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Concept and system design for a ZEBRA battery–intermediate temperature solid oxide fuel cell hybrid vehicle

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Abstract

This paper explores the combination of a sodium–nickel chloride (ZEBRA) battery and an intermediate temperature solid oxide fuel cell (IT-SOFC) to form a hybrid power system that is intended for automotive applications. A range of vehicle types, drive cycles and fuels are investigated and compared in terms of their suitability for the pairing of this particular fuel cell and battery technology. In order to avoid the problem of stop–start cycles and load transients on the SOFC, a nominally 'always-on' strategy is investigated for the fuel cell. Sizing of the system is performed for each vehicle/drive cycle by adopting the minimum fuel cell power and battery energy in order to preserve charge neutrality over a 24 h period, while accommodating the requisite vehicle performance characteristics. Weight and volume estimates are reported for the hybrid system and opportunities for efficiency improvement brought about by synergistic operation of the fuel cell and the battery are discussed.

Keywords: Intermediate temperature solid oxide fuel cell; ZEBRA battery; Hybrid vehicle

1. Introduction

The need to reduce emissions through the improvement of vehicle efficiency has motivated automobile manufacturers to investigate alternatives to the internal combustion engine (ICE). Of the technologies investigated, one of the most promising candidates is that of electrical propulsion from electrochemical power systems driving electrical motors. Whether a pure electric, hybrid electric or a fuel cell vehicle, the use of electric drive trains, or electrically assisted traction, presents many attractive benefits for advanced transit systems.

The work presented in this paper is part of project ABSOLUTE (advanced battery solid oxide fuel cell linked unit to maximise efficiency), which is a program of work that aims to combine a ZEBRA battery and an intermediate temperature solid oxide fuel cell (IT-SOFC) to form an all-electric hybrid package that surpasses the efficiency and performance of a purely fuel cell-driven vehicle, as well as extending the range of a purely battery-driven electric vehicle. The use of SOFC technology is employed to gain broader fuel flexibility with simplified fuel processing requirements compared with polymer electrolyte fuel cells (PEFCs); while the high-temperature nature of both the fuel cell and battery offer opportunities for thermal integration of the balance-of-plant (BoP).

The ABSOLUTE project aims to deliver a fully functional, bench-top demonstration system that will allow electrical integration and control strategies to be exercised. This system will be scaled to a ratio of working system/demonstration system of approximately 10:1. Such a system size allows fuel cell control and operation methodologies to be developed at a scale that exposes the generic operational aspects of a

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technologically relevant system, while being convenient for operation in a research laboratory.

The study presented here introduces the methodology of sizing the battery and fuel cell system for a defined vehicle type and drive profile. In accord with the purpose of the vehicle, 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 so that the typical drive cycle is limited by the size of the fuel tank rather than by the size of the battery.

The nature of the ABSOLUTE hybrid can be described as 'battery dominant', since the battery will supply the intermediate energy and immediate power requirement of the vehicle. This hybrid power supply 'balance' is chosen since it is intended that the size of the fuel cell should be minimised to reduce cost and compliment the stage of development of the IT-SOFC technology. By comparison, hybrids such as the Toyota Prius can be described as 'engine dominant' since, in this case, a small battery with high power density is used.

1.1. Electric vehicles

Electric vehicles (EVs) use a range of power sources to drive an electric motor to achieve traction. The source of the electric power is usually electrochemical in the form of batteries or fuel cells, but devices such as ultracapacitors can also be used in hybrids. The main advantages of electric vehicles over ICEs is that they produce no local emissions, they are quiet, have high efficiency energy sources and power trains and, if properly maintained, have the potential to be more reliable due to the relative lack of moving parts. Another important advantage of electrochemical power sources is their ability to recuperate the energy normally dissipated as heat when braking. This 'regenerative braking' allows the electric motor, when run in reverse as a dynamo, to feed electrical energy back into a battery [1].

At the start of the 20th century, there was a prevalence of battery-powered over piston-driven vehicles. Disproportionate improvements in ICE technology and the constraint on range limited by the low specific density of batteries resulted, however, in combustion engines becoming the preferred technology for vehicles. More recently, improvements in battery technology that have conferred lower costs and higher specific power and specific energy have shown that battery power can be competitive and economical for certain vehicle applications [2].

1.2. Hybrid vehicles

A hybrid is a vehicle that operates on more than one power source. Electric/ICE hybrid vehicles combine the advantage of electric traction (efficient part-load performance, fast acceleration, regenerative braking) with the high-quality performance of the ICE at its design point [3]. Various architectures exist for hybrid vehicles, designated according to the extent of hybridisation (i.e., the ratio of power supplied by each source) and the connectivity between the power sources and drive train (i.e., series and parallel hybrids) [4].

All-electric hybrids also exist; the grouping of a battery and a fuel cell is a particularly attractive combination. A 'battery dominant' fuel cell/battery hybrid minimises the overall system size since the fuel cell does not have to be so large as to handle the transient high power requirement of a vehicle. In addition, unlike a pure fuel cell vehicle, regenerative braking can be accessed by virtue of the battery.

1.3. Batteries in automotive applications

The battery technologies that are the main contenders for automotive traction applications are listed in Table 1, together with representative performance values for each technology. It can be seen that the ZEBRA battery compares very well with its competitors, particularly in the area of specific energy.

1.3.1. ZEBRA battery

The sodium–nickel chloride (ZEBRA) battery is a technology that is well developed and has been evaluated extensively as the primary power source in many electric vehicle demon-

Table 1
Comparison of different battery technologies

	VRLA	Nickel cadmium	Nickel metal hydride	Lithium ion	ZEBRA
Specific energy[a] ($Wh\,kg^{-1}$)	34	45	65	110	120
Specific power[b] ($W\,kg^{-1}$)	75	120	90	220	180
Self discharge per month (%)	8	20	30	10	None
Nameplate cycle life	500	1000	500	400	2000
Efficiency[c] (%)	70	80	80	85	90
Cost[d] (£ $kW\,h^{-1}$)	105–175	200–300	250–350	250–1000	70–270
Cost affected by					
Overcharge capacity	Yes	Yes	Yes	Yes	No
Deep cycling	Yes	Yes	Yes	Yes	No
Maintenance	Yes	Yes	Yes	Yes	No
Ambient temperature	Yes	Yes	Yes	Yes	No

Values are intended to be representative for the technology; specific values may vary between manufacturers [5–7].
[a] Averaged figures from available data at 1–5 h discharge rates.
[b] 30 s pulse.
[c] Including self-discharge and healing.
[d] Factory.

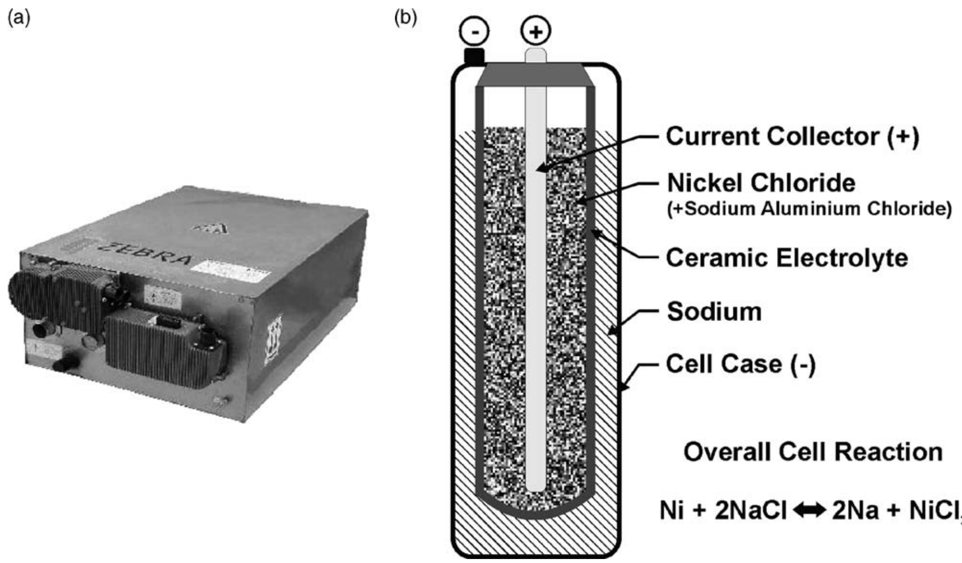

Fig. 1. ZEBRA battery (a) and ZEBRA cell (b).

stration programmes [8]. A ZEBRA single cell and battery are shown in Fig. 1 along with the overall cell reaction. The negative electrode compartment contains molten sodium (when charged) and the positive electrode is nickel/nickel chloride. A strip of copper-cored nickel wire serves as the current-collector at the cathode and the cell case is the current-collector for the anode. Sodium aluminium chloride is added to the nickel chloride, which, when molten, acts as a secondary electrolyte to facilitate contact between the solid nickel chloride and the β-alumina electrolyte.

The charged state lies to the right-hand side of the cell reaction (Fig. 1), and discharge results in the formation of nickel and sodium chloride. Ionic conduction occurs via Na^+ ions through a β''-Al_2O_3 (β-alumina) electrolyte. The β-alumina is a fully dense, non-porous solid with a low Na^+ resistivity at elevated temperatures (5.5 Ω cm at 350 °C) and a high electronic resistivity ($\sim10^{12}$ Ω cm).

The electrochemistry of the cell reaction and electrolyte material affords the following advantages with this battery technology:

- no self-discharge (a problem for lead–acid and nickel–metal-hydride)
- no gassing (lead–acid and nickel–cadmium require venting)
- 100% coulombic efficiency (accurate measurement of capacity possible)
- capacity independent of rate of discharge
- high charge and discharge efficiency
- high open-circuit voltage (2.58 V at 300 °C)
- high specific energy ($\sim$120 Wh kg^{-1} for complete system); a ZEBRA battery is about 75% lighter than a lead–acid battery with equivalent energy storage
- long calendar life (demonstrated >14 years), with over 2000 nameplate cycles demonstrated
- an ongoing 7-year lifetime has been demonstrated in actual electric vehicles.

When manufactured, the cells are constructed in the discharged state. This means that no metallic sodium is present in the system during assembly. The operating temperature range for the cells is 275–350 °C, but efficient use of thermal insulation means that the outer surface is no more than 5 °C above ambient temperature. The natural cooling rate is of the order of 3 °C h^{-1} with typically only $\sim$90 W of total heat loss when operational for a battery containing over two hundred cells. Although high-temperature operation of the ZEBRA battery means that there is a long start-up (warm-up) time following periods of dormancy, high-temperature operation has the advantage of requiring only facile (air) cooling when operational and the performance of the battery is not affected by the ambient temperature.

Several noteworthy advancements in ZEBRA cell technology have contributed to the impressive performance that this class of battery possesses [8]. A move from a circular to 'clover-leaf' cross-section of the ceramic electrolyte has led to improved power density due to an increase in the electrolyte surface area and reduction in the thickness of the positive electrode, all without increasing the size of the cell. In addition, doping of the positive electrode with iron has afforded significant improvements in the peak power and transient performance of the batteries [9].

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 has 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.

1.4. Fuel cells for automotive applications

The development of fuel cells for automotive applications is being aggressively pursued by the majority of the leading motor vehicle manufacturers. The motivation for this comes from several sources including reducing emissions of carbon dioxide, environmental policy, energy security, and the rising cost of oil.

The polymer electrolyte fuel cell (PEFC) is being explored almost exclusively as the prime mover for fuel cell vehicles; this is largely due to the PEFC's high specific power and the low operating temperature (typically 80 °C) that facilitates rapid start-up times. One of the disadvantages of PEFCs is that the low-temperature operation means that they are intolerant to carbon monoxide, which is produced during the reforming of hydrocarbon fuels. This is a key motivation for trying to raise the operating temperature of PEFCs. By contrast, SOFCs can readily operate on a range of fuels, which include those rich in carbon monoxide.

1.4.1. Solid oxide fuel cells for automotive applications

Examples of the use of SOFCs as the primary traction power source in automotive applications are far less common. For on-board auxiliary power units (APUs), however, Delphi have demonstrated SOFC prototype systems of up to 5 kW_e running on externally-reformed gasoline [10,11]. More recently, SOFCs have started to attract interest as potential power sources for automotive traction. The main benefits and challenges of using SOFCs for automotive applications have been listed by Brandon [12].

The benefits of using an SOFC for automotive applications include the following:

- SOFCs have greater fuel flexibility than low-temperature fuel cells. The high-temperature operation of SOFCs means that carbon monoxide produced in the reforming process of hydrocarbon fuels does not act as a catalyst poison and can itself be used as a fuel source. This advantage means that the fuel-processing plant can be considerably simplified and logistical fuels such as gasoline and diesel become a realistic and cost-effective proposition. Hydrogen can, of course, still be used as a fuel.
- The high-grade heat produced by SOFCs can be used to service the endothermic steam-reforming process.
- Excess heat can also be used to supply cabin heating, and so alleviate a significant portion of the hotel load.
- The cost of materials for SOFCs are potentially lower than that for PEFCs.

The challenges of using an SOFC for automotive applications include:

- SOFC stacks typically have lower specific power than PEFC stacks
- high-temperature SOFCs have poor thermal shock properties and the anodes do not appreciate redox cycling; SOFCs are therefore not suited to repetitive start-up/shutdown cycles.
- long start-up times compared with PEFCs (high-temperature SOFCs typically have a start-up time of several hours)

Many of the disadvantages of using SOFCs in vehicles can be avoided by designing carefully the way in which the vehicle is operated (i.e., by avoiding excessive start-up/shutdown cycles), by hybridisation with another power source (i.e., by using a battery to accommodate the maximum and dynamic loads), or by lowering the operating temperature of the SOFC (so alleviating the thermal cycling issues and also lowering the cost of components).

1.4.2. Intermediate temperature solid oxide fuel cell

Conventional high-temperature SOFCs, typified by developers such as Siemens Westinghouse [13] and Rolls Royce [14], operate in the temperature region of 800–1000 °C. For such systems, high efficiencies can be achieved from integration with gas turbines for large-scale stationary applications. High-temperature operation means that the components of the stack need to be all-ceramic and have special glass seals that are not conducive to rapid thermal changes. For smaller scale applications, there is a trend to move to lower temperatures of operation, into the so-called intermediate temperature (IT) range of 500–800 °C.

By lowering the temperature of operation, a wider choice of materials can be used that allow cost-effective fabrication, particularly in relation to interconnects and balance-of-plant components. Lower temperature operation also affords more rapid start-up and shut-down, reduces the corrosion rate of components, and has the advantage of greatly simplifying the system requirements.

There are two main routes by which SOFCs can be operated at lower temperatures while still attaining comparable performance to the higher temperature technology. The dimensional thickness of the electrolyte can be reduced, so reducing the area specific resistance of the fuel cell and/or materials development can bring about the same result by improving the ionic conductivity of the electrolyte at lower temperatures as well as the performance of the anode and the cathode. For example, the approach pioneered at Imperial College, and now developed by Ceres Power Ltd., uses a ceria gadolinia oxide (CGO) electrolyte of a thickness in the 10–30 μm range with the anode–electrolyte–cathode structure fabricated on a metallic support, to achieve a performance at 500–600 °C that is equivalent to a high-temperature SOFC [15–17]. The higher operating temperature of Versa Power System's IT-SOFC technology (700–800 °C) facilitates the use of integrated thermal reforming. Illustrative performance values of >300 mW cm^{-2} (0.76 V, 725 °C) on 35% internally-reformed natural gas, put this technology at the threshold of the US DoE 2012 goal for SOFC commercial power generation [18].

Although not yet at the stage of full commercialisation, IT-SOFC technology holds tremendous promise for small-scale combined heat and power (CHP) applications, and is considered to be the best option for introducing SOFC technology into the automotive sector.

2. ABSOLUTE vehicle concept

The ABSOLUTE vehicle concept brings together a ZEBRA battery operating at about 300 °C and IT-SOFC technology working in the temperature range of 500–800 °C. The sizing of each system is designed so that (i) the hybrid can supply the power required for satisfactory performance over the required drive cycle, and (ii) the vehicles operate in a regime that is 'charge neutral' or 'fuel limiting', such that the range is not limited by the energy of the battery but by the fuel tank capacity and the ability to refuel.

The melding of these two technologies was inspired by the high-temperature operation of both the battery and fuel cell, as well as the fuel flexibility that high-temperature fuel cells possess. The mutual high-temperature operation of the battery and fuel cell is envisaged to have beneficial effects on the efficiency of a hybrid due to the integration of the balance-of-plant components and thermal synergy. In addition, the high specific energy of the ZEBRA battery allows significant energy buffering to take place, i.e., 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 relatively immature compared with that of the battery, minimising the size of the IT-SOFC makes the system less expensive and more technologically feasible. It is the particularly high specific energy of the ZEBRA battery that affords this advantage.

The ability to use logistic fuels in an SOFC-based system defines the intention of the ABSOLUTE hybrid to provide an option for bridging the transition from hydrocarbon-fuelled vehicles towards a fuelling infrastructure that is largely based on hydrogen.

A diagram representing the ABSOLUTE hybrid concept, is given in Fig. 2. This includes connections for mechanical, chemical, electrical and thermal energy transfer, as well as the data communications and control interface.

The system follows a series hybrid architecture that is commonly employed for all-electric hybrids [4]. Mechanical coupling between the wheels, transmission and motor can occur in both directions to allow 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 (FCM) controls the operation of the fuel cell and balance-of-plant, while 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 [19].

Connection for receiving and delivering external ac power is also included to provide options for mains battery charging and for using the system as a generator for utility and recreational purposes.

The following summarises the potential advantages and features of the ABSOLUTE hybrid system compared with the ICE and other battery/fuel cell technologies:

- all-electric hybrid
  - quiet operation
  - efficient drive train and power source
  - fast acceleration at low speeds
  - regenerative braking
  - electronic control of all aspects of vehicle
  - conducive to the trend for increasing electrification of vehicles
  - lower overall carbon dioxide emissions than ICEs.
- ZEBRA battery
  - rapid dynamic response
  - regenerative braking
  - proven technology in vehicles
  - no emissions
  - high charge/discharge efficiency
  - uncomplicated cooling requirement
  - four times the range of lead–acid batteries of equivalent weight.
- IT-SOFC
  - fuel cell supplies power at a constant rate to the battery to make system charge neutral; the fuel cell is rarely exposed to stop–start cycles or transient loads
  - high efficiency
  - low emissions

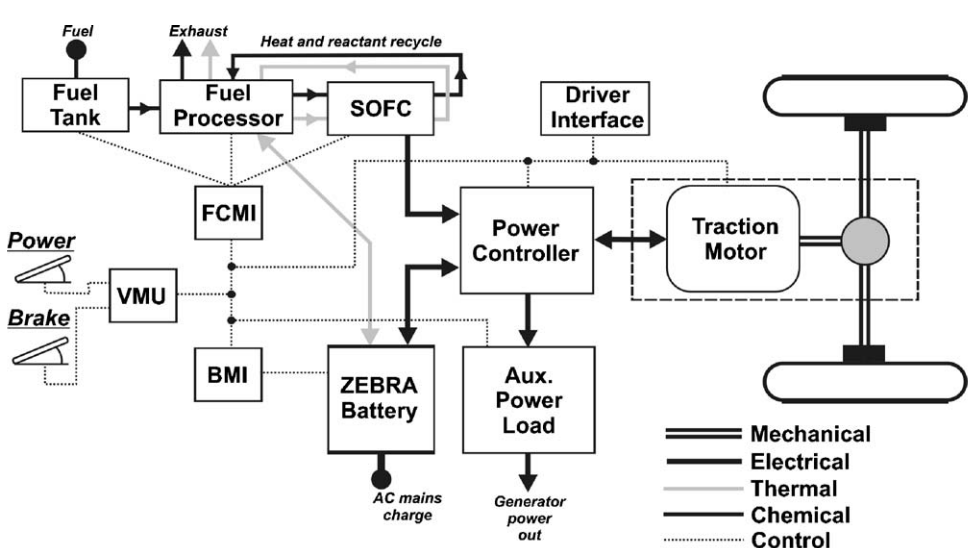

Fig. 2. Illustration of conceptual system architecture of ABSOLUTE hybrid.

- ◦ tolerance to a wide range of fuel types with a vastly simplified fuel processing requirement compared with PEFC technology
- ◦ thermal synergy between fuel cell and battery.

2.1. ABSOLUTE hybrid design methodology

A design methodology is applied that aims to determine the mode of operation, vehicle type and application that best suits the particular combination of fuel cell and battery type chosen for the ABSOLUTE hybrid. An overview of the design process employed in this investigation is presented in Fig. 3. The vehicle and fuel type are first decided; the vehicle's dynamics of linear motion and the choice of drive cycle determine the power cycle. The modelled power cycle, or data from actual vehicle testing, can then be used along with the average daily driving time estimation to define the optimised fuel cell power and battery energy required for charge neutrality over a specific time. The fuel cell specification for a given fuel, and the battery specification for a given maximum power requirement, can then be established and the range, operating time, system weight and volume can be estimated. Once these parameters are determined, a comparison can be made with the original vehicle specification and proposed operational concept to determine whether the battery/fuel cell combination is suitable. Additional steps in the design process can be performed that aim to maximise the efficiency of the system by exploring integration of the two systems and exploiting synergistic aspects of the fuel cell and battery operation.

Certain assumptions about the nature of the hybrid are first made and then challenged in light of the following analysis. The assumptions are as follows:

- The fuel cell is to behave exclusively as a range extender.
- The battery is to provide the maximum power for traction and accommodate all load transients. It also acts as an 'intermediate' energy buffer. This allows the fuel cell and dc–dc converter size to be minimised.
- Battery recharge from the mains is not considered as an option at this point. The system can, of course, accept mains charge if required. In practice, battery recharge will present a better option in certain circumstances e.g., if mains grid recharge is available, then the cost of electricity is lower than that derived on-board from fuel. From a safety perspective, the always-on operation of the fuel cell will not be permissible in certain parking locations.
- The fuel cell is to operate in a predominantly 'always-on' mode (so avoiding excessive redox and thermal cycling during stop–start operations) so as to reduce exposure to load transients while driving.
- The hybrid system should be charge neutral over a 24 h period, i.e., the state-of-charge should be the same at the beginning and end of the 24 h period–nominally fully charged. The bat-

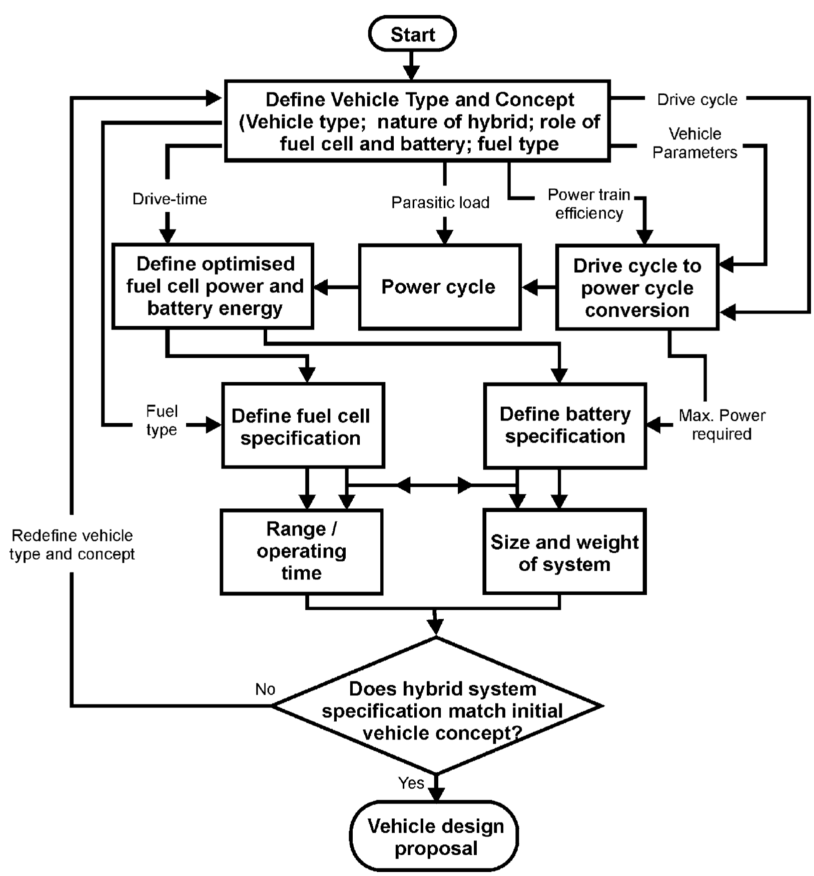

Fig. 3. Flow diagram of design process for sizing fuel cell and battery.

tery provides the power response and acts as an energy buffer, while the fuel tank provides the energy source via the fuel cell.

The design and evaluation process must identify the most suitable vehicle type, drive cycle (application) and fuel for the hybrid vehicle. These options are outlined in the following sections. The criteria for suitability are fuel consumption, vehicle performance and the size and weight compatibility with the vehicle. Cost is not considered in this analysis.

2.2. Fuel type

A vehicle fitted with an SOFC could conceivably have a multi-fuel capability, operating on, for example, hydrogen, butane, LPG (propane), alcohols (methanol, ethanol), natural gas, coal gas, kerosene, diesel or gasoline. In this investigation, consideration is limited to three specific fuels, namely, hydrogen, compressed natural gas (CNG), and liquefied petroleum gas (LPG). The factors that govern the suitability of a fuel include:

- refuelling infrastructure
- local emissions
- efficiency
- on-board processing requirement
- fuel tank size and capacity.

2.2.1. Hydrogen

Pure hydrogen is unquestionably the best fuel for fuel cells. When using pure hydrogen, there is no carbon monoxide present that can poison the catalyst (a problem for the PEFC) and coking-up of the catalyst structure is not an issue as it is for high-temperature fuel cells when operating on hydrocarbon fuel.

The source of the hydrogen must, however, be considered. There is no natural source of hydrogen and presently the most cost-effective means of producing hydrogen is via the steam reforming of hydrocarbons. Combined with the lack of refuelling infrastructure and the problems of on-board storage of hydrogen in sufficient quantities, the future of hydrogen as an automotive fuel is still questionable.

Hydrogen can, of course, be generated on-board from other fuels that are more readily available and possess more developed refuelling infrastructures. Good candidates as fuels for in situ hydrogen generation include compressed natural gas and liquefied natural gas.

2.2.2. Compressed natural gas

The use of SOFC technology affords a much greater fuel flexibility than PEFC technology when balanced against the fuel processing necessary to operate the latter with logistical fuels. Compressed natural gas (CNG), which is composed predominantly of methane, is a fuel that is becoming increasingly popular for ICEs. This is due to the much reduced air polluting emissions and the relaxation of reliance on oil imports that it affords. Since the extensive pipeline infrastructure of natural gas is not matched by the refuelling infrastructure, natural gas vehicles are most commonly applied to fleet vehicles. Taking transit buses as an example, in the USA alone, around 6200 transit buses (11% of total) are run on CNG [20]. In Directive KOM(2001)-547, the EU commission proposed to replace 10% of total automotive fuel consumption with natural gas. This corresponds to over 25 million natural gas vehicles in Europe alone [21]. Such measures are predicted to expand significantly the refuelling infrastructure for CNG.

Another reason for considering CNG is that it is the preferred fuel for the manufacture of hydrogen by reforming. This is because it is easier to process than ‘heavier’ hydrocarbon fuels such as gasoline and diesel and the methane molecule has a high hydrogen-to-carbon ratio. In addition, existing SOFC systems for stationary applications are almost exclusively being optimised to run on methane.

2.2.3. LPG

Liquefied petroleum gas (LPG, Autogas) is predominantly a mixture of propane and butane (minimum of 95% propane) that is stored under pressure in the liquid state. As with CNG, LPG is used extensively as a direct fuel in ICEs. World-wide, there are over 7 million vehicles on the road and the refuelling infrastructure is better established than CNG. Since it is stored in the liquid state, LPG has a higher energy density than CNG and will therefore afford a greater range on a tank-by-tank basis. Since it is composed of ‘heavier’ hydrocarbons (longer alkyl chain lengths) it does, however, have a lower hydrogen-to-carbon ratio than methane and is more difficult to reform into hydrogen.

2.3. Vehicle types

Three vehicle types are considered in this study as candidates for use with the ABSOLUTE hybrid power system, namely: (i) a small city car; (ii) a light duty delivery van; (iii) a taxi (‘black cab’). The parameters chosen to describe these vehicles are given in Table 2. Each type of vehicle is envisaged to operate predominantly in a city, or busy town, where low speeds and

Table 2
Candidate vehicle parameters

Vehicle and drive train parameters	City car	Light delivery van	Taxi
Vehicle weight (kg)	800	950	1834
Driver weight (kg)	80	80	80
Max vehicle weight (kg)	1180	1550	2520
Vehicle weight for model simulation, M (kg)	960	1230	2100
Drag coefficient, C_d	0.32	0.4	0.35
Rolling resistance coefficient, f_r	0.015	0.015	0.031
Equivalent frontal area, A (m^2)	1.8	2	2.25
Acceleration due to gravity, g (m^{-2})	9.8	9.8	9.8
Air density, ρ (kg^{-3})	1.25	1.25	1.25
Vehicle auxiliary load[a] (kW_e)	0.8	0.8	0.8
Proportion of regenerative braking captured, α_{regen}	0.4	0.4	0.4
Motor efficiency[b], η_m	0.93	0.93	0.93
Transmission efficiency, η_t	0.95	0.95	0.95
Power converter efficiency, η_c	0.98	0.98	0.98

[a] No air-conditioning considered.
[b] Brushless DC.

frequent stop–start cycles are encountered, i.e., a mixture of urban and suburban driving but no extended highway driving.

2.4. Vehicle auxiliary load

The electrical load imposed by the auxiliary components is a significant drain on the power supply of the vehicle. There is a trend in vehicle design for the auxiliary load to increase; this is largely due to the increasing use of electronic 'comfort' devices (e.g., air-conditioning, electric windows, audiovisual equipment, communications, satellite navigation, seat heaters) as well as to the increased use of vehicle drive and control devices (e.g., power steering, electric fuel injection pump, vehicle management system, drive-by-wire). The proposed switch from 12 to 42 V battery power is evidence of this trend [22]. Indeed, the increase in auxiliary load is a motivator for the introduction of on-board fuel cell systems as dedicated APUs, particularly for servicing the hotel load of heavy goods vehicles [23].

The auxiliary power load cycle is difficult to predict because some loads are continuous (e.g., fuel pump), others are intermittent (e.g., indicating lights), and yet others are highly dependant on external factors such as the time of day (e.g., use of lights), weather conditions (e.g., windscreen wipers, fog lights) or time of year (e.g., cabin heater and air-conditioning).

The Bosch Automotive Handbook [24] provides examples of typical vehicle electric auxiliary loads, the sum of which is given as a maximum of 1145 W and an average of 600 W. These values include the cabin heater and fuel pump (both unnecessary for an SOFC system from which heat is a usable by-product, and a fuel pump is not required for compressed gas), but not the VMU, BMI or FCMI hardware. The starter motor load (up to 7 kW) and air-conditioning unit (several kW) are also omitted; although a hybrid system does not require a starter motor, air-conditioning would be a significant load which, if considered, could change the nature and energy balance of the system.

In this study, a constant 800 W electrical load is taken to represent the vehicle's auxiliary component power consumption. 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.

2.5. Drive cycle and power cycle

In order to evaluate the performance of the hybrid system under different modes of operation and to compare performance with different vehicle types, a standard basis of operation must be defined. In this study, two driving regimes are considered, one that represents purely urban driving and one that represents a cross between urban and suburban driving. For the urban cycle, the drive cycle ECE-15 is used, and for the urban/suburban drive cycle the new European driving cycle (NEDC) is used to simulate representative driving conditions. Both drive cycles are used extensively in the European Union for assessing vehicle emissions and are valid for vehicle types up to 3500 kg gross weight. The velocity against time profile for the NEDC is given in Fig. 4. The NEDC is composed of four ECE-15 drive cycle modules (representing urban driving conditions) followed by one suburban drive in which the velocity reaches a maximum of 120 km h^{-1}. The NEDC is completed in 1180 s, with a total distance of about 11 km and has an average speed in the urban and suburban sections of 18.7 and 62.6 km h^{-1}, respectively.

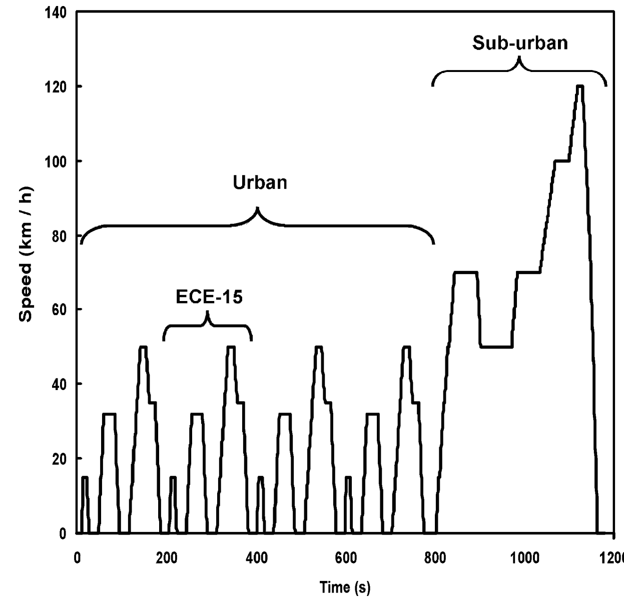

Fig. 4. Drive cycle for new European driving cycle (NEDC).

To determine the electrical load on the power source(s) brought about by driving the vehicle, power cycles must be constructed. The power cycle is calculated by consideration of the vehicle dynamics, determined by the parameters in Table 2, over the course of the drive cycle. The power at the wheels required to move a vehicle on a flat surface is given by [25]

$$P_{\text{wheels}} = \left(Mgf_{\text{r}}v + \frac{1}{2}\rho C_{\text{d}} A_{\text{f}} v^3 + Mv\frac{\text{d}v}{\text{d}t} \right)(-\alpha_{\text{regen}}) \tag{1}$$

where the first term in brackets represents the power required to overcome rolling resistance, the second term is the power to overcome aerodynamic drag, and the third term is the power to accelerate. The α_{regen} term is only active during braking and is the proportion of power captured during regenerative braking. This equation is used to convert the drive cycle into the power cycle for the vehicle.

Assuming that the battery supplies all of the traction power, the power that must be delivered by the battery (P_{batt}) is determined by the motor efficiency (η_{m}), the transmission efficiency (η_{t}) and, if required, the power converter (η_{c}):

$$P_{\text{batt}} = \frac{P_{\text{wheels}}}{\eta_{\text{m}}\eta_{\text{t}}\eta_{\text{c}}} \tag{2}$$

Examples of the power cycle and cumulative energy consumed by the delivery van and city car for a single ECE-15 and extended suburban drive cycle are shown in Fig. 5(a) and (b), respectively. As would be expected, a heavier vehicle with poorer aerodynamic properties requires more power and consequent energy consumption for a given distance travelled.

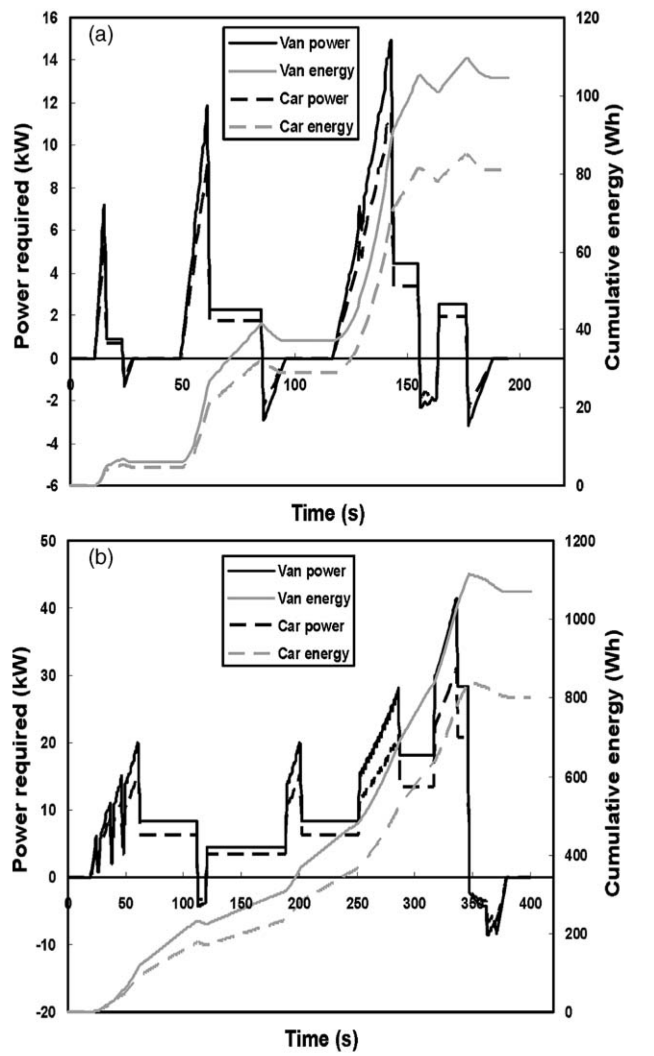

Fig. 5. Power cycle and cumulative energy consumption for city car and light delivery van over (a) ECE15 cycle and (b) extended suburban cycle.

2.6. Conditions for charge neutrality

The basic tenet of the ABSOLUTE hybrid is that the vehicle power system should be charge neutral over a period of at least 24 h and that a nominally ‘always-on’ strategy is adopted for the fuel cell in order to mitigate slow and energy intensive fuel cell start-up procedures that will shorten the lifetime of the fuel cell. Solid oxide fuel cells are particularly conducive to the ‘always-on’ strategy since the cells are predominantly designed for residential combined heat and power (CHP) applications that require the system to be operational and at temperature for the term of its service. Since the lifetime target for such stationary systems is of the order of 50,000 h, a useful life of at least 6 years is expected from such a fuel cell system operational in a vehicle. This section will look at a number of case studies, combining the three vehicle types and two different driving conditions (urban and urban/suburban).

With the fuel cell system operational and delivering power (P_{fc}) and a constant auxiliary load imposed (P_{aux}), the energy consumed from the battery (E_{batt}) is determined by

$$E_{batt} = \int_0^{t_{cycles}} P_{batt}\,dt + (P_{aux} - P_{fc})t_{cycle} \quad (3)$$

Two scenarios for battery and fuel cell sizing are presented. The first (not being considered for the ABSOLUTE hybrid but included for comparison) determines the fuel cell size required for charge neutrality over a single drive cycle. This is the worst case scenario and leads to the largest possible fuel cell size, since no consideration is given to recharge during non-drive time, such as when not operational overnight or during breaks in driving between drive cycles. For this situation, the battery type and energy is irrelevant since the battery is only required to match the power requirement and buffer the energy balance over the course of the power cycle.

The second scenario considers the fuel cell size required to have charge neutrality over a 24 h period based on varying hours of constant back-to-back driving followed by charging of the battery by the fuel cell during non-drive time. In this instance, the fuel cell must have a sufficiently high power output such that the battery is not fully depleted over the driving period and can recharge the battery over the remaining portion of the 24 h period, which is notionally assumed to be an overnight recharge.

2.6.1. Charge neutrality over single drive cycle

The power output requirement of the fuel cell system for charge neutrality over a single drive cycle, including the auxiliary load, is shown in Table 3.

These values, in effect, reflect the size of the fuel cell that would be necessary to operate the vehicle with the battery acting purely as a source of peak power and reservoir for the regenerative-braking energy, averaged over the drive cycle. In practice, a vehicle would not be driven continuously. For an ICE, which does not consume fuel when not operational, the back-to-back drive cycle calculation gives an accurate prediction of fuel consumption. By contrast, the ‘always-on’ concept being investigated for the ABSOLUTE hybrid means that the fuel cell is continuously consuming fuel, therefore a ‘whole-day’ holistic drive cycle must be considered in order to estimate fuel consumption and range.

Table 3
Energy consumed and fuel cell power requirement for charge neutrality over single drive cycle

	ECE15	NEDC
City car		
Energy consumed over single drive cycle (Wh)	124	1169
Fuel cell system power (kW_e)	2.29	3.57
Light duty van		
Energy consumed over single drive cycle (Wh)	148	1532
Fuel cell system power (kW_e)	2.73	4.67
Taxi		
Energy consumed over single drive cycle (Wh)	304	3213
Fuel cell system power (kW_e)	5.6	9.8

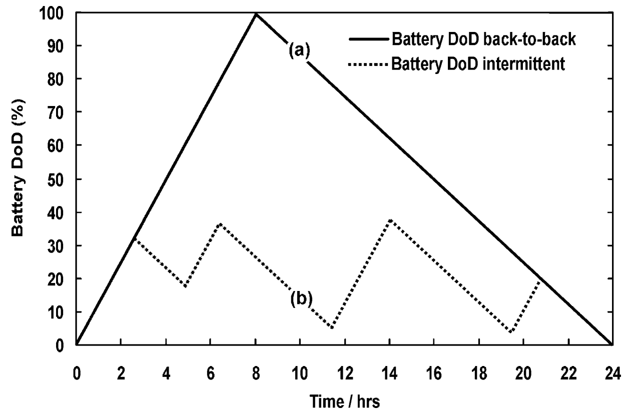

Fig. 6. Illustration of drive time/recharge-time profiles for 8 h of back-to-back drive cycles (profile a) and 8 h of intermittent driving time (profile b). DoD is the depth-of-discharge of the battery.

2.6.2. 'Whole-day' drive cycle

A 'whole-day' drive cycle is determined by the specific application of the vehicle (delivery, commute, taxi, etc.), i.e., 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. For example, if a 'whole day' drive cycle is taken to constitute an 8 h period of back-to-back drive cycles followed by 16 h of non-drive time in which the battery is recharged, then the optimum situation, for which the size of the fuel cell is minimised, involves close to complete discharge of the battery during the 8 h working period, followed by continuous charge of the battery overnight as shown in Fig. 6 profile (a).

A back-to-back series of drive cycles represents the worst case scenario for determining the energy of the battery. In practice, for the battery to be charge neutral over a 24 h period, it does not matter if the drive cycles are back-to-back in a single block of time, only the total time spent driving compared with the total time of recharging is of concern. Therefore, both profiles (a) and (b) in Fig. 6 amount to the same requirement of fuel cell power. The maximum battery energy is required, however, only when all driving is done in a single back-to-back block. It is under this condition that the high specific energy of the ZEBRA battery is conducive to buffering the energy demand of the system, and consequently minimises the size of the fuel cell.

In this simulation, a constant fuel cell power is delivered over the entire day. The effect of varying the fuel cell power over the drive cycle, performing start–stop operations and operating the fuel cell in stand-by mode on fuel consumption and system efficiency requires a reliable model of the fuel cell system. Such a model and analysis will be the subject of a future paper.

The values of the optimum fuel cell power and battery energy are determined by performing an energy balance over a 24 h period. Eq. (4) is the balance of energy consumed from the battery during drive time to that returned to the battery during non-drive time; this determines the fuel cell power requirement. Eq. (5) is the balance of energy consumed from the battery during drive time to the energy of the battery required to sustain the charge over the periods of drive time and determines the

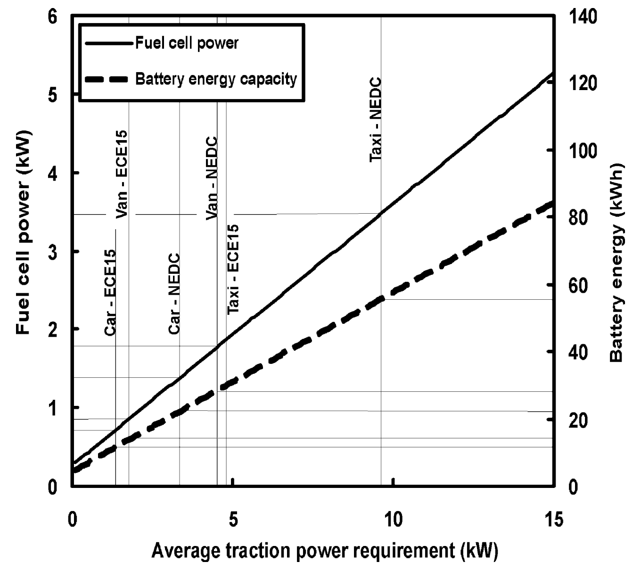

Fig. 7. Fuel cell power and battery for range of average traction power requirements for charge neutrality over a 24 h period with a drive time of 8 h.

battery's energy requirement

$$P_{\text{auxc}}t_{\text{drive}} + P_{\text{traction}}t_{\text{drive}} - P_{\text{fc}}t_{\text{drive}} = P_{\text{fc}}t_{\text{recharge}} \quad (4)$$

$$P_{\text{auxc}}t_{\text{drive}} + P_{\text{traction}}t_{\text{drive}} - P_{\text{fc}}t_{\text{drive}} = E_{\text{batt,cap}} \quad (5)$$

P_{aux}, P_{traction} and P_{fc} are the average auxiliary load, average traction power and fuel cell power, respectively; t_{drive} is the drive time; t_{recharge} the time spent recharging; $E_{\text{batt,cap}}$ is the energy of the battery.

The optimum fuel cell power and battery energy for a range of average traction power requirements is shown in Fig. 7, values are highlighted for each of the vehicle/drive cycle combinations. The data considers a fuel cell delivering constant power over the whole-day with an 8 h back-to-back series of drive cycles.

Taking a light delivery van operating over the NEDC drive cycle as an example, Fig. 8 gives the optimum fuel cell power and

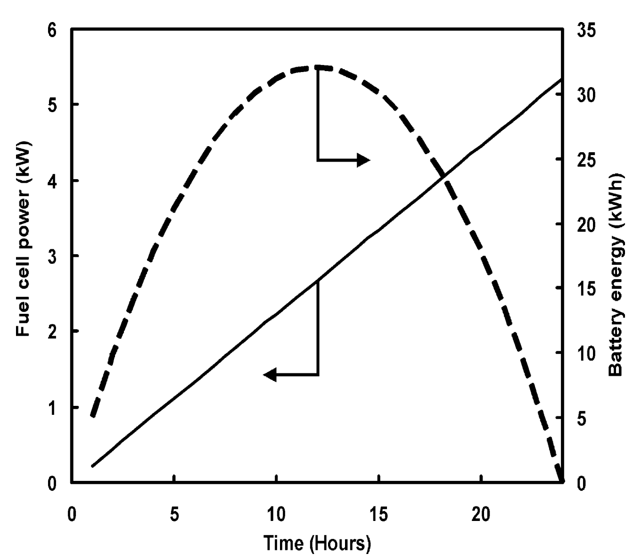

Fig. 8. Fuel cell power and battery energy required for light-delivery van operation on NEDC drive cycle for operation over a range of drive times.

battery energy required for operation from zero to 24 h of drive time. It can be seen that the fuel cell power increases monotonically with increasing operating time; the extreme case of constant use over a whole day corresponding to the situation for a purely fuel cell-powered car. It should be remembered that although an SOFC of this power could supply the gross energy requirement of the vehicle, it would not be able to accommodate the high power and dynamic response requirements.

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. For drive times greater than 12 h, the increased power of the fuel cell means that the energy of the battery does not need to be so large.

The generic set of data for the fuel cell power and battery energy requirement is shown in Fig. 9 for varying average traction power requirements and drive time. If the ratio of fuel cell power to battery energy is considered for each vehicle/drive cycle, it is found that each varies in the same fashion over the range of driving times, regardless of the vehicle/drive cycle combination. The variation of this ratio with drive time is given in Fig. 10. The ratio changes little over the period of total drive time expected for most vehicle applications (i.e., less than 12 h per day), but increases drastically beyond this into a region of operation where the fuel cell would become the primary energy and power source, i.e., it delivers the average traction power with the battery peak shaving the high power regions of acceleration and accepting the regenerative braking energy.

2.7. Fuel storage and range comparison

The nature of the fuel and its method of storage are critical in determining the range, weight and volume of the overall system. Storage of hydrogen is particularly difficult due to its relatively low energy density when in the gaseous state. Several hydrogen storage strategies exist and include: liquefied hydrogen stored in cryogenic vessels [26], metal hydrides [27] and carbon nanostructures [28]. On-board storage of compressed hydrogen gas (CHG) is by far the most developed technique and is therefore the method used most extensively in the existing hydrogen-powered fuel cell demonstration vehicle fleets. For this reason, CHG is considered as the hydrogen storage medium in this study.

The fuel economy of the three vehicles, operating on the various fuels and drive cycles is shown in Fig. 12. In order to compare the data, the gasoline volumetric equivalent is used to take account of the differing chemical energy of each fuel. The range that can be obtained from a single 50 l tank for each of the scenarios is shown in Fig. 13. To obtain these figures, the following assumptions were made:

- fuel cell operating at 0.65 V per plate
- fuel utilisation is equal to 70%
- natural gas and LPG are composed of 100% methane and propane, respectively

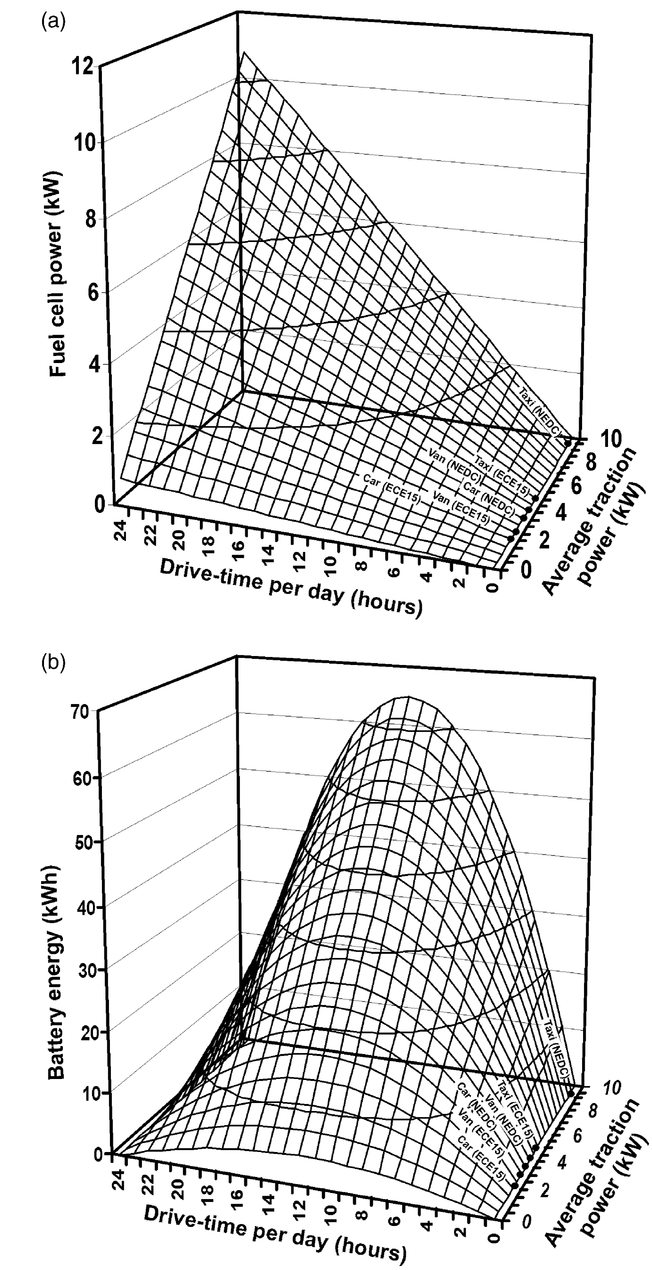

Fig. 9. (a) Fuel cell energy and (b) battery energy requirement for charge neutrality over 24 h period for varying drive time and average traction power.

- the LPG tank is filled to 80% of the 50 l tank capacity (to leave expansion space) and an LPG density of 0.509 kg l^{-1} is used
- fuel processing takes place via steam reforming which transforms all of the hydrocarbon fuel to H_2 and CO
- the parasitic load of the fuel cell system is composed of the air blower which consumes 10% of the power of the stack and a constant 100 W load due to control electronics
- the CNG and CHG are both pressurised to 250 bar.

On a weight basis, the amount of fuel required to satisfy a given stack power increases in the order CHG < CNG < LPG. Unlike in stationary applications, however, in which the fuel is supplied constantly from an external source, the storage method

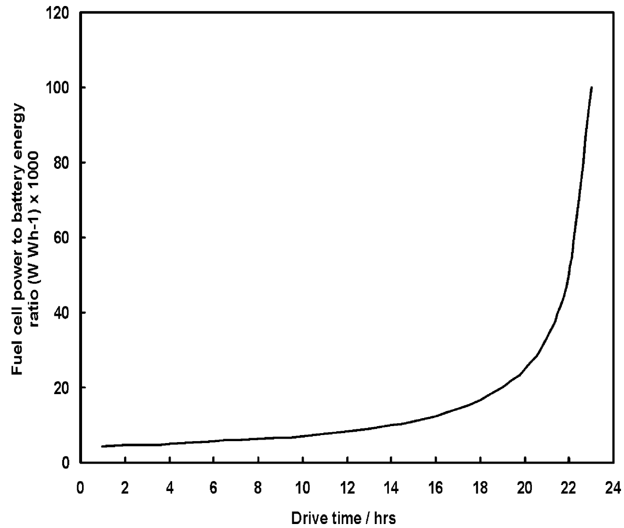

Fig. 10. Ratio of fuel cell power to battery energy with drive time. Profile is irrespective of vehicle or drive cycle type.

and the specific energy of the fuel that can be accommodated on-board a vehicle is the overriding consideration. Due to the difference in specific energy of the fuels and the 'extra' hydrogen produced in the steam reforming reaction that is 'won' from the water, it transpires that the operating time for a given tank size increases in the order CHG < CNG < LPG.

Considering the gasoline-equivalent fuel economy, CHG and LPG have a similar fuel consumption but that of CNG is significantly lower. On the gasoline-equivalent basis, LPG does not compare well compared with its range performance; this is because LPG does not contain as much chemical energy as gasoline or hydrogen on a gravimetric basis. Nevertheless, LPG has the advantage over CNG and CHG of being stored in the liquid state, which allows a far greater vehicle range to be achieved for a given tank size than either of the other fuels that are stored in the gaseous state.

For all of the scenarios shown in Figs. 11 and 12 there is an increase in range and fuel economy with increasing drive time per day. This is a consequence of the constant parasitic load on the fuel cell system (taken to be 100 W irrespective of stack size), which consumes a greater proportion of the gross power as the fuel cell size becomes smaller (i.e., total drive time becomes shorter). Therefore, for a smaller fuel cell, a greater proportion of the fuel is spent on the parasitic load than on charging the battery.

For gaseous fuel storage, both metallic and carbon composite gas cylinders are available [29]. A 50 l steel tank weighs about 70 kg and a composite tank about 25 kg at standard operating pressures of around 250 bar. With hydrogen as a fuel, it is clear that to ensure adequate operating time when adopting an 'always-on' strategy, either multiple fuel tanks are used or higher pressure operation is employed. Carbon composite tanks that can handle pressures up to 700 bar have been developed but come with cost and weight penalties [29].

Since CHG does not provide the range required for continuous fuel cell operation at the power requirements of the vehicles

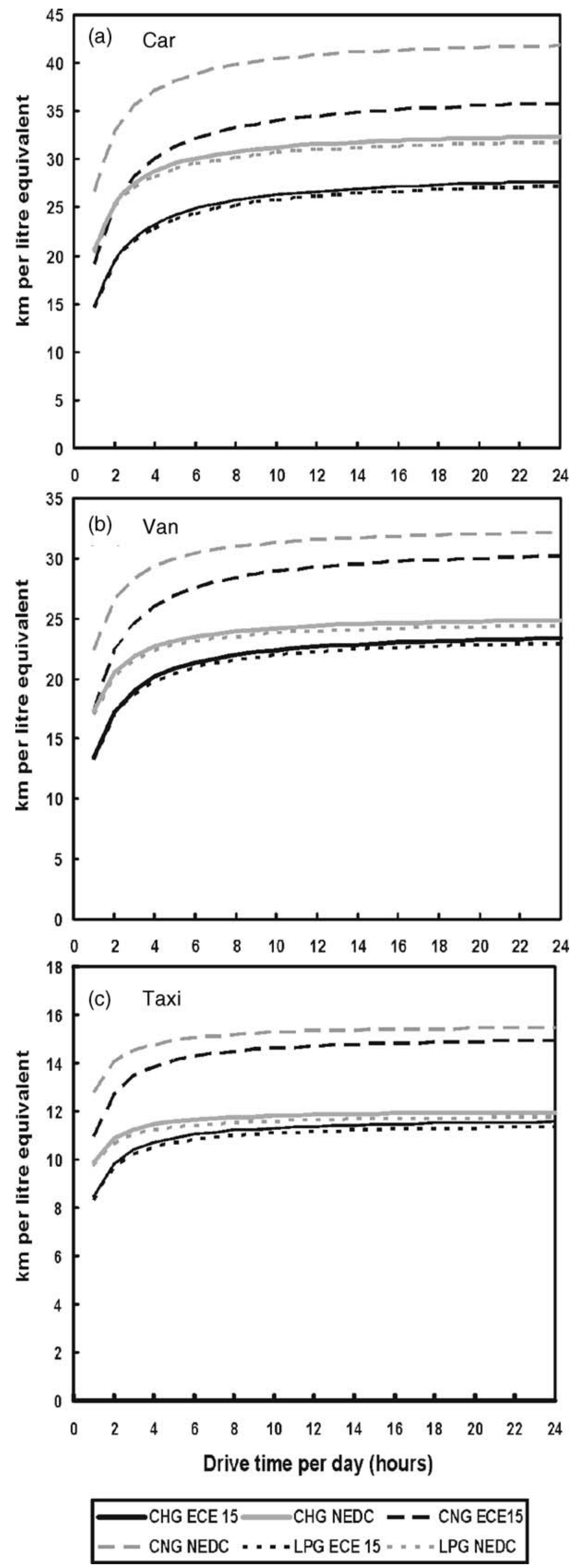

Fig. 11. Gasoline equivalent fuel economy of (a) car, (b) van and (c) taxi for operation on various fuel and drive cycles for IT-SOFC/ZEBRA hybrid.

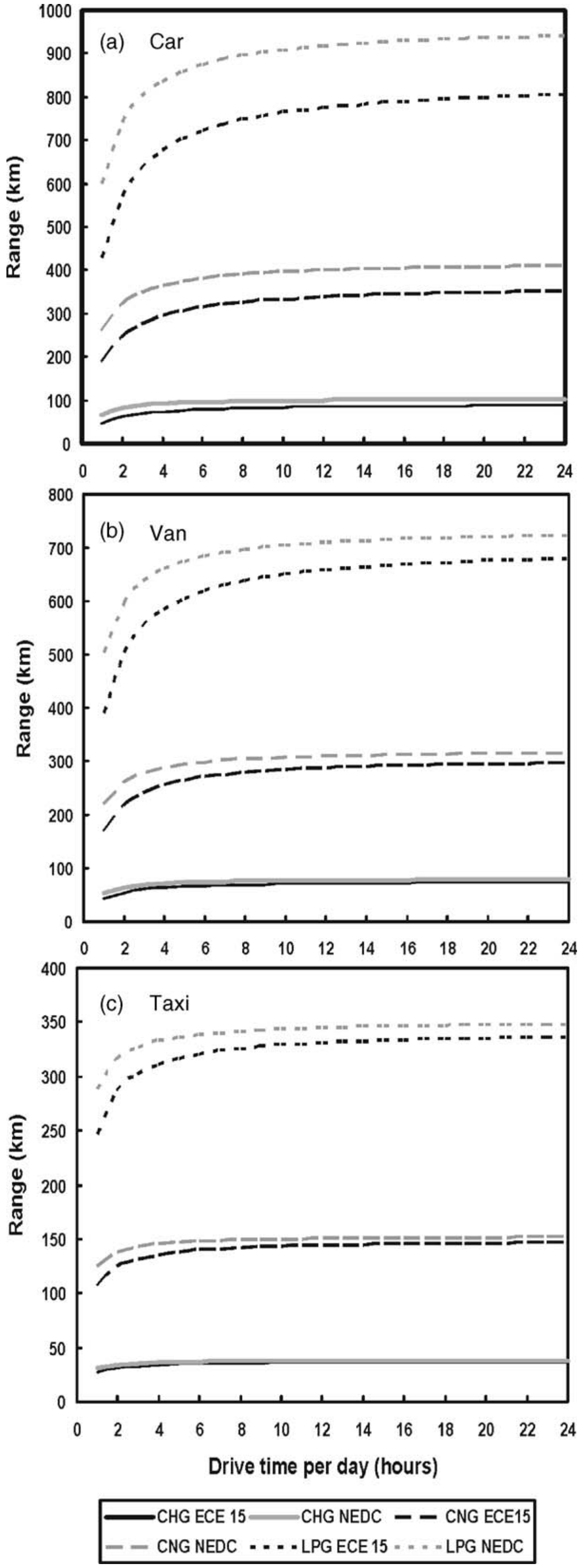

Fig. 12. Range based on tank size of 50 l for (a) car, (b) van and (c) taxi for operating on various fuels and drive cycles for a fuel for the IT-SOFC/ZEBRA hybrid.

investigated, and because it does not fit the profile of the ABSOLUTE hybrid as operating on a fuel with an existing refuelling infrastructure, hydrogen is dismissed as a suitable fuel for the ABSOLUTE hybrid system. The range afforded by LPG and the gasoline equivalent fuel consumption of CNG make both of these fuels promising candidates.

In addition, it should be remembered that for a hydrocarbon fuel, steam is required for the reforming reaction (assuming that steam reforming is the reforming method used). Eq. (6) shows the generic steam reforming reaction for straight-chain alkane hydrocarbons, Eq. (7) the subsequent shift reaction, and Eq. (8) is the effective overall reaction

$$C_nH_{2n+2} + nH_2O \rightarrow nCO + (2n+1)H_2 \quad (6)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (7)$$

$$C_nH_{2n+2} + 2nH_2O \rightarrow nCO_2 + (3n+1)H_2 \quad (8)$$

In practice, in order to avoid carbon formation within the reformer, sufficient steam is added to the fuel to exceed the stoichiometric ratio. Taking LPG as an example, and assuming a steam-to-carbon ratio of 2.5, then the difference in density between water and LPG in the condensed form, means that a water tank approximately 2.8 times larger than that of the LPG tank is required to service the steam reforming reaction. A water tank of this size would not be feasible for most practical vehicle types. It is therefore a requisite that condensation of product water from the fuel cell, or partial recycling of the off-gas from the fuel cell, is used in order to preserve the water balance of the fuel cell system. The feasibility of this last approach will be demonstrated in a future publication.

2.8. Sizing of hybrid system

2.8.1. Sizing of battery

So far, only the energy of the battery has been considered as a requirement to compliment the fuel cell for a given vehicle/drive cycle. No consideration has been given to the open-circuit voltage (OCV), peak power, size or weight of the battery.

The maximum power requirement at the wheels is primarily determined by the maximum acceleration rate required for the vehicle [30]. Eq. (9) gives an approximation of the power required to accelerate a vehicle from zero to v_f in time t_a. The first term represents the power required to accelerate the vehicle mass, the second term the power to overcome the tyre rolling resistance, and the third term accounts for the aerodynamic drag

$$P_{max} = \left(\frac{M}{2t_a}(v_f^2 + v_b^2)\right) + \frac{2}{3}Mgf_r v_f + \frac{1}{5}\rho C_d v_f^3 \quad (9)$$

Taking a motor base speed (v_b) of 30 km h^{-1} [30], and specifying a reasonable acceleration performance of 0–50 km h^{-1} in 6 s, and 0–100 km h^{-1} in 20 s for each vehicle, the maximum power at the battery required to accelerate the vehicle (including the inefficiencies shown in Table 2), are given in Table 4.

The power-to-energy ratio of the battery required to accommodate the peak power due to acceleration and the requi-

Table 4
Peak power requirements for three vehicle types based on maximum acceleration requirement

Vehicle	Peak battery power (kW) for acceleration	
	0–50 km h^{-1} (6 s)	0–100 km h^{-1} (20 s)
Car	26.2	29.9
Light duty van	33.6	38.7
Taxi	60.5	69.5

site energy with respect to the total drive time over a 24 h period for the various vehicle/drive cycle combinations are listed in Fig. 13. A symmetrical 'bathtub' profile is observed with higher values at short and long drive times. Apart from the extremes of drive time, the power-to-energy ratio averages around 2. The ratio for typical ZEBRA cells is of the order of 2, but can be tailored by varying the surface area-to-volume ratio.

In order to match the battery's OCV to the electric motor's rated voltage, maximum power and overall energy, the ZEBRA cells can be configured in a range of parallel and series combinations. For batteries of the size required for vehicular applications, the number of cells required is sufficient to accommodate the OCV required to drive brushless dc motors directly (typically >300 V).

The ZEBRA battery is commercially available in a number of different cell types and battery configurations, which cover a range of energy and power levels. Examples of air-cooled-battery types commercially available that fall within the automotive regime of operation are listed in Table 5. These batteries can also be considered as modules that can be combined to satisfy the vehicles power and energy storage requirements.

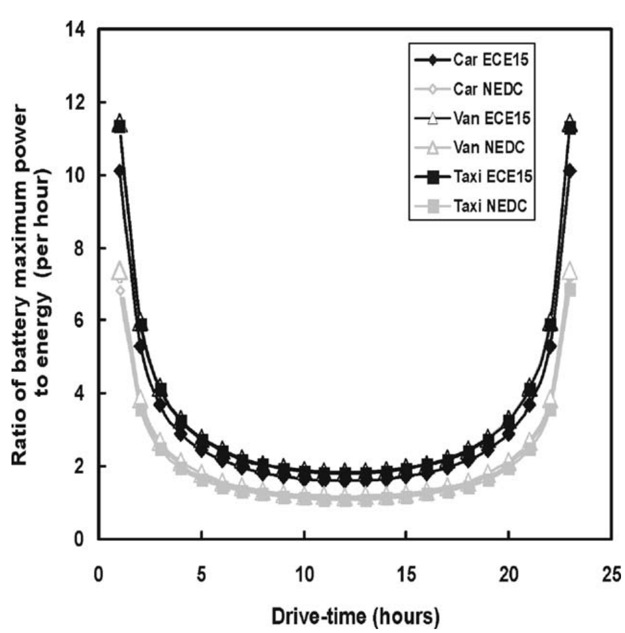

Fig. 13. Graph of ratio of maximum power to energy of battery with drive time for charge neutrality over 24 h period.

Table 5
Commercially available ZEBRA batteries applicable to traction power

Battery Type	Z5	Z21	Z23	Z33	Z35	Z44
Number of cells	216	240	180	144	108	220
Max power (kW)	32	26.4	26	20.1	15.1	21.7
Rated energy (kWh)	17.8	13.6	17.6	14.1	10.6	14.2
Capacity (Ah)	64	44	114	152	38	50
OCV(V)	278/557	310	155	93	278	284
Min operating voltage (V)	186	207	103	62	186	189
Max discharge current (A)	224	224	336	350	112	175
Weight (kg)[a]	184	136	155	125	96	123
Volume (l)	116	85	98	81	64	81
Thermal loss (W)	<110	<95	<95	<80	<70	<86

[a] For complete system including cooling and management system.

2.8.2. *Fuel cell stack sizing*

Once the optimum power requirement of the fuel cell system has been determined, it is necessary to establish the size of the fuel cell stack. Two main pieces of information are required to do this. First, it is necessary to specify the operating point (voltage and current density) of the stack and, secondly, the parasitic load incurred by the fuel cell system must be determined.

There are two ways in which a fuel cell can satisfy a specific electrical power requirement, namely, either the stack is operated at a relatively high power density (with associated decrease in efficiency) or it is operated at a relatively low power density and made larger (increased weight, size and cost). In this work, a rated operating voltage of about 0.65 V per cell is taken to represent a trade-off between cell power and efficiency; this is within the region for IT-SOFC technology [31].

The parasitic load of the fuel cell is predominantly composed of the power to drive the air blower and the power to drive the sensors, actuators, and control electronics. To perform the calculations in this work, an air blower power equal to 10% of the gross stack power is used with a constant 100 W load associated with the control system.

More informed prediction of the parasitic load and the size of the stack and BoP components can be obtained from fuel cell system modelling; this will be the subject of a future publication. Presently, estimation of the fuel cell system weight and size is achieved by considering the targets and demonstrated values of comparable technology.

Various fuel processing methods exist that convert hydrocarbons into hydrogen-rich mixtures suitable for the fuel cell [32]. Partial oxidation is a popular method since it allows relatively rapid start-up and can be performed dry. Nevertheless, steam reforming was chosen as the fuel processing method for the ABSOLUTE hybrid for the following reasons:

- steam reformer technology is well developed
- steam reformers can be used with a range of fuels
- no introduction of oxygen is required (as for partial oxidation)
- negligible soot and ethylene output (a problem for partial oxidation reforming)
- high hydrogen yield—the highest efficiency of all of the reforming technologies

Table 6
Target values for 5 kW_e SOFC systems for vehicular applications [11,33]

Property	Delphi	Webasto
Weight (kg)	50	50
Volume (l)	44	50
Electrical efficiency (%)	36/41 (1/3 and full load, respectively)	25 (maximum power)
Start-up time from ambient (min)	10	20 (1 min from warm)
Fuel	Gasoline (POx reforming)	Diesel/gasoline (POx reforming)
Load time (h)		6000
Hot time (h)		25000–40000
Stack power density ($kW_e\,l^{-1}$)	0.2 (demonstrated)	0.4

- in the case of the partial internal reforming option, the endothermic nature of the reaction has a cooling effect on the stack, and thus less air is required for this purpose.

Steam reforming does have the problem of long start-up time and poor transient response. If, however, an 'always-on'/constant load strategy is adopted for the IT-SOFC, the disadvantages of steam reforming are less of an issue.

2.8.3. Hybrid system size and weight estimation

Reports and targets have been set for SOFC systems for both vehicle range extenders and APUs [12]. The targets set for 5 kW_e systems that are being developed by Delphi and Webasto are summarized in Table 6.

Estimates of the weight and volume of complete SOFC systems are highly dependent on the effectiveness of the process integration or 'pinch' technology [34]. This is the way in which the system's BoP components can be integrated to minimise materials use and maximise the efficiency of heat-transfer processes. For example, physical integration of the afterburner and reformer is a common strategy. For the purpose of determining the suitability of the hybrid system for different vehicle types, weight and volume estimates can be calculated based on established values for the ZEBRA battery and realistic targets for the fuel cell system. 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 [35]. Somewhat more conservative targets, commensurate with the shorter term aims of Webasto and Delphi, of 100 $W\,kg^{-1}$ and 100 $W\,l^{-1}$ are selected for the ABSOLUTE IT-SOFC system. ZEBRA cell values of 145 $Wh\,kg^{-1}$ for specific energy and 330 $Wh\,l^{-1}$ for energy density are employed. Based on these values, Fig. 14 shows the weight and volume estimate for the combined fuel cell system and battery, excluding the weight of the fuel tank, based on the energy requirement of the battery. Note that at low drive times (about <2 h), the size of the fuel cell will be determined by the power requirement of the battery.

By comparison with the profiles in Fig. 9, it can be seen that the battery dominates the weight of the system and a large proportion of the volume. The maximum weight and size of

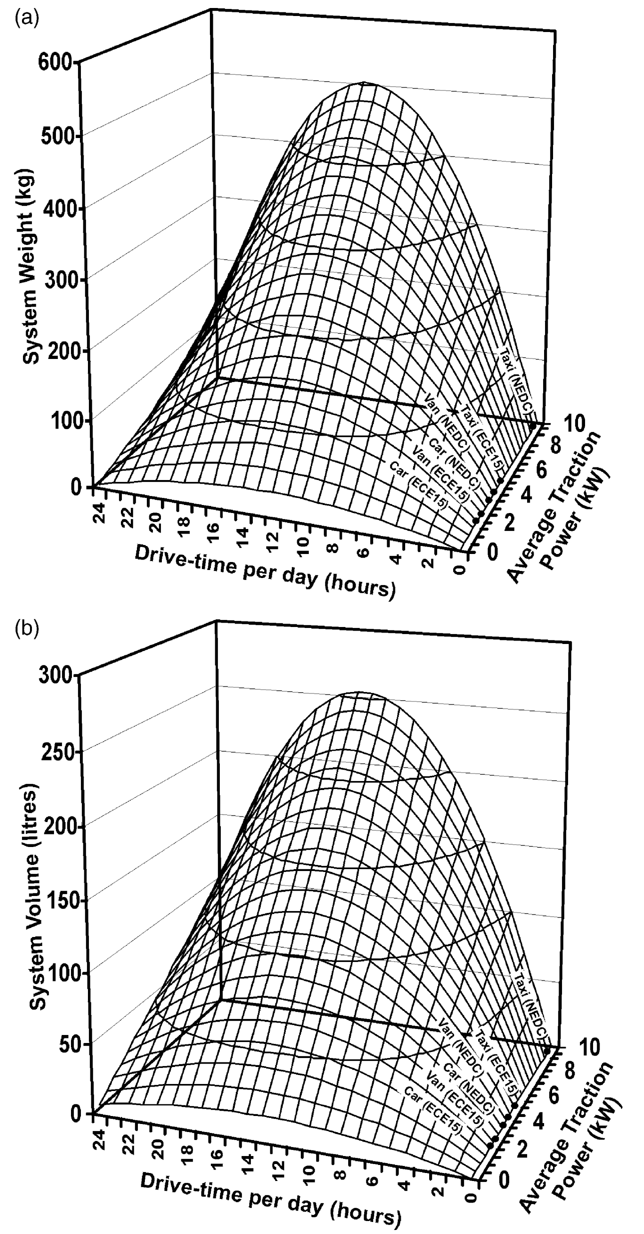

Fig. 14. (a) Hybrid system volume and (b) weight estimates for range of drive time and average traction power requirements.

the hybrid occurs close to the maximum specific energy of the battery (12 h of drive time).

3. Discussion

3.1. Suitability of ABSOLUTE hybrid for different vehicle types

The preceding analysis allows an estimate to be made of the ABSOLUTE hybrid's suitability for different vehicle types based on the size, volume, fuel type and fuel consumption under different modes of driving (drive cycle and drive time per day).

As can be seen from the difference in fuel cell size required for charge neutrality over a single drive cycle and that for a 'whole-day' drive cycle, the 'always-on' strategy for the fuel cell results in a significant reduction in the size of the fuel cell required. The 'always-on' mode of operation also suites the nature of the steam reforming fuel processing method and fuel cell type.

It can be considered that traversing the drive time axis is effectively varying the balance of fuel cell and battery power (degree of hybridisation) required for operation. At long total drive times, the vehicle is predominantly fuel cell driven. That is, the battery accommodates the peak power requirement and absorbs the regenerative braking, while the fuel cell serves the average traction power. This can be seen by the ratio of fuel cell power to battery energy, as shown in Fig. 10. Such a mode of operation is not conducive to the ABSOLUTE hybrid, since this requires a large fuel cell (and dc–dc converter) and a battery with a high power density and low energy density—not a feature of the ZEBRA battery. At a short drive time, although only a small energy capacity is required from the battery, the power-to-energy ratio of the battery must be high in order to achieve suitable acceleration performance, as can be seen in Fig. 14. This may require specially designed cells or over-sizing of the energy capacity in order to meet the power requirement. Fuel efficiency also decreases at short drive time (and consequently small stack size) due to the constant parasitic load of the fuel cell.

Against these observations, it is concluded that the ABSOLUTE hybrid is best suited to operation in the 2–8 h per day regime; a longer drive time results in prohibitively large battery size requirements. It should be remembered, however, that the sizing of the battery is based on the worst-case scenario of the entire drive time grouped in a single block. In practice, breaks in driving due to rest stops, making deliveries, etc. will significantly reduce the battery size required.

For a system sized for a certain average drive time, the hybrid can, of course, remain charge neutral for shorter drive times. In such circumstances, the fuel cell power can be turned-down such that the battery is fully charged over the requisite time (in this case 24 h), likewise the fuel cell can be turned-down to recharge the battery over extended periods of recharge (greater than 24 h). Operating the fuel cell at lower power can result in higher efficiency operation. On the other hand, operating the fuel cell too far below the design point will result in a disproportionate amount of power being expended in servicing the parasitic load, with a consequent reduction in fuel efficiency.

With regard to fuel selection, CHG was discounted as a suitable fuel due to the limitations imposed on the vehicle's range as a result of insufficient hydrogen storage capacity. Both CNG and LPG are considered suitable fuels based on their range and fuel efficiency; they also lend themselves well to fuel processing using steam reforming.

3.2. Control strategy

Although a nominally 'always-on' constant rated power strategy has been considered in this analysis, in practice it will sometimes be prudent to stop the fuel cell and allow it to cool, e.g., during extended periods of non-drive time. Other alternative modes of operation for the fuel cell include:

- operation at maximum power during heavy use or when the battery approaches prematurely high depth-of-discharge
- running on standby to maintain the fuel cell temperature and service the parasitic load of the system if the battery is fully charged
- cold start-up of the fuel cell, during which the battery supplies the traction power without recharge from the fuel cell
- adjusting the power output of the fuel cell to suit the length of non-drive time between use
- accepting mains power for recharge of the battery
- delivering power to external loads such as recreational equipment or residential power.

Each of these modes of operation will lead to a departure from the results of the idealised analysis conducted in this work. In order to determine properly the effect on fuel consumption, a system model of the fuel cell is required in order to determine the efficiency for non-standard modes of operation.

3.3. Options for fuel cell and battery systems integration

The electrical integration between the battery and fuel cell has been described; in addition to this, there are several aspects of the stand-alone operation of both these components that warrant consideration for integration.

The main drawback of using high-temperature electrochemical power sources is that they need to be heated to the desired operating temperature and once there, maintained at that level. It is conceivable that a level of physical integration between the fuel cell stack and the cells of the battery could be achieved such that a thermal synergy could be exploited. A high level of integration between the stack and the BoP components is necessary, however, to ensure optimum efficiency of the fuel cell system [36]. This integration is technologically challenging and takes precedence over the potential benefits that physical integration of fuel cell and battery may bring. Therefore, although there is scope for such in the future, attempts at physical integration should initially be confined to the stack and BoP, with the focus on packaging of the fuel cell system and battery into a space-saving 'single box' enclosure with low heat loss, vacuum insulation technology.

Fuel cell system modelling will be used to evaluate the option of using 'waste' heat from the IT-SOFC to service the thermal requirement of the battery. There is also the option of using the heat from the battery, produced when delivering power, to augment air-stream preheating. Since both systems require air blowers (for cooling purposes and reactant delivery), the option of using a single blower is likely to alleviate some of the parasitic loss in the system.

Integration of control electronics is an obvious step to improve efficiency and reduce cost. The power that is required to run the VMU, BMI and FCMI discretely will be greatly reduced if circuit-board level integration is implemented.

4. Conclusion

A concept for an electric vehicle hybrid power source has been presented that combines a ZEBRA battery and IT-SOFC. When considering operation of the hybrid over a whole-day, as opposed to that during a drive cycle, and allowing for battery recharge from the 'always-on' fuel cell during non-drive time, an IT-SOFC of a reasonable size (less than 5 kW_e) can be used to satisfy the energy requirements for most light-duty vehicles. The high specific energy of the ZEBRA battery means that the battery can act as an 'energy buffer' and so minimise the size of the fuel cell and dc–dc converter located between the fuel cell and battery.

CNG and LPG are considered to be suitable fuels for the hybrid, but CHG is discounted due to limitations on range.

Future work will use a model of the fuel cell system to predict the performance of the hybrid under 'non-standard' modes of operation (e.g., during stand-by mode and extended non-drive time periods) and thus evaluate fuel consumption, overall efficiency and the conditions for thermal self-subsistence. The model also allows the extent of thermal integration between the fuel cell and the battery to be determined.

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