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FC vehicle hybridisation: an affordable solution for an energy-efficient FC powered drive train

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Abstract

Fuel cells (FCs) have potential as clean and efficient energy sources for automotive applications without sacrifice in performance or driving range. However, the complete FC system must operate as efficiently as possible over the range of driving conditions that may be encountered while maintaining a low cost. To achieve this target, a storage unit can be introduced in the FC system to reduce the size of the fuel cell that is the most expensive component. This “hybrid” concept would not only reduce the drive train total cost but it also allow the recover of the braking energy and the operation at the voltage–current point of maximum efficiency for the FC system. Pro-and-cons of the “full-power” versus the “hybrid” configuration are shown in this work. The “Hybridisation rate” or “Hybridisation degree”, a parameter expressed by the relationship between two installed powers, the generation power and the traction power, is also introduced and it is demonstrated that for each category of hybrid vehicles there is an optimal value of hybridisation degree. The storage systems considered are based on high power batteries or ultra capacitors (UCs) or a combination of them. A preliminary design of a sport utility vehicle (SUV) using a combined storage system and a FC energy source (called *Triple Hybrid*), is proposed. Finally, the experience of the Italian industry in this field is also reviewed.

Keywords: Fuel cells; Internal combustion engine; Duty cycle

1. Introduction

With the rapid rate of advance in fuel cell (FC) technology and major resources from the automotive industry being directed at commercialisation of FC propulsion systems for transportation, it looks more promising than ever that FCs would soon become a viable alternative to internal combustion engines (ICE). One benefit that has been driving the development of FCs for automotive applications is the potential for a clean and efficient on-board energy production without any sacrifice in performance or driving range of the vehicles. However, to fully achieve the potential energy savings of a fuel cell vehicle (FCV) it is mandatory to recover the braking energy and ensure the operation of the FC system at the maximum efficiency over the entire range of driving conditions encountered. This key target can be reached by a hybridisation approach as for internal combustion engine powered hybrid electric vehicles (HEV). Fuel cell hybrid electric vehicles (FCHEV) would present the advantages from the cleaner and more efficient energy source combined with the energy savings typical of electric vehicles. Both cars and busses of these types have been designed and produced by the world’s major carmakers, like Honda, Nissan, Fiat, IVECO, Scania, etc.

2. Pro and cons of FCV hybridisation

What are the advantages of HEVs versus conventional vehicles? Because of the secondary power source, generally a battery pack, HEVs can [1]:

- Reduce the ICE torque and speed transients, thus attaining fuel economy and emission reductions.
- Achieve the ICE operating point of maximum efficiency during the cycles, thus reducing the size of the engine (see Fig. 1).
- Recover the braking energy.

The issues in FCVs are a bit different because torque and speed transients are not a problem from the emission and fuel consumption point of view. The traction system is

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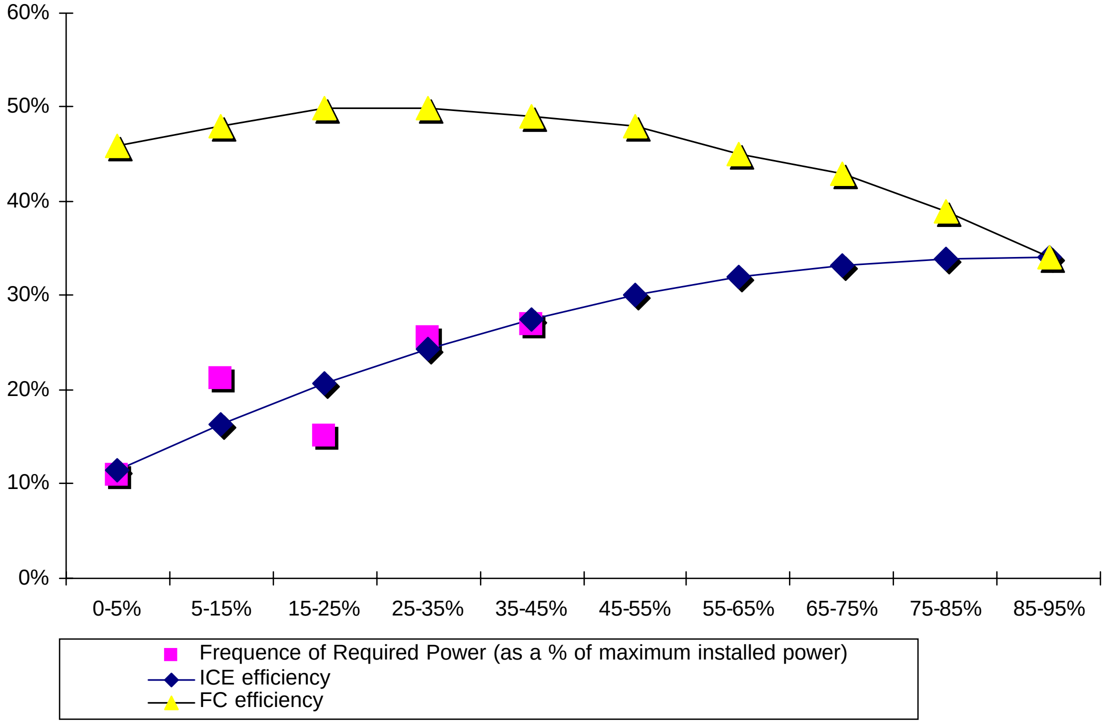

Fig. 1. Frequency (ECE-15 cycle) of vehicles power requirement (as a percentage of maximum installed power) graph and typical ICE and FC efficiencies vs. the same percentage.

electrically connected to the generation system so that the drive cycle speed transients generally do not influence the generator efficiency. In addition, the FC efficiency curve better matches the energy use during urban cycles (see Fig. 2) and the optimisation of the generator during the cycle is not longer required. In comparison with a thermal motor, the efficiency peak of a FC is more toward the middle-low power and therefore it is better adapted to urban cycles [2]. Nevertheless, an automotive fuel cell system could still benefit from a storage unit because of the size reduction and to prevent excessive operation at light loads or ON/OFF operation due to minimum power requirements.

Summarising, a storage unit can be employed together with FCs in order to:

- reduce the size of the FC (that is the most expensive component of the system) thus reducing the drive train total cost;
- reduce the power transients thus simplifying the “balance of plant” configuration and enhancing its efficiency. Basically, a hybrid system has the flexibility to optimise the combination of component characteristics and energy management strategy parameters to nullify the fuel economy impacts of a slow responding fuel cell system [3];

Fig. 2. Irisbus hydrogen-fuelled, FC powered bus operating in the city of Turin.

Table 1
Characteristics of different FC powered bus architectures considered by Ansaldo Ricerche

	FC (full-power)	FC + battery	FC + UC	FC + battery + UC (series configuration)
Architecture	Step-up chopper without galvanic insulation Chopper and braking resistor	High-frequency dc/dc converter with galvanic insulation	Customised electronics	High-frequency dc/dc converter with galvanic insulation dc/dc converter for current sharing Battery and UC in series
Power	Chopper: 165 kW	dc/dc: 65 kW	FC: 65 kW UC: 100 kW	Main dc/dc: 65 kW
Volume	80/100 l chopper + 380 l resistor	510 mm × 540 mm × 320 mm	40 l	600 mm × 540 mm × 320 mm
Weight	80/100 kg chopper + 90 kg resistor	50 kg	30 kg	70/75 kg
State-of-the-art	Prototypes (Ballard bus)	Under test on FC bus prototype	Preliminary study	Feasibility analysis in progress

- reduce the start-up power transients that may strongly affect the performance depending on the FC system configuration, e.g. direct hydrogen or methanol powered. In case of cold start-up, the on board energy storage can be used to accelerate the system heating and to move the vehicle throughout this phase; and
- recover the braking energy, that is produced and made available in form of electricity (otherwise this energy will be dissipated thermally).

With regard to the latter point, road-test monitoring performed by ENEA on Altra (12 m) busses in Terni, demonstrated a reduced fuel consumption of 1.4 kWh/km that is 22% less of the 1.8 kWh/km recorded in the absence of the braking energy recovery. Analogous results were obtained with the small Altrobus vehicle on the ENEA roller bench. Referring to cars, roller bench tests performed at Argonne National Laboratory (ANL) on Toyota *Prius* and Honda *Insight* [4], gave a fuel consumption reduction associated with the braking energy recovery ranging from a minimum of 3.5% (highway duty cycle (DC)) to a maximum of about 20% on urban duty cycles such as the Japanese J10-15 and the urban American cycles (LA4 and NYCC).

Finally, “Full-power” drive train configuration busses present another problem. Since FCs are not regenerative, they cannot accept energy from braking, thus mechanical brakes need to be designed to dissipate all the kinetic energy. This problem already exists for conventional buses, especially if the duty includes frequent hill climbing. “Eddy current” devices, helped when possible by exhaust braking, generally represent the solution.

Obviously, these advantages require a greater system complexity, but not necessarily a heavier or more expensive generation system electronics. For example, in the FC bus (shown in Fig. 2) manufactured by Irisbus [5,6] for the city of Turin, the full-power electronic (step-up chopper) is heavier and more expensive (+30%) than a solution adopting the “FC + battery” power system. The latter consists of a smaller high-frequency dc/dc converter, directly derived from current practice in conventional hybrids and therefore reliable. Similar is the case of UC storage, or battery + UC storage (mixed or “hybrid” storage) for which preliminary study from Ansaldo Ricerche show that the power electronics weight is reduced with respect to full-power FC systems. In Table 1 is shown a comparison of four different solutions examined by Ansaldo. The UC storage solution appear to be ideal in terms of weight, overall dimensions and costs (at least with respect to electronics).

2.1. Cost related considerations

In vehicles devoted predominantly to urban use, the hybridisation presents an economic advantage due to the strong cost difference between a FC generator and a battery storage, the latter being much less expensive. It is foreseen that the specific cost (US$/kW) difference between will remain high. The DOE cost objective (2010) for FCs (FreedomCar Program) is US$ 45 per kW while the specific cost goal for high power energy storage program is about US$ 20 per kW [7]. In conclusion, for a fixed installed maximum power the overall cost of a hybrid system is expected to be lower than of a full-power system.

3. Hybrid vehicles classification and hybridisation degree

In a hybrid electric vehicle the storage system must be able to:

1. recover the otherwise dissipated braking energy;
2. level the peak power required (load levelling), thus enabling the generator to deliver a constant power, e.g. the average required power (such power could be adjusted to the demand fluctuation throughout time with very slow transients if the primary source is an IC engine); and
3. deliver continuously the additional power required.

Therefore, a correctly designed storage system should contemporarily meet to requirements: (i) the *maximum power output* necessary to compensate the difference between the generator power and the maximum power required by the vehicle (forecasted maximum power) and (ii) the *energy content* sufficient to avoid the complete discharge during any power demand period (required storage

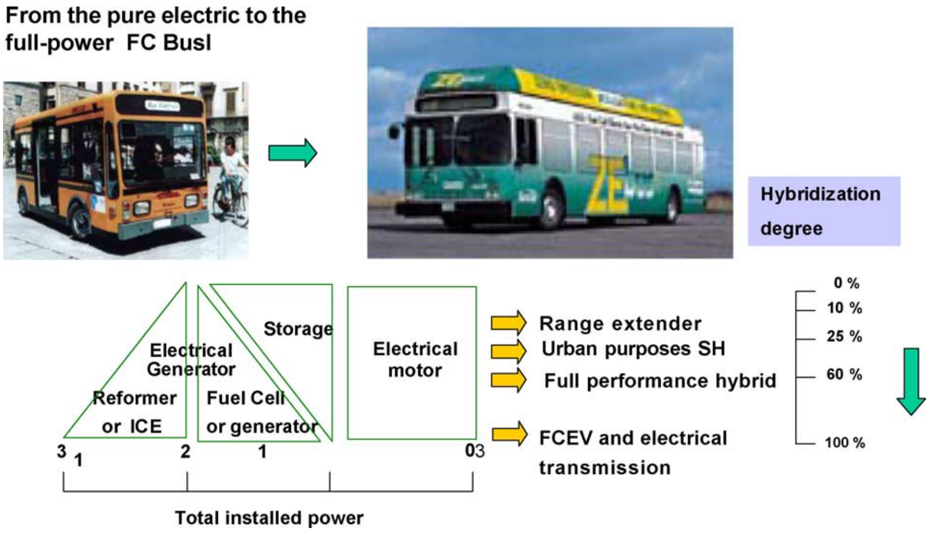

Fig. 3. Schematic representation of HEV classification.

energy). The value of these two design parameters depends on two main factors: the driving cycle, and the hybrid system configuration. In series hybrid vehicles like fuel cell hybrids electric vehicles (FCHEV) the system configuration can be represented by an index called “Hybridisation rate” or “Hybridisation degree” that is expressed by the ratio between the installed power source (generator) and the power required for traction:

$$\text{hybridisation degree} = \frac{P_{\text{gen}}}{P_{\text{tract}}}.$$

This concept, proposed by OAATs [7] in the “Vehicle High-Power Energy Storage Program”, allows to state specific objectives for energy storage requirements that differ for different types of hybrid electric vehicles, among which FCHEVs are a particular case. In terms of HEV classification, the full spectrum of series HEV (Fig. 3) starts from pure-electric vehicles (only batteries) to full-power fuel cell vehicles (FCEV) and ICE powered vehicles with electrical transmission (diesel–electric).

FCHEVs, hybrid vehicles in which the primary generator is a fuel cell, can certainly be classified according to the aforementioned HEV classification. Table 2 lists fuel cell powered vehicles already on the road. Most of them are FCHEVs characterised by a high hybridisation degree with the lower values seen for urban busses. For the HEV classification criteria (storage point of view) the FC powered cars listed in Table 2 can be considered as “power assisted” HEV. The majority of these vehicles have a storage system composed by a high power battery which are, in four cases (VW *Bora HyMotion*, Honda FCX-V3, Mazda *Demio* FC-EV, bus Man), integrated or replaced by ultra capacitors (UCs). It is important to point out that Toyota’s *Kluger V* uses the same battery pack of the *Prius*, a conventional hybrid with more than 100,000 units already manufactured, to benefit of the same reliability and affordability. The storage pack used in Ford’s *Focus* is most probably the same of the *Escape*, a SUV hybrid that will be launched on the marked since 2003.

4. Optimal hybridisation degree

The differences in duty cycles of urban buses, generally repeated and therefore easily foreseeable, and cars, unpredictable mixed urban and extra urban cycles, make very difficult to define a general optimal hybridisation degree. According to Table 2, the hybridisation is generally high (up to 100%) in cars and low in busses. In the following two cases will be distinguished, general-purpose vehicles, like cars, and urban busses.

4.1. General-purpose vehicles

As a result of the high power primary energy source (IC engine or fuel cell), vehicles with high hybridisation rate (see Table 2) mainly uses the storage unit for braking energy recovery and management of acceleration quick transients. Indeed, these vehicles have a small storage capacity compared with vehicles with lower hybridisation rate. For example, the storage capacity installed on the Honda *Civic IMA* (a “power assist” hybrid) is only a half of that on Toyota *Prius* (a “dual mode” hybrid) even though both vehicles belong to the medium class. The availability of a high power generation makes it possible (in most cases) to continuously balance generator power and load even if transients are slow and controlled. As a consequence, the power flows in the vehicle can be managed with the generator always on (defined as “load following” mode, opposite to thermostatic or ON/OFF operation) and a duty cycle close to 100%. The load-following mode shows a positive effect especially in vehicles powered by a fuel cell, whose performance curve is flatter than ICE (see Fig. 1).

Table 2
Characteristics of prototype FC powered vehicles

Vehicle	Class	Traction power (kW)	FC power (kW)	Storage system and power	Hybridisation rate (%)
Honda FCX-V4	Compact car	49	78	UC	N/A (100)
Mazda Demio FC-EV	Compact car	N/A	20	20 kW, UC	50
Fiat 600 FCHEV	Compact car	30	7	26 kW	23
Ford Focus	Midsized car	67	85	15 kW, Ni–MH	100
VW Bora HyMotion[a]	Midsized car	75	75	30 kW, UC	100
Toyota Kluger V[b]	SUV	80	90	20 kW, Ni–MH	100
Nissan X-Terra	SUV	N/A	75	25/16 kW Li-ion	75
Daimler-Chrysler, Jeep Commander	SUV	N/A	75	Ni–MH, 230 kg[c] 50 kW (?)	N/A
Solectria[d]	Autobus 10.5 t	2 × 75	50	100 kW	33
Irisbus FC bus	Autobus 15 t	162	60	100 kW	37
Man Berlino 2002[e]	Autobus 15 t	2 × 75	120	UC	80
Scania[f]	Autobus 15 t	150	50	100 kW	33
Toyota[g]	Autobus 15 t	2 × 80	90	70 kW	56
Thor Ind./ISE[h]	Autobus 15 t	150	60	90 kW	40
Georgetown University[i]	Autobus 18 t	186	100	100 kW	53

[a] SAE Automotive Engineering International, July 2002.

[b] "Development of Fuel Cell Hybrid Vehicle", Tadaichi Matsumoto, Nobuo Watanabe, Hiroshi Sugiura, Tetsuhiro Ishikawa, TOYOTA MOTOR CORPORATION, EVS-18, October 2001, Berlin.

[c] http://www.daimlerchrysler.de/research/htr2001/pdf_e/energy2_e.pdf.

[d] "Design of a Fuel Cell Hybrid Electric Heavy-Duty Vehicle", A. Tarnow et alii, EVS-18, Berlino, Ottobre 2001.

[e] "Hydrogen Powered Fuel Cell Buses Meet Future Transport Challenges", Karl Viktor Schaller, Christian Gruber, and "Diesel-electric Drive Systems for City Buses: Improvement of Efficiency by using Double Layer Capacitors as a high Power Storage", Karl-Viktor Schaller, Stefan Kerschl, Karlheinz Dörner, EVS-18, Berlino, Ottobre 2001.

[f] Axane (Nuvera/Air Liquide) brochure, EVS-18, Berlino, Ottobre 2001.

[g] Toyota brochure, EVS-18, Berlino, Ottobre 2001.

[h] "The Hybrid Electric FC bus: a city bus option", R. Riegel et alii, 14th World Hydrogen Energy Conference, Montreal 2002.

[i] Georgetown University brochure, EVAA, Sacramento, Dicembre 2001.

The power fluxes within the FCHEV drive system are illustrated in Fig. 4 [8]. Considering a vehicle mission of time length T_{miss}, during which the generator power setting P_{s}^{*} is maintained constant (the generator operates on a ON/OFF operation), it is possible to define the following mission parameters:

- P_{mg}, average generator power during the mission:

$$P_{\mathrm{mg}} = \frac{1}{T_{\mathrm{miss}}} \int_{T_{\mathrm{on}}} P_{\mathrm{s}}^{*}\, \mathrm{d}t \tag{1}$$

- P_{att}, average drive power demand when $P_{\mathrm{load}} > 0$, that is the power demand during active phases (braking phases are excluded):

$$P_{\mathrm{att}} = \frac{1}{T_{\mathrm{miss}}} \int_{T_{\mathrm{att}}} P_{\mathrm{load}}\, \mathrm{d}t \tag{2}$$

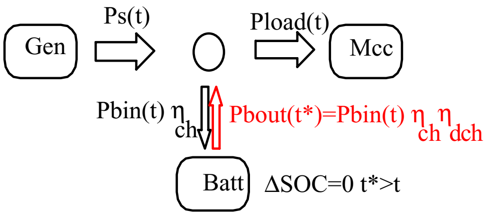

Fig. 4. Schematic representation of the instant power fluxes between the HEV subsystems.

- DC_{t}, "theoretical duty cycle", or calculated duty cycle, expressed in %, given by the ratio:

$$\mathrm{DC}_{\mathrm{t}} = \frac{P_{\mathrm{att}}}{P_{\mathrm{s}}^{*}} \tag{3}$$

- DC_{r}, "real duty cycle", or measured duty cycle, given by the ratio:

$$\mathrm{DC}_{\mathrm{r}} = \frac{P_{\mathrm{mg}}}{P_{\mathrm{s}}^{*}} \tag{4}$$

As for the P_{mg} definition, DC_{r} is also equal to the ratio of the generator ON time and T_{miss} (mission time) and therefore can be easily obtained from roller bench tests. For example, using the experimental data sets obtained for the ENEA mobile laboratory hybrid vehicle in the roller bench test facility at ENEA shown in Fig. 5, it is possible to plot the parameter DC_{r} versus DC_{t} (see Fig. 6).

Since the 20 kWh lead–acid battery pack storage unit does not operate with 100% efficiency due to several energy loss mechanisms, it is important to identify the mission operating conditions in which the hybridisation would give a benefit to the overall energy balance. The $\mathrm{DC}_{\mathrm{r}}/\mathrm{DC}_{\mathrm{t}}$ ratio can be used as an index to evaluate the benefit obtained by the system hybridisation. In fact, if the braking energy recovered is larger than the energy losses of the storage battery, than the measured duty cycle (DC_{r}) is lower than the theoretic one (DC_{t}) because the generator is ON for a time shorter

Fig. 5. Picture of the roller bench test facility at ENEA Casaccia Research Centre.

than it would be necessary without system hybridisation. In general, it is possible to distinguish three cases:

- $DC_r < DC_t$ or $DC_t/DC_r > 1$, battery energy balance is positive;
- $DC_r = DC_t$ or $DC_t/DC_r = 1$, battery energy balance is neutral;
- $DC_r > DC_t$ or $DC_t/DC_r < 1$, battery energy balance is negative.

In Fig. 6, the straight line represents the neutral case where $DC_r = DC_t$ that corresponds to the condition in which the storage unit does not affect the overall energy balance. The experimental curve evaluated with the tests on the above-mentioned vehicle, crosses the neutral case for DC_t equal to 0.78. For theoretical duty cycles lower than 0.78 it is found that $DC_r > DC_t$, i.e. the energy loss of the storage unit is larger than the braking energy recovered thus the use of the storage unit is not justified. On the other hand, DC_r higher than DC_t is found for values of the latter larger than 0.78, i.e. the storage unit gives a net benefit.

The validity of the proposed index (DC_t/DC_r) has been experimentally verified by measuring the fuel efficiency in

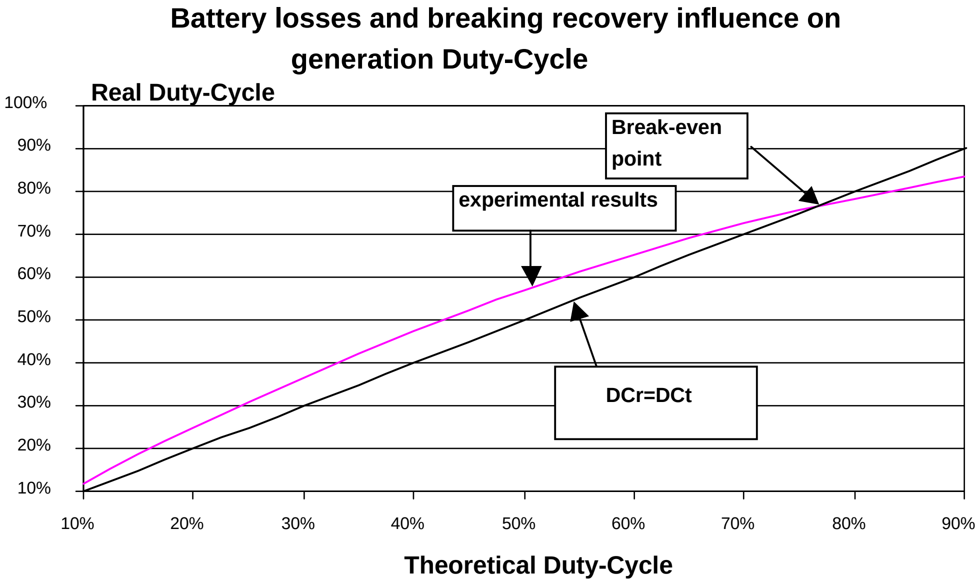

Fig. 6. DC_r vs. DC_t, plot for the *ENEA mobile laboratory hybrid vehicle* equipped with a 10 kW diesel engine and a 20 kWh lead–acid battery pack storage unit.

Table 3

Experimental parameters determined for the *ENEA mobile laboratory hybrid vehicle* as determined by roller bench tests in various mission profiles having different duty cycles

Vehicle type	Cycle type	Fuel consumption (kg/h)	P_s* (W)	P_{mg} (W)	Actual duty cycle (%)	P_{att} (W)	Energy efficiency (=P_{att}/fuel consumption) (%)
1.5 t HEV	ECE15	1.96	9000	4704	52.3	4653	19.8
	ECE15	1.94	8000	4779	59.7	4658	20.0
	ECE15	1.82	7000	4684	66.9	4568	20.9
3.5 t HEV	ECE15	2.19	9000	7012	77.9	7251	27.6
	J10-15	2.36	9000	6980	77.6	7370	26.0
	UDDS	2.58	9000	7930	88.1	9140	29.5

roller bench tests. The experimental data reported in Table 3 show that the efficiency was higher for those missions having a higher duty cycle and lower when the duty cycle is smaller. However, it is not always preferable to operate the vehicle in the upper part of the curve, were $DC_t > DC_r$, as the overall system performance has to be taken into account considering both the performance of the system hybrid part (converter, storage pack and control system), and the performance of the generator itself. If the generator performance is high in a wide range of P_{gest} than it is always better to operate the vehicle above the breakthrough point, i.e. in condition very close to a "load following" mode. To operate in such a way, a high hybridisation rate is needed. On the highways, for example, P_{att} is high, so P_{mg} must be high too, i.e. a high hybridisation rate is the ideal solution to reduce the fuel consumption.

Hence, from the energy point of view, general-purpose vehicles equipped with a fuel cell generator surely benefit of a power storage unit which does not exceed 20–30% of the maximum traction power (sufficient to recover most of the braking energy) that accounts for a hybridisation rate of about 70%. Indeed, the hybridisation rate of sedans selected by most of car manufacturers is close to 100% (see Table 2) because the vehicle design was generally derived from "full-power" version, like VW *HyPower* and Ford *Focus*, or hybrid versions were obtained by simply adding a braking energy recovery device. This approach does not give any plant cost reduction—except for the opportunity of managing the cell more smoothly, while designing a simpler generation system would translate into savings in management costs. This lead to a more general question: is there an optimal value of the hybridisation degree from the point of view of fuel economy that would also allow weight and cost reduction of fuel cells? An indication can be obtained by examining the results reported by many researchers that have simulated the behaviour of vehicles in many different cycles and compared the results for different hybridisation degrees.

The first work relating to optimisation of hybrid vehicles includes efforts at the University of California Davis [2], indicated that benefits are highly cycle dependent. In particular, for the FUDS cycle a 17% increase in fuel economy was evaluated while for the high power US 06 driving cycle a decrease (−20%) in fuel economy was calculated. In both cases a hybrid load-levelled configuration was used.

However, other control strategies such as the load-following control strategy, work better than a thermostatic (ON/OFF) operation. The results obtained by the National Renewable Energy Laboratory and the Virginia Polytechnic University and State Institute (Table 4) [9], using the ADVISOR model of the FCHEV, showed for a PNGV class sedan an increase in fuel economy also for aggressive cycles like US 06. Another point is that FC downsizing is more effective for urban cycle, like UDDS.

In another paper [10], (results are also reported in Table 4) the same authors used the optimisation tools linked to ADVISOR and demonstrated that for a 1800 kg SUV, the optimal hybridisation degree ranges from 55% for the European NEDC to 71% for the US 06. Moreover, the study demonstrated that the optimisation for the NEDC cycle produced a vehicle that provided excellent off-cycle fuel economy performance. Finally, DOE 2001 Annual Progress Report "Fuel Cells for Transportation", presented at Future Car Congress (Arlington, June 2002) reports the optimisation study for a hybrid SUV powered with a hydrogen-fuelled fuel cell. The best design consisted of a 64 kW (net) fuel cell, a 124 kW traction motor and a 105 kW battery pack, corresponding to a hybridisation degree of 51%.

4.2. Urban busses

The average power required for a urban bus is always a fraction of the maximum power required by the traction motor. Moreover, missions are predictable. The average power can be easily estimated and a preliminary hybridisation degree can be calculated by the following formula:

$$\mathrm{HD} = \frac{P_{\mathrm{average}}}{P_{\max}}$$

Table 4

Optimal hybridisation degree for different types of vehicles

Vehicle type	Mass (kg)	Average fuel economy (%)	Optimal hybridisation degree		
			UDDS	NEDC	US 06
PNGV	1200	+70	0.3	–	0.8
SUV	2900	+30	0.85	–	0.8
SUV	1800	–	–	0.55	0.71

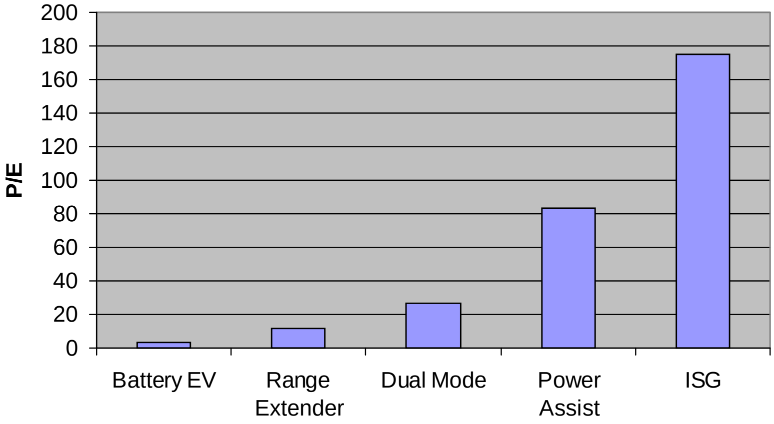

Fig. 7. Storage unit P/E ratio required in different HEV categories.

Thus, if the power required by the motor is shared between two devices an economic benefit from cost reduction exists as storage devices heavier but cheaper than fuel cells are made. As a matter of the fact, storage devices having specific power equal to or higher than power generators are available at a lower cost than FC. As a consequence, available urban busses have hybridisation rate lower than general-purpose vehicles, e.g. from 33% of Solectria to 80% of Mann (see Table 2). In this way, the power system cost as well as the management cost is greatly reduced when compared with a full-power system since braking energy recovery can also be performed.

5. Storage systems requirements: P/E ratio and storage systems

The relationship between two mission-dependent parameters, the pulse discharge power (P) and the total available energy (E), is useful to correctly design the vehicle storage system. For the "power assist" and "dual mode" hybrid categories considered by OATT, the power/energy ratio (P/E) is calculated to be 83 W/Wh and 27 W/Wh, respectively. In general such a ratio can be calculated for any kind of storage device by dividing its specific power (W/kg) by its specific energy (Wh/kg). For instance, available traction batteries have a P/E ratio between 1 and 4 that is good for pure EV but far too low for hybrid applications. High power lead–acid or Ni–MH batteries offer more adequate P/E ratios, approx. 10 W/Wh, with specific power and energy of about 300 W/kg and 30 Wh/kg for the former, 4–500 W/kg and 50–70 Wh/kg for the latter. UCs benefit from higher P/E ratios exceeding 100 W/Wh since the specific power is very high, up to 1000 W/kg, and the specific energy is less than 5 Wh/kg.

Conceptually speaking, a storage system having the P/E ratio required by the considered hybrid vehicle's typical mission, would have all the power needed for the cycle power peaks without storing more energy than necessary. The P/E ratio is shown in Fig. 7 for the whole range of HEV.

UCs seem to be more suitable than batteries to satisfy in a balanced way the energy and power requirements of "power assist" hybrids like FCHEV [11]. High-power lead–acid or Ni–MH batteries would accumulate a useless excess of energy (FC powered vehicles are considered ZEV) and would be detrimental to the overall performance because of the high weight.

6. Batteries and UCs: other pro and cons

Indeed, for a proper choice of the HEV storage system there are other problems to be considered also that are related to the system reliability, life and cost. For example, the UC cycle life is longer than the battery life, up to 5000 h (and more) in a urban cycle (Fig. 8). For the same specific power, the cycle (discharge/charge) efficiency is higher too, ranging from 90 up to 98%, thanks to the lower internal resistance (Fig. 9). This is a very important point to stress; since the storage is smaller in a hybrid vehicle than in a "pure-electric" vehicle, the low internal resistance of the storage unit is much more important in the former than in the latter.

UCs show an advantageous effective braking energy recover over batteries, which require mechanical braking before electric braking to prevent their over-stressing. In fact, UC are limited in storage capacity but not in current, so that the braking energy recover can be more complete and effective. Finally, batteries have difficulty functioning in cold weather creating significant inconveniences, whereas UCs can operate successfully in wide temperature ranges, extending to as low as $-40\,^{\circ}$C.

7. The triple hybrid: fuel cell + battery + ultracapacitor

Table 5 lists the performance and the cost of prototype (Saft) and commercially available HEV storage systems [13]. No commercially available HEV storage system based

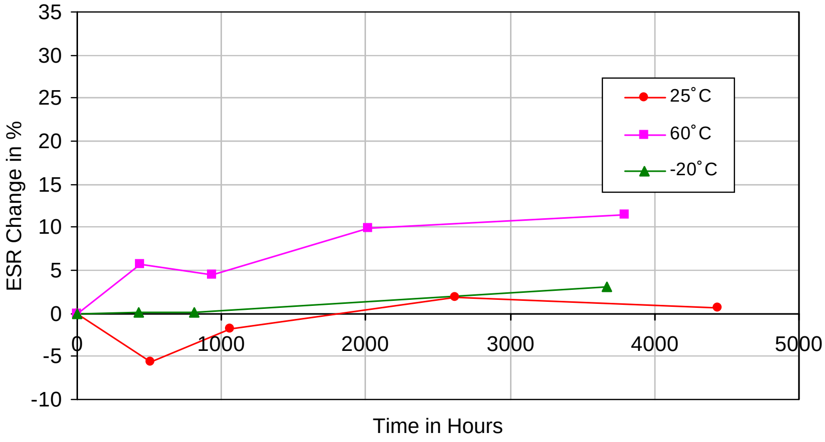

Fig. 8. Variation of internal resistance (ESR) vs. time at different temperatures. Data are kindly provided by Maher (Maxwell) [12].

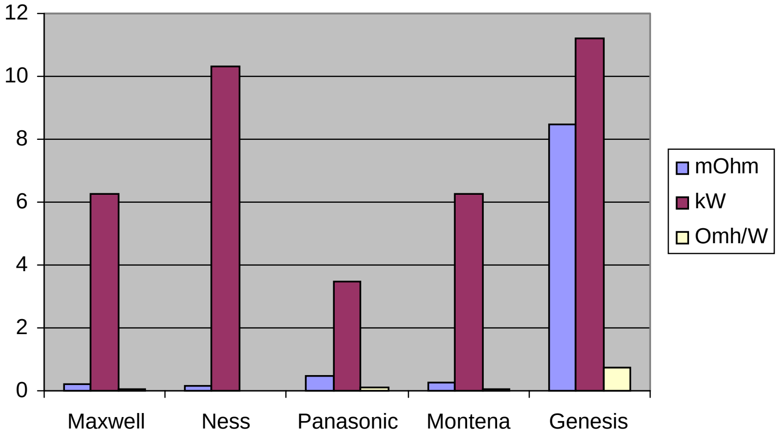

Fig. 9. Comparison of the characteristics of several UCs (Maxwell, ness, Panasonic, Montena) and high-power lead–acid battery (Genesis).

on UCs exists because the present cost of these devices is too high for this application. For example, a prototype city car storage system (total capacity 67 F, nominal voltage 120 V), composed by EPCOS B48710 UCs, would cost about US$ 8000. The economic feasibility of this innovative solution, with respect to the usual approach for hybrid vehicles, is strongly tied to the cost reduction forecast of UCs. As stated earlier, these devices are currently very expensive, however, manufacturers like Epcos and Maxwell PowerCache, anticipated a drastic reduction since the base materials used in their construction (carbon cloth or carbon particulate for the electrodes and the organic solvent for the electrolyte) pose no significant barrier to affordable cost in quantities typical of the automotive market. According to PowerCache and Epcos, an approximate cost of US$ 0.01–0.02 per F is forecasted by the year 2004 for a production at volumes in the millions, corresponding to US$ 10–20 per Wh. However, to further reduce the total costs, it would be desirable to combine the characteristic of UC and batteries, as illustrated in Fig. 10, by load levelling the generator–battery system with UCs, which have high power density. In this way it would be possible to regenerate

Table 5
Characteristics of high power batteries and UCs

	W/kg	Wh/kg	*P*/*E*	Specific cost
Ni–MeH (Ovonic 12HEV60)	550	68	8	US$ 1000 per kWh
Li-ion (Saft 12 Ah)	370	125	15	–[a]
High power Li metal (Avestor)	521	45	12	N/A
Pb (Genesis 13 Ah)	250	25	10	US$ 250 per kWh
Ucs	800	3.7	216	N/A

[a] “The cost ratio is almost 2-to-1, lithium-ion being more expensive than nickel metal hydride”, M. Anderman, A.A. Batteries, EV World Update 2.11.

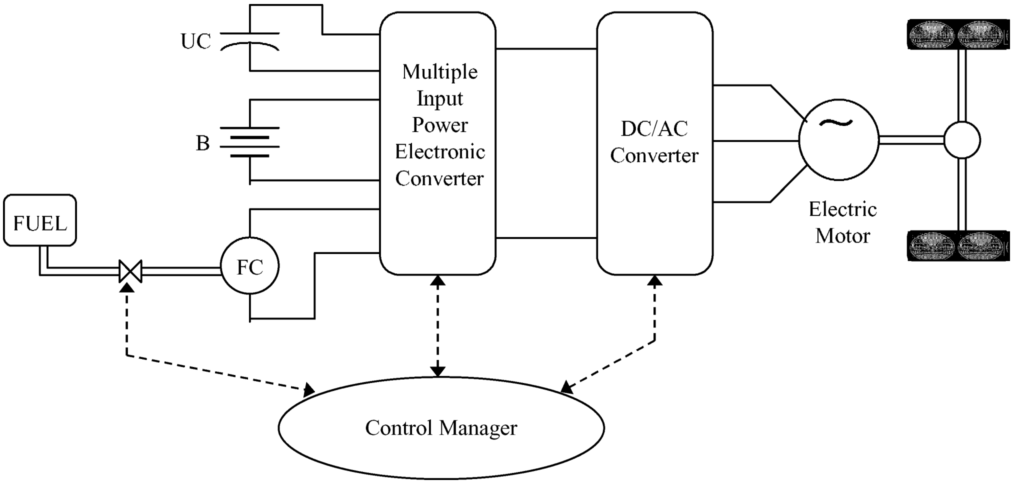

Fig. 10. Schematic illustration of a *triple hybrid* (FC + UC + battery) HEV.

Fig. 11. The 35 kW prototype of a *triple hybrid* (FC + UC + battery) jointly developed by ENEA and University of ROMA TRE.

the braking energy with high efficiency and to supply the stored energy during acceleration in order to reduce the peak power requirements of the FC–battery unit [14–17].

A 35 kW prototype of such a propulsion system (Fig. 11) has been jointly developed by ENEA and University of ROMA TRE to conduct laboratory experiments and validate a control strategy [18,19]. The UC pack must supply all the power required by traction that exceed the generator–battery system rated power, if its state of charge is greater than a specified minimum. When the power required to operate the vehicle is lower than the generator–battery rated power, the UCs can be charged with the excess power. Whenever regenerative braking operations occur, energy is stored in the UC pack, provided this device is not fully charged otherwise the braking energy is recovered into the battery.

Such a hybrid storage system could achieve an optimum value of the P/E ratio (Fig. 12) at a lower cost and

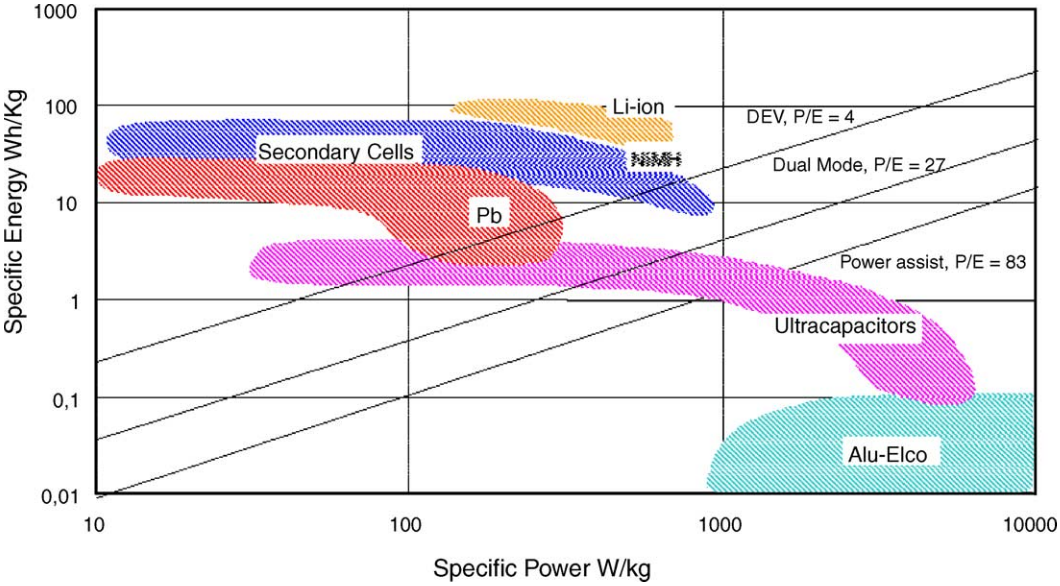

Fig. 12. Ragone plot and P/E ratio for several electric storage systems.

weight than a Ni–MH battery, with increased reliability [15].

7.1. *Triple hybrid: a preliminary design for a SUV*

In a previous article [20], it was discussed the sizing of a hybrid storage system composed by batteries and UCs for the "Range-extender" hybrid vehicle Fiat 600 FCHEV whose hybridisation degree is about 20%. The same procedure can be applied to a different vehicle, a sport utility vehicle (SUV) that being a general-purpose vehicle requires a higher hybridisation degree (about 50–60%). At this level of hybridisation the FCHEV is to be considered as a "Power assist" vehicle and the P/E mission value indicated by OATT is $P/E = 83$. The storage battery/UC composition is expressed by the equation:

$$\frac{M_{\mathrm{b}}}{M_{\mathrm{UC}}} = \frac{E_{\mathrm{sUC}}\,P/E - P_{\mathrm{sUC}}}{P_{\mathrm{sb}} - E_{\mathrm{sb}}\,P/E} \qquad (5)$$

where $P_{\mathrm{sb}}, E_{\mathrm{sb}}, P_{\mathrm{sUC}}, E_{\mathrm{sUC}}$ are the specific power and energy of the battery and the ultracapacitor packs, respectively.

A hybrid storage system is composed by UCs and lead–acid batteries (see Table 5), the calculated ratio is:

$$\frac{M_{\mathrm{b}}}{M_{\mathrm{UC}}} = 0.23 \quad \text{or} \quad \frac{M_{\mathrm{UC}}}{M_{\mathrm{b}}} = 4.39$$

The DOE optimisation study for a hydrogen-fuelled FC powered SUV indicated as the best design the combination of a net 64 kW FC with a 124 kW traction motor and a 105 kW battery pack. Since the necessary power is 105 kW, the weight of the batteries is obtained by resolving the equation:

$$M_{\mathrm{b}}\,P_{\mathrm{sb}} + \frac{M_{\mathrm{b}}\,M_{\mathrm{UC}}}{M_{\mathrm{b}}\,P_{\mathrm{sUC}}} = P_{\mathrm{tot}} \qquad (6)$$

where M_{b} is the unknown weight. It is therefore:

$$M_{\mathrm{b}} = \frac{105,000}{77 + (4.39 \times 800)} = 29\,\mathrm{kg}$$

$$M_{\mathrm{UC}} = 4.39 \times 29\,\mathrm{kg} = 128\,\mathrm{kg}$$

$$\text{total weight} = 157\,\mathrm{kg}$$

Considering the commercial availability of batteries and UCs is possible to propose a simple and immediate solution, for example, combining three 12 V/26 Ah batteries (each module weighs 10.8 kg) and 197 2.5 V/2550 Farad UCs (each module weighs 0.6 kg). This solution is very interesting, because the "Hybrid Storage" concept requires a system composed by a 42 V (36 V discharge) lead acid battery (30 kg) and a 130 kg UCs bank instead of a 525 kg battery pack (for Nickel Metal Hydride, total weight derives from the relation: 105 kW/200 W/kg = 525 kg). The use of high-performance lithium-metal batteries (AVESTOR) would reduce to about one forth the weight of the battery pack with respect to lead acid. However, the absolute weight reduction would be only about 15 kg, that would not compensate the supposed cost increase. Nevertheless, the forecasted extremely high cycle life of the lithium-metal batteries could reopen the issue if they will be industrially produced at lower cost.

The "Hybrid Storage" system would even have a lower cost if the UCs unitary cost will drop to US$ 0.01–0.02 per F.

8. Italian experiences on HEV busses

The first Italian experience on HEV busses was achieved within the Eureka project and dates back to the period from the late 1980s to the early 1990s. Alkaline-type FCs developed by Belgian company Elenco and Ni–Cd batteries by Saft were installed on a prototype bus, a Van Hool 18 m articulated bus. This experience was followed by a second, supported by a European Union, to explore the use of hydrogen fuel obtained by water electrolysis with hydroelectric energy from power plants in Quebec. A PEM-type FC, developed by De Nora, was installed together with a conventional onboard lead–acid battery on a prototype transformed bus (Macchi Ansaldo 12 m ex-trolley bus). Currently, Ansaldo Ricerche is engaged with different partners to implement a FC bus, developed from the City Class 12 m Irisbus body, equipped with a generation system composed of a fuel cell and a battery pack properly integrated by a dc/dc converter. The scope of such development is the industrial manufacturing and following marketing of the system. The prototype is presently being road-tested.

In all the above-mentioned applications, the FC generation system is supported by a battery. The FC is used as the primary energy source; it is adjusted to output a slowly variable power while the battery balances any quick load change. Compared with hybrids equipped with ICE-generator units, the FC solution is preferable as it reduces emissions and increases global efficiency, beside no revolving parts are installed. Nevertheless, it must be observed that the above-mentioned benefits are only due to the replacement of the ICE with the FC, while accumulators play the same role in both cases. Thus, it cannot be excluded that FC powered vehicles can experience the same problems experienced by accumulators installed on ICE hybrid electric vehicles due to the very heavy duty cycle performed especially in uses as passenger service in the public transportation sector. Hence, the relevance of several studies aiming at defining advantages deriving from a more rational use of accumulators. Among them, are the use of supercapacitors or ultracapacitors has been suggested to replace or support the accumulator battery, as discussed before.

9. Conclusions

Considering the unique characteristics of the fuel cell technology, the motivation supporting for the hybridisation of ICE-based vehicles (enhance the efficiency and the emission control) does not apply to fuel cell vehicles. Nevertheless, FC-based hybrid systems, undoubtedly more complex from an engineering point of view, would still offer the following advantages:

(1) Braking energy recovery.
(2) Power peak shaving during fast transient.
(3) Reduced cold start-up time, mainly in vehicle with on-board reformer.
(4) Reduced total system cost.

The amount of energy saved only by braking energy recovery is highly cycle dependent, in the range from 3.5 to 20%, but high enough to justify by itself the realisation of a hybrid system.

Peak shaving is another important issue, especially in non-hydrogen fuelled FC vehicles, because the response time of some subsystems (typically the fuel processor) is much larger than the transient times required by the driving cycle. The onboard electrical storage system acting as a buffer during peak power request, makes the vehicle more comfortable to drive. It also reduces or eliminate the inconvenience of the cold start-up. During the time required by some subsystems to be fully operative (maximum for the fuel processor) the “external” power in the storage unit can be used for a quick vehicle start-up even if the power produced by the FC system is very low.

Finally, the projected cost of the automotive storage system would be lower even considering the projected reduction of the FC cost (US$ 20 per kW compared to US$ 45 per kW) in case of mass production. Thus it is easy to predict that for a given vehicle performance, an hybrid power train will be always cheaper than a full-power FC drive train, especially in those applications (urban transportation) where the ratio of peak/average power is higher.

The optimal hybridisation degree is very dependent on the vehicle type and duty cycle. In general, general-purpose vehicles require higher hybridisation degree than urban busses. This is due to the higher peak/average power ratio and easiness of predicting the average power of urban busses, because their missions are more predictable than for private cars in mixed (urban/suburban) driving cycles.

Finally, the combined use of batteries and ultracapacitors appears to be very promising for the best optimisation of the storage system. The higher cost of such a hybrid storage system would be balanced by its better efficiency and longer lifetime.

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