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OPTIMAL DESIGN AND DYNAMIC SIMULATION OF A HYBRID SOLAR VEHICLE

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ABSTRACT

The paper deals with a detailed study on the optimal sizing of a solar hybrid car, based on a longitudinal vehicle dynamic model and considering energy flows, weight and costs. The model describes the effects of solar panels area and position, vehicle dimensions and propulsion system components on vehicle performance, weight, fuel savings and costs. It is shown that significant fuel savings can be achieved for intermittent use with limited average power, and that economic feasibility could be achieved in next future, considering the expected trends in costs and prices.

INTRODUCTION

In the last years, increasing attention has been spent towards the applications of solar energy to cars. Various solar car prototypes have been built and tested, mainly for racing and demonstrative purposes [1] [2].

Despite a significant technological effort and some spectacular outcomes, several limitations, such as low power density, unpredictable availability of solar source and energetic drawbacks (i.e. increase in weight and friction and aerodynamic losses due to additional components), cause pure solar cars to be still far from practical feasibility. On the other hand, the concept of a hybrid electric car assisted by solar panels appears more realistic [3][4][5][6][7]. In fact, due to relevant research efforts [8], in the last decades Hybrid Electric Vehicles (HEV) have evolved to industrial maturity. These vehicles now represent a realistic solution to important issues, such as the reduction of gaseous pollution in urban drive as well as the energy saving requirements. Moreover, there is a large number of drivers utilizing daily their car, for short trips and with limited power demand. 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 passenger (i.e. the driver) [9]. The above considerations open promising perspectives with regard to the integration of solar panels with "pure"-electric hybrid vehicles (i.e. "tri-hybrid" cars), with particular interest in the opportunity of storing energy even during parking phases.

In spite of their potential interest, solar hybrid cars have received relatively little attention in literature [7]. An innovative prototype has been developed at Western Washington University [5][6] in the 90s, adopting advanced solutions for materials, aerodynamic drag reduction and PV power maximization with peak power tracking. Other studies and prototypes on solar hybrid vehicles have been presented by Japanese researchers [3][4] and at the Queensland University [10].

Although these works demonstrate the general feasibility of such an idea, detailed presentation of results and performance, along with a systematic approach to solar hybrid vehicle design, seem still missing in literature. Therefore, appropriate methodologies are required to address both the rapid changes in the technological scenario and the increasing availability of innovative, more efficient components and solutions. A specific difficulty in developing a Hybrid Solar Vehicle (HSV) model relates to the many mutual interactions between energy flows, power-train balance of plant and sizing, vehicle dimension, performance, weight and costs, whose connections are much more critical than in either conventional or hybrid electric vehicles. Preliminary studies on energy flows in an HSV has been recently conducted by the authors [11][12]. The current paper presents a more detailed study on the optimal sizing of a solar hybrid car. The optimization analyses are based on a longitudinal vehicle dynamics model, developed to account for, besides the impact of weight and costs, also the influence of energy flows and adopted control strategies.

STRUCTURE OF THE SOLAR HYBRID VEHICLE

Different architectures can be applied to HEVs: series, parallel, and parallel-series. These two latter structures have been utilized for two of the more widely available hybrid cars in the market: Toyota Prius (parallel-series) and Honda Civic (parallel). Instead, for solar hybrid vehicles the series structure seems preferable [7], due to its simplicity, as in some recent prototypes of HSV [10]. With this approach, the Photovoltaic Panels (PV) assist the Electric Generator EG, powered by the ICE, in recharging the battery pack B in both parking mode and driving conditions, through the electric node EN. The electric motor EM can either provide the mechanical power for the propulsion or restore part of the braking power during regenerative braking (Figure 1). In this structure, the thermal engine can work mostly at constant power (P_{AV}), corresponding to its optimal efficiency, while the electric motor EM can reach a peak power P_{EM}:

$$P_{EM} = \theta P_{av} \tag{1}$$

In order to estimate the net solar energy captured by PV panels in real conditions (i.e. considering clouds, rain etc.) and available for propulsion, a solar calculator developed at the US National Renewable Energy Lab has been used [13]. Four different US locations were considered, ranging from 21° to 61° of latitude, based on 1961-1990 time series. The calculator provides the net solar energy for different panel positions: with 1 or 2 axis tracking mechanism or for fixed panels, at various tilt and azimuth angles.

The most obvious solution for solar cars is the location of panels on roof and bonnet, at almost horizontal position. Nevertheless, two additional options can be accounted for: (i) horizontal panels (on roof and bonnet) with one tracking axis, in order to maximize the energy captured during parking mode; (ii) panels located also on car sides and rear at almost vertical positions. The maximum panel area can be estimated as function of car dimensions and shape, by means of a simple geometrical model [12].

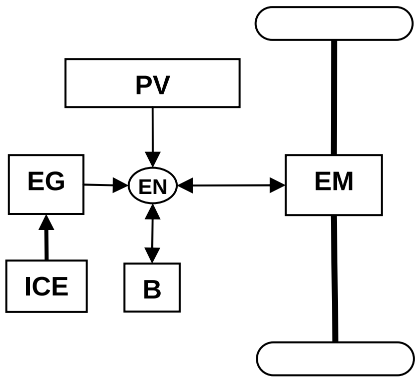

Figure 1 - *Scheme of the series hybrid solar vehicle.*

The energy from PV panels can be obtained summing up the contribution from parking (p) and driving (d) periods. While in the former case it is reasonable to assume that the PV array has an unobstructed view of the sky, this hypothesis could fail in most driving conditions. Therefore, the energy captured during driving can be reduced by a factor β<1. In order to estimate the fraction of daily solar energy captured during driving hours (h_d), it is assumed that the daily solar energy is distributed over h_{sun} hours. A factor α<1 is then introduced to account for further degradation due to charge and discharge processes in the battery for energy taken during parking. The net solar energy available for propulsion, stored during both parking and driving modes, can therefore be expressed as:

$$E_{s,p} = \eta_p A_{PV} e_{sun} \frac{h_{sun} - h_d}{h_{sun}} \alpha \tag{2}$$

$$E_{s,d} = \eta_p A_{PV} e_{sun} \frac{h_d}{h_{sun}} \beta \tag{3}$$

Where e_{sun} is the average daily energy captured by solar panels in horizontal position. Hereinafter, e_{sun} is assumed equal to 4.3 kWh/day, which corresponds roughly to a latitude of 30° in June month. The energy required to drive the vehicle during the day E_d (kWh) can be computed as function of the average positive power P_{av} (kW) and driving hours h_d:

$$E_d = \int_{h_d} P(t) \cdot dt = h_d P_{av} \tag{4}$$

The instantaneous power is estimated starting from a given driving cycle, for assigned vehicle data, integrating a vehicle longitudinal dynamic model. Thus, required driving energy E_d depends on vehicle weight and vehicle cross section, which in turn depend on the sizing of the propulsion system components and on vehicle dimensions, related to solar panel area. The contribution of solar energy to the propulsion can be therefore determined as:

$$\lambda = \frac{E_{sun}}{E_d} = \frac{E_{s,p} + E_{s,d}}{E_d} \tag{5}$$

The fuel consumption for both conventional vehicle (ICE) and HSV can be then computed and compared. Of course, in parallel with fuel savings, corresponding reduction in pollutants and CO_2 emissions with respect to the conventional vehicle is also achieved.

WEIGHT MODEL

A parametric model for the weight of an HSV can be obtained adding the weight of the specific components (PV panels, battery pack, ICE, Generator, Electric Motor, Inverter) to the weight of the HSV body. This latter has been obtained starting from a statistical analysis of small commercial cars (CC). A linear regression analysis has been performed (see Table 1), considering weight *W* ($W_{body,CC}$), power *P* and vehicle dimensions (length *l*, width *w*, height *h* and their product *V*=*lwh*), for 15 commercial cars, with power ranging from 9.5 kW to 66 kW [12]. In order to use these data to estimate the base weight of the HSV ($W_{body,HSV}$), the contribution of the components not present in the series hybrid vehicle (i.e. gearbox, clutch) has been subtracted. The CC car body also includes other components (thermal engine, electric generator, battery) that will be considered separately for the hybrid car model; the weight of ICE is estimated as function of peak power, whereas the influence of electric generator and battery has been neglected (their weights are of course much lower than the corresponding components needed on the hybrid car).

Table 1 – *Regression analysis for commercial car body mass.*

#	Variables	R^2
1	$W=k_1+k_2P$	0.894
2	$W= k_1+k_2P+k_3l+k_4w+k_5h$	0.973
3	$W= k_1+k_2P+k_3V$	0.946

Thus, the body (i.e. $W_{body,HSV}$) and whole (W_{HSV}) mass of the HSV can be expressed as:

$$\begin{aligned} W_{body,HSV} &= W_{body,CC}\left(P_{ICE,CC}, V\right) + \\ &\quad - P_{ICE,CC}\cdot\left(w_{ICE} + w_{gear}\right) \end{aligned} \tag{6}$$

$$\begin{aligned} W_{HSV} &= W_{body,HSV} + \\ &\quad + P_{EG}\cdot\frac{w_{ICE}}{\eta_{EG}} + P_{EG}\cdot w_{EG} + P_{EM}\,w_{EM} \\ &\quad + A_{PV}\,w_{PV} + w_{B,u}\cdot N_B \end{aligned} \tag{7}$$

The number of modules required to balance the HSV maximum power is estimated as follows:

$$N_B = \frac{P_{EM} - P_{EG}}{P_{B,u}} \tag{8}$$

where $P_{B,u}$ is the nominal power of a single battery module. The power of the electric machine (P_{EM}) is computed assuming a constant Power to Weight ratio (PtW_{HSV}), corresponding to a 1250 kg conventional car (CC) powered by a 75 kW gasoline engine:

$$PtW_{HSV} = \frac{P_{ICE,CC}}{W_{body,CC}} \tag{9}$$

$$P_{EM} = PtW_{HSV}\cdot W_{HSV} \tag{10}$$

COST ESTIMATION

In order to assess the benefits provided by HSV with respect to conventional vehicles, both the additional costs, due to hybridization and solar panels, and achievable fuel savings are to be estimated. The additional cost C_{HSV} can be expressed starting from the estimated unit cost of each component:

$$\begin{aligned} C_{HSV} &= P_{EG}\cdot\frac{c_{ICE}}{\eta_{EG}} + P_{EG}\cdot c_{EG} + A_{PV}\,c_{PV} \\ &\quad + P_{\max}c_{EM} + C_B N_B - \Delta C_{ICE} \end{aligned} \tag{11}$$

The last term accounts for cost reduction for Internal Combustion Engine in HSV (where it is assumed $P_{ICE} = P_{EG}/\eta_{EG}$) with respect to conventional vehicle (where $P_{ICE} = P_{ICE,CC}$).

The daily saving with respect to conventional vehicle can be computed starting from fuel saving and fuel unit cost:

$$S = \left(m_{f,CC} - m_{f,HSV}\right)\cdot c_f \tag{12}$$

The pay-back, in terms of years necessary to restore the additional costs with respect to the conventional vehicle, can be therefore estimated as:

$$PB = \frac{C_{HSV}}{n_D S} = \frac{C_{HSV}}{300S} \tag{13}$$

For further details about the meaning and the values of some of the parameters introduced in eqs. 2 through 13, the reader is addressed to a previous work [12].

VEHICLE DYNAMIC MODEL

In a previous paper [12], an extended optimization analysis was conducted to investigate the effects of latitude, costs, prices and layout on optimal vehicle structures, in terms of panel area, vehicle dimension and weight. The results presented have been obtained by computing the fuel savings of the HSV with respect to the conventional vehicle with a simplified approach, assuming average values for fuel consumption in the two cases and average yearly solar data. Although being sufficient to assess the general feasibility of HSV and to understand the impact of the main variables on costs and energy saving, this approach does not allow accurately evaluating the effects of vehicle weight and dimensions on inertial and aerodynamic forces during the driving cycle. Moreover, a more precise analysis is required to analyze the effects of control strategies on energy flows, also considering seasonal effects on solar energy. In order to overcome these limitations, a longitudinal vehicle model has been developed to simulate the dynamic behavior of both HSV and conventional vehicle over a driving cycle, based on a dynamic vehicle simulator developed by the authors [15]. Battery, electric motor and generator have been simulated by the ADVISOR model [16].

ENGINE CONTROL FOR HSV

In most electric hybrid vehicles, a charge sustaining strategy is adopted: at the end of a driving path, the battery state of charge should remain unchanged. With a solar hybrid vehicle, a different strategy should be adopted, since battery can be 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. For this end, the internal combustion engine should be operated whenever possible at maximum efficiency, corresponding to power P_{opt}. If the energy required to restore battery charge is lower than the amount corresponding to a continuous use at P_{opt} throughout the driving time h_d (case B), an intermittent operation can be adopted (cases A1-A2). In case that more energy is required, the internal combustion engine is operated at constant power between P_{opt} and P_{max} (case C). The different operating modes can be described by the variable ϕ, ranging from 0 to $\phi_{max} = P_{max} / P_{opt}$, as described in Table 2.

The optimal ϕ value is found by imposing that the energy provided by ICE and PV panels during the driving hours guarantees a charge sustaining strategy over the whole day. This condition is expressed as:

$$\Delta SOC_{day}(\phi) = \int_0^{24h} dSOC(\phi)dt = \\ = \Delta SOC_d(\phi) + \Delta SOC_p = 0 \quad (14)$$

Table 2 – *Engine control strategies for HSV.*

A1	$\phi < 1$	$P_{ICE} = 0$	$0 < t < \phi h_d$
A2	$\phi < 1$	$P_{ICE} = P_{opt}$	$\phi h_d < t < h_d$
B	$\phi = 1$	$P_{ICE} = P_{opt}$	$0 < t < h_d$
C	$1 < \phi < \phi_{\max}$	$P_{ICE} = \phi P_{opt}$	$0 < t < h_d$

Assuming that the driving schedule, of duration h_d hours, is composed of a sequence of ECE-EUDC cycles, eq. (14) can be satisfied by iteratively solving, over one cycle, the following nonlinear equation:

$$\Delta SOC_{ECE}(\phi) = \frac{-\left|\Delta SOC_p\right|}{N_{cycles}} \quad (15)$$

where N_{cycles} is evaluated as function of each module duration T_{cycle} (h):

$$N_{cycles} = \frac{h_d}{T_{cycle}} \quad (16)$$

Figures 2 through Figure 4 show the model outputs for a selected HSV configuration, simulated over an ECE-EUDC driving cycle and controlled according to the strategies defined in Table 2.

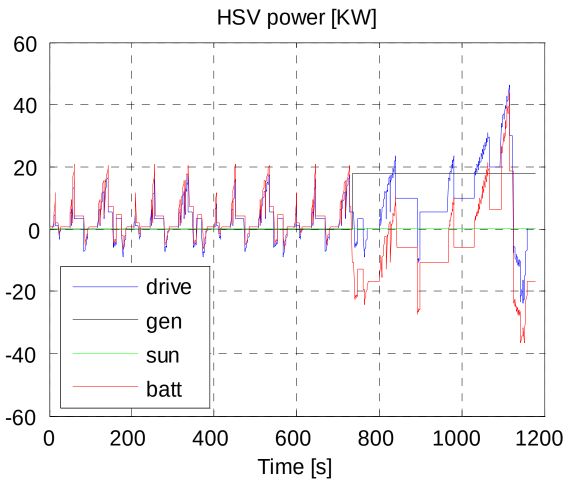

Figure 2 – *Power contributions for the ECE-EUDC cycle ($A_{PV,H}$ = 3 m^2, P_{EG} = 35.5 kW, l = 4.2 m, w = 1.75 m, h =1.5 m).*

Since, for the selected case, the optimal ϕ is lower than 1, the thermal engine can be operated at constant load and speed corresponding to its highest efficiency in an intermittent way, as shown in Figure 2 (black line). According to the imposed control strategy, the engine operates during the latter part of the driving cycle, when the power requested to drive the vehicle reaches its highest values (blue line); this way the engine power is supplied to the driveline without being stored into the batteries, thus minimizing charge/discharge losses in the peak power time window (1050 – 1150 s). On the other hand, in the former part of the transient, the drive power is exclusively supplied by the batteries (red line) that experience a decrease of State of Charge (SOC), as shown in Figure 3. This trend is inverted around 700 s, when the engine is switched on and, due the low-power demand, is mainly devoted to recharge batteries until 800 s (see Figure 3). Afterwards, the engine concurs with batteries to power the vehicle, resulting in a dramatic decrease in SOC in the latter part of the transient (1050 – 1150 s), when the batteries are requested to supply most of the drive power.

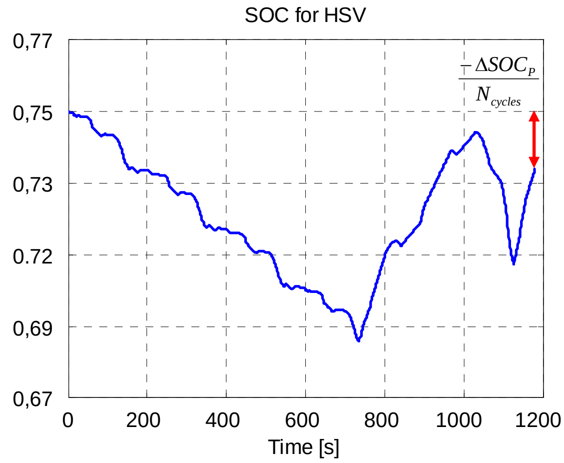

Figure 3 – *Battery state of charge($A_{PV,H}$ = 3 m^2, P_{EG} = 35.5 kW, l = 4.2 m, w = 1.75 m, h =1.5 m).*

The occurrence of an initial discharging process, followed by a recharging one, results in further benefits for batteries losses since the lower is the SOC, the more efficient is the recharging phase. Due to the constraint introduced by eq. (15), the final SOC differs from the initial value by a fraction of the amount of energy stored during the parking hours.

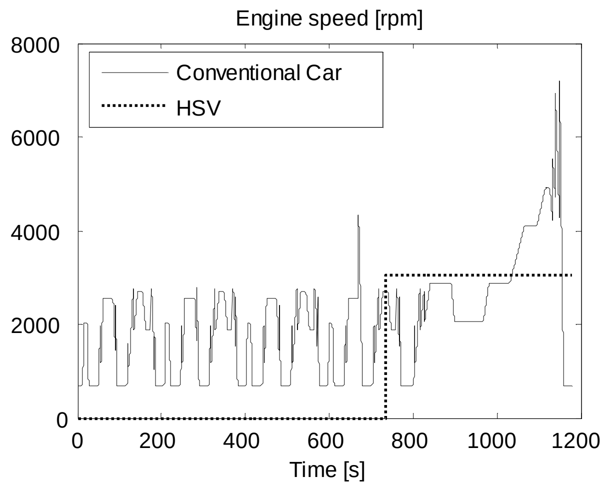

Figure 4 – *Comparison between CC and HSV rpm over the ECE-EUDC cycle ($A_{PV,H}$ = 3 m^2, P_{EG} = 35.5 kW, l = 4.2 m, w = 1.75 m, h =1.5 m).*

Figure 4 shows a comparison of engine speeds in case of hybrid and conventional vehicle, evidencing that in the latter case (solid line), the ICE works in most cases at partial loads, with higher values of specific fuel consumption.

It is worth mentioning here that other strategies are possible, such as letting the ICE run during parking mode too: in that case, the engine can be used to restore battery charge by working always at its maximum efficiency.

PARAMETRIC ANALYSIS

In order to evaluate the energetic benefits of HSV configuration with respect to conventional vehicle, a parametric analysis has been carried out, ranging the electric generator (EG) power from 10 to 60 KW and the PV area from 0, corresponding to pure hybrid electric vehicle, to 6.5 square meters. The analysis has been performed by imposing a constant overall max power (i.e. P_{EM}) to vehicle weight ratio; therefore a decrease of EG power is compensated by an increase of battery modules, which in turn results in a weight increase and finally in a greater overall power. In this analysis, vehicle dimensions have been kept constantly equal to the reference vehicle ones (l = 4.2 m; w = 1.75 m; h = 1.5 m).

The analysis has been aimed at comparing the fuel consumption of conventional and Hybrid Solar vehicle, along a time horizon corresponding to a number of driving hours h_d = 2. Figure 5 shows the expected trend of vehicle mass vs. EG power: as the EG power is increased, the number of battery modules, needed to maintain the imposed maximum power, is reduced. This behavior results in a lighter vehicle since specific EG power (kW/kg) is greater than specific battery power. Furthermore the figure shows that the introduction of panels results in an quasi-linear increase of mass.

The dependence of the control variable ϕ on EG power is shown in Figure 6: according to the control strategy adopted, as the power is increased the EG provides the requested energy in a shorter time, thus reducing the operation time. Particularly, when the EG power is lower than 15 kW, the operation at the optimal power (P_{opt}) does not guarantee the requested energy. Thus, the EG is forced to work at a greater power with reduced efficiency ($\phi > 1$). This behavior results in the fuel savings trends shown in Figure 7, indicating the poor benefits in case of EG power lower than 15 kW. This trend is improved with the introduction of the panels, which compensate for the EG low efficiency operation by recharging the batteries during parking hours.

It can also be observed that the benefits achieved by the series hybrid vehicle without solar panels, with respect to the conventional vehicle, are relatively limited in this case, if compared with some results achieved by parallel HEV adopting advanced control strategies [8]. This result is due to the cascade energy losses associated with both the hybrid series configuration and influence of driving cycle; in case of pure urban cycle (ECE cycle), the gain in fuel economy, for the same hybrid vehicle without panels, reaches up to 30 %. This is due to both the low-efficient operation of the conventional vehicle ICE and the higher benefits provided by regenerative braking in urban driving.

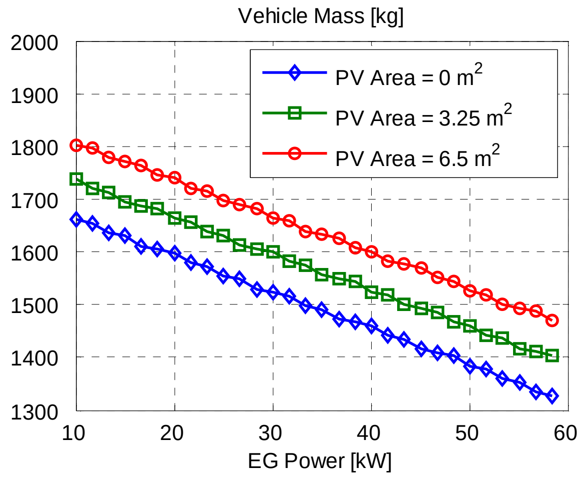

Figure 5 – *Vehicle weight vs. electric generator power for different panels area.*

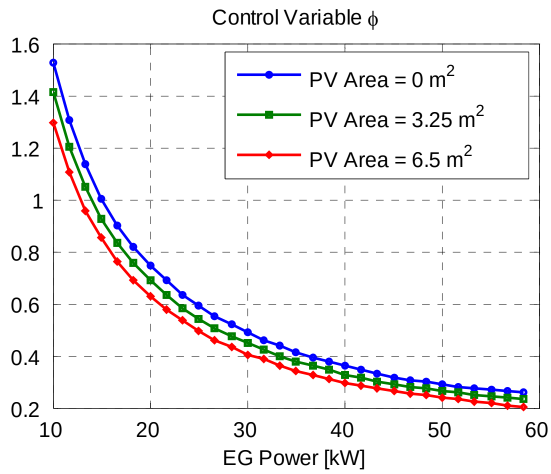

Figure 6 – *Control variable ϕ vs. electric generator power for different panels area.*

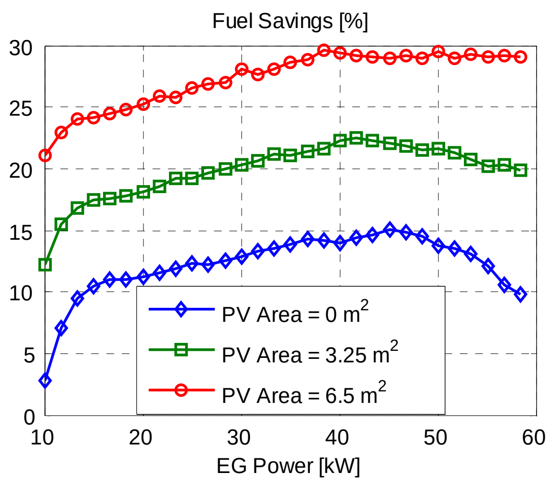

Figure 7 – *Fuel savings vs. electric generator power for different panels area.*

As the power is increased over 15 kW, the EG operates at max efficiency (ϕ < 1) and the fuel savings exhibit an improvement with a best value detected in the range [40 – 45 kW]. Figure 7 also evidences that significant improvements in fuel economy can be achieved by introducing the panels, with max values approaching 30 % of savings with respect to conventional vehicle, in case of 6.5 m^2.

OPTIMIZATION APPROACH

The models presented in the previous chapters allow to achieve the optimal design of the HSV via mathematical programming, considering both technical and economic aspects. The payback is assumed as objective function, while design variables X are represented by electric generator power P_{EG}, horizontal panel area $A_{PV,H}$ and car dimensions (*l*,*w*,*h*).

$$\min_X PB(X) \tag{17}$$

$$G_i(X) \leq 0 \qquad i = 1, N_G \tag{18}$$

The inequality constraints G_i express the following conditions:

i) Car dimensions, length to width and height to width ratios within assigned limits, as addressed by the available database on commercial vehicles.

ii) PV panels area compatible with car dimensions, according to the given geometrical model.

OPTIMIZATION ANALYSIS

The optimization analysis has been carried out by minimizing the *PB* evaluated by eq. (13). The reference vehicle (i.e. conventional car) considered to evaluate the daily saving (i.e. eq. 10) has the following specifications: P_{ICE} = 75 kW; $W_{body,CC}$ = 1250 kg; *l* = 4.2 m; *w* = 1.75 m; *h* = 1.5 m. Table 3 summarizes the results obtained by applying the optimization criteria defined through eqs. (17) and (18).

Table 3 – *Optimization results for different fuel cost and PV technology scenarios.*

#	c_f €/kg	c_{PV} €/m^2	η_P [/]	$A_{PV,H}$ [m^2]	P_{EG} [kW]	PB [yrs]	Fuel Savings [%]
1	1.77	800	0.13	0	35.5	6.1	14
2	1.77	800	0.13	3	35.5	9.9	20.4
2_{bis}	1.77	800	0.13	3	35.5	9.1	37.4
3	1.77	200	0.13	4	37	5.6	23.3
4	3.54	200	0.16	5.6	38.4	2.4	31.3

Case 1, representing a series HEV without solar panels, is considered as reference, with a payback of 6.1 years and a fuel economy of 14 % with respect to the conventional vehicle. The addition of solar panels (e.g. case 2, $A_{PV,H}$ = 3 m^2) allows getting a 6.4 % gain in fuel economy, but results in a higher payback (from 6.1 to 9.9 years), due to the actual costs of fuel and panels. In case of ECE driving cycle (case 2_{bis}), the fuel savings reach up to 37.4 %, though the payback only decreases to 9.1 years; this is due to the relatively small weight of fuel cost in case of urban driving, where the vehicle runs for a small distance.

The HSV can represent the optimal solution considering the occurrence of one (case 3) or all (case 4) of the following circumstances: a) PV cost reduction (by a factor 4); b) fuel cost doubling; c) panel efficiency increase from 0.13 to 0.16. The variations in price and cost are significant but not unrealistic, considering actual trends of reduction and increase for solar component costs and oil prices, respectively.

CONCLUSION

A comprehensive model for the study and the optimal design of a solar hybrid vehicle with series architecture has been presented. The model describes energy flows between horizontal and/or vertical solar panels, internal combustion engine, electric generator, electric motor and batteries, considering vehicle longitudinal dynamics and the effect of control strategies. Vehicle weight is predicted, starting from a database of commercial vehicles, considering the effects of powertrain sizing. The effects of vehicle dimensions on aerodynamic losses and maximum panel area also can be accounted for. The model predicts the additional costs with respect to conventional vehicles, and the pay-back.

It has been shown that significant savings in fuel consumption and emissions can be obtained with an intermittent use of the vehicle at limited average power, compatible with typical use in urban conditions during working days. This result has been obtained with commercial PV panels and with realistic data and assumptions on the achievable net solar energy for propulsion. 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.

Future developments may concern a systematic study of optimal configuration for various driving cycles and latitudes, also considering seasonal variations of the solar energy, more accurate study of control strategies, including possible application of on-board optimization coupled with provisional methods for car load and solar energy based on Recurrent Neural Network.

The results obtained by optimization analysis over a ECE/EUDC cycle have shown 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.

In order to validate the model, a prototype of Hybrid Solar Vehicle with series structure is being developed at DIMEC, within a project funded by EU [17].

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

$E_{s,p}$: Solar energy stored during parking hours (kWh)

$E_{s,d}$: Solar energy stored during driving hours (kWh)

η_p: PV efficiency

A_{PV}: PV surface (m^2)

λ: contribution of solar energy to propulsion

w_{ICE}: ICE weight to power ratio (kg/kW)

w_{gear}: Gearbox weight to power ratio (kg/kW)

w_{EM}: Electric motor weight to power ratio (kg/kW)

w_{EG}: Electric generator weight to power ratio (kg/kW)

$w_{B,u}$: Single battery module weight (kg/kW)

w_{PV}: PV specific weight (kg/m^2)

P_{EG}: Electric generator power for HSV

η_{EG}: Electric generator efficiency

c_{ICE}: ICE cost to power ratio (Eur/kW)

c_{EG}: Electric generator cost to power ratio (Eur/kW)

c_{PV}: PV specific cost (Eur/m^2)

c_{EM}: Electric motor cost to power ratio (Eur/kW)

c_B: Single battery module cost (Eur)

c_B: Single battery module cost (Eur)

c_f: fuel unit cost (Eur/kg)

n_D: number of days per year in the pay-back analysis

ΔSOC_{day}: state of charge variation over the whole day

ΔSOC_d: state of charge variation in driving phases

ΔSOC_p: state of charge variation in parking phases