer’, while the fuel cell is required to satisfy the overall energy demand.

To evaluate and compare the performance of vehicles, it is usual to use a standard drive cycle. In this study, the new European driving cycle (NEDC) [7] is used, which represents a

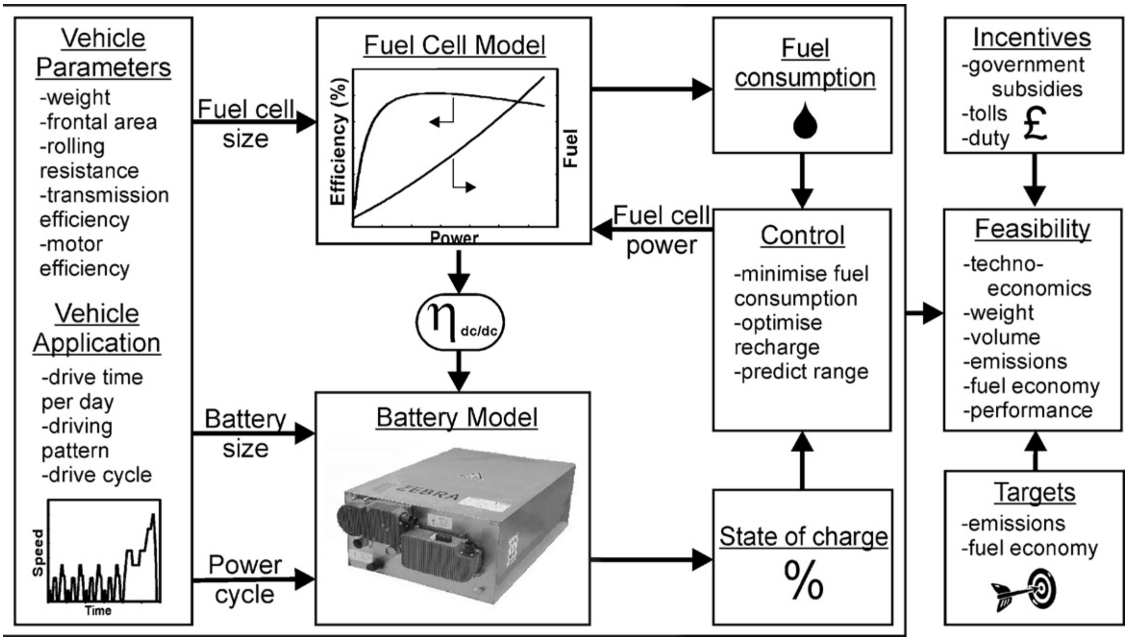

Fig. 2. Illustration of the modelling methodology followed to assess the feasibility of the ABSOLUTE hybrid vehicle.

cross between urban and suburban driving. An NEDC is completed in 1180 s with a total distance of ca. 11 km and has a maximum velocity of 120 km h^{-1} and an average speed in the urban and suburban sections of 18.7 and 62.6 km h^{-1}, respectively.

Using the set parameters and drive cycle, the corresponding power cycle (required from the battery) can be calculated. All the details on the calculation of the power cycle can be found in Ref. [1]. This accounts for various efficiency losses, namely motor efficiency, transmission efficiency and power converter efficiency; all the remaining efficiency losses in the hybrid system considered are taken into account by the fuel cell and battery models explained next. Initially, the suitability of the ABSOLUTE hybrid was analysed for different fuels and vehicle types. A city car, light duty van and a metropolitan taxi were then considered running on compressed hydrogen gas (CHG), compressed natural gas (CNG) and liquefied petroleum gas (LPG) [1]. However, the work presented here focuses only on the light duty van running on CNG.

Following the diagram in Fig. 2, knowledge of the power cycle and the driving and recharging time periods enables the sizing of the battery and fuel cell. The values for the optimal fuel cell power and battery energy are determined by performing an energy balance over a 24 h period. To determine the fuel cell power requirement, it is necessary to balance the energy consumed from the battery during the drive time (including all the auxiliaries) to that provided to the battery by the fuel cell. Once the fuel cell power is known, the total energy required to fully charge the battery, and thus, the necessary battery energy capacity can be determined [3].

Fig. 3(a) shows the optimal fuel cell power and battery energy for a delivery van operating over the NEDC drive cycle for operation from 1 to 24 h of drive time per day [3]. The data considers a fuel cell delivering constant power over a whole-day drive cycle with a varying number of hours of back-to-back drive cycles, and is used in the calculations in Section 3. The values in Fig. 3 are based on a vehicle weight of 1230 kg (all the remaining parameters considered can be found in [1]) and do not consider the influence of varying fuel cell/battery size on vehicle size. The effect of hybrid powertrain weight on the vehicle dynamics is discussed in Section 4.3.1. The figure shows that the fuel cell power increases with increasing operating time and that the extreme case of constant use over a whole day corresponds to a fuel cell powered vehicle with battery peak power assist. The profile for the battery's energy shows a maximum at 12 h of operation. The longer the period of drive time, the larger the fuel cell power output required, due to less non-drive recharge time being available. The simple energy balance calculations need to be corrected when the total energy of the battery is low, in order to deliver sufficient power to accommodate the requisite acceleration performance of the vehicle. This correction is evident for low and high driving times as seen in Fig. 3(a). The level of battery energy correction depends on the power-to-energy ratio; for the ZEBRA battery a representative value of 1.8 W Wh^{-1} is taken.

In Section 3, the basis of calculation of the lifecycle cost analysis is the case where a light delivery van, operating over the NEDC drive cycle, is driven continuously for 6 h and is later charged for a period of 18 h. For this case, the battery capacity is 26.6 kWh and the fuel cell has a net power output of 1.48 kW.

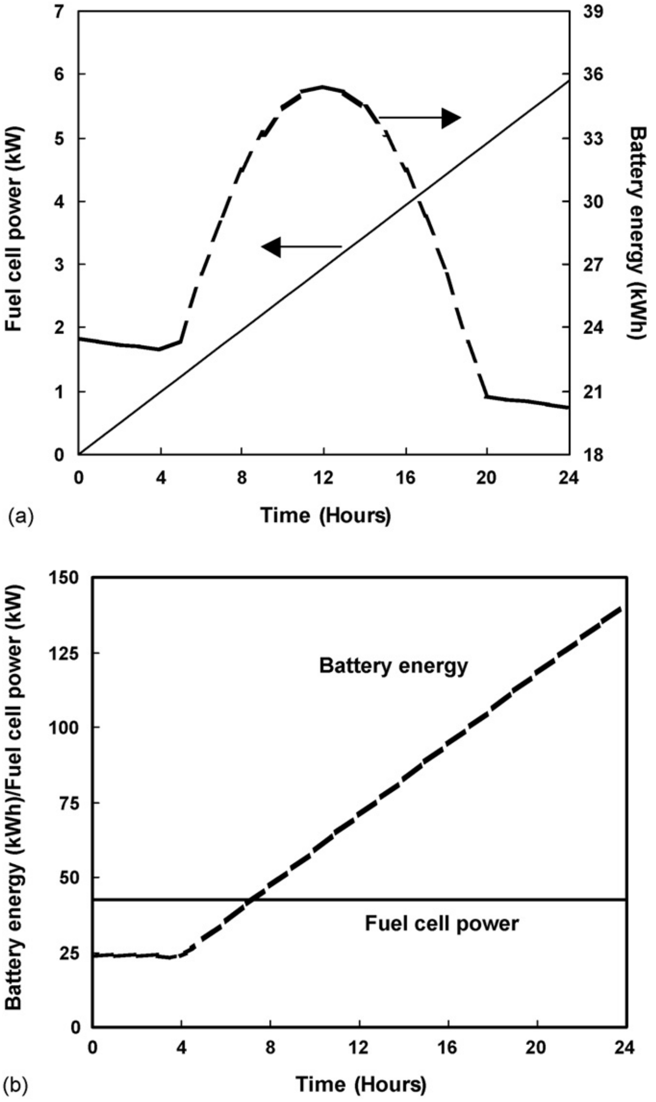

Fig. 3. Light delivery van operating on the NEDC drive cycle over a range of drive times: (a) hybrid vehicle fuel cell power and battery energy required; (b) battery-only vehicle energy and fuel cell-only vehicle power required.

To validate the methodology used to size the hybrid vehicle and test it against realistic driving conditions and different options of recharging (that aim at minimising fuel consumption), use is made of both a battery [3] and a fuel cell system model [4], as implied by Fig. 2. The use of these models is important in determining battery and fuel cell efficiency values that are subsequently used to correct the vehicle sizing strategy [3].

A 5 kW$_e$ IT-SOFC system model operating on methane has been developed [4] and two temperature regimes of operation of the stack were considered (500–650 °C using external reforming and 700–850 °C using partial internal reforming). The net system efficiency for each IT-SOFC type was found to be very similar (ca. 48% at the design point). In terms of system integration between battery and fuel cell it was found that direct thermal integration, involving the use of the hot exhaust gas from the fuel cell to maintain the heat of the battery, is not suitable for the lower temperature IT-SOFC (without wasting excess fuel or using a lower fuel utilisation), but potentially viable for the higher temperature IT-SOFC system. However, electrical heating of the battery via the fuel cell is considered to be the preferred solution [4].

An overarching model was built in MATLAB/SIMULINK that uses the state-of-charge input from the battery model, and efficiency and fuel consumption data provided by the SOFC model to evaluate the hybrid performance. By considering whole-day drive cycles for various vehicle applications, this model allows the size of the battery and fuel cell to be tuned, and the fuel economy, range and CO_2 emissions to be determined for more sophisticated driving patterns than the back-to-back scenario described previously.

Here, data provided by the modelling methodology described is used as a basis for performing a feasibility study on the proposed hybrid system. Factors such as techno-economics, vehicle weight and volume, CO_2 emissions and fuel economy can all be quantitatively calculated based on the previous analysis. Other factors to be taken into account include government incentives, technology targets, and safety factors, etc.

3. Techno-economic analysis

The aim of this analysis is to evaluate the feasibility of a hybrid SOFC/ZEBRA battery vehicle. For that purpose, a lifecycle cost analysis is performed for the hybrid vehicle and compared to the cases of battery-only and fuel cell-only vehicles as well as to current internal combustion engine vehicles. The analysis is made based only on the power source and neglects, at this stage, savings arising from displaced components, and/or addition/reduction in costs associated with the shift to the production of an all-electric vehicle. Both the initial capital cost, based on present and future cost estimates, and fuel consumption cost are taken into account. As explained above, the present analysis is based on the operation of a light delivery van with various power sources, assuming operation on the NEDC drive cycle over different drive times per day and charge neutrality for the battery over a 24 h period. For the hybrid vehicle, the calculated fuel cell power and battery energy for operation over a range of drive times has been presented in Fig. 3(a) and are used here. To size the battery-only vehicle, a similar analysis as for the hybrid vehicle was adopted, where the fuel cell power is set to zero. Note that this case also requires a correction of the resultant battery energy required such that the power source always guarantees the peak power of 42.3 kW to achieve suitable acceleration performance. Fig. 3(b) presents the calculated battery-only vehicle battery energy as well as the fuel cell power for the case of a fuel cell-only vehicle.

For the lifecycle cost analysis, the capital cost associated with the chosen power source and either fuel or electricity consumption are taken into account. It is assumed that maintenance costs are the same independently of the power source and are therefore neglected in the present analysis. Depending on the vehicle type, the total costs are thus calculated by:

$$\begin{aligned}\mathrm{Cost}_{\mathrm{hybrid}} &= \mathrm{CC}_{\mathrm{hybrid}} + \mathrm{CC}_{\mathrm{motor}} + \mathrm{Cost}_{\mathrm{fuel}} = \mathrm{CC}_{\mathrm{battery}} + \mathrm{CC}_{\mathrm{FC}} \\ &\quad + \mathrm{CC}_{\mathrm{motor}} + \mathrm{Cost}_{\mathrm{fuel}} = E_{\mathrm{battery}}\mathrm{UC}_{\mathrm{battery}} + P_{\mathrm{FC}}\mathrm{UC}_{\mathrm{FC}} \\ &\quad + P_{\mathrm{peak}}\mathrm{UC}_{\mathrm{motor}} + N_{\mathrm{days}}24P_{\mathrm{fuel\,cell}}\mathrm{UC}_{\mathrm{CNG}} \\ &\quad \times \mathrm{U}_{\mathrm{cons,methane}}\rho_{\mathrm{methane}} \end{aligned} \tag{1}$$

$$\begin{aligned}\mathrm{Cost}_{\mathrm{battery\,only}} &= \mathrm{CC}_{\mathrm{battery}} + \mathrm{CC}_{\mathrm{motor}} + \mathrm{Cost}_{\mathrm{electricity}} \\ &= E_{\mathrm{battery}}\mathrm{UC}_{\mathrm{battery}} + P_{\mathrm{peak}}\mathrm{UC}_{\mathrm{motor}} \\ &\quad + N_{\mathrm{days}}E_{\mathrm{battery}}\mathrm{UC}_{\mathrm{electricity}}\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{Cost}_{\mathrm{fuel\,cell\,only}} &= \mathrm{CC}_{\mathrm{FC}} + \mathrm{CC}_{\mathrm{motor}} + \mathrm{Cost}_{\mathrm{fuel}} \\ &= P_{\mathrm{peak}}\mathrm{UC}_{\mathrm{FC}} + P_{\mathrm{peak}}\mathrm{UC}_{\mathrm{motor}} \\ &\quad + N_{\mathrm{days}}24P_{\mathrm{peak}}\mathrm{UC}_{\mathrm{CNG}}\mathrm{U}_{\mathrm{cons,methane}}\rho_{\mathrm{methane}}\end{aligned} \tag{3}$$

$$\begin{aligned}\mathrm{Cost}_{\mathrm{ICE}} &= \mathrm{CC}_{\mathrm{ICE}} + \mathrm{Cost}_{\mathrm{petrol}} = P_{\mathrm{peak}}\mathrm{UC}_{\mathrm{ICE}} \\ &\quad + N_{\mathrm{days}}t\vartheta_{\mathrm{average}}\mathrm{UC}_{\mathrm{gasoline}}\mathrm{U}_{\mathrm{cons,gasoline}}\end{aligned} \tag{4}$$

Note that this analysis considers the price of the technology to the customer as opposed to the cost of producing it to the manufacturer. However, for the sake of readability, cost and price will be used interchangeably throughout this publication.

Eq. (1) refers to the calculation of the total cost of the hybrid vehicle. This consists of the battery cost, the fuel cell cost, the electric motor and power electronics cost, and the fuel cost associated with the CNG consumption by the hybrid vehicle. Eq. (2) represents the calculation of the total costs of the battery-only vehicle, which includes the battery, electric motor and power electronics cost, as well as the cost associated with electricity consumption. Eq. (3) is for the case of a fuel cell-only vehicle and thus takes into account the fuel cell cost, the cost of the electric motor and power electronics, and the cost of fuel. The final power source considered is the ICE vehicle, for which Eq. (4) gives the cost estimate that consists of the price of the ICE and the cost of gasoline. The price of the battery is calculated based on the total capacity of the battery and its price per kWh. The same is true for the fuel cell price where this is a function of the stack power and the unit price per kW defined next. Note that in the case of the fuel cell-only vehicle the power of the stack is the peak power required by the vehicle. This is also the power value used to calculate both the ICE and electric motor costs. For the hybrid vehicle it is important to note that it is assumed that the fuel cell is always on, thus the factor 24 (h) in Eqs. (1) and (3), and that the fuel consumption is provided by the fuel cell system model [4] and depends on the fuel cell power. The price of electricity to charge the battery is a function of the battery energy capacity and the gasoline consumption (and cumulative cost) depends on the average vehicle speed and drive time.

Table 1
Parameters used in the techno-economic analysis

Parameter	Value
CNG price, $\mathrm{UC}_{\mathrm{CNG}}$	£0.65 kg^{-1} [9]
CNG fuel duty	£0.09 kg^{-1} [8]
Methane energy, $\mathrm{UE}_{\mathrm{methane}}$	9 $\mathrm{kWh\,m}^{-3}$
Methane density at 1 bar	0.645 $\mathrm{kg\,m}^{-3}$
Methane consumption, $U_{\mathrm{cons,\ methane}}$	0.230 $\mathrm{m}^3\,\mathrm{h}^{-1}\,\mathrm{kW}^{-1}$
Gasoline price, $\mathrm{UC}_{\mathrm{gasoline}}$	£0.989 L^{-1}
Gasoline duty	£0.5019 L^{-1} [8]
Gasoline fuel economy (av. gasoline consumption), $U_{\mathrm{cons,\ gasoline}}$	15.4 $\mathrm{km\,L}^{-1}$ [11]
Electricity price, $\mathrm{UC}_{\mathrm{electricity}}$	£0.10 kWh^{-1} [10]
Electricity VAT	5% [10]
Fuel cell efficiency, $\eta_{\mathrm{fuel\ cell}}$	48.4% [3]
Battery efficiency, η_{battery}	89% [3]
Fuel cell price range, $\mathrm{UC}_{\mathrm{fuel\ cell}}$	£400–3000 kW^{-1}
Battery price range, $\mathrm{UC}_{\mathrm{battery}}$	£70–305 kWh^{-1}
ICE price range, $\mathrm{UC}_{\mathrm{ICE}}$	£10–40 kW^{-1}
Power electronics and electric motor price, $\mathrm{UC}_{\mathrm{motor}}$	£11 kW^{-1} [14]
ICE power, P_{ICE}	42.3 kW[a]
Average traction power required, P_{traction}	5.10 kW[a]
Average speed for NEDC drive cycle, $\upsilon_{\mathrm{average}}$	33.6 $\mathrm{km\,h}^{-1}$[a]
Auxiliary power requirement, $P_{\mathrm{auxiliary}}$	800 W [1]
Maximum power requirement, P_{peak}	42.3 kW[a]
Battery power to energy ratio, $\mathrm{PE}_{\mathrm{battery}}$	1.8 $\mathrm{W\,Wh}^{-1}$ [1]

[a] For a light delivery van operating in the NEDC drive cycle.

3.1. Parameters used for the techno-economic analysis

Table 1 presents all the parameters used in the techno-economic analysis, which derive from current literature, market prices or estimated prices. The fuel cell and battery efficiency, and methane consumption values, were calculated using both the fuel cell system model and battery model mentioned above [3,4]. The electrical requirement of the fuel cell is considered as an 'internal' parasitic load that is accounted for in the efficiency and rated power of the fuel cell system. The average traction power required, average speed for the NEDC drive cycle and maximum power requirement are all for a light delivery van operating over the NEDC drive cycle. More details on the vehicle parameters can be found in reference [1]. Where there exists scope for uncertainty in price (due to existing production cost variability in the case of the ICE or a dependence on meeting projected cost targets when in mass production in the case of the battery and fuel cell) a range of values have been considered in order to assess price sensitivity.

3.1.1. Gasoline, CNG and electricity price and duty

Due to volatility in fuel prices and duty, two different scenarios are considered; one where current UK prices and UK tax values are used, and one where no tax or fuel duty is considered. This allows for a more informed analysis, where future tax regulations do not influence the present conclusions (see Section 3.2). Fuel and electricity prices are also presented in Table 1. The values for fuel duty are based on current UK duty rates for unleaded gasoline and natural gas [8]; the UK government has agreed to maintain the duty differential between CNG and diesel on a rolling 3 year basis [9]. The gasoline price quoted is the current UK pump retail price (August 2006). The price of CNG at the pump was found to vary significantly between supplier and the market price of natural gas; the value used here is an average value per kilogram of fuel [9]. The electricity price for the battery-only vehicle, was taken from EDF Energy retail price (August 2006) [10]. This corresponds to the Fixed Price 2010 Tariff, after which the electricity price is expected to further increase.This is a UK centric analysis with respect to fuel and electricity costs and duty. When necessary, costs in US dollars have been converted to UK pounds (£1 = \$1.901, 31 August 2006).

3.1.2. Gasoline fuel economy

Fig. 6(a) shows the average fuel economy (for combined urban and highway cycles) against engine size for over 2500 cars in the UK and was obtained from the VCA database (VCA is the Vehicle Certification Agency, an Executive Agency of the United Kingdom Department for Transport and the United Kingdom's national approval authority for new road vehicles, agricultural tractors and off-road vehicles) [11]. These data include mainly gasoline and diesel vehicles but also gasoline hybrid, LPG and bi-fuel CNG vehicles. In 1993, exhaust emission limits, generally referred to as Euro I standards, were introduced for new cars which resulted in the adoption of advanced emission control techniques. More stringent emission limits came into effect in 1997 (Euro II) and 2001 (Euro III). However a further tightening of the emissions limits, referred to as Euro IV, began on the 1st January 2005 and will be fully in force by 1st January 2007. Fuel economy and CO_2 emissions (in Section 4) used in this paper are based on the Euro IV standards for car emissions [11]. From the data in Fig. 6(a), and considering a light delivery van with an engine capacity between 1 and 2 L, an average fuel economy value of 15.4 $\mathrm{km\,L}^{-1}$ was used in this study.

3.1.3. Battery price range values

In 2003, Galloway and Dustmann published a report that looked at the issues of materials cost, availability and recycling of ZEBRA batteries [12]. At the time, materials costs for large volume production stood at \$28 kWh^{-1}; the cost of nickel has since increased substantially (by a factor of ca. 3); however, taking a long-term price projection of \$16 kg^{-1} for nickel, a figure of \$35 kWh^{-1} is reached for the raw materials of the battery (primarily nickel, sodium chloride and boehmite for the beta alumina conducting ceramic). At a production rate of 100,000 Z5 batteries per year the price projection is £70 kWh^{-1}. The current retail price of ZEBRA batteries when purchased in volumes of 100 is ca. £305 kWh^{-1}. These two values are used as the bounds for comparison of current state-of-the-art and projected battery price. The paper also shows that a shortfall in the availability of nickel is unlikely (this is not so for lithium based batteries) since, in volume, the battery related share of nickel demand is only 5% of the total annual world production. Successful recycling of ZEBRA batteries (in 20 t loads) has also been demonstrated by the US company INMETCO (PA).

3.1.4. Fuel cell system price range values

As for the battery, a price range for the fuel cell system needs to be defined. The SECA program provides the most authoritative and wide ranging performance and cost targets for SOFC technology. SECA, the Solid State Energy Conversion Alliance [13], is a US coalition composed of industry groups who individually plan to commercialize SOFC systems for pre-defined markets; of research and development institutions involved in solid-state activities; and of government organizations that provide funding and management for the program. The SECA alliance was formed to accelerate the commercial readiness of SOFCs in the 3–10 kW range for use in stationary, transportation, and military applications. Various major fuel cell companies are involved in this alliance, all with the program specific cost target of $\$400\,\text{kW}^{-1}$ (£210.4 kW^{-1}) for SOFC systems in volume production (factory cost). GE and Delphi are reported to have made significant advances in the reduction of SOFC stack costs, surpassing the SECA target for 2006. Their estimated costs were $\$294\,\text{kW}^{-1}$ for a 4.24 kW Delphi stack and $\$254\,\text{kW}^{-1}$ for a 5.4 kW GE stack [13].

In this study it was found more appropriate to define a fuel cell system price range that allows for a better analysis of the hybrid viability. For that purpose a lower limit of £400 kW^{-1} and an upper limit of £3000 kW^{-1} were set.

3.1.5. ICE price range values

ICE manufacturing costs are rarely made known. In addition, the cost of manufacture is dominated by the facility cost of the manufacturing plant coupled with the volume throughput, both of which vary widely between manufacturers. Here it was decided to have a lower limit of £10 kW^{-1} for the engine price (this includes the transmission, exhaust and cooling) and an upper limit of £40 kW^{-1}.

3.1.6. Power electronics and electric motor price

In hybrid electric vehicles, control functions are provided by electronics, both power electronics and signal electronics, which are responsible for the dynamic response of both the fuel cell and the battery, as well as the charge management of the battery. The price estimates used here are based on the current technology status reported in the Review of the Research Program of the FreedomCAR and Fuel Partnership [14]. Power electronics, including the inverter and controller, are cited at $\$6\,\text{kW}^{-1}$ (£3.14 kW^{-1}) and electric motors at $\$15\,\text{kW}^{-1}$ (£7.86 kW^{-1}). These values are based on a 30 kW continuous series powertrain.

3.2. Lifecycle cost analysis results

Fig. 4 presents the lifecycle cost analysis, considering capital and running costs for 5 years of vehicle operation for a light delivery van with various power sources.

For this analysis, operation on the NEDC drive cycle over 6 h of drive time per day, and charge neutrality for the battery over a 24 h period, is assumed. The power sources considered include the ZEBRA battery/IT-SOFC hybrid, battery-only, fuel cell-only and internal combustion engine options for comparison. As mentioned above, two cases are analysed: the first one, Fig. 4(a), considers the current (low manufacturing volume) battery price in Table 1, and taxed fuels/electricity, while the second case, Fig. 4(b), assumes the lower battery price, representative of high volume battery manufacture, with untaxed fuels/electricity. The purpose of analysing both these cases is to assess the feasibility of a hybrid vehicle for both current and future scenarios. The absence of fuel duty in Fig. 4(b) attempts to truly assess the effect of running costs in a scenario where natural gas does not benefit from lower taxation compared to gasoline and diesel.

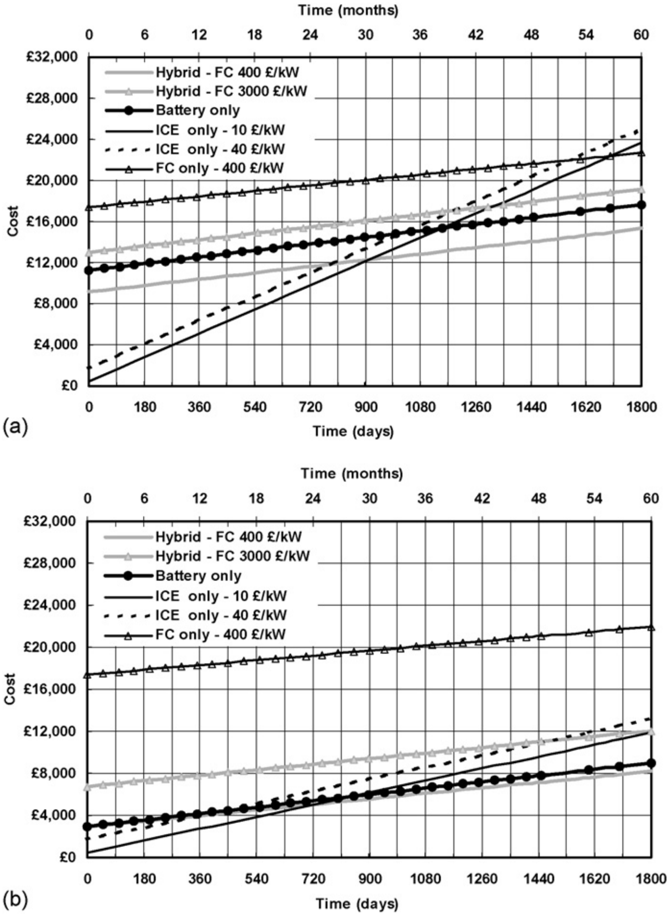

Fig. 4. Predicted capital and running costs over 1800 days of vehicle operation for a light delivery van with various power sources assuming operation on the NEDC drive cycle over 6 h of drive time per day and assuming charge neutrality over a 24 h period: (a) current battery price and taxed fuels; (b) volume manufacture battery price and untaxed fuels.

Analysing the results in Fig. 4 it can be seen that the displacement up the y-axis at zero days represents capital costs of each power source to the consumer, whereas the gradient represents the running costs (fuel/electricity). It can be seen that moving from the first scenario to the second results in a reduction in the capital cost of the hybrid and battery-only systems of between a factor of 2 and 3.5. In moving from a taxed to a non-taxed scenario it can be seen that the running cost of the hybrid and battery-only systems does not decrease appreciably, whereas for the ICE case, the decrease in running cost of approximately 50% is significant.

Fig. 4 allows various conclusions to be drawn. The first refers to the fuel cell-only vehicle case. As can be seen, the lower price

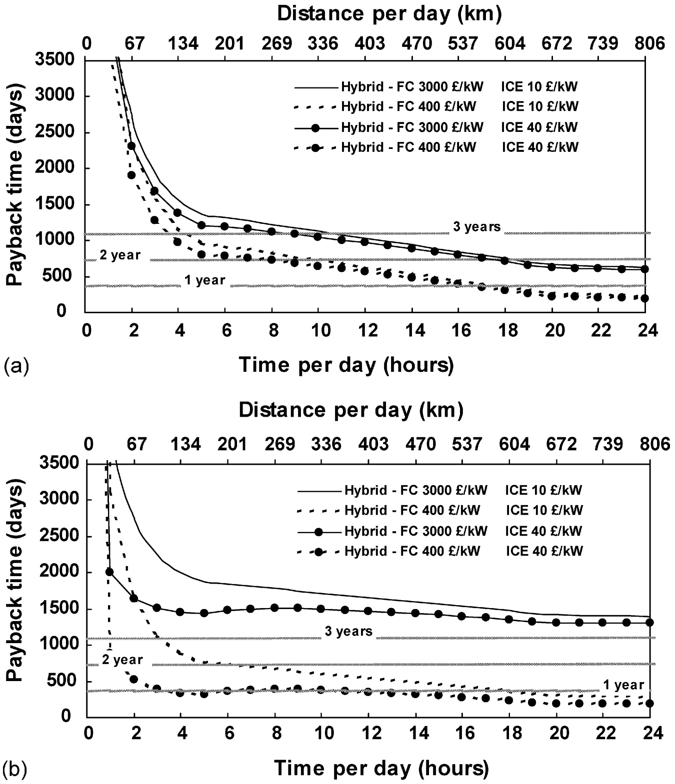

Fig. 5. Payback time for the operation of a hybrid SOFC/battery light delivery van assuming operation on the NEDC drive cycle over a range of drive times/distances and assuming charge neutrality over a 24 h period: (a) current battery price and taxed fuels; (b) volume manufacture battery price and untaxed fuels.

prediction is shown, for which the initial capital cost is still much higher than any of the other power source option. It is estimated that for a fuel cell-only solution to be competitive, the price of a fuel cell system would have to be reduced to ca. £150 kW^{-1} for both scenarios. However, a fuel cell-only vehicle would always require the use of an oversized fuel cell, sufficient to deliver vehicle peak power.

Fig. 4 demonstrates that a hybrid vehicle is economically competitive when compared with a battery-only vehicle. However, a battery-only vehicle driving 6 h per day implies a battery at least 25% larger than the one used for the corresponding hybrid (Fig. 3). This is because, in the hybrid option, the fuel cell is continuously charging the battery, achieving the same range. The difference between the two cases becomes even more noticeable for increasing drive time per day as Fig. 3 clearly shows. This is associated with a corresponding weight and volume penalty, as discussed in Section 4.3.

Fig. 5 presents the payback time compared with an ICE operating on gasoline (this is the time after which the combination of the capital and running cost of the hybrid system becomes less than the ICE running on gasoline) as a function of the number of hours of driving time (or distance driven) per day.

It is clear from Fig. 5 that increasing drive time per day decreases the payback time substantially. Accordingly, Figs. 4 and 5 show that the hybrid vehicle is an economically attractive option for commercial vehicles with long drive times, such as delivery vehicles or taxis, but are less economically attractive for vehicles with short drive times per day (i.e. private vehicles used for short commutes).

Comparing the hybrid battery/fuel cell system with the ICE, it can be seen that the payback time for a hybrid vehicle in relation to an ICE vehicle depends on the price assumed for the fuel cell system, the battery and the internal combustion engine. However, for the case where the price of the fuel cell is £400 kW^{-1} (lower price limit) and as long as the drive time is longer than 4 h, the payback time is always <3 years. For the worst-case scenario, where the fuel cell price is taken as £3000 kW^{-1}, the payback time is still <5 years. Fig. 5(b) corresponds to the case where no road fuel duty has been taken into account and thus neglects the current, and the likely future, low fuel duty value in place on CNG. In the case where the battery has reached volume production prices at £70 kWh^{-1} and current fuel duty values remain unchanged then the payback time would be <2 years, independently of the fuel cell or ICE prices.

4. Feasibility considerations

The above analysis has shown that SOFC/battery hybrids are potentially a technically and economically viable powertrain option for certain vehicle applications, particularly those involving long drive times per day (commercial vehicles). However, additional factors must also be considered, including fuel economy, weight, volume and CO_2 emissions. These factors are addressed in the following sections.

4.1. Fuel economy and range

For a light delivery van operating with 6 h drive time per day, the fuel cell system model [4] predicts a methane fuel consumption of 5.27 kg (over a 24 h period), corresponding to a gasoline equivalent fuel economy of 25.1 km L^{-1}, almost twice that of the average gasoline vehicle fuel economy reported in Section 3.1.2. In order to compare this fuel economy against the 'rest of the pack', Fig. 6(a) compares the fuel economy for the range of vehicles in the VCA database (including hybrids and alternative fuel vehicles) [11] to that of the ABSOLUTE hybrid. Since the vehicle type in question will have an engine capacity between 1 and 2 L, comparison should be made in this area, which incidentally is the region of highest fuel economy. It can be seen that fuel economy predictions for the ABSOLUTE hybrid compare well with the range of vehicles on the road and bodes well for taking the concept forward to a prototype stage.

CNG is generally stored on-board vehicles in cylinders at a maximum pressure of around 200 bar. Given that a typical UK natural gas contains around 85–90% methane and that the density of CNG at that pressure is 0.18 kg L^{-1}, then ca. 65% of a 50 L CNG tank would be consumed during a 24 h period (when driving 6 h per day). However, vans can be fitted with single or double 80 L cylinders, or with a single 120 L cylinder, depending on the space available and the vehicle range required. A 120 L cylinder would afford a refuelling period of 4 days if driving 6 h per day. This figure is equivalent to the range obtained from

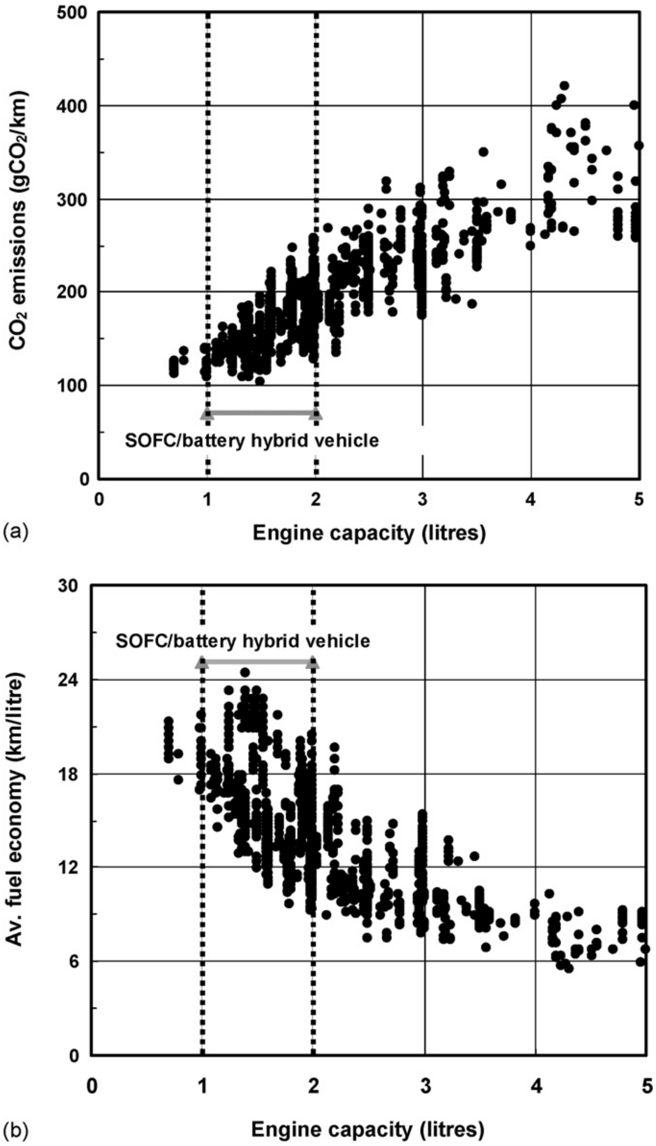

Fig. 6. (a) Average fuel economy and (b) average CO_2 emissions (for combined urban and highway cycles) against engine size for over 2500 new gasoline and diesel cars on sale in the UK (Euro IV standards).

a gasoline-fuelled vehicle with a 50 L tank and the fuel economy figure of 15.4 km L^{-1} reported above (see Section 3.1.2 and Fig. 6).

4.2. CO_2 emissions

Associated with an improvement in fuel economy are reductions in greenhouse gas emissions, particularly carbon dioxide. At the Kyoto Conference on Climate Change in December 1997, some developed countries agreed to legally binding targets to reduce their greenhouse gas emissions in response to warnings over global climate change. Following this, the European Commission and the European Automobile Manufacturers Association (ACEA) came to an agreement in July 1998 that committed ACEA to reduce the CO_2 emissions from new passenger cars by over 25% to an average CO_2 emission figure of 140 g km^{-1} by 2008. This represents one of the most significant industry agreements on reducing greenhouse gas emissions and it has led to more fuel-efficient vehicles being brought to the market. Japanese and Korean motor manufacturers have now reached similar voluntary agreements. Various government or local incentives have been introduced since. Depending on the country/state/city in which the vehicle is being operated, the level of CO_2 emissions may have a significant bearing on operating cost. Road tax may depend on the emission profile or, as is the case in London, a congestion charge (currently £8 per day) is waived for low CO_2 emissions vehicles [15]. In recent years, the UK government has also reformed its main vehicle taxation policies to reward the purchase of clean, low carbon vehicles. Drivers of fuel-efficient cars now pay lower vehicle excise duty and company car tax, and Enhanced Capital Allowances reward companies for purchasing highly fuel-efficient cars. In February 2005, the government announced a fuel efficiency colour coded labelling scheme for new cars sold in the UK. The labels display the same bands as those used for vehicle excise duty and give car buyers an immediate indication of how much tax they can expect to pay depending on their choice of vehicle. The labels also highlight fuel efficiency, showing motorists how much they can expect to pay in fuel bills in a typical year for a particular car. The lower band in this scheme refers to vehicles that have CO_2 emissions lower than 100 g CO_2 km^{-1}. All car brands in the UK have signed up to the introduction of the voluntary labelling scheme. The government has also introduced fuel duty incentives for clean, low carbon fuels and is committed to maintaining this differential for at least another 3 years [16,17]. It therefore follows that the techno-economic case presented in Section 3 is likely to be even more promising when such incentives are factored in.

Fig. 6 shows the average CO_2 emissions (for combined urban and highway cycles) against engine size for over 2500 new gasoline and diesel cars on sale in the UK, commensurate with the fuel economy data presented in Section 3.1.2 [11]. From the data in Fig. 6, and considering that the average engine capacity of a light delivery van is between 1 and 2 L, it can be seen that the average CO_2 emission value is in the region of 160 g km^{-1}. As an example, from another source of typical CO_2 emission data, a Renault Kangoo van with a 1.15 L gasoline engine will typically release 146 g CO_2 km^{-1} [18].

For the hybrid vehicle under study, based on the modeling methodology and strategy adopted, the CO_2 emissions would be 71.6 g km^{-1}. This value is calculated based on the CO_2 in the exhaust stream predicted by the SOFC system model [4] and taking into account the size of the fuel cell and the average speed of the NEDC drive cycle (33.6 km h^{-1}). The hybrid vehicle therefore offers very low CO_2 emissions characteristics and would belong to the lowest emissions band set by the UK government [17].

4.3. Weight and volume analysis

The weight and volume of the hybrid powertrain is vitally important for determining suitability for the application. There

Table 2
Gravimetric and volumetric specific power density values

Fuel cell system	
Gravimetric specific power density	100 W kg^{-1}
Volumetric specific power density	100 W L^{-1}
Battery system	
Gravimetric specific power density	180 Wh kg^{-1} [22,25]
Volumetric specific power density	276 Wh L^{-1} [22]
ICE (inc. transmission, exhaust and cooling)	
Weight per engine volume (cylinder)	160 kg L^{-1}
Electric motor and control system	
Gravimetric specific power density	917 W kg^{-1} [14]
Volumetric specific power density	2683 W L^{-1} [14]

will always be pressure to reduce overall vehicle weight in order to maximise performance (especially acceleration) and fuel economy, but there will come a limit at which the powertrain weight and volume will no longer be fit for purpose.

In order to estimate the weight of the hybrid powertrain, representative values of fuel cell and battery weight and volume have been taken along with dc motor and ICE powertrain values. Table 2 summarises the values used. The battery values are well known from production experience [22]. Reports and targets have been set for SOFC systems for both vehicle range extenders and APUs [19]. Delphi and Webasto have reported weight and volume target values for a 5 kW$_e$ SOFC system for vehicular applications of around 50 kg and 50 L [6,20]. Estimates of the weight and volume of complete SOFC systems are highly dependent on the effectiveness of the process integration. For example, physical integration of the afterburner and reformer is a common strategy. The US DoE has set 2015 targets for fuel cell auxiliary power systems of 150 W kg^{-1} for the specific power and 170 W L^{-1} for the power density [21]. Somewhat more conservative targets, commensurate with the shorter-term aims of Webasto and Delphi, are selected for the ABSOLUTE IT-SOFC system (see Table 2).

The weight of ICEs varies somewhat from gasoline to diesel, the value of 160 kg L^{-1} of engine capacity is taken as representative of a gasoline engine passenger car, including transmission, cooling and exhaust (but not the fuel tank or fuel). As with the electric motor price, weight and volume estimates are derived from the 2003 status of the technology report [14]. Power electronics are cited at 11 kW kg^{-1} and 11.5 kW L^{-1} and the motor at 1 kW kg^{-1} and 3.5 kW L^{-1} for the gravimetric and volumetric power density, respectively.

Fig. 7 presents the comparison of the weight and volume estimates between a fuel cell-only, battery-only and hybrid vehicle as a function of the number of hours of drive time per day. It can be seen that the hybrid vehicle is a viable option even for long driving hours. The fuel cell-only and battery-only options would however require a much higher volume and have a much higher weight, which would affect the vehicle performance and imply an increase in the power required and so complicate the energy balance calculation as discussed in the following section.

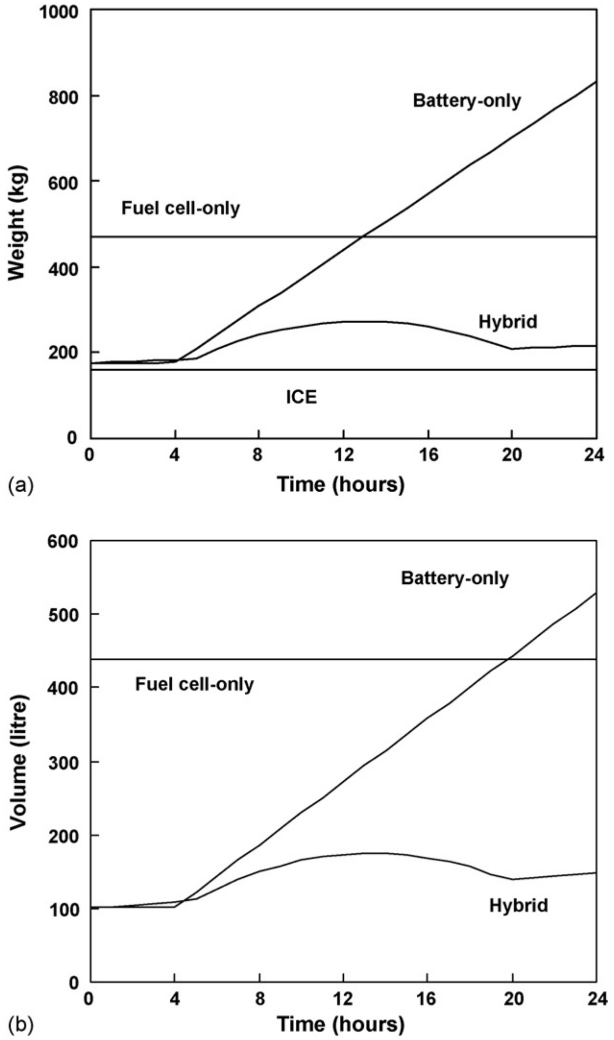

Fig. 7. (a) Weight and (b) volume calculated for the power sources analysed as a function of drive time per day, excluding fuel.

Fuel storage has not been included in the present analysis. As an example, a 50 L steel cylinder carrying CNG compressed to 200 bar, would weigh 70 kg. However, using composite technology a weight saving of between 50 and 75% can be realized compared to metal vessels [23].

4.3.1. *Effect of hybrid powertrain weight on vehicle dynamics*

The analysis presented previously [1] covers a range of driving scenarios in terms of the hours (or km) of drive time per day and the vehicles considered. Although this analysis is valid in terms of energy balance and power requirement, the volume of the battery and fuel cell system may not be suitable for the application, or may be so heavy that it significantly contributes to vehicle weight and so affects the vehicle dynamics calculations used to derive the power cycle. Fig. 8 illustrates the sensitivity of overall vehicle weight and consequent increase in average power requirement due to the hybrid powertrain weight. It can be seen that the percentage increase in weight and power requirement is more pronounced for smaller vehicles; however,

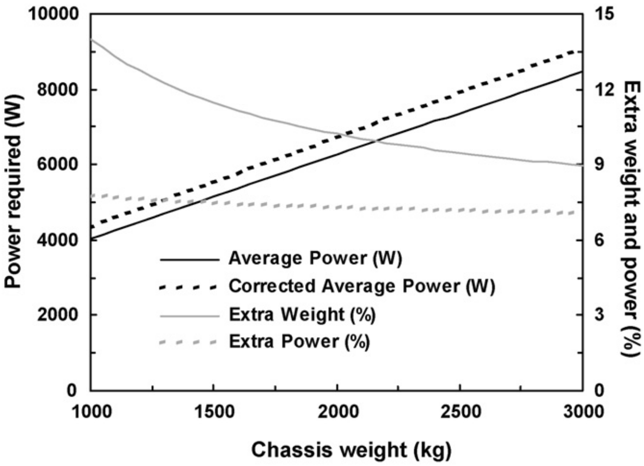

Fig. 8. Sensitivity of overall vehicle weight and consequent increase in average power requirement due to the hybrid powertrain weight.

the extra power requirement remains below 8% of the average power required without the powertrain, over the range of chassis weights considered, and is therefore not considered significant at this stage.

4.4. Additional considerations

4.4.1. Start-up/shut-down

The ABSOLUTE hybrid vehicle relies on the fact that both the ZEBRA battery and the SOFC operate on an "always on" mode. This means that the battery remains hot during non-driving time and that the fuel cell is at least required to produce enough power to keep the battery at its operating temperature and service all of the auxiliaries in the system. Such a mode of operation avoids long start-up time for the battery and reduces the number of thermal cycles required from the SOFC. The ZEBRA battery is a high temperature battery; it is estimated that this cools-down 2 °C an hour if not under charge [24] and that it requires up to 8 h to be at its operating temperature if started from cold. For this reason, the ZEBRA battery remains hot during non-driving time with power derived from the battery itself [24].

Since the ABSOLUTE hybrid is battery dominant, with a relatively small SOFC, the battery has enough energy (if charged) to guarantee the vehicle operation during fuel cell start-up. The small size of the SOFC also means that the start-up time can be reduced in relation to larger systems.

4.4.2. SOFC thermal cycling

One of the main limitations related with SOFC technologies is related with their capacity to sustain repeated thermal cycles without performance degradation. The "always-on" operation mode adopted for the SOFC/battery hybrid vehicle has been adopted, among other factors, to reduce the number of thermal cycles that the SOFC has to undergo. However, much progress has been made in this area, for example, Versa Power Systems Ltd. have reported promising results of less than 0.05% loss in voltage per thermal cycle after 250 thermal cycles from 750 °C to room temperature [25].

4.4.3. Operating temperature range

The ability of a vehicle to start from cold is an important consideration. This is a problem for polymer electrolyte fuel cell technology, as is the ability to cool a device generating many tens of kilowatt yet relying on only a few tens of degree centigrade temperature difference between the stack and ambient. For an SOFC operating >500 °C, heat dissipation is less of a concern and both battery and fuel cell technology have no problem delivering immediate power in cold conditions given that they should nominally always be at the operating temperature. System operation over an external temperature range of −50 °C to +50 °C should not therefore present a significant challenge.

4.4.4. Exhaust emissions

In addition to reduced CO_2 emissions, the fuel cell system will have almost zero noxious gas (SO_x and NO_x) emissions, so removing the requirement for a catalytic converter.

4.4.5. Fuel distribution infrastructure

In the UK, as in many countries, there exists an extensive natural gas distributed network of pipelines to feed domestic and industrial installations. Developing a CNG distribution network for vehicles could therefore take advantage of the existing infrastructure. However, at present, the Natural Gas Vehicle Association recognises less than 20 refuelling stations in mainland UK [9], while the LPG infrastructure is well developed. Given the use of steam reforming technology, it is quite reasonable that a duel-fuel option of CNG and LPG could be applied to this hybrid technology.

4.4.6. Durability

It is important to consider the lifetime of the respective technologies when making comparisons. An ICE is generally considered to have an average lifetime of the order of 298,000 km [23]; for a vehicle operating on the NEDC drive cycle for 6 h per day, this is equivalent to 1478 days of operation (for comparison with the hybrid case in Fig. 4). The durability targets intended for SOFCs operating in relatively steady-state conditions – as is the case here – are >40,000 h, corresponding to 1667 days of operation on the same basis. So, with a lifetime of the battery and motor likely to be over 10 years, the durability of the hybrid is not considered to be limiting. However, the residual value of the hybrid after 2–5 years of use (when most delivery vans are resold) is difficult to assess, as the second-hand market would be uncertain for such a 'new' technology (at least in the early years after introduction).

4.4.7. Safety

ZEBRA batteries have been demonstrated in over 200 electric and hybrid electric vehicles in many sites around the world in collaboration with leading automotive manufacturers such as Zytek-Smart, Renault, Mercedes, BMW and Fiat. These batteries have an excellent reliability and safety record, the technology having been extensively safety tested for fire, impact, penetration, submersion, etc. It is also the only battery type to have successfully completed the EUCAR safety tests. The lack of demonstration examples precludes comment on the safety record of SOFCs in vehicles, but the development of SOFC APUs by Delphi and others can be expected to address this in due course.

4.4.8. Added value

An all-electric hybrid of this nature affords certain features that give added value compared to an ICE vehicle. For example, the versatility of distribution of the power source around the vehicle structure allows different chassis architectures to be explored, which should give great passenger space and be optimised for different applications. Electric vehicles have excellent acceleration and the fuel cell could, in addition, be used for remote generation for utility and recreational purposes.

5. Conclusions

This paper has focused on a system analysis for the combination of a sodium-nickel chloride (ZEBRA) battery operating at 300 °C and an intermediate temperature solid oxide fuel cell (IT-SOFC) operating at 500–800 °C to form a hybrid power system for automotive applications.

The hybrid SOFC/ZEBRA battery vehicle has various technical benefits. In addition to the common advantages provided by an all-electric vehicle of having quiet operation, an efficient drive train and power source, fast acceleration at low speeds, regenerative braking, electronic control of all aspects of the vehicle, and lower overall CO_2 emissions than an ICE vehicle, the ZEBRA battery and SOFC technology also offer other benefits. For the ZEBRA battery these include rapid dynamic response, proven technology in vehicles, high charge/discharge efficiency, uncomplicated cooling requirement, and four times the range of equivalent weight lead acid batteries. From the solid oxide fuel cell point of a view, the hybridisation with a ZEBRA battery results in a highly efficient fuel conversion, a constant power supply to the battery (to make the system charge neutral), and the use of the fuel cell in a situation where it is rarely exposed to stop/start cycles or transient loads. The use of an SOFC also means that the system is tolerant to a wide range of fuel types with a vastly simplified fuel processing requirement compared to PEMFC technology.

It was shown that the hybrid vehicle is economically viable when compared with alternatives such as fuel cell-only vehicles, battery-only vehicles and conventional ICE vehicles. It was also demonstrated that either in a low volume production scenario or a scenario where the technology has achieved maturity enough to be produced in large quantities, but where CNG is not as tax favourable as at present, the hybrid would still be viable. In addition to all the economic factors it has been seen that the proposed hybrid vehicle exceeds the fuel economy of most of the vehicles available today and that its CO_2 emissions are far lower than any limits set by government bodies in establishing a low carbon economy. However, the present analysis has shown that such a vehicle would be most suitable where long driving times per day are involved, as is the case for commercial vehicles, e.g. taxis or delivery vehicles. In terms of comparing the volume and weight of each one of the power sources analysed here, the ZEBRA battery also appears to be a favourable option, when compared with other battery technologies, given that it has one of the highest energy densities available, and has a demonstrated capability to operate over external temperatures of −50 °C to +50 °C.

It is therefore recommended that a SOFC/ZEBRA demonstration unit be built to further explore its viability. Once the technology is fully assessed and optimised, a wide range of applications offer themselves, not only for motive power, but for APUs and off-grid stationary power generation.

Acknowledgments

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References

[1] D.J.L. Brett, P. Aguiar, N.P. Brandon, R.N. Bull, R.C. Galloway, G.W. Hayes, K. Lillie, C. Mellors, M. Millward, C. Smith, A.R. Tilley, J. Power Sources 157 (2006) 782–798.
[2] D.J.L. Brett, P. Aguiar, N.P. Brandon, R.N. Bull, R.C. Galloway, G.W. Hayes, K. Lillie, C. Mellors, M. Millward, C. Smith, A.R. Tilley, J. Fuel Cell Sci. Tech. 3 (2006) 254–262.
[3] N.P. Brandon, P. Aguiar, D.J.L. Brett, R.N. Bull, I. Coop, R.C. Galloway, G.W.G. Hayes, K. Lillie, C. Mellors, M. Millward, A.R. Tilley, IEEE Vehicle Power & Propulsion Conference Proceedings, Windsor, UK, 2006.
[4] D.J.L. Brett, P. Aguiar, N.P. Brandon, J. Power Sources 163 (2006) 514–522.
[5] S. Mukerjee, M.J. Grieve, K. Haltiner, M. Faville, J. Noetzel, K. Keegan, D. Schumann, D. Armstrong, D. England, J. Haller, C. DeMinco, Proceedings of the SOFC VII, PV 2001-16, New Jersey, Electrochem. Soc. (2001) 173.
[6] J.J. Botti, M.J. Grieve, J.A. MacBain, SAE World Congress, Detroit, Michigan, 2005, SP-1973.
[7] W. Kimberly (Ed.), Bosch Automotive Handbook, Professional Engineering Publishing Ltd., London, 2004, pp. 568–569.
[8] http://www.hmrc.gov.uk/ (August 2006).
[9] http://www.ngva.co.uk/ (August 2006).
[10] http://www.edfenergy.com/ (August 2006).
[11] http://www.vcacarfueldata.org.uk/ (August 2006).
[12] R.C. Galloway, C.H. Dustmann, ZEBRA Battery—Materials Cost Availability and Recycling, EVS-20, Long Beach, CA, November 15–19, 2003.
[13] http://www.netl.doe.gov/seca/ (August 2006).
[14] Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report, National Research Council, The National Academies Press, Washington DC (2005) (http://darwin.nap.edu/books/0309097304/html).
[15] http://www.cclondon.com/ (August 2006).
[16] http://www.lowcvp.org.uk/ (August 2006).
[17] http://www.dft.gov.uk/ (August 2006).
[18] http://www.smmtco2.co.uk/co2search2.asp (August 2006).
[19] N.P. Brandon, in: R.H. Thring (Ed.), Fuel Cells for Automotive Applications, Professional Engineering Publishing, London, 2004, pp. 31–41.
[20] J. McEntree (Ed.), The Fuel Cell Review, 2004.
[21] K.-A. Adamson, “US Hydrogen and Fuel Cell R&D Targets and 2005 Funding”, Fuel Cell Today, 2005, on-line article (www.fuelcelltoday.com).
[22] MES-DEA Technical Datasheet P-Type battery, April 2003.
[23] R. Funck, in: R.W. Vielstich, H.A. Gasteiger, A. Lamm (Eds.), Handbook of Fuel Cells—Fundamentals, Technology and Applications, vol. 3, John Wiley and Sons, Ltd., New York, 2003, pp. 83–88;
http://www.fueleconomy.gov/feg/tech_engine_more.shtml.
[24] D. Linden, Handbook of Batteries, 2nd ed., McGraw-Hill, Inc., New York, 1995.
[25] B. Borglum, E. Tang, M. Pastula, J. Kelsall, R. Petri, Development of solid oxide fuel cells at Versa Power Systems. Proceedings of the 2006 Fuel Cell Seminar, Hawaii, US, 2006, pp. 135–138.