A PARAMETRIC STUDY OF THE DESIGN VARIABLES FOR A HYBRID ELECTRIC CAR WITH SOLAR CELLS.

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ABSTRACT. *Various prototypes have demonstrated the feasibility of light cars powered with solar energy. While the case of cars powered only by the sun seems not yet feasible for practical uses, the concept of a small electric hybrid car assisted by solar cells appears more realistic. In the paper, a systematic study on the sizing and the performance of a vehicle combining thermal engine, electric motor and generator, battery and solar cells is presented, in order to evaluate their features in terms of car power, weight and fuel savings.*

KEYWORDS *Hybrid Vehicles, Solar Energy, Photovoltaic, Internal Combustion Engine, Automotive Vehicles, Electric Motor.*

1 INTRODUCTION

In last years, increasing attention has been spent toward the applications of solar energy to cars. Various prototypes of solar cars have been built and tested, mainly for racing [6] [7] [19] and demonstrative purposes [1] [4] [8], also to stimulate young students toward energy saving and automotive applications [3]. Despite of a significant technological effort and some spectacular outcome, the limitations due to low density and unpredictable availability of solar source, the weight associated to energy storage systems, the need of minimizing weight, friction and aerodynamic losses make these vehicles quite different from the current idea of a car (Fig. 1). While the case of cars powered only by the sun seems not yet feasible for practical uses, the concept of an electric hybrid car assisted by solar cells appears more realistic [17] [2] [18] [20]. In fact, in last decades Hybrid Electric Vehicles (HEV) have evolved to industrial maturity, after a relevant research effort [9] [10]. These vehicles now represent a realistic solution to the reduction of gaseous pollution in urban drive and to energy saving, thanks to the possibility of optimizing the recourse to two different engines and to perform regenerative braking. Nevertheless, the need of mounting on-board both thermal and electrical machines and a battery of significant capacity makes these vehicles heavier than the conventional ones, at the same power, while solar cars require very limited weight. Therefore, the feasibility of a hybrid vehicle where solar energy can provide a significant contribution to propulsion is of course questionable.

In spite of their potential interest, solar hybrid cars have received relatively little attention in literature. An innovative prototype (Viking 23) has been developed at Western Washington University [17][18] in the 90's, adopting very advanced solutions for materials, aerodynamic drag reduction and PV power maximization with peak power tracking. Another study on a solar hybrid vehicle has been presented by Japanese researchers [20], with PV panels located on the roof and on the windows of the car. Fuel consumption savings up to 90% could be achieved in some conditions. A further prototype of solar hybrid car powered with a gasoline engine and an electric engine has been proposed and tested by other Japanese researchers [2]. In this case, a relevant amount of the solar energy was provided by PV panels located at the parking place, while only a small fraction was supplied by PV panels on the car. The hybridization lead to a significant weight increase (350 kg), due to the adoption of lead batteries, probably too heavy for such application.

Although these studies demonstrate the general feasibility of this idea, a systematic approach to the design of a solar hybrid vehicle seems still missing. Moreover, the technological scenario is rapidly changing, and new components and solutions can be available. In the following, a study on the optimal sizing of a solar hybrid car will be presented.

Fig. 1 – A prototype of Solar Car

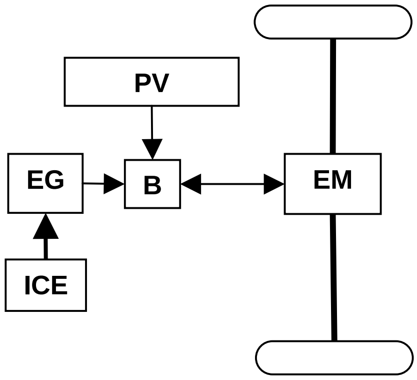

Fig. 2 – Scheme of the Hybrid Solar Vehicle (see Nomenclature)

2 THE SOLAR HYBRID CAR MODEL

As it is known, two different architectures can be applied to HEV's. In the Series Hybrid Vehicles the ICE powers an electric generator (EG) for recharging the battery pack (B), while the vehicle is powered by an electric motor (EM). The ICE is sized for a mean load power and works at constant load with reduced pollutant emissions, high reliability and long working life. On the other hand, in this configuration the energy flows through a series of devices (ICE, generator, battery pack, electric motor, driveline) each with its own efficiency, resulting in a reduction of the power-train global efficiency [9]. In the parallel architecture, both ICE and EM are mechanically coupled to the transmission and can simultaneously power the vehicle. This configuration offers a major flexibility to different working conditions, but requires more complex mechanical design and control strategies. In this paper, due to its greater simplicity and to recent advances in electric motor and generator technology, we assumed a series architecture for the Solar Hybrid Vehicle. In this case, the Photovoltaic Panels (PV) concur with the Electric Generator EG, powered by the ICE, to recharge the battery pack B both in parking mode and in driving conditions. The electric motor EM can both provide the mechanical power for the propulsion and restore part of the braking power during regenerative braking (Fig.2). Nevertheless, this study could be adapted to a parallel architecture with minor changes, and the conclusions seem not strictly limited to the particular structure considered.

3 ENERGY FLOWS

In order to estimate in a realistic way the net solar energy captured by PV panels and available to the propulsion, a solar calculator developed at the US National Renewable Energy Lab has been used [11]. In Table I the net average energy per month is reported for four different US locations, ranging from 21° to 61° of latitude, based on 1961-1990 time series. It can be observed that, except at highest latitudes and during winter time, there is not a significant reduction in the captured energy assuming a horizontal position of the PV panel with respect the ‘optimal’ tilt angle, roughly corresponding to the latitude. Therefore, all the following computations have been performed for horizontal position.

Table I – Average Energy [KWh] for four different sites for a crystalline silicon PV system rated 1 KW AC at SRC, for horizontal and optimal (=latitude) tilt angles.

	San Antonio		Chicago		Honolulu		Anchorage	
Month	0°	29.53°	0°	41.78°	0	21.33°	0°	61.17°
1	85	120	50	95	108	137	2	23
2	100	125	71	106	117	139	21	60
3	136	152	108	132	150	161	63	115
4	144	146	136	143	155	154	99	124
5	165	154	167	157	176	164	139	139
6	169	153	168	149	173	156	140	125
7	185	170	172	157	179	164	132	121
8	170	169	140	140	175	170	95	102
9	138	151	111	131	160	168	60	88
10	124	154	85	123	136	157	22	53
11	93	130	48	81	110	137	4	40
12	79	117	38	70	104	135	0	16
Year	1589	1741	1294	1485	1742	1842	778	1004
Day	4.353	4.770	3.545	4.068	4.773	5.047	2.132	2.751

The PV panels should be located on the roof and on the hood of the car. In order to maximize the solar energy for a given car length, additional panels could be located along the sides of the car, almost in vertical position. In this case, the energy would depend on azimuth angle, latitude and season. Assuming a random vertical orientation, the energy is roughly 50% respect to horizontal position, over a yearly base (Table II).

Table II – Average Yearly Energy [KWh] for four different sites for a crystalline silicon PV system rated 1 KW AC at SRC, for horizontal and four vertical positions.

	Horiz.	Vertical					Mean Vert./Horiz.
Location	0°	N	E	S	W	Mean	%
San Antonio	1589	354	796	960	894	751	47.3
Chicago	1294	312	743	962	728	686	53.0
Honolulu	1742	383	951	873	934	785	45.1
Anchorage	778	216	500	807	514	509	65.5

The energy can be obtained summing the contributes during parking (p) and driving (d) periods, obviously during daytime. While in the former case it is reasonable to assume that the PV array has an unobstructed view of the sky, this hypothesis could probably fail in driving conditions, where shadow can be due to the presence of trees, buildings and other obstacles. Therefore, the energy captured during driving can be reduced by a factor $\beta<1$. 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 (h_{sun} =10). Anyway, this hypothesis does not affect the total energy to the PV panel, provided on daily basis. The values reported in Table I take into account the efficiency of the devices (i.e.inverter, cables) to produce AC current, but do not consider the further degradation due to charge and discharge processes in the battery. A factor $\alpha<1$ is then introduced to account for this effect. The net solar energy available to the propulsion can therefore be expressed as:

$$E_{sun} = E_p + E_d = \eta_p A_{PV} e_{sun} \frac{h_{sun} - h_d}{h_{sun}} \alpha + \eta_p A_{PV} e_{sun} \frac{h_d}{h_{sun}} \alpha\beta \tag{1}$$

The energy required to drive the vehicle during the day can be expressed as function of the average power P_{av} and the driving hours h_d:

$$E_d = \frac{1}{3600} \int_{h_d} P(t) \cdot dt = \frac{1}{3600} h_d P_{av} \tag{2}$$

The contribution of solar energy to the propulsion can be therefore determined:

$$\varphi = \frac{E_{sun}}{E_d} \tag{3}$$

This term evidently also represents the relative reduction in fuel consumption and in the emissions of pollutants and CO_2 with respect to the hybrid electric vehicle without PV panels. Of course, more relevant benefits can be achieved with respect to a conventional vehicle, thanks to the optimized recourse to thermal and electric engine and to regenerative braking due to hybrid concept.

4 CALCULATION OF MASS

In order to compare the mass of the solar hybrid car with those corresponding to commercial cars, a regression analysis of weight and of power to weight (PtW) ratio versus power for different small commercial cars has been performed. The results obtained with a first order polynomial are described in Fig. 3. The dotted lines represent the confidence region containing the 50% of the predictions. It can be observed that the car with the most favorable ratio between power and weight is almost 20% lighter than the average value. Therefore, it is realistic to assume that, with proper choice of components and materials and with careful design, the solar hybrid car can exhibit a weight corresponding to 90% of the "average" commercial car, at the same power (γ=0.90). In order to use these data to estimate the base weight of the hybrid solar car (i.e. without battery, electric motor and generator and solar panels), it may be observed that these data include also the weight of some components not present in the hybrid car (i.e.gearbox), and of other components (electric generator, battery) that would be computed separately for the hybrid car (their weights are of course much lower than the corresponding components needed on the hybrid car). Thus, the mass of the solar hybrid car can be expressed as:

$$M_{car} = \gamma M_{base}(P_{\max}) + m_{PV} A_{PV} + m_{EG} P_{av} + m_{EM} P_{\max} + m_{Batt} E_p \tag{4}$$

The various terms are commented in the following:

- The base mass of the car (chassis with filled reservoirs, thermal engine, driver of 75 kg) is estimated as function of the maximum power, starting from a regression over commercial cars. This base value is reduced by a factor γ=0.90, consistently with the considerations above reported.

- The mass of PV panels depend on their area.
- The mass of the electric motor EM is considered as function of the maximum power, while the mass of electric generator EG is function of the average power (a peak factor of 2, ratio between maximum power and average power, has been assumed).
- The mass of the battery depends on its capacity C, related to the energy to be stored during parking mode. In order to assure efficient charge and discharge processes, it is assumed that C is 4 times greater that the energy stored during parking mode.

$$C = \lambda E_p \tag{5}$$

5 SOLAR HYBRID CAR PERFORMANCE AND ENERGY SAVING

The relative contribution of solar energy to propulsion has been estimated by varying the number of driving hours per day (from 1 to 10), and for a range of average power (0-20 KW), considering the average yearly net solar energy obtainable in San Antonio (Tab.I), with 6 m^2 of PV panels in horizontal position. It may be observed that, in case of "continuous" use (h_d=10), the solar energy can satisfy completely the required energy only at very low power (about 1 KW), of course not compatible with normal uses (Fig. 4). It also emerges that if the car is used in intermittent way and at limited average power, a significant percent of the required energy can be provided by the sun. 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. These data are compatible with the use of a small car for one or two persons in a typical working day, in urban conditions. Of course, a battery of adequate capacity is needed in this case.

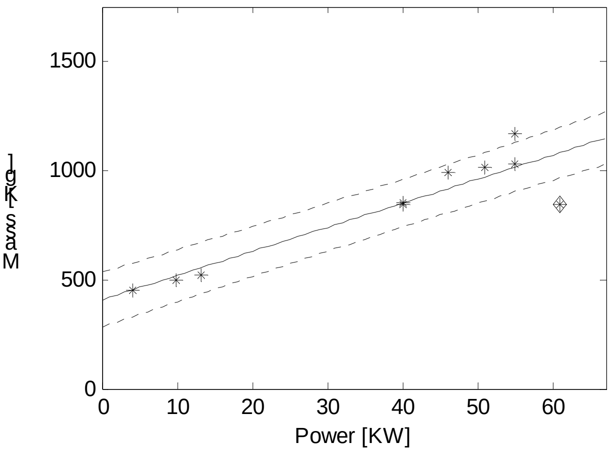

Fig. 3 – Mass versus Power for commercial cars

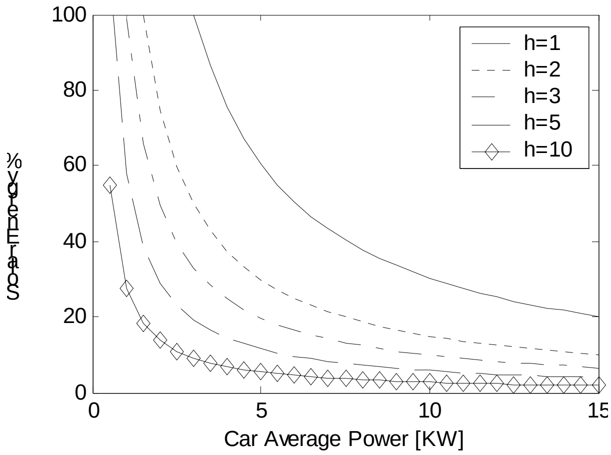

Fig. 4 - Solar energy vs. average power

So the question becomes: can the performance of a solar hybrid vehicle with average power ranging from 5 to 15 KW be comparable with the ones achievable by a commercial car? To this purpose, the mass (and weight) of the solar hybrid car has been estimated for various average power and driving hours. In Fig. 5 the mass of each component and the total mass versus peak power are plotted. The corresponding Power to Weight Ratio have been compared with the ones of commercial cars (Fig. 6). It can be observed that, for peak power greater than 5 KW, the PtW values for the two cases are comparable. At a given peak power, slightly lower PtW values are computed for intermittent use (h_d=1) with respect to "continuous" use (h_d=10), since a greater battery capacity is needed in the former case to store the solar energy during parking time. The relative solar contribution obtainable for various locations and months are reported in Fig. 7. It may be observed that the solar contribution can raise up to 40% during summer time, at lowest latitudes, while is negligible in Alaska during winter time, as expected. These values agree with the results obtained by other researchers for solar hybrid vehicles [20].

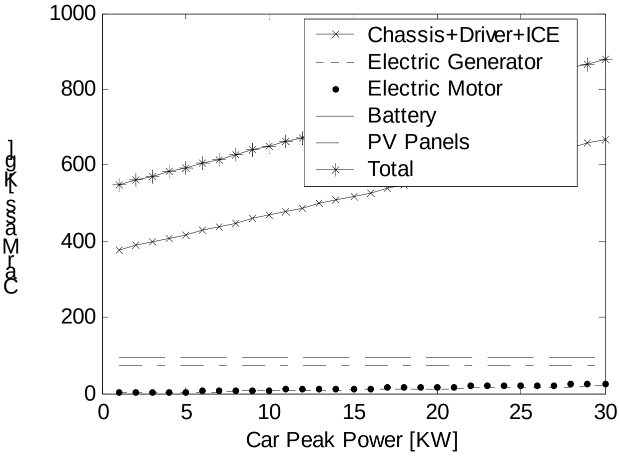

Fig. 5 – Car Mass vs Peak Power

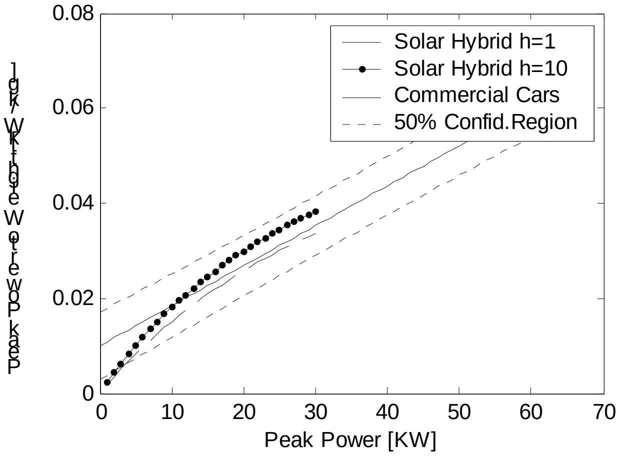

Fig. 6 – Power to Weight for commercial cars and for Solar Hybrid Car

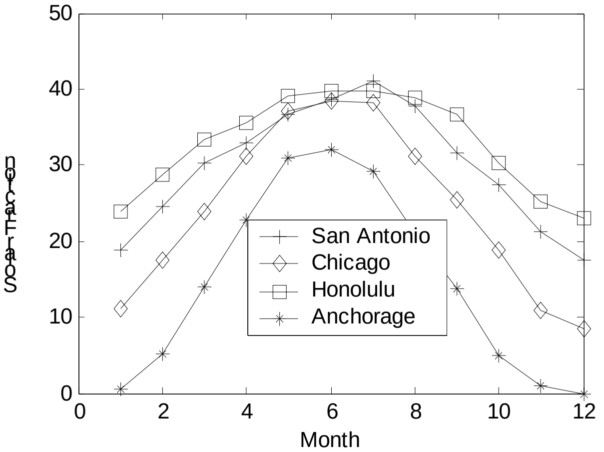

Fig. 7 – Solar Fraction in various locations and months (P_{av}=5 KW, h_d=2)

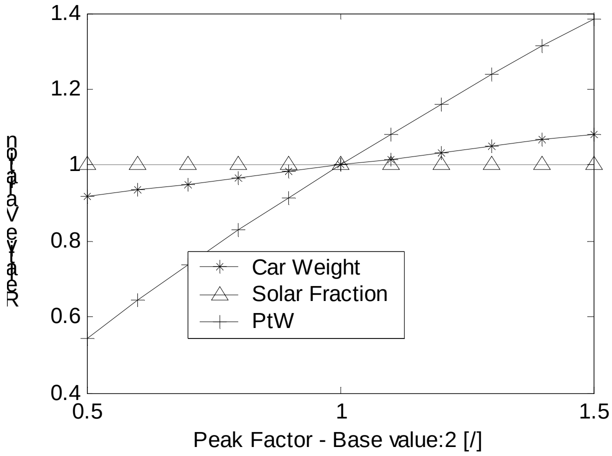

Fig. 8 – Sensitivity Analysis. Effects of Peak Factor.

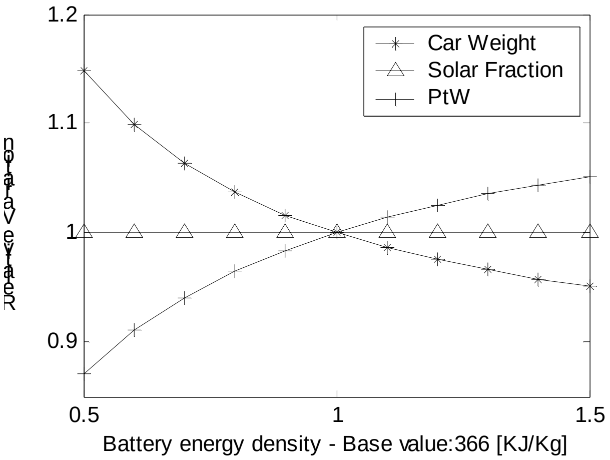

Fig. 9 – Sensitivity Analysis. Effects of Battery Energy Density

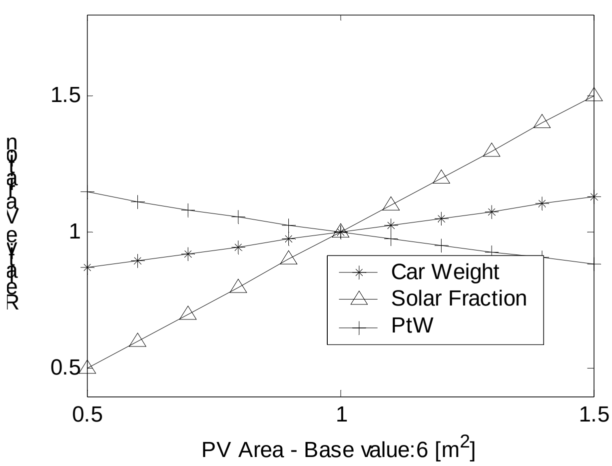

Fig. 10 – Sensitivity Analysis. Effects of PV Area.

In order to check the sensitivity of the results to the various assumptions, a systematic analysis has been performed, evaluating the relative variation of Car Weight, Power to

Weight and Solar Fraction with respect all the variables, starting from nominal conditions. Due to space constraints, only some typical results are presented. It can be observed that the Peak Factor exerts of course a relevant influence on PtW, but also affects Car Weight (Fig. 8) due to its effect on the EM size. Also, a 5% increase in PtW can be achieved by increasing battery capacity of 50% (Fig. 9). A 50% increase in PV area produces of course an equal increase in solar fraction, but produces a growth in car weight of about 10% (Fig. 10).

6 CONCLUSIONS

A parametric study on global energy flows and on the weight of components for a solar hybrid vehicle with series architecture has been presented. It has been shown that significant savings in fuel consumption and emissions, up to 40% depending on latitude and season, 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 photovoltaic panels of last generation, with nominal efficiencies approaching 30%, may result in a 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. Further studies seem necessary to extend this analysis to other configurations (i.e. parallel hybrid vehicle), to estimate the solar energy achievable with more articulate geometrical distribution of the PV panels. Moreover, although the results obtained in terms of comparison of the weight to power ratio are encouraging, a more detailed model for car chassis, relating power, weight, aerodynamic drag, length and surface for PV panels, could be needed.

Finally, the actual and future costs of the various alternatives should be considered, to verify the practical applicability of the proposed vehicle for commercial use. Although this proposal seems still far from economic feasibility, it is reasonable to expect further reductions in costs for PV panels, batteries and advanced electric motors and generators, while unfortunately further 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.

NOMENCLATURE

Symbol	Description	Unit	Value(s)
λ	Ratio between battery capacity and daily stored energy	/	4
γ	Reduction factor respect to base car weight	/	0.90
θ	Peak factor (ratio between EM and EG power)	/	2
α	Energy degradation due to charge and discharge process	/	0.90
β	Solar energy reduction due to shadow during daytime driving	/	0.90
η_{PV}	PV efficiency	/	0.13
A_{PV}	PV area [1]	m^2	6
e_{sun}	Average net solar energy @ SRC rated power of 1 KW [11]	KWh/day	4.353
h_d	Daily driving hours	/	1-10
h_{sun}	Daily hours	/	10
m_{Batt}	Battery energy density (Lithium-Ion) [13]	KJ/Kg	366
m_{EG}	Electric Generator Unit Mass [12]	Kg/KW	0.62
m_{EM}	Electric Motor + Inverter Unit Mass [12]	Kg/KW	0.81
m_{PV}	PV unit mass (crystalline silicon)	Kg/m^2	12
PtW	Power to Weight Ratio	KW/Kg	

B	Battery	ICE	Internal Combustion Engine
EG	Electric Generator	PV	Photovoltaic Panel
EM	Electric Motor		

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