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Solar energy for cars: perspectives, opportunities and problems.

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Abstract: Sustainable Mobility issues are gaining increasing attention both among specialists and in public opinion, due to the major impact of automotive systems on carbon dioxide production, climate changes and fossil fuel depletion. Recently, increasing efforts are being spent towards the application of solar energy to electric and hybrid cars, also thanks to the decreasing cost and to the increasing efficiency of photovoltaic panels, but the possibility to apply solar energy to cars is still considered as a questionable issue. The paper is therefore articulated as answers to common and possible questions about the perspectives, opportunities and problems related to application of solar energy to cars, also on the base of the research performed by the authors on Hybrid Solar Vehicles.

1 WHY SHOULD WE CHANGE OUR CARS?

In the last years, there is an increasing awareness about the need to achieve a more sustainable mobility, allowing meeting the mobility needs of the present without compromising the ability of future generations to meet their needs (Kyoto Protocol, 1997). The most pressing arguments towards new solutions for personal mobility are the following:

- 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 and India; as a consequence, energy consumption and CO_2 emissions related to cars and transportation are expected to increase;
- fossil fuels, largely used for car propulsion, are doomed to depletion; their price is still growing, and is subject to large and unpredictable fluctuations;
- transportation has a marked impact on acoustic and atmospheric pollution in urban areas: consequently, there is an increasing trend to create emissions-free urban areas accessed only by ULEV’s (ultra low emissions vehicle) or ZEV’s (zero emissions vehicle).

2 WHY SOLAR ENERGY?

The Kyoto Protocol, and the subsequent decisions taken at various political levels, have emphasized the recourse to renewable energy sources as one of most effective solution to such problems. Is it therefore natural to wonder about possible use of solar energy for automotive applications.

The conversion from light into direct current electricity is based on the researches performed at the Bell Laboratories in the 50’s, where the principle discovered by the French physicist Alexandre-Edmond Becquerel (1820-1891) was applied for the first time. The photovoltaic panels, working thanks to the semiconductive properties of silicon and other materials, were first used for space applications.

The diffusion of this technology has been growing exponentially in recent years, due to the pressing need for a renewable and carbon-free energy. World solar PV installations were 2.826 gigawatts peak (GWp) in 2007, and 5.95 gigawatts in 2008, with a 110% increase. The amount of solar energy is impressive: the 89 petawatts of sunlight reaching the Earth's surface is almost 6,000 times more than the 15 terawatts of average electrical power consumed by humans (Smil, 2006). The applications range from power station, satellites, rural electrification, buildings to solar roadways and, of course, transport.

3 WHAT ARE EFFICIENCY AND COSTS OF PHOTOVOLTAIC PANELS?

Most of the today PV panels, with multi-crystalline technology, have efficiencies between 11% and 18%, while the use of mono-crystalline silicon allows to increase the conversion efficiency of about 4%. The recourse to multi-junction cells, with use of materials as Gallium Arsenide (Thilagam et al, 1998), and to concentrating technologies (Segal et al., 2004), has allowed to reach 40% of cell efficiency. Anyway, the cost of these latter solutions is still too high for a mass application on cars.

About price of solar modules, the market has experienced a long period of falling down of the prices since January 2002 up to May 2004. Afterwards, prices began rising again, until 2006-2007. This inversion has been attributed to the outstripping of global demand with respect to the supply, so that the manufacturers of the silicon needed for photovoltaic production cannot provide enough raw materials to fill the needs of manufacturing plants capable of increased production (Arsie et al., 2006; see also www.backwoodssolar.com). After 2008, the prices began to fall down again, both in USA and in Europe.

According to some recent studies (Neil C., 2006), PV panels added to hybrid cars could be even more cost effective than PV panels added to buildings. The incremental cost of solar PV panels on hybrid cars and displacing gasoline could have a payback period much shorter than the payback for solar PV panels on buildings and displacing electricity. This result has been also confirmed by some evaluations recently made by the author, aimed to the estimation of pay-back time of moving and fixed solar roofs for a PV assisted vehicle at different latitudes (Coraggio et al., 2010).

4 A SOLAR PANEL ON A CAR: IT IS WORTH IT?

The potential advantages of solar energy are clear, but their limitations too: it is intermittent, due to the effects of relative motion between Earth and Sun, and variable in time, due to weather conditions. But the most serious limitation for direct automotive use concerns its energy density: the amount of radiation theoretically incident on Earth surface is about 1360 W/m^2, and only a fraction of this energy can be converted as electrical energy to be used for propulsion. Considering that the space available for PV panels on a normal car is limited (from about 1 m^2 in case of panels outfitting ‘normal’ cars to about 6 m^2 for some solar cars), it emerges that the net power achievable by a solar panel is about two order of magnitude less that the power of most of today cars.

But this simple observation, that explains the scepticism about solar energy in most of the automotive community, is based on the misleading habit to think in terms of power, instead of energy. In fact, for a typical use in urban driving (no more than one hour per day, according to recent Statistics for Road Transport, with an average power between 7 and 10 kW, considering a partial recovery of braking energy), the net energy required for traction can be about 8 kWh per day, while a PV panel of 300 W can operate near to its maximum power for many hours, if properly located and controlled: in these conditions, the solar contribution can represent a rather significant fraction, up to 20-30%, of the required energy (Arsie et al., 2006).

It therefore emerges that benefits of solar energy can be maximized when cars are used mostly in urban environment and in intermittent way, spending most of their time parked outdoor, and of course in countries where there is a “sufficient” solar radiation.

5 IS A SOLAR VEHICLE CONVENIENT ONLY IN TROPICAL COUNTRIES?

In most of solar cars, solar panels are fixed and located at almost horizontal position. This solution, although the most practical by several points of view, does not allow to maximize the net power from the sun. In Fig. 1 the mean yearly incident energy corresponding to different position of solar panels is presented, for different latitudes. The data have been obtained by PVWatts, based on a database of real data covering about 30 years, for different locations in USA. It can be observed that a moving panel would increase the solar contribution from about 46%, at low latitudes, up to 78%, at high latitudes. Of course, the adoption of a moving roof could be feasible only for parking phases, where on the other hand many cars in urban environment spend most of their time. The real benefits would be lower than the ones indicated in the graph, due to the energy spent to move the panel and to possible kinematic constraints preventing perfect orientation.

Also, in order to maximize the solar contribution, transparent panel could be incorporated in the windows, and the lateral surface of a car could be also covered by solar panels. Their possible fragility in case of lateral impacts would represent a possible problem; the recourse to thin film technology could reduce these risks. An estimation of the increase in incident energy can be obtained by considering the mean incident energy on a vertical surface, with random orientation: with respect to the energy incident at horizontal position, their contribution is about 45%, at low latitudes, but up to 65% at higher latitudes (Fig. 1). It therefore emerges that the adoption of a moving roof for parking phases, and the utilization of windows and lateral surfaces too, would allow a significant increase of incident energy with respect to the sole utilization of the car roof. Moreover, this increment is particularly significant at high latitudes, so contributing to enlarge the potential market of solar assisted vehicles.

A study on the benefits of a moving solar roof for parking phases in a Hybrid Solar Vehicle has been recently performed. A kinematic model of a parallel robot with three degrees of freedom has been developed and validated over the experimental data obtained by a small scale real prototype. The effects of roof design variables are analyzed, and the benefits in terms of net available energy assessed by simulation over hourly solar data at various months and latitudes. The results will be presented shortly (Coraggio et al., 2010).

6 WHY HYBRID SOLAR VEHICLES?

Several prototypes of solar cars, powered only by the sun, have been built and tested, since '70s. These vehicles were not intended as day-to-day transportation devices, but are rather demonstration vehicles and engineering exercises (Ozawa et al., 1998; Gomez de Silva and Svenson, 1993). But, in spite of some spectacular advances, the high costs, the need of minimizing weight, friction and aerodynamic losses and the absence, in most cases, of a storage system of adequate capacity able to assure a regular operation without solar radiation make these vehicles quite different from the current idea of car.

Instead, the idea to apply PV panels on a Hybrid Electric Vehicle appears more realistic. The attention to such vehicles dates to the 90's, when some pioneering prototypical applications appeared (Seal and Campbell, 1995). In recent years, the French company Venturi has realized different concept cars, including Venturi Astrolab (Fig. 2), presented as the first hybrid solar vehicle in sale. And, recently, a model of Toyota Prius integrated with a solar panel has been produced; in this case the solar energy is used to power the air conditioning system.

A wide overview over the Vehicle Integrated Photo Voltaic (VIPV) is reported by Letendre et al. (2003). The opportunities offered by the integration of electric vehicles with grid and stationary systems are remarked (Vehicles connected To Grid, V2G; Plug-in Hybrid Electric Vehicle, PHEV). But, despite their potential interest, solar hybrid cars have received relatively little attention in literature until a few of years ago (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.

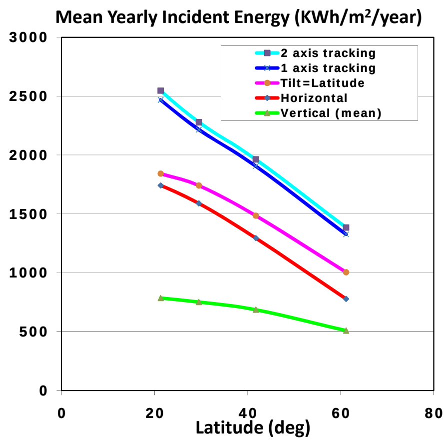

Fig. 1. Effects of panel position and latitude on incident energy

Fig. 2. The Hybrid Solar Vehicle Astrolab, produced by Venturi

7 SO, PUT A SOLAR PANEL ON A HYBRID ELECTRIC VEHICLE. IS THAT ALL?

It would be simplistic to consider the development of a Hybrid Solar Vehicle as the sole addition of photovoltaic panels to an existing vehicle. In fact, the development of HEV's, despite it was based on well-established technologies, has shown 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 redesign and optimization of the whole vehicle-powertrain system, considering the interactions between energy flows, propulsion system component sizing, vehicle dimension, performance, weight and costs. In the following, some of these aspects are described, also based on the author's direct experience on Hybrid Solar Vehicles.

7.1 SOLAR PANEL CONTROL

The surface of solar panels on a car is limited, with respect to most stationary applications, and it is therefore important to maximize their power extraction. There are several problems, that make this challenge difficult. For example, the need of connecting cells of different types within the same array usually leads to mismatching conditions. This may be the case of using standard photovoltaic cells for the roof and transparent ones, in place of glasses, connected in series. All these aspects are of course enhanced and complicated during driving, due to orientation changes and shadows.

In order to draw the maximum power at the current solar irradiance level, switching dc-dc converters controlled by means of a Maximum Power Point Tracking (MPPT) strategy are used (Hohm, 2000). Usually, standard MPPT strategies are able to detect the unique peak of the power vs. voltage characteristic of the PV array, but may fail in presence of multiple peaks due to mismatching (Egiziano et al., 2007). More advanced approaches, based on a detailed modelling of the PV field (Jain, 2006; Liu, 2002), are then required.

7.2 OPTIMAL DESIGN OF HYBRID SOLAR VEHICLES

A study on the optimal design of a Hybrid Solar Vehicle has been performed at the University of Salerno, considering performance, fuel consumption, weight and costs of the components (Arsie et al., 2007, 2008). The study, that has determined optimal vehicle dimensions and powertrain sizing for various scenarios, has 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 (Fig. 3) has also been developed (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). Several studies on energy management and control have been performed. While the actual prototype (HSV-A, Fig. 4) is penalized by a non optimal choice of their components, also due to budget limitations, the simulation model validated over the prototype data shows that very interesting values of fuel economy could be reached by improving the efficiency of solar panels (from 12% to 18%) and optimizing battery capacity and weight (HSV-B), and further reducing vehicle weight by adoption of Lithium-Ion batteries instead of original Lead-Acid (HSV-C).

Fig. 3. A prototype of Hybrid Solar Vehicle with series structure developed at the University of Salerno.

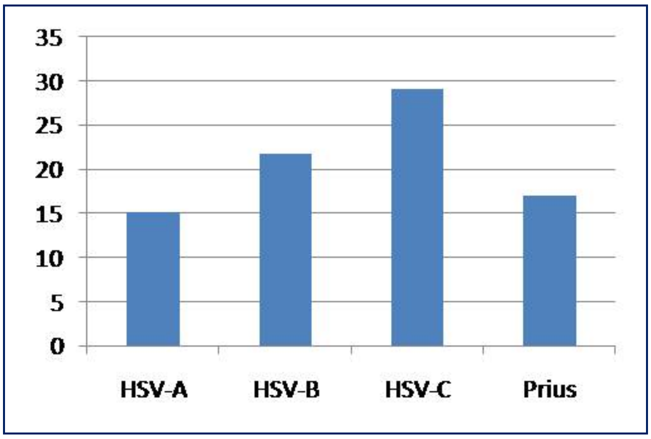

Fig. 4. Fuel Economy (km/l) on ECE Cycle - HSV vs. Toyota Prius. A – actual prototype. B – PV eff.=18% - Batt.=75 Ah. C – B+ 20% weight off – Lithium-Ion Batt.

7.3 MANAGEMENT AND CONTROL OF ENERGY FLOWS

The energy management of Hybrid Solar Vehicles, in spite of many similarities with HEV’s, could not simply borrowed from the solutions developed for HEV’s: in fact, while in these latter a charge sustaining strategy is usually adopted, in HSV’s the battery can be recharged also during parking time by solar energy, and therefore a charge depletion strategy has to be followed during driving, as it happens for Plug-In Hybrid Electric Vehicles (PHEV) (Marano et al., 2009). At the end of driving cycle the final state of charge (SOC) should be sufficiently low to leave room for the solar energy to be stored in the battery in the next parking phase. On the other hand, the adoption of an unnecessary low value of final SOC could produce additional energy losses associated to battery operation, so increasing fuel consumption.

In a recent study (Rizzo and Sorrentino, 2010), the effects of different strategies of selection of final SOC are analyzed by simulation over hourly solar data at different months and locations, and the benefits achievable by estimating the energy expected in next parking phase are assessed. The simulations are carried out with a dynamic model of a HSV previously developed (Arsie et al., 2007), including a rule-based (RB) energy management strategy. The results have shown that the estimation of the incoming solar energy in next parking phase produces a more efficient energy management, with reduction in fuel consumption, particularly at higher insulation.

The RB control architecture consists of two loops: i) an external loop, defining the desired final state of charge to be reached at the end of the driving cycle; ii) an internal loop, estimating the average power delivered by the internal combustion engine and SOC deviation. The results of RB strategy have been successfully compared with a benchmark (non implementable) strategy, obtained by means of a Genetic Algorithm (Sorrentino et al., 2009). In the study, a dynamic model considering also the effects of engine thermal transients on fuel consumption and power, related to start-stop operation, has been adopted. The importance of thermal transients in start-stop operation, neglected in most models used for energy management in hybrid vehicles, has been demonstrated by recent experimental studies (Ohn et al., 2008). A method for fuel consumption minimization in Hybrid Solar Vehicle based on Model Predictive Control has also been recently proposed (Preitl et al., 2007).

8 WHAT ABOUT CONNECTIONS WITH GRID?

The presence of a photovoltaic panel on a Plug-in Hybrid Electric Vehicle (PHEV) can enhance the development of Vehicle to Grid (V2G) technology: in this approach, the plug-in vehicles, besides receiving power when parked, can also provide power to the grid (Arsie et al., 2009). Use of PHEV for V2G can provide benefits to both vehicle owner and the power utility company, apart from the reduced tailpipe emissions and increased mileage. Statistical analysis suggest that the use of PHEV to supply energy to the grid is beneficial when the number of vehicle connected to the grid is large (Kempton et al., 2001).

This technology is now spreading: on September 2009, Delaware's Governor signed a law on V2G, requiring electric utilities to compensate owners of electric cars for electricity sent back to the grid at the same rate they pay for electricity to charge the battery (www.udel.edu/V2G/). In this context, it is clear that a solar powered PHEV can contribute to power the grid also using solar energy, that is free and renewable. This opportunity prevents also to waste solar energy provided by PV panels on the car when car batteries are fully charged.

9 HOW COULD SOLAR ENERGY BE USED IN A CONVENTIONAL CAR?

A general remark that can be expressed is that, considering the actual economic crisis, it is unlikely in next few years a substantial number of conventional vehicles could be substituted by PV assisted EV’s and HEV’s, since a relevant investment on production plants would be needed. This fact would of course limit the global impact of this innovation on fuel consumption and CO_2 emissions. Therefore, one may wonder if there is any possibility to upgrade conventional vehicles to PV assisted hybrid.

A proposal of a kit to be distributed in after-market has been recently formulated and patented by the authors (www.hysolarkit.com). Mild-solar-hybridization will be performed by installing in-wheel electric motors on the rear wheels (in case of front wheel drive) and by the integration of photovoltaic panels on the roof. The original architecture will be upgraded with the an additional battery pack and a control unit to be faced with the engine management system by the OBD port. The Vehicle Management Unit (VMU), which would implement control logics compatible with typical drive styles of conventional-car users, receives the data from OBD gate and battery (SOC estimation) and drives in-wheel motors.

The project has been recently financed by the Italian Ministry of Research (www.dimec.unisa.it/PRIN/PRIN_2008.htm). The results will be published, and presented on the cited websites. A more detailed survey on automotive applications of solar energy will be also presented shortly (Rizzo, 2010).

10 IN CONCLUSION?

The integration of photovoltaic panels in electric and hybrid vehicles is becoming more feasible, due to the increasing fleet electrification, to the progresses in terms of PV technology, to the increase in fuel costs and to PV panels cost reduction. Hybrid Solar Vehicles may therefore represent a valuable solution to face both energy saving and environmental issues. Significant benefits 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.

But, despite their development is based on well-established technologies, re-design and optimization of the whole vehicle-powertrain system is required to maximize their benefits. Particular attention has to be paid in maximizing the net power from solar panels, and in energy management and control, where advanced look-ahead capabilities would be required. Interesting perspectives are also related to possible reconversion of conventional vehicles to Mild Hybrid Solar Vehicles.

The perspectives about cost issues of PV assisted vehicles are encouraging. Anyway, as it happens for many innovations, their economic feasibility could not be immediate. But the recent and somewhat unexpected 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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