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Investigation of Battery/Ultracapacitor Energy Storage Rating for a Fuel Cell Hybrid Electric Vehicle

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***Abstract*—Combining high energy density batteries and high power density ultracapacitors in Fuel Cell Hybrid Electric Vehicles (FCHEV) results in a high efficient, high performance, low size, and light system. Often the batteries are rated with respect to their energy requirement in order to reduce their volume and mass. This does not prevent deep discharges of the batteries, which is critical to their lifetime. In this paper, the ratings of the batteries and ultracapacitors in a FCHEV are investigated. Comparison of system volume, mass, efficiency, and battery lifetime due to the rating of the energy storage devices are presented. It is concluded, that by sufficient rating of the battery or ultracapacitors, an appropriate balance between system volume, mass, efficiency, and battery lifetime is achievable.**

***Keywords*—Battery; Energy Management Strategy; Fuel Cell; Hybrid Electric Vehicle; Ultracapacitor**

I. Introduction

In fuel cell systems it is often advantageous to combine the fuel cell with an energy storage device. The energy storage device can heat-up the fuel cell, provide power to the load when the fuel cell is warming-up, supply the peak powers of the load, and capture the negative load power.

When combining batteries and ultracapacitors the system volume and mass can be reduced, because the high energy density of the battery and high power density of the ultracapacitors thereby are utilized [1],[2]. However, this means also that a high fraction of the energy capability of the battery is used, which might be critical to its lifetime. In order to increase the lifetime of the battery in a FCHEV, either the battery, ultracapacitor or both can be overrated. In this paper the ratings of the batteries and ultracapacitors in a FCHEV are therefore investigated, and comparisons between the system volumes, masses, efficiencies, and battery lifetimes are presented.

II. Methodology

In this section the method to size the battery and ultracapacitor is introduced. The used drive cycle, FCHEV configuration and modeling, and energy management and charging strategies are presented.

A. Drive Cycle

This research deals with a low speed (< 15 km/h) vehicle. As no standard drive cycle exists for this kind of vehicle, field measurements at a customer have been performed. In Fig. 1 the vehicle speed is shown for 12 days of operation. Totally N_{day}=24 days of field measurements were conducted. These 24 days of speed profiles is the drive cycle that will be used for the further investigation of the FCHEV.

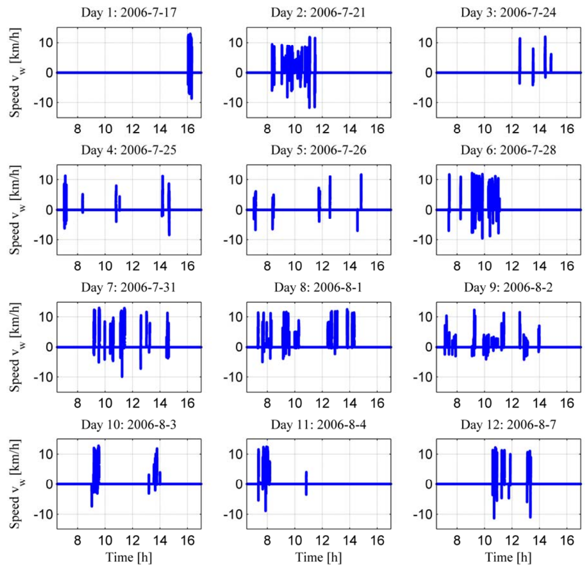

Figure 1. Vehicle seed. 12 days of field measurements.

B. Configuration

Fig. 2 demonstrates the main components of the propulsion and power system and the power flow of the FCHEV. The fuel cell, battery, and ultracapacitors are connected to a common 42V bus through DC/DC converters. It is seen that power flows to or from the electric machines (EM) to the bus through two inverters (Inv). The energy from the methanol storage is fed to the bus through a reformer and the fuel cell stack (FC). Power is also flowing to or from the battery (Bat) and ultracapacitors (UC).

Besides the shaft powers $p_{s,L}$ and $p_{s,R}$, the fuel cell and energy storage devices must also provide power for the light (p_{Light}=200 W when speed ≠ 0), balance-of-plant of the fuel cell system ($p_{BoP}=0.05 \cdot P_{FC,rat}$), the fuel cell stack heater, and the auxiliary devices, i.e. vehicle computer, drivers, control panel, etc. (p_{Aux}=50W, when either the fuel cell or energy storage devices are operating). It is assumed that it takes T_{Heat}=5 minutes to heat up the fuel

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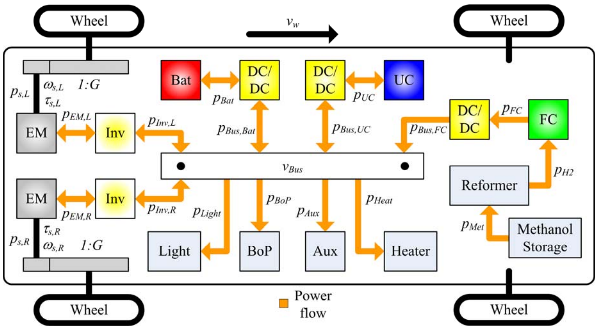

Figure 2. System overview and power flow of the FCHEV.

cell stack, and that the energy required to heat up the stack is E_{Heat}=160Wh. The power to the heater is therefore p_{Heat}=1920W. During the heating-up of the fuel cell, the energy storage devices therefore have to deliver power to both the motors and fuel cell stack heater.

C. *Sizing of Battery and Ultracapacitor*

When analyzing the configuration in Fig. 2 with a fuel cell power rating at $P_{FC,rat}$=1000W and the drive cycle shown in Fig. 1, it turns out that the battery should have a maximum power and energy rating of $P_{Bat,rat,Base}$=6.4kW and $E_{Bat,rat,Base}$=913Wh, respectively. The maximum power and energy rating of the ultracapacitors are $P_{UC,rat,Base}$=17.6kW and $E_{UC,rat,Base}$=14.1Wh, respectively. However, in order to increase the battery lifetime, it will be investigated how the system volume, mass, efficiency, and battery lifetime will be affected if either the battery or ultracapacitor are overrated. The battery will be overrated with an overrating factor $a_{or,Bat}$={1, 2, 3, 4, 5}, and the ultracapacitor will be overrated with an overrating factor $a_{or,UC}$={1, 2, 4, 6, 8, 10}. The power and energy capacity of the battery and ultracapacitor are therefore

$$P_{Bat,\max} = a_{or,Bat} P_{Bat,\max,Base} [W] \quad (1)$$

$$E_{Bat,\max} = a_{or,Bat} E_{Bat,\max,Base} [Wh] \quad (2)$$

$$P_{UC,\max} = a_{or,UC} P_{UC,\max,Base} [W] \quad (3)$$

$$E_{UC,\max} = a_{or,UC} E_{UC,\max,Base} [Wh]. \quad (4)$$

D. *Energy Management Strategies*

Sufficient energy management of the FCHEV is important in order to obtain a high vehicle performance [2]. Two energy management strategies are therefore presented here.

The bus load power is defined as

$$p_{Bus,Load} = p_{Aux} + p_{BoP} + p_{Light} + p_{Heat} + p_{s,L} + p_{s,R} [W]. \quad (5)$$

This load power needs to be divided between the fuel cell, battery and ultracapacitor in a sufficient manner. The energy management strategy that divides the load power is shown in Fig. 3.

Due to the low dynamic properties of the reformer the desired fuel cell bus power $p_{Bus,FC}^*$ is settled by the low

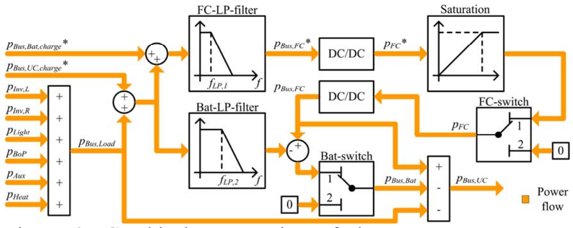

Figure 3. Graphical presentation of the energy management strategy of the FCHEV.

pass filter "FC-LP-Filter" in Fig. 3. The input to the filter is the bus load power $p_{Bus,Load}$ and the requested bus charging powers of the battery $p_{Bus,Bat,charge}^*$ and ultracapacitors $p_{Bus,UC,charge}^*$. From the model of the DC/DC converter of the fuel cell, the requested fuel cell power p_{FC}^* can be calculated. The "Saturation"-block in Fig. 3 insures that the fuel cell does not deliver more power than the rated power $P_{FC,rat}$ or below zero power. During the heating of the fuel cell, the "FC-switch" is in position 2. In this situation the fuel cell power is p_{FC}=0. Otherwise the switch is in position 1.

1) *Energy Management Strategy 1*

With this strategy the battery bus power contribution $p_{Bus,Bat}$ is also determined by a low pass filter, i.e. "Bat-LP-filter". The "Bat-swicth" is therefore in position 1. In this way the battery delivers the DC part of the load that the fuel cell not was able to deliver. The ultracapacitor bus power contribution is therefore given by the difference between the bus load power and the contribution from the fuel cell and battery, i.e.

$$p_{Bus,UC} = p_{Bus,FC} - p_{Bus,Load} - p_{Bus,Bat} [W]. \quad (6)$$

The ultracapacitor therefore acts as a high pass filter, as they only take care of the peak powers with this energy management strategy. This can be seen in Fig. 4, where the bus power and state-of-charge of the energy storage devices are shown.

2) *Energy Management Strategy 2*

When the ultracapacitors are overrated it is not appropriate only to use them for peak powers, as this will not affect the depth-of-discharge of the batteries. It is therefore necessary to operate them as an energy source instead of a pure power source. This is obtained by placing the "Bat-swicth" in position 2. Thereby the battery contribution is zero. However, when the ultracapacitor state-of-charge drops to a critical value $SoC_{UC,crit}$, it is necessary to utilize the battery again. When this happens the "Bat-switch" is placed in position 1.

The bus power and state-of-charge of the energy storage devices when energy management strategy 2 is applied is shown in Fig. 5. In this case the ultracapacitor is overrated with factor $a_{or,UC}$=10. When compared to energy management strategy1, shown in Fig. 4, it is noticed that the load and fuel cell powers are the same. However, as the ultracapacitor in this case has 10 times more energy capacity, it is not necessary to utilize the battery in the shown interval. The battery power is therefore zero, and the battery state-of-charge does therefore not change in the shown interval.

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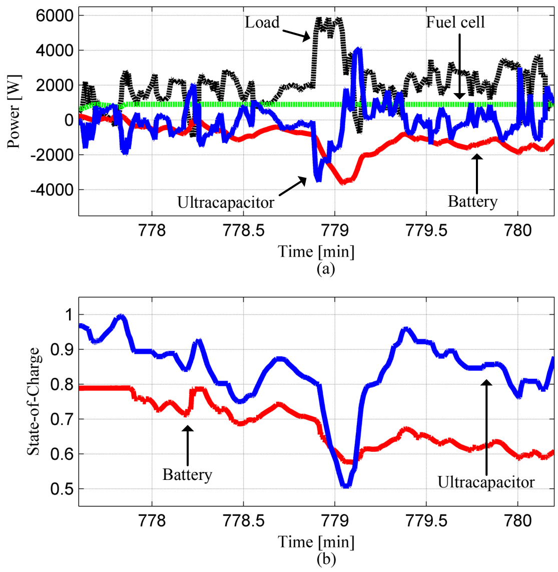

Figure 4. Simulation due to energy management strategy 1. Neither the battery or ultracapacitor is overrated. (a) Bus power contribution. (b) State-of-charge of energy storage devices.

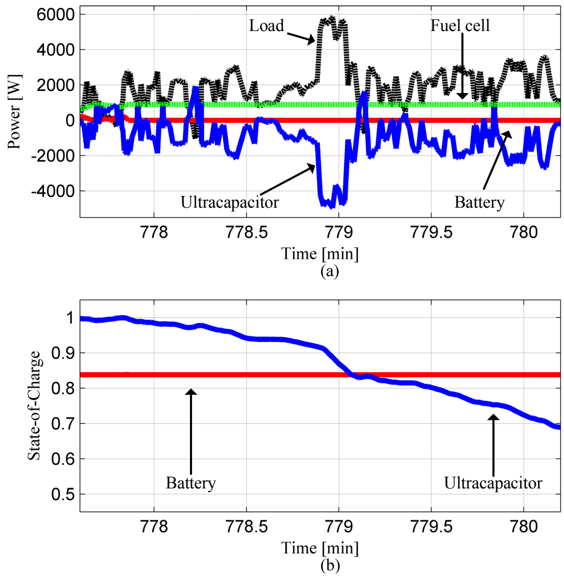

Figure 5. Simulation due to energy management strategy 2. Ultracapacitor overrated with factor $a_{or,UC}$=10. (a) Bus power contribution. (b) State-of-charge of energy storage devices.

3) Selection of Energy Management Strategy

The base rating of the battery and ultracapacitor was under the assumption that the ultracapacitors only was used for peak powers. The maximum energy of the ultracapacitor used for the peak powers is therefore

$$E_{UC,peak,\max} = \left(1 - SoC_{UC,\min}\right) E_{UC,\max} \left[Wh\right]. \quad (7)$$

$SoC_{UC,min}$=0.25 is the minimum allowable state-of-charge level of the ultracapacitor. This energy level has to be available for the peak powers. The critical state-of-charge of the ultracapacitors, that decides when to shift from energy management strategy 1 to 2, is therefore given by

$$SoC_{UC,crit} = SoC_{UC,\min} + \frac{E_{UC,peak,\max}}{E_{UC,\max}} = \frac{1 + \left(a_{or,UC} - 1\right) SoC_{UC,\min}}{a_{or,UC}} \left[-\right] \quad (8)$$

If the vehicle is inactive, i.e. not used by the user, and the ultracapacitor request power, it is chosen to put the "Bat-switch" in position 2. This ensures that the ultracapacitor only is charged from the fuel cell. Thereby the stress of the fuel cell is reduced.

E. Charging Strategy

It is decided to charge the battery with its 5 hour discharge power when it needs to be charged. The requested bus charging power of the battery is therefore

$$p_{Bus,Bat,charge}{}^{*} = \begin{cases} \dfrac{E_{Bat,\max}}{5 \cdot 3600}, SoC_{Bat} < 1 \\ 0, SoC_{Bat} \geq 0 \end{cases} \left[W\right]. \quad (9)$$

When the battery is overrated, the charging power will therefore be bigger. During normal operation it is chosen to charge the ultracapacitors with the fuel cell power rating. However, if the fuel cell is being heated up by the battery, it is chosen to charge the ultracapacitors with the 5 hour discharge power of the batteries in order to reduce the stress of the batteries. Therefore

$$p_{Bus,UC,charge}{}^{*} = \begin{cases} P_{FC,rat}, p_{FC} > 0 \\ \dfrac{E_{Bat,\max}}{5 \cdot 3600}, p_{FC} = 0 \end{cases} \left[W\right]. \quad (10)$$

F. Modeling

Average models are utilized when the power flow, voltages, currents, etc. of the FCHEV are simulated.

1) Electric Machines

The electric machines are of Permanent Magnet Synchronous Machine (PMSM) type. When using the field oriented I_d=0 control, the steady-state dq-model of the electric machines is given by

$$v_q = R_s i_q + \lambda_{pm} \frac{P}{2} \omega_s \left[V\right] \quad (11)$$

$$p_{EM} = \frac{3}{2} v_q i_q \left[W\right] \quad (12)$$

$$\tau_e = \frac{3}{2}\frac{P}{2} \lambda_{pm} i_q = B_v \omega_s + sign\left(\omega_s\right)\tau_C + \tau_s \left[Nm\right]. \quad (13)$$

V_q and v_d are the d and q axis voltages respectively. i_q is the q-axis current, R_s is the stator resistance, λ_{pm} is the flux linkage of the permanent magnet, P is the pole number, p_{EM} is the electric input power of the machine, ω_s and τ_s is shaft angular velocity and torque respectively, τ_e

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is the electromechanical torque, B_v is the viscous friction coefficient, and τ_C is the coulomb friction.

2) Inverter

It is assumed that the inverter loss is due to an equivalent series resistance R_{Inv}. Therefore

$$i_{Inv} = \frac{v_{Bus} - \sqrt{v_{Bus}^2 - 4R_{Inv}p_{EM}}}{2R_{Inv}}[A] \qquad (14)$$

$$p_{Inv} = v_{Bus} i_{Inv} [W]. \qquad (15)$$

i_{Inv} is the inverter input current, and v_{Bus} is the bus voltage.

3) Fuel Cell Stack

The fuel cell stack model is given by

$$v_{FC} = V_{FC,\text{int}} - R_{FC}(i_{FC}) i_{FC} [V] \qquad (16)$$

$$p_{H2} = \frac{M_{H2} N_{FC} LHV_{H2}}{2F} i_{FC} [W]. \qquad (17)$$

v_{FC} and i_{FC} is the fuel cell terminal voltage and current, respectively. $V_{FC,int}$ is the fuel cell open circuit voltage, $R_{FC}(i_{FC})$ is a current depending series resistance, p_{H2} is the hydrogen input power of the fuel cell, M_{H2}=0.00216kg/mol is the hydrogen molar mass, N_{FC} is the number of series connected cells, $LVH_{H2}=120.1 \cdot 10^6$J/kg is the lower heating value of hydrogen, and F=96485C/mol is Faraday's constant.

4) Reformer

It is assumed that the reformer has a constant efficiency of η_{Ref}=0.85% [4]. The power of the methanol is therefore given by

$$p_{Met} = \frac{p_{H2}}{\eta_{\text{Re}f}} [W]. \qquad (18)$$

5) DC/DC Converters

The fuel cell, battery, and ultracapacitor are using the converter topology in Fig. 6. This topology is able to buck and boost the voltage for both positive and negative power levels, i.e. it is a four quadrant converter. It is assumed that the only loss given components of the converter is due to the switch resistances R_T. When the current i_2, and voltages v_1 and v_2 are known, the current i_1 can be calculated. The calculation scheme of current i_1 is given in Table I.

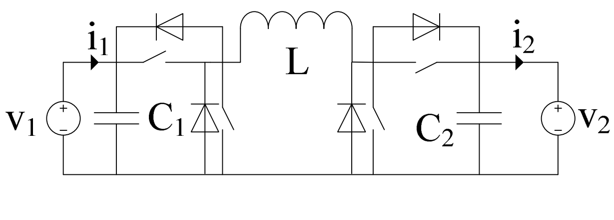

Figure 6. DC/DC converter of the fuel cell, battery, and ultracapacitor.

TABLE I.
DUTY CYCLE AND CURRENT CALCULATION OF DC/DC CONVERTERS

Condition	Duty cycle D [-] and current i_1 [A]
$V_1 \geq v_2$ and $i_2 \geq 0$	$D = \frac{v_2 + 2R_T i_2}{v_1}$
	$i_1 = D i_2$
$v_1 < v_2$ and $i_2 \geq 0$	$D = \frac{2v_2 - v_1 - \sqrt{v_1^2 - 8R_T v_2 i_2}}{2v_2}$
	$i_1 = \frac{i_2}{1-D}$
$v_1 \geq v_2$ and $i_2 < 0$	$D = \frac{v_1 - v_2 - 2R_T i_2}{v_1}$
	$i_1 = (1-D) i_2$
$v_1 < v_2$ and $i_2 < 0$	$D = \frac{v_1 + \sqrt{v_1^2 - 8R_T v_2 i_2}}{2v_2}$
	$i_1 = \frac{i_2}{D}$

6) Ultracapacitor

The ultracapacitors are modeled as a series connection of a capacitor C_{UC} and resistor R_{UC}. Therefore

$$R_{UC} = \frac{V_{UC,\max}^2}{4P_{UC,\max}} [\Omega] \qquad (19)$$

$$C_{UC} = \frac{2E_{UC,\max} 3600}{V_{UC,\max}^2} [F] \qquad (20)$$

$$i_{UC} = \frac{-v_{UC,\text{int}} + \sqrt{v_{UC,\text{int}}^2 - 4R_{UC}p_{UC}}}{2R_{UC}} [A] \qquad (21)$$

$$v_{UC,\text{int}} = v_{UC,\text{int}}(t=0) + \frac{1}{C_{UC}} \int i_{UC} dt \, [V] \qquad (22)$$

$$SoC_{UC} = \left(\frac{v_{UC,\text{int}}}{V_{UC,\max}} \right)^2 [-]. \qquad (23)$$

$v_{UC,max}$ and $v_{UC,int}$ is the maximum and internal voltage of the ultracapacitor, respectively. i_{UC} and p_{UC} is the ultracapacitor current and power, respectively.

7) Battery

In this paper a lead-acid battery is used.

a) Modeling

The battery is also modeled as an internal voltage source $V_{Bat,int}$ with a series resistance $R_{Bat} \cdot rBat_{,pu}(SoC_{Bat})$. Therefore

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$$R_{Bat} = \frac{V_{Bat,\text{int}}^2}{4P_{Bat,\max}} \left[\Omega\right] \qquad (24)$$

$$v_{Bat} = V_{Bat,\text{int}} - R_{Bat} r_{Bat,pu}\left(SoC_{Bat}\right) i_{Bat} \left[V\right] \qquad (25)$$

$$SoC_{Bat} = \begin{cases} 1 + \left|\frac{i_{Bat}}{I_5}\right|^{k-1} \frac{\int i_{Bat} dt}{C_5 3600}, i_{Bat} \le -I_5 \\ 1 + \frac{\int i_{Bat} dt}{C_5 3600}, i_{Bat} > -I_5 \end{cases} \left[-\right] \qquad (26)$$

$$DoD_{Bat} = 1 - SoC_{Bat} \left[-\right]. \qquad (27)$$

R_{Bat} is a series resistance at $SoC_{Bat}=1$, $r_{Bat,pu}(SoC_{Bat})$ is a state-of-charge depending per unit factor, which is utilized in order to model the high resistance at low state-of-charge levels, when the battery is being discharged. $r_{Bat,pu}(SoC_{Bat})$ also models the low charge acceptance, i.e. high resistance, at high state-of-charge levels when the battery is charged. v_{Bat} and i_{Bat} is the battery terminal voltage and current respectively. I_5 is the 5 hour discharge current of the battery, C_5 is the 5 hour discharge Ah capacity, and k is the Peukert constant, which take into account that the battery capacity decreases when the current drawn from it is higher than its 5 hour discharge current [5]. DoD_{Bat} is the battery depth-of-discharge.

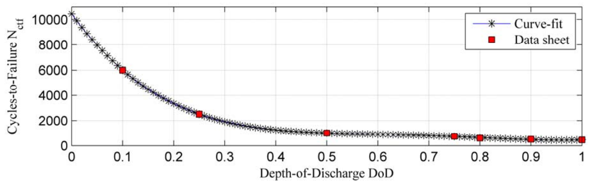

Figure 7. Cycles-to-failure versus depth-of-discharge of a Trojan gel lead-acid battery [6].

b) *Lifetime*

An often used approach to predict the battery lifetime is to count the number of discharge cycles a battery have experienced. In Fig. 7 is shown how many cycles a Trojan deep-cycle gel lead-acid can withstand when it is discharged to a certain depth-of-discharge level. The cycles to failure can be expressed by (37).

$$N_{ctf} = -42418 \cdot DoD^4 - 119140 \cdot DoD^3 + 122320 \cdot DoD^2 - 55583 \cdot DoD + 10449 \left[cycles\right] \qquad (28)$$

By using rain-flow counting method [3], the number of cycles N_{cyc} for each depth-of-discharge level can be counted. The loss-of-lifetime LoL of the battery can then be expressed as [3], [7]

$$LoL = \sum_{DoD_{Bat}=0.01}^{DoD_{Bat}=1} \frac{N_{cyc}\left(DoD_{Bat}\right)}{N_{ctf}\left(DoD_{Bat}\right)} \left[-\right]. \qquad (29)$$

The loss-of-lifetime is a fractional expression of how used the battery is. When LoL=0 the battery have not been used, and when LoL=1 the battery has reach its end-of-life. The expected days of operation of the battery before it reaches its end-of-life is therefore given by

$$N_{day,eof} = \frac{N_{day}}{LoL} \left[days\right]. \qquad (30)$$

G. *System Volume and Mass*

In order to calculate the volume and mass of the propulsion and power system Table II is utilized. The system volume and mass is therefore the accumulation of the volume and mass of the fuel cell stack, battery, ultracapacitor, power electronics (PE), electric machines, and reformer (Ref).

TABLE II.
KEY PARAMETERS OF THE MAIN COMPONENTS OF THE PROPULSION AND POWER SYSTEM

	FC	Bat	UC	PE	EM	Ref
Energy density [Wh/L]	-	71	3.9	-	-	-
Specific energy [Wh/kg]	-	33	3.2	-	-	-
Power density [kW/L]	0.08	-	-	11.5	3.5	1.1
Specific power [kW/kg]	0.2	0.23	4	11	1	0.44

H. *System Efficiency*

The system efficiency is defined as the total energy delivered to the motor shafts relative to the total energy consumption of the methanol during the N_{day} days of operation. Therefore

$$\eta_{sys} = \frac{\sum_{i_{day}=1}^{i_{day}=N_{day}} \int \left(p_{s,L}\left(i_{day}\right) + p_{s,R}\left(i_{day}\right)\right) dt}{\sum_{i_{day}=1}^{i_{day}=N_{day}} \int p_{Met}\left(i_{day}\right) dt} \left[-\right]. \qquad (31)$$

III. RESULTS

A simulation of the FCHEV has been performed due to the charging and energy management strategies. In Fig. 8 the system volume, mass, efficiency, and battery lifetime can be seen when either the battery or ultracapacitors are overrated.

In Fig. 8 (c) it is seen that for the base rating of the energy storage devices, i.e. $a_{or,Bat}=a_{or,UC}=1$, the expected battery lifetime is $N_{day,eof}=152$ days. When the battery capacity is increased with overrating factor $a_{or,Bat}=2$, the lifetime is increased to $N_{day,eof}=424$ days. For $a_{or,Bat}=5$ the lifetime is $N_{day,eof}=1567$ days. However, for this case the system volume in Fig. 8 (a) is also increased more than a factor 2, the system mass in Fig. 8 (b) is tripled, and the system efficiency in Fig. 8 (d) has slightly decreased. The reason that the system efficiency decreases for bigger battery capacity, is that the battery charging power due to (2) and (9) then becomes bigger. Therefore the fuel cell

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must provide more power, which decreases the efficiency of the fuel cell.

In Fig. 8 (e) to (h) the ultracapacitor is overrated. In comparison to the battery overrating the effects are not so significant when the ultrcapacitor is overrated. In Fig. 8 (g) an improvement in battery lifetime is seen. However, the ultracacitors must be overrated with a factor $a_{or,UC}$=10 in order to obtain the same battery lifetime as when the battery is overrated with factor $a_{or,Bat}$=2. For these two cases, the overrating of the battery will provide the smallest and lightest system. The efficiencies are the same. For this specific application it is therefore not beneficial to overrate the ultracapacitor, as better results can be obtained by overrating the battery.

IV. Conclusion

In this paper the energy storage ratings of a battery/ultracapacitor FCHEV has been investigated. The modeling, charging and energy management strategies of the FCHEV have been presented. The system volume, mass, efficiency, and battery lifetime have been compared when either the battery or ultracapcitor are overrated. It is concluded that for this specific application it is not beneficial to overrate the ultracapacitors, as better results can be achieved when the battery is overrated. Significant better battery lifetime can be obtained by oversizing the battery, but this has also a negative effect on the system volume, mass, and efficiency. A sufficient rating of the energy storage devices is therefore a trade-off among several parameters.

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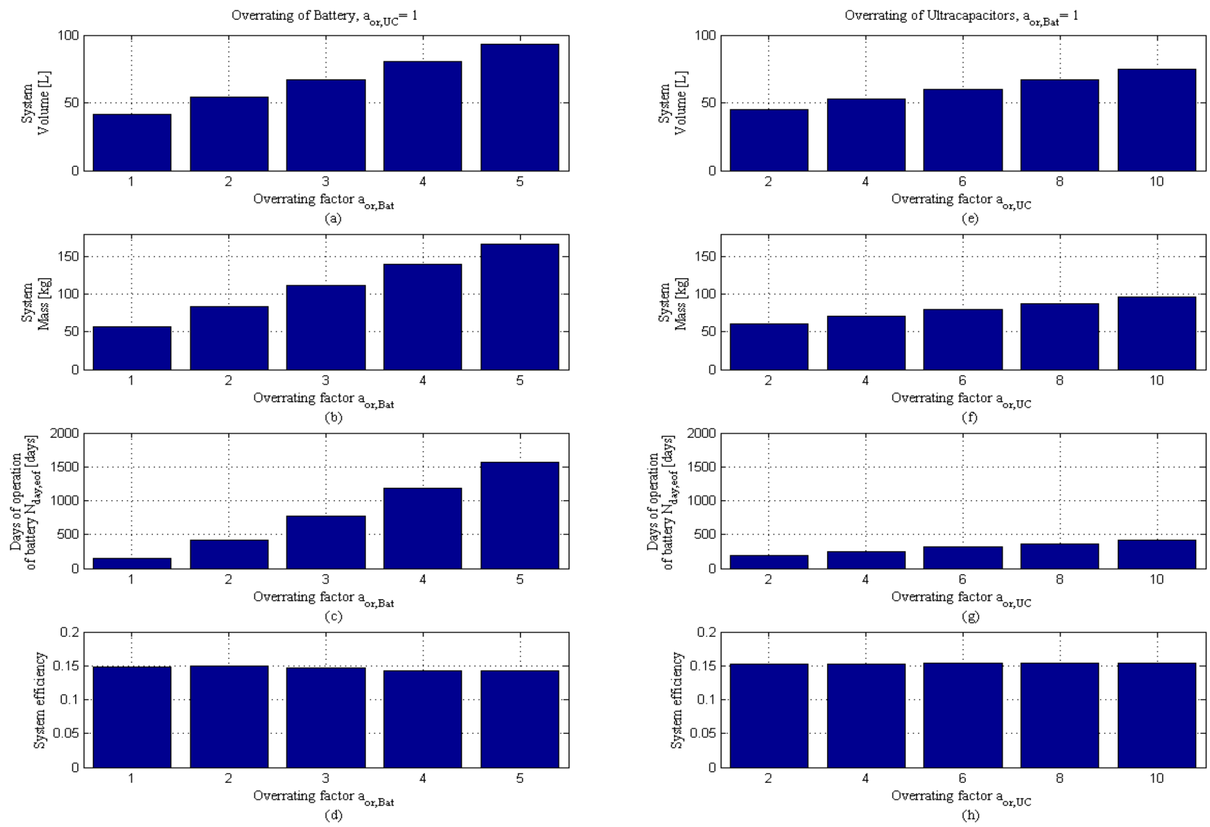

Figure 8. Comparison of system volume, mass, battery lifetime, and efficiency. (a) to (d) Overrating of the battery. (e) to (h) Overrating of the ultracapacitor.

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