© Shutterstock, article DOI: 10.2516/ogst/2012029

Dossier

This paper is a part of the hereunder thematic dossier published in OGST Journal, Vol. 67, No. 4, pp. 539-645 and available online here

Cet article fait partie du dossier thématique ci-dessous publié dans la revue OGST, Vol. 67, n°4, pp. 539-645 et téléchargeable ici

DOSSIER Edited by/Sous la direction de : **A. Sciarretta**

Electronic Intelligence in Vehicles
Intelligence électronique dans les véhicules

Oil & Gas Science and Technology – Rev. IFP Energies nouvelles, Vol. 67 (2012), No. 4, pp. 539-645
Copyright © 2012, IFP Energies nouvelles

539 > Editorial

547 > *Design and Optimization of Future Hybrid and Electric Propulsion Systems: An Advanced Tool Integrated in a Complete Workflow to Study Electric Devices*
Développement et optimisation des futurs systèmes de propulsion hybride et électrique : un outil avancé et intégré dans une chaîne complète dédiée à l'étude des composants électriques
F. Le Berr, A. Abdelli, D.-M. Postariu and R. Benlamine

563 > *Sizing Stack and Battery of a Fuel Cell Hybrid Distribution Truck*
Dimensionnement pile et batterie d'un camion hybride à pile à combustible de distribution
E. Tazelaar, Y. Shen, P.A. Veenhuizen, T. Hofman and P.P.J. van den Bosch

575 > *Intelligent Energy Management for Plug-in Hybrid Electric Vehicles: The Role of ITS Infrastructure in Vehicle Electrification*
Gestion énergétique intelligente pour véhicules électriques hybrides rechargeables : rôle de l'infrastructure de systèmes de transport intelligents (STI) dans l'électrification des véhicules
V. Marano, G. Rizzoni, P. Tulpule, Q. Gong and H. Khayyam

589 > *Evaluation of the Energy Efficiency of a Fleet of Electric Vehicle for Eco-Driving Application*
Évaluation de l'efficacité énergétique d'une flotte de véhicules électriques dédiée à une application d'éco-conduite
W. Dib, A. Chasse, D. Di Domenico, P. Moulin and A. Sciarretta

601 > *On the Optimal Thermal Management of Hybrid-Electric Vehicles with Heat Recovery Systems*
Sur le thermo-management optimal d'un véhicule électrique hybride avec un système de récupération de chaleur
F. Merz, A. Sciarretta, J.-C. Dabadie and L. Serrao

613 > *Estimator for Charge Acceptance of Lead Acid Batteries*
Estimateur d'acceptance de charge des batteries Pb-acide
U. Christen, P. Romano and E. Karden

633 > *Automatic-Control Challenges in Future Urban Vehicles: A Blend of Chassis, Energy and Networking Management*
Les défis de la commande automatique dans les futurs véhicules urbains : un mélange de gestion de châssis, d'énergie et du réseau
S.M. Savaresi

ifp Energies nouvelles

Oil & Gas Science and Technology – Rev. IFP Energies nouvelles, Vol. 67 (2012), No. 4, pp. 563-573
Copyright © 2012, IFP Energies nouvelles
DOI: 10.2516/ogst/2012014

Dossier
Electronic Intelligence in Vehicles
Intelligence électronique dans les véhicules

Sizing Stack and Battery of a Fuel Cell Hybrid Distribution Truck

E. Tazelaar[1]*, Y. Shen[2], P.A. Veenhuizen[1], T. Hofman[2] and P.P.J. van den Bosch[2]

1 HAN University of Applied Science, Ruitenberglaan 26, 6826 CC Arnhem - the Netherlands
2 Eindhoven University of Technology, Den Dolech 2, 5612 AZ Eindhoven - the Netherlands
e-mail: e.tazelaar@han.nl - shenyt66@hotmail.com - bram.veenhuizen@han.nl - t.hofman@tue.nl - p.p.j.v.d.bosch@tue.nl

* Corresponding author

Résumé — Dimensionnement pile et batterie d'un camion hybride à pile à combustible de distribution — Un camion hybride, utilisant une pile à combustible et construit à des fins de démonstration, sert de base à l'étude de l'effet de la taille de la pile (kW) et de la batterie (kW, kWh) sur la consommation d'hydrogène du véhicule. Trois cycles de vitesse définissent les conditions spécifiques de conduite du véhicule : le NEDC pour les véhicules de faible puissance, le CSC et le cycle JE05. L'ECMS (*Equivalent Consumption Minimization Strategy*) est utilisée pour déterminer les consignes pour la pile à combustible et la batterie. Cette stratégie de commande permet d'atteindre une consommation proche du minimum global, obtenu par la programmation dynamique (DP). Le problème de dimensionnement peut être résolu en utilisant la programmation dynamique et l'ECMS a l'avantage, par rapport à la programmation dynamique, de pouvoir être mise en oeuvre en temps réel. Pour le véhicule et matériels considérés, les trois cycles de conduite permettent d'obtenir les puissances nominales optimales pour la pile à combustible à savoir environ trois fois la puissance moyenne demandée par le conducteur. Cela montre que le dimensionnement de la pile à combustible pour la puissance moyenne ou maximale, n'est pas nécessairement optimale vis-à-vis de la sobriété en carburant. La batterie est dimensionnée pour fournir la différence entre la puissance nominale de la pile à combustible et le pic de puissance dans la demande totale en puissance électrique. Le dimensionnement de la batterie est dominée par ses capacités de tenue en puissance. Par conséquent, un taux plus haut entre kW et kWh cause une diminution du poids de la batterie qui à son tour conduit à une consommation d'hydrogène plus basse. La capacité de stockage d'énergie de la batterie ne devient un problème que pour les taux de C-ratio supérieurs à 30. Par rapport à un prolongateur d'autonomie (RE) où la taille de la pile est comparable à la puissance moyenne et où la pile est exploitée sur un niveau de puissance constant, les tailles optimales de piles et de batteries combinée avec ECMS, réduisent significativement la consommation d'hydrogène. Comparé à une stratégie de type RE, l'ECMS fait un bien meilleur usage de la puissance combinée de la pile à combustible et de la batterie, ce qui conduit à une consommation d'hydrogène plus faible et permet également de réduire le poids de la batterie et donc d'améliorer la charge utile.

Abstract — Sizing Stack and Battery of a Fuel Cell Hybrid Distribution Truck *— An existing fuel cell hybrid distribution truck, built for demonstration purposes, is used as a case study to investigate the effect of stack (kW) and battery (kW, kWh) sizes on the hydrogen consumption of the vehicle. Three driving cycles, the NEDC for Low Power vehicles, CSC and JE05 cycle, define the driving requirements for the vehicle. The Equivalent Consumption Minimization Strategy (ECMS) is used for determining the control setpoint for the fuel cell and battery system. It closely approximates the global minimum in fuel consumption, set by Dynamic Programming (DP). Using DP the sizing problem can be solved but ECMS can also be implemented real-time. For the considered vehicle and hardware, all three driving*

cycles result in optimal sizes for the fuel cell stack of approximately three times the average drive power demand. This demonstrates that sizing the fuel cell stack the average or maximum power demand is not necessarily optimal with respect to a minimum fuel consumption. The battery is sized to deliver the difference between specified stack power and the peak power in the total power demand. The sizing of the battery is dominated by its power handling capabilities. Therefore, a higher maximum C-rate leads to a lower battery weight which in turn leads to a lower hydrogen consumption. The energy storage capacity of the battery only becomes an issue for C-rates over 30. Compared to a Range Extender (RE) configuration, where the stack size is comparable to the average power demand and the stack is operated on a constant power level, optimal stack and battery sizes with ECMS as Energy Management Strategy significantly reduce the fuel consumption. Compared to a RE strategy, ECMS makes much better use of the combined power available from the fuel cell stack and the battery, resulting in a lower fuel consumption but also enabling a lower battery weight which consequently leads to improved payload capabilities.

INTRODUCTION

Background

Fuel cell hybrid vehicles are believed to provide a solution to cut down emissions in the long term [1-3]. They provide local zero-emission propulsion and when the hydrogen as fuel is derived from renewable energy sources, fuel cell hybrids enable well-to-wheel zero-emission transportation. A fuel cell hybrid propulsion system comprises a fuel cell system, an electric energy storage system like a battery and an electric drive train. The ratings of these components in terms of kW and kWh and the Energy Management Strategy (EMS), define the performance of the vehicle.

Prototypes of fuel cell hybrid vehicles presented in literature show remarkable differences in the ratings of their main propulsion system components [4-7]. Some vehicles are essentially battery based electric vehicles with a fuel cell system as Range Extender [4, 6], where others have a fuel cell system with a stack power comparable to the power level of the electric motor [4, 7]. In general, studies that discuss component sizes in hybrid propulsion systems do not result in one clear sizing rule [8-11]. The existence of storage in a hybrid propulsion system complicates the sizing issue and makes it a dynamic optimization problem [12]. As a consequence, key performance figures such as acceleration time or top speed are not sufficient to size the components of the propulsion system and complete driving cycles are needed to define the performance required and the minimum component specifications. Such driving cycles are available for different vehicles, traffic conditions and purposes [13].

In particular for fuel cell based hybrid vehicles, fuel consumption is an important performance indicator as the possibilities to carry abundant quantities of hydrogen within the vehicle are limited and costly. As presently hydrogen per unit of energy is more expensive than traditional fuels [14], the significance of fuel consumption as a performance indicator increases proportionally. Moreover, an increase in the fuel consumption of the propulsion system directly reduces the driving range of the vehicle.

When fuel consumption is taken as the key parameter, designing a fuel cell hybrid propulsion system is finding those sizes of fuel cell stack and electric storage system that realize minimum fuel consumption, under the condition that the specified driving cycle is still feasible. The fuel consumption also depends on how the propulsion system is operated. This operation is defined by the Energy Management Strategy (EMS) of the vehicle. Conversely, the choice of the EMS affects the optimal component sizes of the propulsion system. Therefore, an EMS has to be defined to solve the sizing problem.

In literature, a variety of Energy Management Strategies is presented. Rule-based strategies such as fuzzy logic and related control techniques are proposed [15]. In [16] efficiency maps are used to decide on the operation of the system. Energy Management Strategies based on the State Of Charge (SOC) of the battery are described in [17-20]. A last group of Energy Management Strategies tries to approximate the ultimate (off-line) minimum fuel consumption by solving the fuel consumption optimization problem with a typical control law to enable a real-time implementation [10, 12, 21-24]. For implementation, most of these strategies need a real-time estimation of the SOC of the battery, which is not trivial [25]. In [26] not the SOC but the directly measurable voltages in the system are used as controlled variables.

Although different in complexity, robustness and performance, all these Energy Management Strategies present some solution to the dynamic optimization problem of minimizing fuel consumption considering a specified driving cycle. As their task is to determine when to charge or discharge the battery, an estimate of the future of the driving cycle is part of any real-time EMS and the accuracy of this estimate effects its performance. Estimators are proposed, for instance based on power distributions from the past [21] or navigation data [27]. Although some estimation of the

future is needed for all *real-time* EMS, this does not hold for the EMS problem as part of sizing the propulsion system. During the vehicle design phase, where also component sizing takes place, the driving cycle can be considered to be fully known. Therefore, in this case the EMS problem could be solved off-line using Dynamic Programming (DP). Nevertheless, using an real-time EMS better supports the practical value of the optimal sizing found. Hence, an online EMS (ECMS) is used in this study. The minimum in the fuel consumption from DP is considered a benchmark for the results found with ECMS.

Objectives

This study examines the relation between the fuel consumption and the sizes of the fuel cell system and battery for a fuel cell hybrid distribution truck. Such a truck would operate mainly in an urban traffic environment with frequent starts and stops (traffic lights, delivery, etc.). As its hybrid propulsion system enables regeneration of energy during deceleration, a hybrid distribution truck can benefit from these transients. Also for the owner of a truck, fuel consumption will generally be a higher priority compared to a passenger car.

Initial costs for stack and storage are not considered as fuel cells are commercially still an emerging technology with major cost reductions expected.

An existing prototype of a fuel cell hybrid distribution truck is the subject of this study. This choice enables model validation and an approximation of reality as close as possible. Originally the truck was built as prototype to demonstrate the possibilities of fuel cell hybrid trucks. The objective of this study is to make a next step in the design of the hybrid propulsion system by deriving optimal sizes for fuel cell system and battery that enable a minimum fuel consumption.

Outline of the Paper

In Section 1, this paper first discusses the reference vehicle and its propulsion system. In Section 2, the performance expected from the vehicle is specified in terms of driving cycles. The sizing problem is defined as an optimization problem. Part of this optimization problem is the minimization of the fuel consumption, which is considered a nested optimization problem with its own problem definition. To enable a mathematical solution for both optimization problems, models of the stack, auxiliaries and battery are presented in Section 3. Section 4 then describes the problem solution methods and Section 5 presents some simulation results. Section 6 presents a discussion of the results. Then, conclusions are drawn.

Figure 1

Light-duty fuel cell hybrid distribution truck [28].

1 VEHICLE UNDER STUDY

The vehicle under study is the Hytruck, a modified 7.5t Mitsubishi Canter (see *Fig. 1* and also [28]). It was built as prototype to demonstrate the possibilities of emission free propulsion in urban distribution, using hydrogen. The truck has two in-wheel electric motors [29] at the rear wheels and a lithium-ion battery system. A fuel cell system [30] is added as *Range Extender*. Intentions are to design and build a next generation truck based on the lessons learned from this prototype. Therefore, it is interesting to examine the optimal size of the propulsion system with respect to its fuel consumption. The propulsion system of the prototype serves as a reference. The main specifications of the truck are listed in Table 1.

TABLE 1

Main initial parameters considered truck

Parameter	Description	Value	Unit
M	Vehicle weight	4 600	kg
GVW	Gross Vehicle Weight	7 500	kg
A	Vehicle frontal area	4.4	m^2
f_r	Coefficient of rolling resistance	0.015	-
c_x	Coefficient of air resistance	0.7	-
m_j	Equivalent mass rotating parts	200	kg
$P_{EM\,max}$	Total power electric motors	60	kW

The reference propulsion system comprises a fuel cell stack system and a storage system, as indicated in Figure 2. The fuel cell system consists of three PEM stacks and auxiliaries as a humidifier, air compressor, hydrogen supply valve, recirculation pump, purge valve and a two-stage cooling system. A pack of Li-ion batteries serves as energy

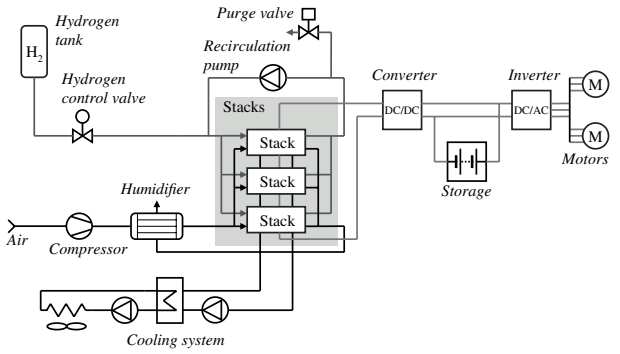

Figure 2

The hybrid propulsion system.

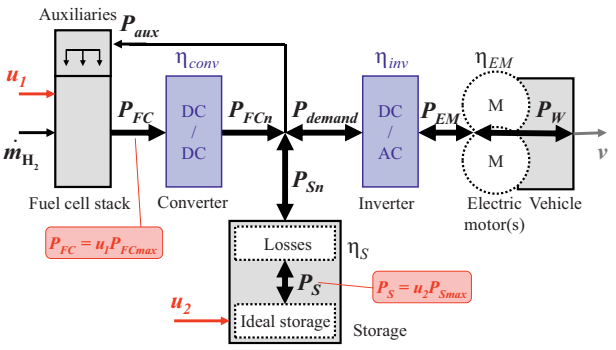

Figure 3

Outline of the hybrid propulsion system.

storage system. A DC/DC-converter and an inverter interconnect the fuel cell system, battery and the motors.

The reference fuel cell stack system has a nominal maximum output power $P_{FC\,max}$ of 16 kW and a peak power of 20 kW. The battery pack has a capacity $E_{S\,max}$ of approximately 25 kWh and a nominal maximum output power $P_{Sn\,max}$ of 25 kW. It is therefore considered a battery with a C-rate of 1, although its peak power for 30 seconds approaches 50 kW. The C-rate is the ratio between the maximum continuous power the battery can provide (kW) and its storage capacity of the battery (kWh). Both in-wheel motors can handle almost double the rated nominal power during a limited time. The rated maximum power of the fuel cell stack, the rated maximum power of the battery and the rated energy storage capacity of the battery pack are subject to the optimization defined in Section 2.

2 PROBLEM DEFINITION

2.1 Definition of the Propulsion System

For a proper problem definition, the propulsion system is reduced to the block diagram of Figure 3. The electric layout of the truck under study is taken for reference. This layout is referred to as the energy hybrid structure, where the battery defines the voltage on the DC-bus. This energy hybrid structure prevails with respect to fuel consumption [11].

2.2 Performance Specification

The objective of the study is to define a propulsion system enabling the vehicle to drive a predefined driving cycle with a minimum of fuel consumption. This fuel consumption is taken as performance indicator. The New European Driving Cycle (NEDC) was especially designed to evaluate fuel consumption. The 'Low Power' version of this cycle (NEDC LP), where the speed in the high velocity section in the NEDC is reduced to a maximum of 90 km/h, is used as reference for the vehicle under study. As this NEDC Low Power cycle does not reflect real life traffic conditions, also two truck-specific cycles are used: the American City Suburban Cycle (CSC) and the Japanese 2005 heavy duty driving cycle (JE05) [13]. Both cycles represent an urban traffic environment where the JE05 includes a distance on a main road, representing Tokyo driving conditions. The characteristics of the driving cycles are summarized in Table 2

TABLE 2

Driving cycle characteristics

	NEDC LP	CSC	JE05	Unit
Traveled distance	9.9	10.75	14	km
Average velocity	35.0	22.8	27.0	km/h
Maximum velocity	90.0	70.5	88.0	km/h
Max. acceleration	1.04	1.14	1.59	m/s^2

The speed profiles for the three driving cycles are presented in Figure 4. Note the reference truck originally was not designed to realize these driving cycles.

2.3 Definition of the Sizing Problem

The sizing problem yields the optimal sizes of the battery and fuel cell system that minimize the fuel consumption necessary to drive the specified cycles. The size of the fuel cell system is defined by the maximum stack power $P_{FC\,max}$. The maximum battery power $P_{S\,max}$ and battery capacity $E_{S\,max}$, which equals the rated battery power times its C-rate (*see Sect. 1*), define the storage. Therefore, the sizing problem can also be expressed as:

$$(P^*_{FC\,max}, P^*_{S\,max}) = \arg \min_{P_{FC\,max}, P_{S\,max}} \mathcal{J}(P_{FC\,max}, P_{S\,max}) \quad (1)$$

under the condition that the vehicle is able to drive the specified cycle v. The function $\mathcal{J}$ represents the cumulated

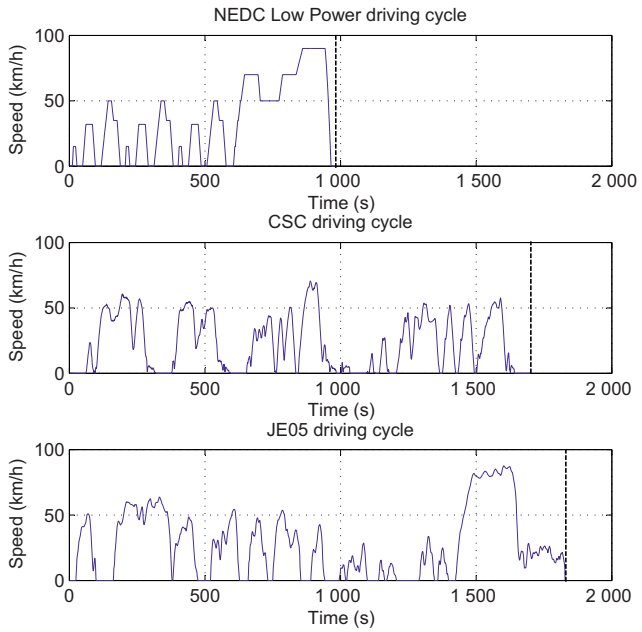

Figure 4

The NEDC Low Power, CSC and JE05 driving cycles. The dash-dotted line indicates the end of the cycle.

minimum fuel consumption. A brute force optimization is performed in finding the optimal set of design parameter $\left(P^*_{FC\,max}, P^*_{S\,max}\right)$ for the fuel cell stack and battery pack.

To solve this sizing problem, a vehicle model is needed including the changes in vehicle weight associated with size variations of fuel cell stack and battery. In addition, an Energy Management Strategy (EMS) is needed, defining the operation of the fuel cell system and battery leading to minimum fuel consumption.

2.4 The Energy Management Problem

Given the size of the fuel cell stack $P_{FC\,max}$ and battery $E_{S\,max}$, the total mass M of the vehicle is defined and the power at the wheels P_W to drive the specified cycle v can be calculated. Using the efficiency maps of the motors and inverter, the power at the wheels P_W converts into the power P_{demand} demanded from the fuel cell system and battery. The energy management problem is the problem of balancing the demanded power over fuel cell stack and battery such that the overall fuel consumption is minimal. This optimization problem is defined as:

$$u_1{}^* = \arg\min_{u_1} \int_{t=0}^{t_{final}} \dot{m}_{fuel}\left(u_1\right) dt \tag{2}$$

where u_1 is the control signal defining the power delivered from the fuel cell system (*see Fig. 3*). The solution to this energy management problem defines the trajectory $u_1{}^*$, minimizing Equation (2) under the conditions that the driving cycle is realized and that no rated powers are exceeded:

$$\eta_{conv} P_{FC} - P_{aux} + P_{Sn} - P_{demand} = 0 \tag{3}$$

$$P_{FC\,min} \leqslant P_{FC} \leqslant P_{FC\,max} \tag{4}$$

$$P_{Sn\,min} \leqslant P_{Sn} \leqslant P_{Sn\,max} \tag{5}$$

The maximum power constraints for the fuel cell stack and the battery pack represent the interlinking design parameters at the sizing optimization problem *(cf. Eq. 1)* at vehicle system level. It is assumed that the maximum battery discharge power equals the maximum battery charge power, *i.e.* $P_{Sn\,min} = -P_{Sn\,max}$. In addition, solutions are limited to those that fulfill the constraint that the State Of Charge (SOC) of the battery at the end of the driving cycle equals or exceeds the SOC at the start:

$$\mathrm{SOC}(t_{final}) \geqslant \mathrm{SOC}(0) \tag{6}$$

This constraint enables the vehicle to not only drive one driving cycle but to continue normal operation over its lifetime. Constraints on a minimum or maximum SOC are not included in the optimization problem and only checked afterwards, as only the power ratings and not the storage capacity of batteries provide a true limitation [22, 31]. No plug-in functionality is assumed. Constraint (6) also enables comparison of the fuel consumption for different configurations and Energy Management Strategies. The variables in the constraints are further explained in Section 3.

3 MODEL EQUATIONS

3.1 Vehicle

The power for traction at the wheels P_W to overcome the air resistance, rolling resistance and to deliver the power for acceleration and deceleration is derived from the speed profile v as:

$$P_W = \frac{1}{2}\rho A c_x v^3 + M g f_r v + \left(M + m_j\right) v \frac{dv}{dt} \tag{7}$$

For a negative power for traction, it is assumed that 60% of the power is available for regeneration. As the impact of the efficiencies of electric motor η_{EM} and inverter η_{inv} depend on the direction of the energy flow, relation (8) between the power demand P_{demand} and P_W distinguishes between motoring ($P_W \geq 0$) and regeneration ($P_W < 0$):

$$P_{demand} = \begin{cases} \frac{1}{\eta_{EM}} \frac{1}{\eta_{inv}} P_W & P_W \geq 0 \\ 0.6 \eta_{EM} \eta_{inv} P_W & P_W < 0 \end{cases} \tag{8}$$

The total mass of the truck M depends on the mass of the battery (related to $E_{S\,max}$) and the mass of the fuel cell system (related to $P_{FC\,max}$). Based on the reference vehicle,

these masses are assumed linear with the rated power and capacity of fuel cell stack and battery:

$$M = M_0 + \frac{1}{\rho_{P,FC}} P_{FC\,max} + \frac{1}{\rho_{E,S}} E_{S\,max} + M_{payload} \quad (9)$$

Here, M_0 is the initial vehicle weight, including propulsion system components such as hydrogen tank and auxiliaries, except for the fuel cell stack and battery. The additional weight is defined by the power density of the fuel cell system $\rho_{P,FC}$, the energy density of the battery $\rho_{E,S}$ and the weight of the payload $M_{payload}$. For the truck under study, the power density of the fuel cell stack is taken 130 W/kg and the battery energy density is taken 100 Wh/kg, corresponding to 100 W/kg based on a C-rate of one. A fixed payload of 1 700 kg is assumed.

3.2 Fuel Cell System

The fuel cell stack converts hydrogen as fuel into electric energy. The relation between the fuel cell power P_{FC} and hydrogen consumption $\dot{m}_{fuel}$ is given by:

$$\dot{m}_{fuel} = \frac{P_{FC\,max}}{H_{H_2}} \left[\mu_2 \left(\frac{P_{FC}}{P_{FC\,max}} \right)^2 + \mu_1 \frac{P_{FC}}{P_{FC\,max}} + \mu_0 \right] \quad (10)$$

where $H_{H_2} = 121$ MJ/kg represents the lower heating value of hydrogen.

Relation (10) is presented in Figure 5 as a fit to the fuel consumption data measured on the reference fuel cell stack.

The fuel consumption expressed in Equation (10) is increased by 4% to account for the average purge losses.

Various models to represent the auxiliary power are presented in literature [12, 32]. They vary in relating the auxiliary power linear or quadratic to the stack current or stack power. In this study, the auxiliary power P_{aux} is related to the fuel cell stack power P_{FC} according:

$$P_{aux} = P_{FC\,max} \cdot \left[\gamma_2 \left(\frac{P_{FC}}{P_{FC\,max}} \right)^2 + \gamma_1 \frac{P_{FC}}{P_{FC\,max}} + \gamma_0 \right] \quad (11)$$

Over the operating window used in the application (from $P_{FC\,min} = 0.2 P_{FC\,max}$ to $P_{FC\,max}$), the relation between the auxiliary power and fuel cell power tends to a linear relation with $\gamma_2 = 0$, $\gamma_1 = 0.125$ and $\gamma_0 = 0.063$. Measurements on an identical stack with comparable auxiliaries in a test facility [33] confirm this linear relation.

3.3 Battery

The net battery power is approximated using the battery model of Figure 6 [12, 34].

The open clamp voltage V_{OC} in this battery model is a function of the SOC of the battery. The battery SOC represents the amount of charge stored, related to the maximum capacity of the battery:

$$\mathrm{SOC}(t) = \frac{1}{Q_{max}} \int_{\tau=0}^{t} I_S(\tau) d\tau \quad (12)$$

where Q_{max} represents the battery charge capacity.

Based on the battery model of Figure 6 with its internal resistance R_S and open clamp voltage V_{OC}, the power P_S from the ideal internal voltage source relates to the power P_{Sn} at the terminals of the battery as:

$$P_S = V_{OC} I_S \quad (13)$$

$$P_{Sn} = V_{OC} I_S - I_S^2 R_S \quad (14)$$

$$\Rightarrow P_{Sn} = P_S - P_S^2 \frac{R_S}{V_{OC}^2} \quad (15)$$

and consequently:

$$P_S = \frac{V_{OC}^2}{2R_S} \left(1 - \sqrt{1 - 4 P_{Sn} \frac{R_S}{V_{OC}^2}} \right) \quad (16)$$

For the battery under study, the relation between its open clamp voltage V_{OC} and State Of Charge (SOC) is unknown.

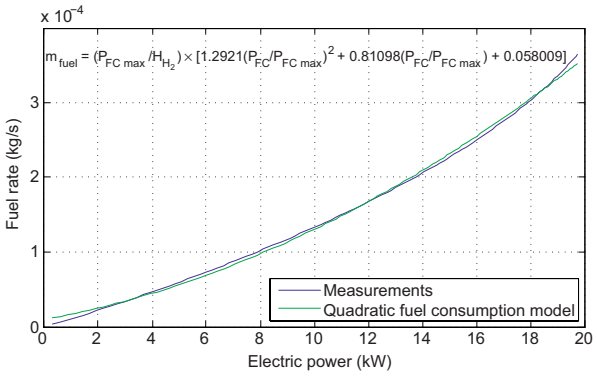

Figure 5

Fuel consumption related to stack power.

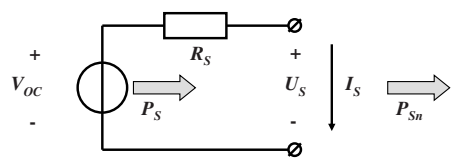

Figure 6

Battery model.

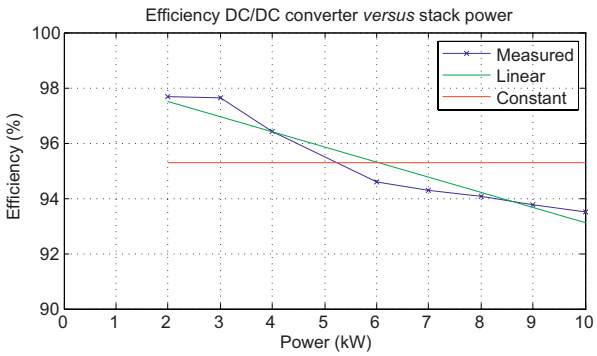

Figure 7

Measured efficiency DC/DC converter.

As approximation, normalized ADVISOR [35] data for a comparable Li-ion battery was used initially. As the deviations in the SOC over the driving cycles compared to the size of the battery appear very small (< 5%), in the Energy Management Strategy, the open clamp voltage is considered a constant. As a result, the SOC directly reflects the State Of Energy (SOE) of the battery.

3.4 Converters

Figure 7 shows the efficiency of an existing DC/DC converter of a fuel cell hybrid propulsion system. This efficiency shows a minor dependency on the converted power. A linear relation with the converted power largely models this dependency. Still, compared to other losses in the system, the error when using a constant efficiency is small. In addition, most of the time the converter operates in a confined operating window, further reducing the impact of such model error. Therefore, in this study, the DC/DC converter between fuel cell system and battery and the inverter to the motors are modeled by the average efficiency of their efficiency maps.

4 METHOD

4.1 Solving the Energy Management Problem

As discussed in the Introduction, sizing the propulsion system is an off-line activity. Therefore, an off-line solution method as Dynamic Programming (DP) to find the global optimum to the nonlinear energy management problem suffices. As general approach, DP includes the equality constraints and active inequality constraints into the cost function or performance index using Lagrange multipliers [36, 37]. The nonlinear optimization problem, Equation (2), including the equality constraint (6) expressed according (12) results in:

$$u_1{}^* = \arg\min_{u_1} \left[\int_{t=0}^{t_{final}} \dot{m}_{fuel} dt + \lambda \frac{1}{Q_{max}} \int_{t=0}^{t_{final}} I_S \, dt \right] \tag{17}$$

Here, equality constraint (3) is used to reduce the equations to one control variable u_1. The solution to this extended optimization problem results in an optimal control vector $u_1{}^*$ that minimizes the fuel consumption and satisfies the constraint on the SOC of the battery (12). The procedure to derive control vector $u_1{}^*$ includes an anti-causal derivation of the Lagrange multiplier. In an off-line optimization as DP, backwards solving Lagrange multipliers is possible, as all information is available *a priori*. To solve the sizing problem, this suffices. Still an implementable real-time solution of the energy management problem increases the relevance of this study. Therefore, the Equivalent Consumption Minimization Strategy (ECMS) [12, 24, 38] is used. ECMS is one of the optimizing strategies discussed in the Introduction. It uses a control law to derive the Lagrange multiplier λ, avoiding any anti-causal calculation. This enables a real-time implementation although by definition the solution provided by ECMS will be suboptimal. In the ECMS used in this study the Lagrange multiplier or weight on the equivalent costs is taken as a constant λ_0. Both numerical studies [31] as mathematical studies based on a simplified battery model [21], motivate that with this simple control law ECMS closely approaches the benchmarked minimum fuel consumption calculated using DP. This property makes ECMS attractive as method to solve the energy management subproblem in the search for optimal sizes for the fuel cell system and battery.

4.2 Solving the Sizing Problem

The sizing problem is solved performing a sensitivity analysis on the fuel consumption for different sizes of the fuel cell system and battery. Based on the maximum stack power $P_{FC\,max}$, the batteries maximum power $P_{S\,max}$ and using the C-rate of the battery its storage capacity $E_{S\,max}$ are derived from the simulations including the EMS under study. Next the fuel consumption is mapped against the fuel cell stack size and the battery size to locate their optimal sizes providing the global minimum in fuel consumption.

5 RESULTS

5.1 The Energy Management Strategy

To determine the optimal sizes for stack and battery considering a minimum fuel consumption, also the Energy Management Strategy should minimize this consumption. As discussed in Section 4.1, an optimizing strategy as ECMS

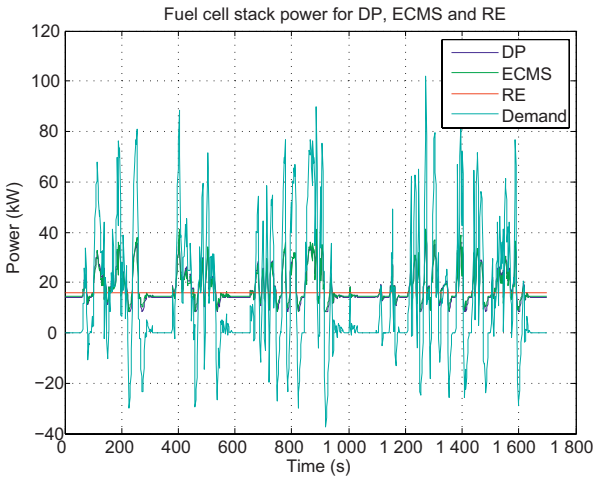

Figure 8

Stack operation for DP, ECMS and RE as Energy Management Strategy.

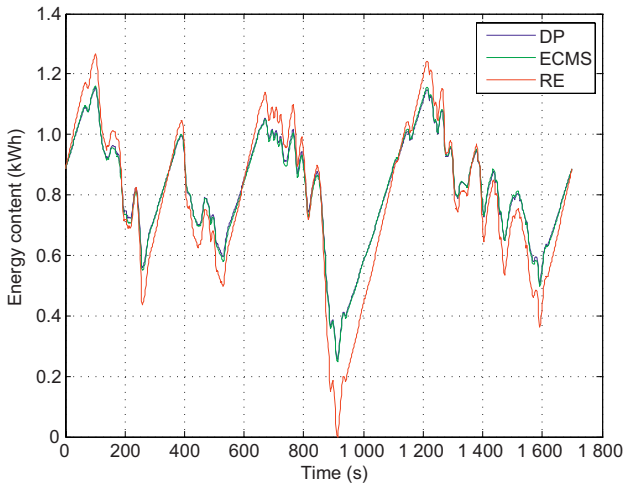

Figure 9

Energy content of the battery for DP, ECMS and RE as Energy Management Strategy (battery capacity 65 kWh).

approaches the DP benchmark and still enables real-time implementation. To motivate this statement, a comparison is made between three Energy Management Strategies: DP, ECMS and Range Extender (RE) mode, where the fuel cell stack is operated at a constant power level, derived from a previous run. The results for the propulsion system with a stack size of 41 kW and a battery size of 65 kW and the CSC as driving cycle are presented in Figures 8 and 9. Figure 8 presents the operation of the fuel cell stack for the three different Energy Management Strategies and Figure 9 presents the corresponding energy content of the battery. All three strategies enable the required driving cycle and are neutral to the energy content of the battery over the cycle but clearly the ECMS resembles the DP benchmark much closer than the Range Extender strategy.

In addition, Figure 10 presents the fuel consumption for the three Energy Management Strategies for different sizes of stack and battery. The sizes of both stack and battery are varied in relative large steps of 10 kW to reduce the computing time for the DP benchmark. Over the component sizes examined, the resulting fuel consumption for ECMS is on average 0.5% over the DP benchmark with a maximum deviation of 2%. Given the sizes of stack and battery, the Range Extender mode is at least 6% over the DP benchmark. This supports the choice for ECMS as optimizing Energy Management Strategy to examine the component sizes in more detail.

5.2 Sizing

With ECMS as Energy Management Strategy, the impact of component sizes on the fuel consumption of the vehicle is

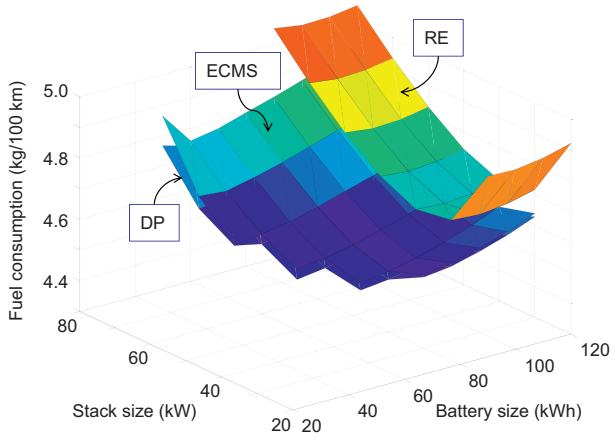

Figure 10

Fuel consumption for different sizes of stack and battery and DP, ECMS and RE as Energy Management Strategy (CSC).

examined for all three required driving cycles. Figure 11 shows the fuel consumption of the vehicle for the NEDC Low Power driving cycle, related to the sizes of the fuel cell stack and the battery. Only component sizes that result in a feasible solution are presented. Figure 11 shows a minimum fuel consumption of 4.73 kg/100 km at a fuel cell stack size of 68 kW and a battery size of 61 kWh. As indicated in the contour plot of Figure 11, these values are on the edge of a feasibility region, where the required driving cycle is feasible. The borders of the feasibility region are defined by the ability of the propulsion system to deliver the peak power and the ability of the fuel cell stack to deliver the energy required.

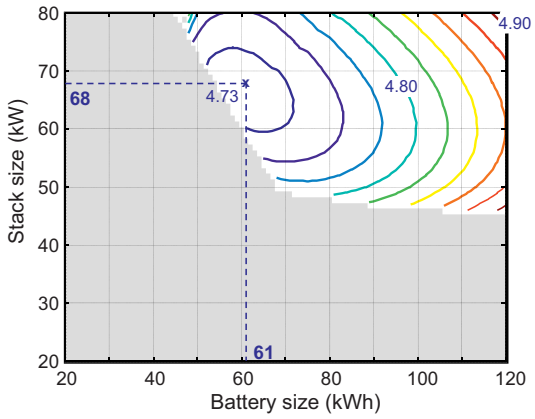

Figure 11

Contour plot of the fuel consumption in kg/100 km for different stack and battery sizes. ECMS is used as EMS (NEDC Low Power cycle).

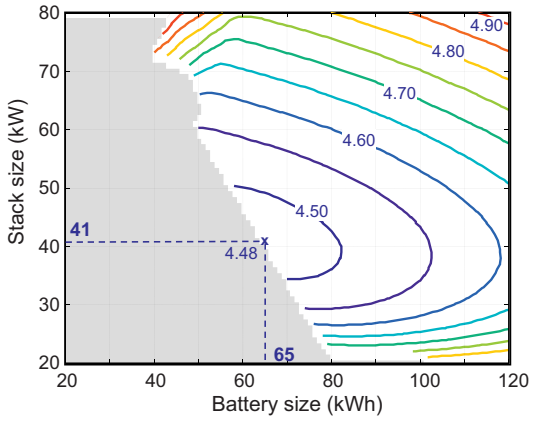

Figure 12

Contour plot of the fuel consumption in kg/100 km for different stack and battery sizes. ECMS is used as EMS (CSC cycle).

Figure 12 presents the resulting fuel consumption for the CSC as driving cycle. The optimal sizes of stack and battery are 41 kW and 65 kWh respectively, with a resulting minimum fuel consumption of 4.48 kg/100 km. Figure 13 shows the results for the Japanese JE05 driving cycle. Here, the optimal sizes of stack and battery are 47 kW and 71 kWh respectively, resulting in a fuel consumption of 4.39 kg/100 km.

6 DISCUSSION

6.1 Results per Driving Cycle

Table 3 summarizes the resulting optimal sizes of the fuel cell stack and battery for the driving cycles under study.

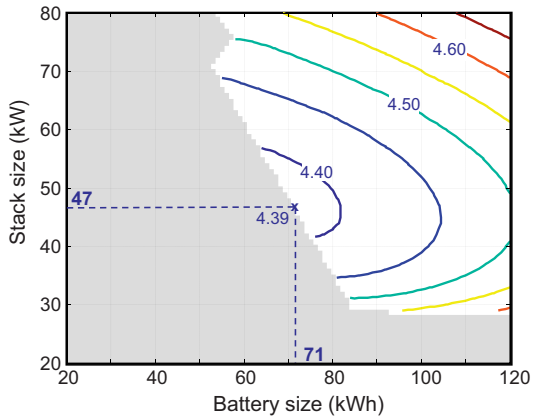

Figure 13

Contour plot of the fuel consumption in kg/100 km for different stack and battery sizes. ECMS is used as EMS (JE05 cycle).

The artificial NEDC Low Power cycle results in a much higher optimal stack size compared to the more realistic CSC and JE05 cycles. This is explained from the higher average speed of the NEDC Low Power cycle *(see Tab. 2)*. Nevertheless, the differences in fuel consumption between the cycles are within 8%.

TABLE 3

Optimal component sizes for different driving cycles

	NEDC Low Power	CSC	JE05	Unit
FC stack	68	41	47	kW
Battery	61	65	71	kW
Fuel consumption	4.73	4.48	4.39	kg/100 km
Average demand	22.4	13.6	16.3	kW
Peak demand	112	102	112	kW
$P_{FC\,max}/P_{demand}$	3.0	3.0	2.9	(-)

6.2 Observations for Sizing

Most fuel cell hybrid vehicles so far have a fuel cell stack rated the average power demand, or close to the maximum power for traction *(Sect. 1.1)*. For the vehicle under study, Table 3 also includes the maximum and average power demand, given the optimal sizes for the propulsion system. Although all three driving cycles are different, the ratio between the fuel cell stack size and the average power demand approximates 3. This ratio refers to the presented hardware only and depends on battery and fuel cell stack specifications [39]. More important, it demonstrates that average or maximum values do not inevitably represent the minimum in fuel consumption. Next step is a more fundamental study on this subject as attempt to derive an engineering rule on sizing.

6.3 Feasible Component Sizes

Figure 10 not only illustrates that ECMS as Energy Management Strategy approximates the DP benchmark, it also shows that compared to Range Extender mode, ECMS provides already feasible solutions at much smaller battery sizes. As in Range Extender mode the fuel cell stack power does not follow the transients in the power demand, this strategy needs larger battery sizes to enable the power required by the driving cycle. Stated differently, ECMS enables smaller component sizes, even when minimizing the fuel consumption is not considered. This observation supports the statement that a fuel cell hybrid vehicle should not be considered an electric battery vehicle with a fuel cell system to extend its range. A proper design of a fuel cell hybrid propulsion system needs a reconsideration of all its components.

6.4 Sensitivity Against the C-rate of the Battery

The deviation in stored energy over time is small compared to the capacity of the battery. As illustrated in Figure 9 for the CSC cycle, about 1 kWh of battery capacity is needed compared to 65 kW of battery power. Therefore, the battery has to be sized on its power handling capabilities. A battery technology with a higher C-rate will reduce the fuel consumption as it decreases the vehicle mass. As example, the CSC as driving cycle is evaluated for a battery with an assumed C-rate of 4. The resulting optimal fuel cell stack power decreases from 41 to 34 kW and the battery size shifts from 65 kWh (65 kW) to 38 kWh (159 kW). The resulting fuel consumption is 4.06 kg/100 km. This 10% fuel consumption reduction is directly related to the reduction in empty vehicle weight from 5 190 kg to 4 884 kg. Still, less than 3% of the battery capacity is used. Under the assumption that half of the rated battery capacity can be used effectively, battery capacity only becomes an issue for battery technologies with C-rates over 30. For batteries, such C-rates are not expected in the near future. Despite some disadvantages, the power handling capabilities of supercapacitors may provide a further improvement of the fuel efficiency of the vehicle.

CONCLUSIONS

Given the fuel cell hybridized distribution truck as case, optimal stack and battery sizes with respect to a minimum fuel consumption are examined for three driving cycles. For all three cycles, the optimal stack size is three times the average power demand. This demonstrates that sizing the fuel cell stack the average or maximum power demand, as observed for many existing fuel cell stack vehicles, is not necessarily optimal with respect to a minimum fuel consumption. For the considered hardware, a stack size of 68 kW for the NEDC Low Power, 41 kW for the CSC and 47 kW for the JE05 driving cycle represent a minimum fuel consumption. Despite these differences in stack size, fuel consumption ranges only between 4.39 and 4.73 kg/100 km.

The battery size is dominated by its power handling properties and is rated by the power difference between the peak power in the power demand and the rated fuel cell stack power. As only a small part of the energy storage capacity of the battery is used, its capacity will not be an issue in sizing. Therefore, batteries with a higher maximum C-rate directly reduce vehicle weight and consequently reduce the fuel consumption.

With respect to sizing, compared to a Range Extender Energy Management Strategy, an optimizing Energy Management Strategy as ECMS enables smaller battery sizes, as it better utilizes the combined power available from fuel cell stack and battery. This enables a lower propulsion system weight and consequently a lower fuel consumption and/or improved payload capabilities. The study also demonstrates a fuel cell hybrid should not be considered an EV with a fuel cell system as Range Extender. In the design of the propulsion system, all its components should be reconsidered as part of one optimization.

ACKNOWLEDGEMENTS

The authors wish to thank NedStack Fuel Cell Technology B.V. for providing the specifications of the fuel cell system and auxiliaries. Also the support of Hytruck enabling model validation of the truck is greatly acknowledged.

REFERENCES

1 Cannon J.S., Azimi L.S. (1995) *Harnessing hydrogen: The key to sustainable transportation*, Inform.

2 McNicol B.D., Rand D.A.J., Williams K.R. (2001) Fuel cells for road transportation purposes - yes or no? *J. Power Sources* **100**, 1-2, 47-50.

3 Rifkin J. (2003) *The Hydrogen Economy*, Tarcher, ISBN 978-1585422548.

4 Harris K. (2007) Comparison of four fuel cell battery hybrid power trains in bus applications, in *EVS 23*, Anaheim, CA, 2-5 Dec.

5 Quinn T. (2007) Hickam air force base fuel cell vehicle fleet and hydrogen infrastructure, in *Proc. Fuel Cell Seminar*, San Antonio, Texas, 15-19 October.

6 Saxe M., Folkesson A., Alvfors P. (2008) Energy system analysis of the fuel cell buses operated in the project: Clean urban transport for europe, *Energy* **33**, 689-711.

7 Takano J., Kaji H., Ysohida H., Nagoshi K. (2009) Development of Honda FCX, in *Proc. EVS 24*, Stavanger, Norway, 13-16 May.

8 Ahluwalia R.K., Wang X., Rousseau A. (2005) Fuel economy of hybrid fuel-cell vehicles, *J. Power Sources* **152**, 233-244.

9 Han J., Kokkolaras M., Papalambros P. (2006) Optimal design of hybrid fuel cell vehicles, in *Proc. FUELCELL 2006-97161*. ASME 2006 4th International Conference on Fuel Cell Science, Engineering and Technology (FUELCELL2006), Irvine, California, 19-21 June, pp. 273-282.

10 Hofman T., Steinbuch M., van Druten R.M., Serrarens A.F.A. (2008) Hybrid component specification optimisation for a medium-duty hybrid electric truck, *IJHVS* **15**, 2/3/4, 356-392.

11 Minggao Ouyang, Liangfei Xu, Jianqiu Li, Languang Lu, Dawei Gao, Qicheng Xie (2006) Performance comparison of two fuel cell hybrid buses with different powertrain and energy management strategies, *J. Power Sources* **163**, 1, 467-479.

12 Guzzella L., Sciarretta A. (2005) *Vehicle propulsion systems, introduction to modeling and optimization*, Springer.

13 Dieselnet. www.dieselnet.com, January 2010.

14 Hellgren J. (2007) Life cycle cost analysis of a car, a city bus and an intercity bus powertrain for year 2005 and 2020, *Energy Policy* **35**, 1, 39-49.

15 Dawei Gao, Zhenhua Jin, Qingchun Lu (2008) Energy management strategy based on fuzzy logic for a fuel cell hybrid bus, *J. Power Sources* **185**, 1, 311-317.

16 Feroldi D., Serra M., Riera J. (2009) Energy management strategies based on efficiency map for fuel cell hybrid vehicles, *J. Power Sources* **190**, 2, 387-401.

17 Barsali S., Pasquali M., Pede G. (2002) Definition of an energy management technique for series hybrid vehicles, in *Proc. EVS 19*, Bexco, Busan, Korea, 19-23 October.

18 Erdinc O., Vural B., Uzunoglu M. (2009) A wavelet-fuzzy logic based energy management strategy for a fuel cell/battery/ultra-capacitor hybrid vehicular power system, *J. Power Sources* **194**, 1, 369-380. *XIth Polish Conference on Fast Ionic Conductors*, Grybów, Poland, 14-18 Sept. 2008.

19 Zhenhua Jiang, Lijun Gao, Dougal R.A. (2007) Adaptive control strategy for active power sharing in hybrid fuel cell/battery power sources, *IEEE Trans. Energy Convers.* **22**, 2, 507-515.

20 Valero I., Bacha S., Rulliere E. (2006) Comparison of energy management controls for fuel cell applications, *J. Power Sources* **156**, 1, 50-56. Selected papers from the *2nd France-Deutschland Fuel Cell Conference*, Belfort, France, 29 Nov.-2 Dec. 2004.

21 Bernard J., Delprat S., Guerra T.M., Büchi F.N. (2010) Fuel efficient power management strategy for fuel cell hybrid powertrains, *Control Eng. Pract.* **18**, 4, 408-417.

22 Kessels J.T.B.A., Koot M.W.T., van den Bosch P.P.J., Kok D.B. (2008) Online energy management for hybrid electric vehicles, *IEEE Trans. Vehic. Technol.* **57**, 6, 3428-3440.

23 Koot M.W.T., Kessels J.T.B.A., Jager de A.G., van den Bosch P.P.J. (2006) Fuel reduction potential of energy management for vehicular electric power systems, *IJAP* **1**, 112-131.

24 Paganelli G., Ercole G., Brahma A., Guezennec Y., Rizzoni G. (2001) General supervisory control policy for the energy optimization of charge-sustaining hybrid electric vehicles, *JSAE Rev.* **22**, 4, 511-518.

25 Pop V., Bergveld H.J., Notten P.H.L., Regtien P.P.L. (2005) State-of-the-art of battery state-of-charge determination, *Meas. Sci. Technol.* **16**, 12, R93-R110.

26 Thounthong P., Raël S., Davat B. (2006) Control strategy of fuel cell/supercapacitors hybrid power sources for electric vehicle, *J. Power Sources* **158**, 1, 806-814.

27 Hochkirchen T., Eifert M., Rienks M., Ress C., Etemad A., Boerger M. (2007) Driving route situation prediction for vehicle performance optimization, US Patent 2007/0010933.

28 Hytruck. www.hytruck.nl, February 2010.

29 E-traction. www.e-traction.com, February 2009.

30 Nedstack. www.nedstack.com, March 2010.

31 Hofman T., Steinbuch M., Van Druten R., Serrarens A. (2007) Rule-based energy management strategies for hybrid vehicles, *IJEHV* **1**, 1, 71-94.

32 Thorstensen B. (2001) A parametric study of fuel cell system efficiency under full and part load operation, *J. Power Sources* **92**, 1-2, 9-16.

33 Veenhuizen P.A., Bruinsma J.J., Tazelaar E., Bosma J., Zafina I.L. (2009) Fuel cell hybrid drive train test facility, in *Proc. EVS 24*, Stavanger, Norway, 13-16 May.

34 Jossen A. (2006) Fundamentals of battery dynamics, *J. Power Sources* **154**, 2, 530-538. Selected papers from the *Ninth Ulm Electrochemical Days*.

35 Wipke K.B., Cuddy M.R., Burch S.D. (1999) Advisor 2.1: a user-friendly advanced powertrain simulation using a combined backward/forward approach, *IEEE Trans. Vehic. Technol.* **48**, 6, 1751-1761.

36 Bellman R. (1957) *Dynamic Programming*, Princeton University Press.

37 Bryson A.E. (1999) *Dynamic optimization*, Addison Wesley Longman.

38 Rodatz P., Paganelli G., Sciarretta A., Guzzella L. (2005) Optimal power management of an experimental fuel cell/supercapacitor-powered hybrid vehicle, *Control Eng. Pract.* **13**, 1, 41-53.

39 Tazelaar E., Veenhuizen B., van den Bosch P., Grimminck M. (2011) Analytical solution and experimental validation of the energy management problem for fuel cell hybrid vehicles, in *Proc. EEVC*, Brussels, 26-28 October.

Final manuscript received in January 2012
Published online in July 2012

Copyright © 2012 IFP Energies nouvelles

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than IFP Energies nouvelles must be honored. Abstracting with credit is permitted. To copy otherwise, to republish, to post on servers, or to redistribute to lists, requires prior specific permission and/or a fee: Request permission from Information Mission, IFP Energies nouvelles, fax. +33 1 47 52 70 96, or revueogst@ifpen.fr.