Hybrid Solar Vehicles: Perspectives, Problems, Management Strategies

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ABSTRACT

Hybrid Solar Vehicles (HSV), derived by integration of Hybrid Electric Vehicles with Photo-Voltaic sources, may represent a valuable solution to face both energy saving and environmental issues, particularly in urban driving. Previous studies have also shown that economic feasibility could be achieved in a near future. After a presentation of the perspectives and the problems related to the use of such vehicles, the paper focuses on their management strategies, evidencing some significant differences with respect to the case of Hybrid Electric Vehicles.
In order to develop a supervisory control for an HSV prototype under development at University of Salerno, a study on the performance achievable by an intermittent use of the ICE powering the electric generator is presented. The results obtained by the application of Genetic Algorithms (GA) to the optimal energy management of an HSV with series structure are discussed. The optimal powering strategy accounts for fuel mileage and state of charge, also considering solar contribution during parking mode and the effects of engine thermal transients on fuel consumption and HC emissions. The effects of power-train, vehicle and external variables on optimal strategies are also studied and discussed.

Key-words: Hybrid Vehicles, Solar Energy, Photovoltaic Panels, Genetic Algorithm

INTRODUCTION

In the last years, increasing attention is being spent towards the applications of solar energy to electric and also to hybrid cars. But, while cars only fed by sun do not represent a practical alternative to cars for normal use, the concept of a hybrid electric car assisted by solar panels appears more realistic. The reasons for studying and developing a Hybrid Solar Vehicle can be summarized as follows:

- fossil fuels, largely used for car propulsion, are doomed to depletion; their price tends to increase, and is subject to large and unpredictable fluctuations (Fig. 1);

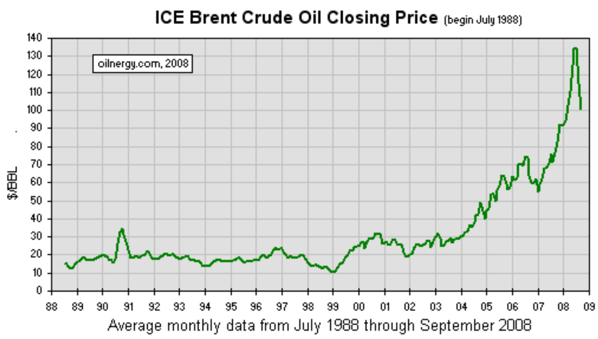

Fig. 1 - Trends in oil price (http://www.oilnergy.com/1obrent.htm)

- the CO_2 generated by the combustion processes occurring in conventional thermal engines contributes to the greenhouse effects, with dangerous and maybe dramatic effects on global warming and climatic changes;
- the worldwide demand for personal mobility is rapidly growing, especially in China (Fig. 2) and India; as a consequence, energy consumption and CO_2 emissions related to cars and transportation are increasing;

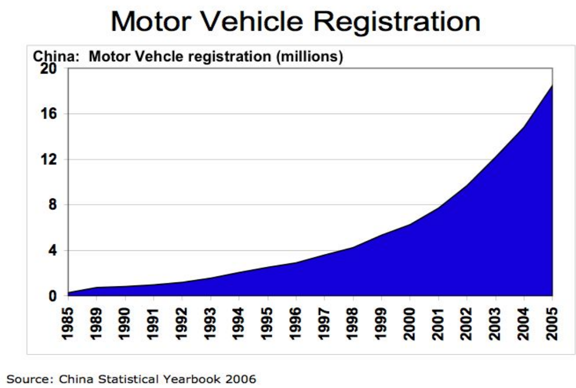

Fig. 2 - Motor vehicle registration in China (Millions)

- solar energy is renewable, free and largely diffused, and Photovoltaic Panels are subject to continuous technological advances in terms of cell efficiency (**Fig. 5**); their diffusion is rapidly growing (**Fig. 7**), while their cost, after a continuous decrease and an inversion of the trend occurred in 2004, appears quite stable in last years (**Fig. 6**) (Arsie et al., 2006 II);

- solar cars (**Fig. 8**), in spite of some spectacular outcomes in competitions as World Solar Challenge, do not represent a practical alternative to conventional cars, due to limitations on maximum power, range, dimensions and costs;
- Hybrid Electric Vehicles (HEV) have evolved to industrial maturity, and represent now a realistic solution to important issues, such as the reduction of gaseous pollution in urban drive as well as the energy saving requirements.

SOLAR HYBRID VEHICLES

Therefore, in principle, Hybrid Solar Vehicles (HSV) could sum up the advantages of HEV and solar power, by the integration of Photovoltaic Panels in a Hybrid Electric Vehicle. But it would be simplistic to consider the development of a HSV as the simple addition of photovoltaic panels to an existing Hybrid Electric Vehicle. In fact, the development of HEV's, despite it was based on well-established technologies, showed how considerable research efforts were required for both optimizing the power-train design and defining the most suitable control and energy-management strategies. Analogously, to maximize the benefits coming from the integration of photovoltaic with HEV technology, it is required performing accurate re-design and optimization of the whole vehicle-powertrain system. In these vehicles, in fact, there are many mutual interactions between energy flows, propulsion system component sizing, vehicle dimension, performance, weight and costs, whose connections are much more critical than in conventional and also in hybrid cars.

Another difference between HEV and HSV may concern their structure. In fact, the prevailing architectures for HEV are parallel and parallel-series, while in case of HSV the series structure seems preferable (Letendre et al., 2003). Despite some known disadvantages (higher efficiency losses due to more energy conversion stages), series structure is simpler and may offer some advantages:

- It more suitable for plug-in and V2G applications (the generator can be used as co-generator when the vehicle is parked at home).
- Due to absence of mechanical links between generator and wheels, very effective vibration insulation can be achieved, with less constraints for vehicle layout.
- Advanced techniques for noise reduction (i.e. active noise reduction) could be more easily applied, since the engine can work at fixed conditions.
- Engines specifically optimized for steady operation can be used (i.e. D.I. stratified charge engines, Micro gas turbine, and other solutions not suitable for classical vehicles due to lack of stability or low efficiency in the whole operating range).
- It is compatible with the use of in-wheel motors with built-in traction control and anti-skid.
- It will potentially act as a bridge towards the introduction of hybrid fuel cell powertrains.

A possible layout of a HSV with series structure is presented in Fig. 3, with reference to the symbols presented in the nomenclature.

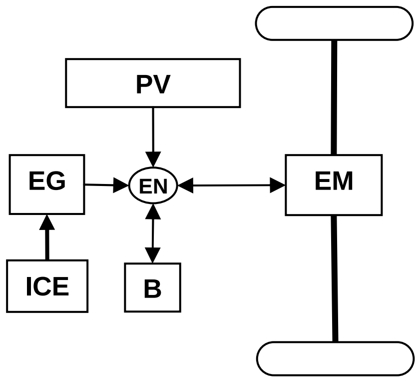

Fig. 3 - Scheme of a series hybrid solar vehicle

In spite of these encouraging perspectives, the use of solar energy on cars has been considered with a certain skepticism by most users, including automotive engineers. This may be due to the simple observation that the net power achievable in a car with current photovoltaic panels is about two order of magnitude less than maximum power of most of today cars. But a more careful analysis of the energy involved demonstrate that this perception may be misleading. In fact, there is a large number of drivers utilizing daily their car for short trips and with limited power demand. For instance, some recent studies conducted by the UK government report that about 71 % of UK users reach their office by car, and 46 % of them have trips shorter than 20 minutes, mostly with only one person on board, i.e. the driver (www.statistics.gov.uk/CCI/nscl.asp?ID=8100).

In those conditions, the solar energy collected by solar panels on the car along a day may represent a significant fraction of the energy required for traction (Arsie et.al, 2005, 2006 I,II).

SOLAR HYBRID VEHICLES AND V2G

Hybrid Solar Vehicles seem particularly suitable also in a framework of Vehicle to Grid (V2G) concept (Letendre et al., 2003; Lund & Kempton, 2008; Tomic & Kempton, 2007; Turton & Moura, 2008). In a V2G approach, plug-in electric, hybrid or fuel cell vehicles, when parked, can both absorb energy from the grid (Plug-In Vehicles) or also give energy to it (**Fig. 4**). The key to realizing economic value from V2G is related to precise timing of its grid power production to fit within driving requirements while meeting the time-critical power "dispatch" of the electric distribution system. V2G may therefore provide a means by which to utilise the spare power capacity available in each parked vehicle and avoid the need to maintain the excess conventional electricity generation capacity currently required to provide regulation, spinning reserves and peak power. In that sense, V2G technologies represent a paradigm shift in how the energy and mobility markets are related (Turton & Moura, 2008). Moreover, the battery pack of parked EV or HEV can enhance the capabilities of stationary photovoltaic installations.

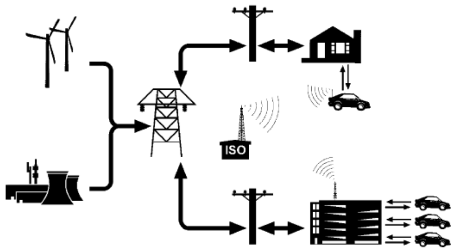

Fig. 4 – Scheme of the Vehicle to Grid (V2G) Concept

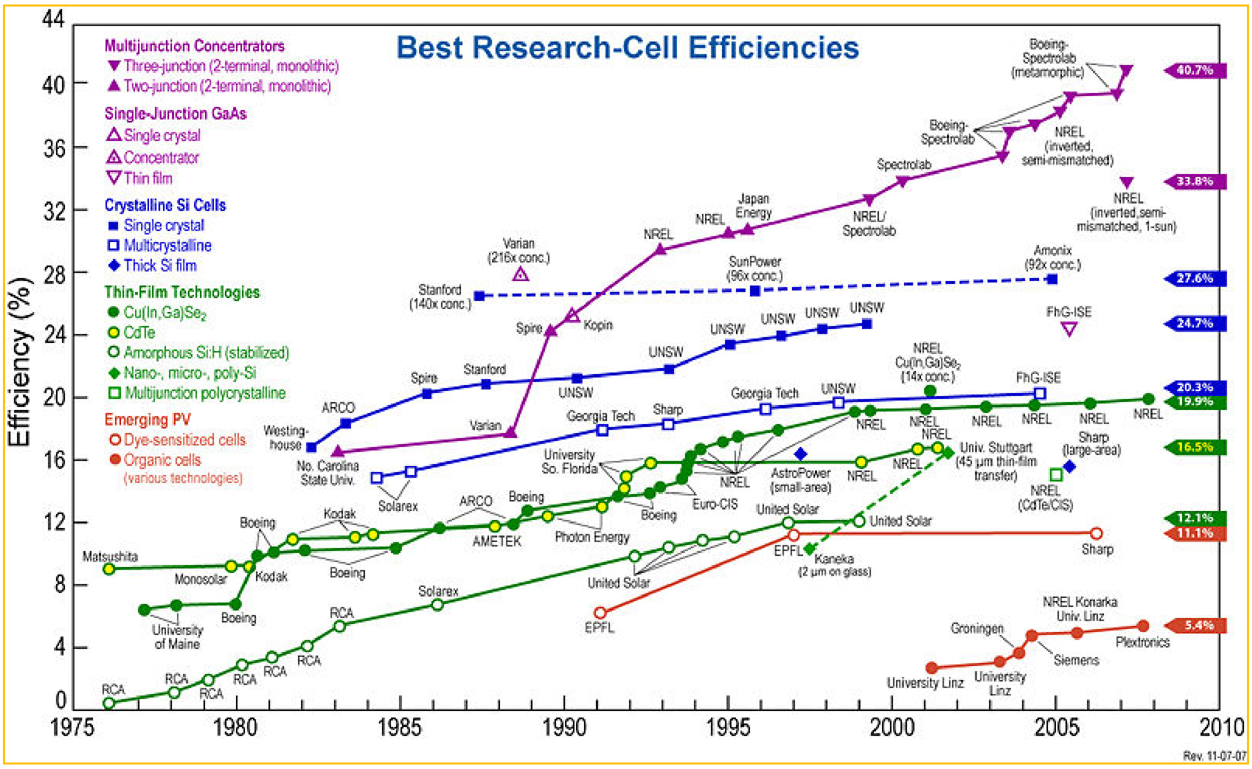

Fig. 5- Trends in photovoltaic panels efficiency (L.L. Kazmerski, NREL)

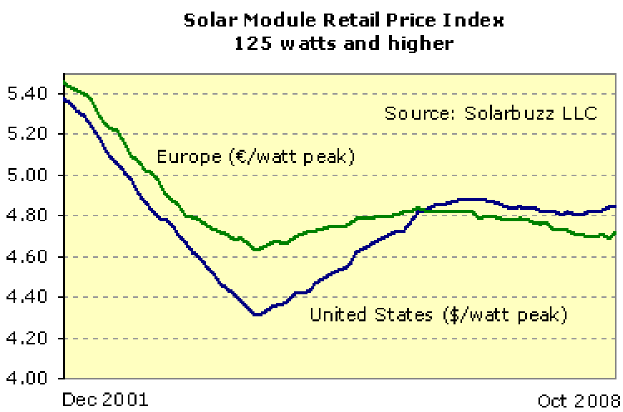

Fig. 6 – Trends in PV module price
(http://www.solarbuzz.com/)

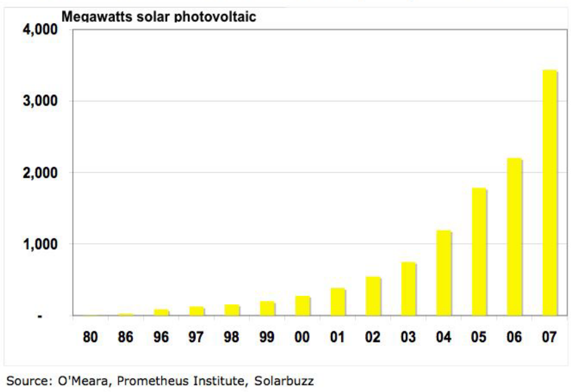

Fig. 7 – Trends in PV production

Fig. 8 – A Prototype of Solar Car

Fig. 9 - Venturi Automobiles' Astrolab, the first commercially available PV integrated hybrid

With respect to EV and HEV, additional advantages can be foreseen for the Hybrid Solar Vehicles in V2G mode: these vehicles allow to transfer to the grid the surplus of energy generated by photovoltaic panels, for instance during a long term parking. Moreover, particularly in a solar hybrid vehicle with series structure (Fig. 3), the engine generator group could be used as co-generator, producing both electrical energy and heat (CHP) when the vehicle is parked at home.

STUDIES ON SOLAR HYBRID VEHICLES

Despite their potential interest, solar hybrid cars have received relatively little attention in literature (Letendre et al., 2003), particularly if compared with the great effort spent in last years toward other solutions, as hydrogen cars, whose perspectives are affected by critical issues regard to hydrogen production, distribution and storage.

Some prototypes have been developed in last decade in Japan (Saitoh et al., 1992, Sasaki et al., 1997), at Western Washington University (Seal, 1995; Seal and Campbell, 1995), at the Queensland University (see for instance www.itee.uq.edu.au/~serl/UltraCommuter.html) and, more recently, by the French company Venturi (**Fig. 9**).

A prototype of Solar Prius (**Fig. 10**) has also been recently developed by Solar Electric Vehicles, equipped with a PV panel of 16% nominal efficiency (Simburger et al, 2006; Simburger & Simburger, 2006). It has been estimated that the PV Prius can have a range based on solar power alone between 5 and 8 miles per day, and that it can consume between 17% and 29% less gasoline than the standard Prius.

Some educational projects in that area have also been developed (Wellington, 1996; Lu et al., 2007, Arsie et al., 2006 I), and a multi-lingual website (www.dimec.unisa.it/Leonardo) has been developed by the authors within a project financed by EU.

Fig. 10 - A PV Prius

Although these works demonstrate the general feasibility of such vehicles, detailed presentations of results and performance are still lacking. Moreover, relatively little effort has been recently dedicated to solar hybrid vehicle design and control, at least in open literature. A comprehensive model for the optimal design of a hybrid solar vehicle with series structure, considering performance, weight and costs, has been formulated by the authors and presented in previous papers (Arsie et al.,2005, 2006 I, 2006 II). It is shown that, if the car is used in intermittent way and at limited average power, a significant percent, about 20-40%, of the required energy can be provided by the sun, for a car with about 3 m^2 of panels at 24% efficiency. For instance, a car operating for 2 hours a day at 5 KW or for 1 hour at 10 KW can save about 30% of fuel, with respect to the hybrid vehicle without PV panels (greater savings can be achieved with respect to a conventional vehicle). The results of an optimal design analysis, also considering weight and costs, have shown that economic feasibility (pay-back between 2 and 3 years) could be achieved in a medium term scenario, with mild assumptions in terms of fuel price increase, PV efficiency improvement and PV cost reduction. A prototype of HSV with series structure has also been developed (Arsie et al., 2006, Adinolfi et al., 2008), within the framework on an educational project funded by EU (Leonardo project I05/B/P/PP-154181 "Energy Conversion Systems and Their Environmental Impact, www.dimec.unisa.it/leonardo).

An overview on the ongoing research on the study of real time control of solar panels (MPPT techniques and their implementation) and to the development of converters specifically suited for automotive applications is available by previous papers of the authors (Arsie et al., 2006, I) and in other references (Cacciato et al., 2004 I and II; Egiziano et al, 2006 I and II; Femia et al, 2005).

A method for fuel consumption minimization based on Model Predictive Control has been recently proposed (Preitl et al., 2007). The aspects related to the engine generator management in case of intermittent use have been focused in other papers, both for HEV vehicles (Ohn et al., 2008) and for HSV vehicles (Arsie et al., 2007 II, 2008), and will be further analyzed in the next paragraphs.

CONTROL ISSUES FOR HYBRID SOLAR VEHICLES

Although HSV have many similarities with HEV, for which numerous studies on energy management and control have been presented in last decade (Arsie et al., 2004; Bauman et. al, 1998; Guzzella et al., 1999; Powell et al., 1998), there are also some significant differences between these kind of vehicles. In particular, the presence of solar panels and the adoption of a series structure may require to study and develop specific solutions for optimal management and control of an HSV.

As it is known, in most HEV a charge sustaining strategy is adopted: at the end of a driving path, the battery state of charge should remain unchanged. With a HSV, a different strategy should be adopted as battery is charged during parking hours as well. In this case, a different goal can be pursued, namely restoring the initial state of charge within the end of the day rather than after a single driving path (Arsie et al., 2007).

Moreover, the series configuration suggests to operate the engine in an intermittent way at constant operating conditions, i.e. corresponding to the minimum fuel consumption. In such case, the engine-generator system may be designed and optimized to maximize its efficiency, emissions and noise at design point, while in current automotive engines the maximum efficiency is usually sacrificed to the need of assuring stable operation and good performance in the whole operating range. In case of ICE intermittent operation, the effects exerted on fuel consumption and emissions by the occurrence of thermal transients in engine and catalyst should be considered. These effects are neglected in most studies on HEV, where a steady-state approach is usually used to evaluate fuel consumption and emissions.

In order to develop a supervisory control to be implemented on the vehicle, a more accurate analysis of the optimal ICE power distribution over an arbitrary driving cycle has to be performed. In fact, the intermittent operation of the ICE produces the occurrence of thermal transients both in engine and in catalyst, so influencing fuel consumption and emissions. These effects should be analyzed and taken into account for energy flow management and control, also in order to develop suitable solutions for vehicle thermal management. A method based on the application of Genetic Algorithms (GA) is presented in the following.

OPTIMIZATION OF ELECTRIC GENERATOR SCHEDULING BY MEANS OF GENETIC ALGORITHM

In case of intermittent ICE scheduling, the optimal EG power trajectory can be found by solving the following constrained optimization problem:

$$\min_X \int \dot{m}_{f,HSV}(X)dt \qquad (1)$$

subject to the constraints

$$\Delta SOC_{day} = SOC_f - SOC_0 + \Delta SOC_p = 0 \qquad (2)$$

$$SOC > SOC_{\min} \qquad (3)$$

$$SOC < SOC_{\max} \qquad (4)$$

where $\dot{m}_{f,HSV}$ is the HSV fuel consumption [kg], SOC_f and SOC_0 are the initial and final state of charge in the driving phase, respectively, and ΔSOC_p is the SOC increase due to PV recharging during vehicle parking. It is worth mentioning here that driving and parking hours are set to 1 and 9, respectively.

The decision variables X include number of EG-on events N_{EG}, along with corresponding starting time $t_{0,EG,i}$, duration $\Delta t_{EG,i}$ and EG power level $P_{EG,i}$, where i is the i-th EG-on event.

The first constraint (i.e. Eq. 2) allows to restore the initial state of charge within the end of the day, also considering parking phases.

The other constraints (i.e. Eqs. 11 and 12) were defined accounting for internal resistance dependence on battery state of charge. For lead-acid batteries in the SOC range [0.55 0.9] both charging and discharging resistances are fairly constant while being close to their minimum values (Adinolfi et al., 2008). Therefore in this analysis SOC_{min} and SOC_{max} were set to 0.55 and 0.9, respectively.

The problem stated by Eqs. (1) through (4) involves both integer (e.g. N_{EG}) and real variables, thus falling in the field of Mixed Integer Programming (MIP) problems. Among the several techniques that can be adopted to solve such problems, genetic algorithms (GA) is one of the most efficient (Sakawa et al., 2001) and has thus been selected for optimizing EG scheduling on a hybrid solar vehicle. The GA search was performed in Matlab environment by means of the GAtbx tool developed by (Chipperfield et al.). Details about GA optimization techniques can be found in the abundant literature on the topic, which the reader is addressed to (Sakawa et al., 2001; Chipperfield et al., 1994; Zitzler, 1999).

For the current application, the following operating parameters were assumed for the GA search procedure:

Table 1 – GA operating parameters.

Population size	70
Number of generations	100
Crossover probability	0.8
Mutation probability	0.033

A binary representation of the decision variables was selected, as reported in Table 2.

Table 2 – Binary representation of the optimization problem.

Decision variable	Definition range	Precision	Number of bits
N_{EG}	[1 8]	1	3
t_{EG} (min)	[0 78/ N_{EG}]	0.073/ N_{EG}	10
Δt_{EG} (min)	[0 78/ N_{EG}]	0.073/ N_{EG}	10
P_{EG} (kW)	[0 43]	0.040	10

Optimization results

The GA optimization was applied to minimize the fuel consumption for a driving cycle composed of 4 ECE-EUDC cycles, as the one shown on Figure 11. HSV fuel consumption was simulated by means of the backward longitudinal vehicle model presented in (Adinolfi et al., 2008). In the analysis the effect of thermal transients on ICE performance and HC emissions were also taken into account following the approach proposed in (Arsie et al., 2007 II, 2008). Table 3 lists the specifications of the reference HSV.

Table 3 – HSV specifications.

ICE power [kW]	46
Fuel	gasoline
PEG [kW]	43
PEM [kW]	90
Number of battery modules [/]	27
PV horizontal surface $A_{PV,H}$ [m^2]	1.44
Coefficient of drag (C_d)	0.4
Frontal area [m^2]	2.6
Weight [kg]	1465

Table 4 summarizes the results of the current optimization task and also compares new outputs with previous ones obtained by derivative-based minimization (DBM) algorithm (Arsie et al., 2008). Such comparison indicates that the GA search method (i.e. column “GA” in Table 4) suggests a lower number of ECE-on events, which in turn results in a slightly higher fuel consumption and significantly lower HC emissions, as compared with classical method (i.e. column “DBM” in Table 4).

The reduction in HC emissions not only depends on the lower number of EG-on events, but also on the higher GA average engine temperature (see Table 4 and Figure 12), which of course determines a higher conversion effectiveness of the catalyst.

It is worth remarking that both HC emission levels reported in Table 4 are well below the EURO 5 gasoline emission standard (i.e. 0.1 g/km, Tona et al., 2008), thus confirming the benefits related to ICE intermittent use. Figure 13 shows the required power at wheels, optimal EG and battery trajectories and SOC variation. Particularly, Figure 13 indicates that the GA search method was able to bound SOC variation within the desired limits (i.e. 0.55 and 0.9).

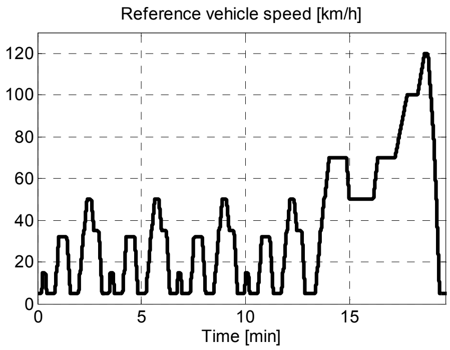

Fig. 11 – ECE-EUDC driving module

Finally, a further optimization analysis was run considering an increase in PV horizontal area from 1.44 to 3 m^2. Such configuration upgrade results in a fuel consumption reduction down to 2.28 kg.

Table 4 – Optimization analysis.

Optimization outputs	DBM	GA 1
N_{EG}	4	3
Fuel consumption [kg]	2.41	2.48
HC emissions 1 (g)	1.13	0.85
Average engine temperature [°C]	65	68
Max SOC [/]	0.79	0.88
Min SOC [/]	0.65	0.58
HC emissions 2 (g/km)	0.025	0.018

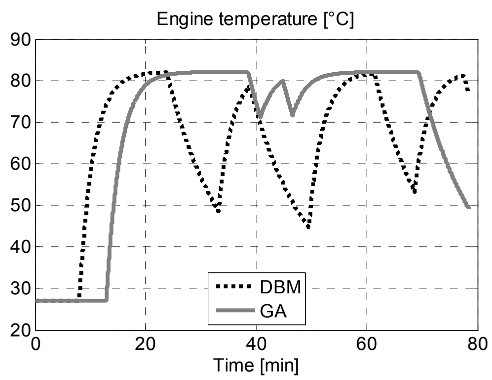

Fig. 12 – Comparison between temperature trajectories simulated in DBM and GA optimization task

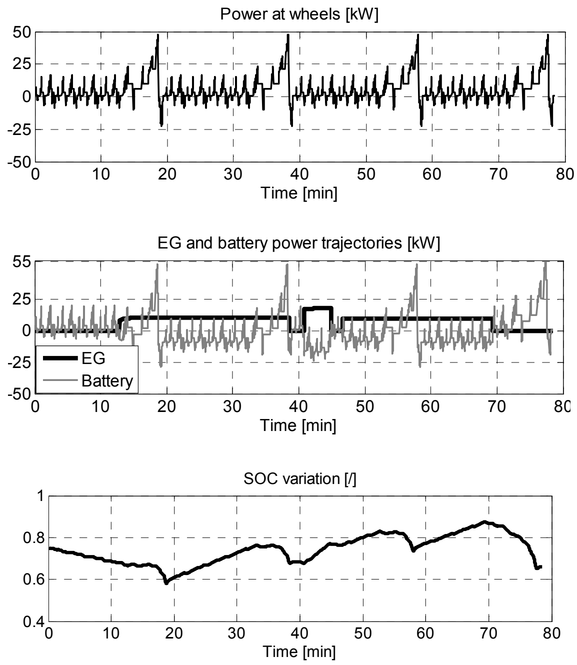

Fig. 13 – Time trajectories yielded by the GA optimization

CONCLUSIONS

Hybrid Solar Vehicles, derived by integration of Hybrid Electric Vehicles with Photo-Voltaic sources, may represent a valuable solution to face both energy saving and environmental issues, but relatively little research effort has been spent in this direction. Despite their development is based on well-established technologies, accurate re-design and optimization of the whole vehicle-powertrain system is required to maximize the benefits coming from the integration of photovoltaic with HEV technology.

Particularly, the electric generator management plays a key role toward the achievement of such benefits. Previous studies had shown that significant savings in fuel consumption and emissions can be obtained with an intermittent use of the vehicle. In the paper, the optimization of the EG scheduling has been presented, based on the GA search method. The results suggests a lower number of EG-on events, which in turn results in a slightly higher fuel consumption and significantly lower HC emissions (from 0.025 to 0.018 g/km), as compared with classical minimization method. The reduction in HC emissions not only depends on number of EG-on events, but also on the higher GA average engine temperature, which of course determines a higher conversion effectiveness of the catalyst. It is worth remarking that both HC emission levels are well below the EURO 5 gasoline emission standard, thus confirming the benefits related to ICE intermittent use. The results were obtained with commercial PV panels and with realistic data and assumptions on the achievable net solar energy for propulsion. Scenario analyses performed by increasing PV horizontal area from 1.44 to 3 m^2 evidence a further reduction of fuel consumption from 2.48 down to 2.28 kg for the assumed driving cycle.

The future adoption of last generation photovoltaic panels, with nominal efficiencies approaching 35%, may result in an almost complete solar autonomy of this kind of vehicle for such uses. By adopting up to date technology for electric motor and generator, batteries and chassis, power to weight ratio comparable with the ones of commercial cars can be achieved, thus assuring acceptable vehicle performance.

Finally, the results of the presented analyses show that the hybrid solar vehicles, although still far from economic feasibility, could reach acceptable payback values if large but not unrealistic variations in costs, prices and panel efficiency will occur. Considering recent trends in renewable energy field and actual geo-political scenarios, it is reasonable to expect further reductions in costs for PV panels, batteries and advanced electric motors and generators, while relevant increases in fuel cost could not be excluded. Moreover, the recent and somewhat surprising commercial success of some electrical hybrid cars indicates that there are grounds for hope that a significant number of users is already willing to spend some more money to contribute to save the planet from pollution, climate changes and resource depletion.

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The prototype of EV has been provided by Automobile Club Salerno.

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NOMENCLATURE

c_f [€/kg]	Fuel cost
c_{PV} [€/m^2]	PV Panel cost
PB [yrs]	Pay-Back
SF [%]	Solar fraction
η_P [/]	Panel efficiency

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BIPV	Building Integrated Photo Voltaic
EG	Electric Generator
EM	Electric Motor
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
HSV	Hybrid Solar Vehicle
ICE	Internal Combustion Engine
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photo-Voltaic
V2G	Vehicle to Grid
VIPV	Vehicle Integrated Photo Voltaic