Proceedings of the 10th World Congress on Electrical Engineering and Computer Systems and Sciences (EECSS'24)
Barcelona, Spain - August 19 - 21, 2024
Paper No. EEE 119
DOI: 10.11159/eee24.119

The Solar Boost: Pushing Hybrid Car Limits with Photovoltaic Energy

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Abstract - In the context of growing concerns about climate change and the need for more sustainable solutions, solar energy used on electric vehicles offers a blend of green technology and energy mobility. This not only represents a direct reduction in emissions, but also has the potential to become a key component in future transportation and energy infrastructure. Through tests conducted on a hybrid car, the Toyota Auris, we observed that solar panels can not only power the vehicle but can also offset energy consumption during idle situations or provide auxiliary power for functions like air conditioning. This could significantly reduce reliance on charging stations, especially in areas with high solar exposure. Furthermore, the use of solar energy on vehicles can be integrated with urban infrastructure, making it possible to create parking areas equipped with solar panels or charging facilities that convert sunlight into electrical energy, thus optimizing the charging process. However, there are significant challenges to address. The efficiency of solar panels, initial production and integration costs, as well as their durability are aspects that require further research. Also, consideration must be given to how weather variations and exposure to sunlight can affect performance. This paper provides a detailed look at current research, developments, and future applications of solar energy in the automotive sector, highlighting the ways in which solar technology can revolutionize the automotive industry.

Keywords: solar energy, electric vehicles, sustainable mobility, solar panels, energy consumption, efficiency of solar panels, sustainability**.**

1. Introduction

The paper makes a significant contribution through practical testing on the Toyota Auris hybrid car, providing empirical evidence of the operational efficiency of solar panels integrated into the vehicle. In contrast to theoretical studies, this research offers tangible proof that solar panels not only have the capability to propel the vehicle but also play a crucial role during idle periods. The observed ability of solar panels to offset energy consumption when the vehicle is stationary, particularly by providing auxiliary power for functions like air conditioning, underscores the practical utility of solar energy beyond direct propulsion.

The integration of photovoltaic (PV) technology into electric and hybrid cars has garnered increasing attention in recent years and reflects a broader commitment to advancing sustainable transportation solutions. As technology evolves and challenges are addressed, the integration of solar panels into the automotive industry, holds the potential to contribute significantly to the transition towards cleaner and more energy-efficient mobility.[1-6]

Recent research highlights the potential of solar vehicles, particularly in urban environments. A study conducted by Ciências U Lisboa and Instituto Dom Luiz, in collaboration with French and Luxembourg partners, investigated the viability of solar vehicles in 100 cities across five continents. The study found that solar energy could provide between 11 and 29 kilometers of range per day, effectively reducing the need for charging by half. This research indicates that solar-powered vehicles are most effective in locations with high solar potential, such as Africa, the Middle East, southern Europe, and Southeast Asia, but they also hold promise in other regions like China, North America, and Australia. The study also addressed the challenge of shading in urban environments, which can reduce the efficiency of solar cars, but concluded that this is not a significant limitation to their widespread adoption.[7]

Studies in the literature regarding the use of photovoltaics on conventional cars, namely those intended for general use rather than specific competitions, focus on applications for ventilating the passenger compartment during parking [8-10]. These studies suggest that photovoltaic technology can be applied to internal combustion engine vehicles as well.

1.1 Solar-Powered Cars

A solar-powered car uses solar energy captured by solar panels mounted on the vehicle's surface - typically on the top, side, and hood. These panels contain photovoltaic cells that directly convert solar energy into electrical energy. Although the name suggests they are entirely or partially solar-powered.

1.2 Solar-Powered Hybrid Electric Cars

A hybrid vehicle uses two or more different energy sources for propulsion. Commonly, this term refers to hybrid electric vehicles (HEV), which combine solar energy with electric energy stored in batteries. Hybrid cars boast the best energy efficiency in the industry, and many models are available on the market.

Toyota has started its work from last decade and it is present in two variant one with full BEV where power is drawn from grid (G2V) and another one is assisted with PV. Recently, a new model (Prius Prime) assisted with solar panels for traction has been introduced in the Japanese market [11]. Also Hunday has revealed a version of its Sonata hybrid vehicle with PV roof [12]. Even FIAT has claimed its ground-breaking work in 2009 by introducing Phylla supported by PV and fuel cells [13].

Recently, at the 2019 Geneva International Motor Show, FIAT announced the upcoming electric vehicle, called Centoventi. This new vehicle can be customized by choosing a roof integrating an innovative Solar Panel. A total power of 50 Watts is generated by the solar panel to ventilate the car cabin during parking and to power the innovative digital display arranged under the tailgate that closes the rear volume [14].

2. INTEGRATING SOLAR TECHNOLOGY IN HYBRID CARS

Solar technologies made significant advancements in the past decade, and their integration into hybrid vehicles is a natural progression in the effort to reduce dependence on fossil fuels and minimize CO2 emissions. Hybrid cars, already equipped with batteries for electric energy storage, offer an excellent platform for harnessing solar energy.

The most common type of solar technology used in these applications is the photovoltaic (PV) solar panel. These panels directly convert sunlight into electricity through solar cells, typically made from silicon.

Solar photovoltaics is the only case in which it is possible to create a sort of ‘‘short supply chain’’ by using the primary energy from the Sun directly on a car (Fig. 1). In all other cases, primary energy is first incorporated into an ‘‘energy vector’’ (fossil fuel, biofuel, electricity, hydrogen, etc) and then transported, distributed, sold and taxed. By using directly the primary energy con the vehicle, through photovoltaic panels, the energy consumption, costs and CO2 emissions involved in the standard supply chain are avoided.[15]

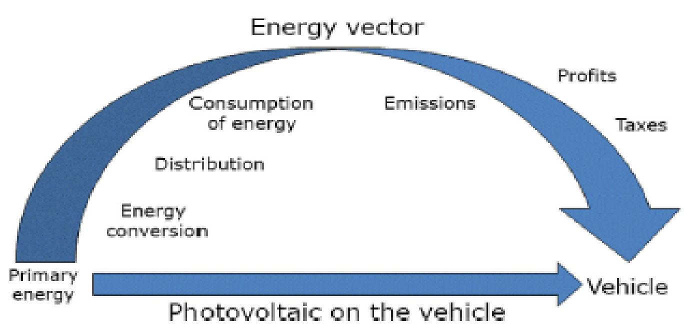

Fig. 1 Use of photovoltaic on the vehicle: short supply chain. [15]

In the pursuit of sustainable mobility, the integration of solar technology into hybrid cars represents a significant leap forward. The core idea is to use photovoltaic (PV) panels to harness solar energy, thereby reducing fuel consumption and enhancing the vehicle's range. However, the effectiveness of this integration hinges on efficient energy management and the ability to adapt to varying environmental conditions. The research introduces a fuzzy logic-based strategy for managing energy in hybrid systems, which includes PV panels, hydrogen subsystems, and batteries. This approach not only meets the load energy demand but also extends the lifetime of system components by optimizing the balance between energy production, consumption, and storage.[16].

2.1. Vehicle-mounted solar panels

By mounting solar panels on the vehicle's surface, especially on the roof, they can capture sunlight and generate electricity during the day. This generated electricity can be used immediately to power various vehicle systems or stored in the battery for later use.

3.Scientific Assuptions

The energy produced during a running period of a vehicle may be calculated by the formula:

$$E_d = \eta A_p E_{sun} \frac{h_{sun} - h_d}{h_{sun}} \alpha \quad (1)$$

where:

E_d = the output energy during the running period;

η = the efficiency of a photovoltaic panel;

A_p = the area of the photovoltaic panel;

E_{sun} = the energy provided by the sun;

h_{sun} = total exposure time of the solar panel to sunlight;

h_d = the period which solar panels do not receive sunlight;

α = efficiency losses during the running period;

The energy produced during the parking period of a vehicle may be calculated by the formula:

$$E_p = \eta A_p E_{sun} \frac{h_{sun} - h_d}{h_{sun}} \qquad \beta \quad (2)$$

where:

E_p = the output energy during the parking period;

ηP = PV panel efficiency;

AP = PV surface area;

E$_{sun}$ = the energy provided by the sun;

β = efficiency losses during the parking period.

Total energy = Driving time energy + Parking time energy:

$$E=Ed+Ep \tag{3}$$

Energy conversion efficiency

$$Efficiency(\eta) = \frac{Useful\ Energy\ Output}{Total\ Energy\ Input}\ 100\% \tag{4}$$

4. Experimental Setup

4.1. Materials and Methods

- Flexible Solar Panel (100Wp);
- PWM Controller;
- Connecting Cables;
- Clamping magnets;

In the study, the experiment focused on the efficient integration of solar energy into automotive powertrains.

4.1.1. Solar panel

A flexible 100Wp solar panel with magnetic mount was used. This type of flexible solar panel has the advantage of being able to be mounted on a variety of surfaces and better adapt to the shape of the roof of the car. (Fig. 1)

Solar panel parameters

- Material:Monocrystalline Silicon
- Maximum Power(Pmax):100Wp±3%
- Maximum Power Voltage (Vmp):18V
- Maximum Power Current (Imp):5.56A
- Open-Circuit Voltage (Voc):22.50V
- Short-Circuit Current (Isc):5.81A
- Nominal Operating Cell Temp.(NOCT):-45to 80°C
- Maximum System Voltage:DC1000V
- Maximum Series Fuse:15A
- Weight: 1.1kg ; Thickness: 1.5mm
- Length: 97.4 cm ; Width: 56.5 cm

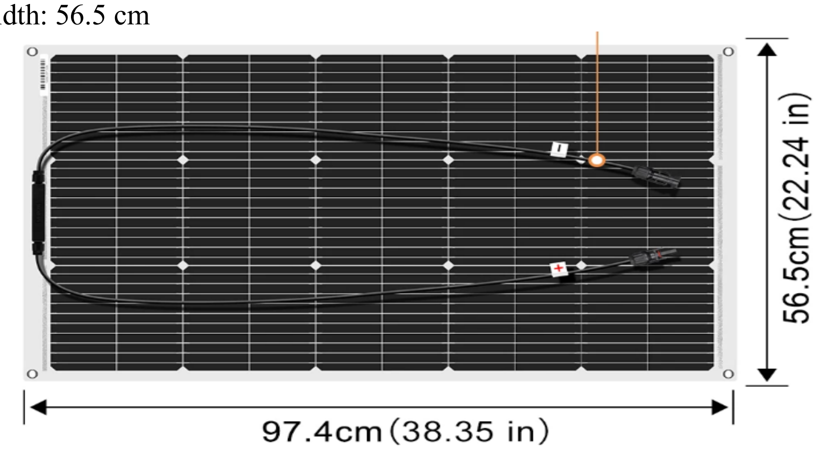

Fig. 1 – Solar panel used

4.1.2. Mounting of systems on the vehicle

For the solar panel, clamping magnets were used, ensuring a simple and easy installation on the roof of the car (tests have been done on Toyota Auris). (Fig. 2)

Fig. 2 – Solar panel mounted on the car

Solar photovoltaic panel mounted on the vehicle serve to recharge the battery, particularly when the vehicle is parked. Illustrated in Figure 3 is a simplified diagram outlining the integration of the solar system with the electric powertrain. The rooftop PV module are linked to a solar charge controller functioning as both a Maximum Power Point Tracker (MPPT) and a DC/DC converter. This controller elevates the voltage from the PV panels (24 V DC) to match the battery voltage (96 V DC) for the connection with the hybrid system battery. The Battery Management System (BMS) oversees the charging and discharging processes of the battery. Concurrently, an additional Vehicle Management Unit (VMU) incorporates the real-time control strategy for the electric powertrain and interfaces with all subsystems, including the driver infotainment display.

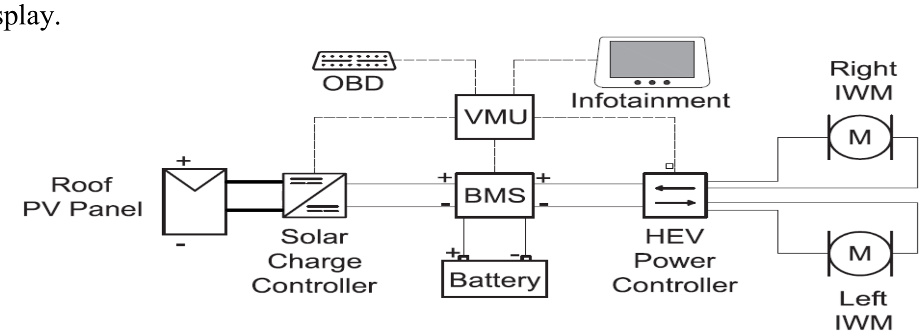

Fig. 3 – Solar panel mounted on the car

4.2. Practical Experiments

4.2.1.Experiment 1: Variation in energy output over 10 days

In the initial experiment, we closely monitored the energy production of a 100Wp flexible solar panel over a 10-day period. The primary objective was to understand how daily variations in solar light intensity at this specific time influence the panel's efficiency.

The energy output of the solar panel exhibited fluctuations based on the intensity of sunlight. On days characterized by high sunlight intensity, the panel approached its maximum capacity of 100Wp. Conversely, on days with lower sunlight intensity, the energy output proportionally decreased (Fig. 4).

Observation:

The objective of Experiment 1 is to elucidate how daily variations in solar irradiance at 14:00 influence the panel's efficiency, defined by the relation (4):

The recorded values for daily energy output (in watt-hours) are as follows:

- Day 1: 70 Wh
- Day 2: 90 Wh
- Day 3: 82 Wh
- Day 4: 77 Wh
- Day 5: 60 Wh
- Day 6: 80 Wh
- Day 7: 90 Wh
- Day 8: 85 Wh
- Day 9: 70 Wh
- Day 10: 80 Wh

These measurements were consistently taken each day. To calculate efficiency (η) for each day, we can use the formula mentioned earlier, where Useful Energy Output is the recorded energy output for the day, and Total Energy Input is the maximum capacity of the solar panel (100Wp). The results can be incorporated into the discussion to provide a detailed insight into the efficiency variations over the 10-day period.

Fig.4 Graph for the solar panel over 10 days

4.2.2.Experiment 2: Variation in energy production and solar light intensity over a day

In the second experiment, our focus was on examining the variation in the energy production of the solar panel throughout a day (Fig. 5).

Methodology:

For this experiment, the following components were utilized:

- A solar panel with known specifications (100Wp solar panel), mounted on the roof of the car with optimal orientation toward the south to maximize exposure to sunlight.
- A lux meter for measuring light intensity.
- An inverter and a multimeter were employed to measure the power produced by the solar panel.

Measurement Setup:

To ensure accurate measurements, we implemented a detailed measurement setup:

1. The lux meter was positioned 1 meter away from the solar panel, in a location allowing direct measurement of incident light intensity.
2. The inverter and multimeter were connected to the solar panel to record real-time power generation.
3. Measurements were taken at 30-minutes intervals throughout the day to obtain a detailed representation of the variability in energy production.

Results:

Solar light intensity began to rise at sunrise, reaching a peak at noon and gradually declining towards sunset. The solar panel's energy production mirrored this trend, achieving peak efficiency around noon.

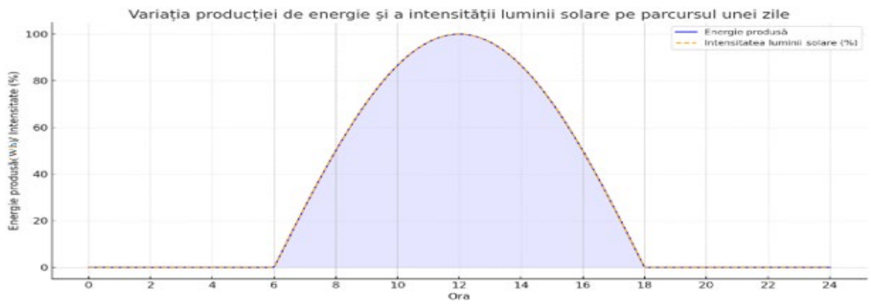

Fig. 5 Graph of the variation in light intensity throughout the day

4.2.3.Experiment 3: Integration of the solar panel into a hybrid car

Context and Purpose

In an attempt to harness solar energy for automotive applications, one approach was taken in Experiment 3. On August 18, 2023, starting at 14:00 and concluding at 15:30, a 100Wp solar panel, consisting of three identical zones, was integrated into a Toyota Auris hybrid car. The experiment aimed to evaluate the solar panel's impact on the vehicle's fuel consumption in real-world conditions, with the temperature outside reaching 30 degrees Celsius.

Methodology

A single 100Wp flexible solar panel, featuring three identical zones, was securely mounted on the roof of the car, using magnets. The strategic placement aimed to maximize sun exposure. The car followed a 104 km route from Continental, Strada Salzburg 8, Sibiu 550018, to the destination in Scoreiu, completing a round trip. (Fig. 6)

The solar panel was seamlessly connected to the car's electrical system, providing direct power or charging the hybrid battery.

Fig. 6 The route for the experiment

Results:

•without the solar panel, the Toyota Auris had an average consumption of 5.5 l/100km;

• with the solar panel installed, the consumption dropped to an average of 4.5 l/100km;

This represents an 18% reduction in fuel consumption, attributed to the additional power supplied by the solar panel on a hybrid car.

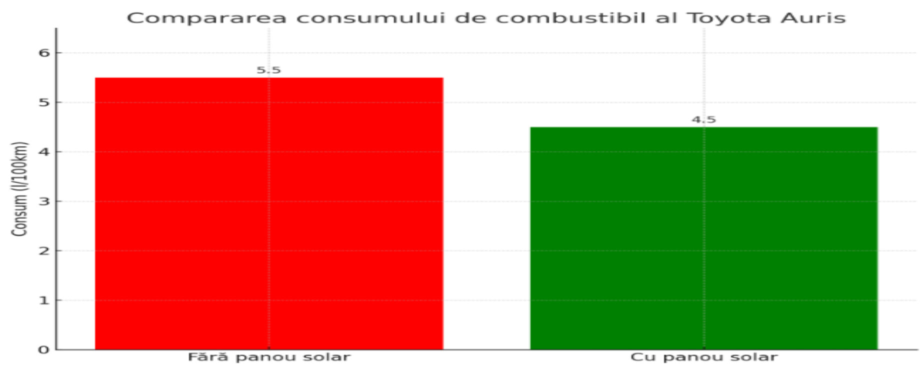

Fig. 7 Fuel consumption

Figure 7 visually illustrates the substantial impact of the solar panel on fuel consumption during the 104 km journey. The integration of the solar panel reduced the car's fuel consumption from 5.5 l/100km to 4.5 l/100km. It is important to note that the solar panel, comprising three identical zones, was affixed to the car's roof using magnets.

4.2.4.Experiment 4: Integration of the solar panel into an electric car

Context and Purpose

Considering the growing popularity of electric vehicles and the ongoing desire to extend their range, the potential of adding a 100Wp solar panel to an electric vehicle was explored. The objective was to assess how much additional energy could be generated by the solar panel and how this impacts the vehicle's range.

Methodology

A 100 Wp solar panel was mounted on the surface of an electric vehicle. It was assumed that the panel operates efficiently for 8 hours a day, generating an average of 80.4 Wh per hour, as per the results of Experiment 1, where output was measured over 10 days. The produced energy is stored and utilized efficiently by the vehicle.

Results:

- the 100Wp solar panel generated 0.643 kW/h of energy in one day.
- this additional energy allowed the vehicle to travel an extra 4.88 km per day.
- without the solar panel, the vehicle can travel 100 km with the energy stored in its battery.
- with the additional energy generated by the solar panel, the car can travel another 4.88 km, bringing the total range to approximately 104.88 km. (Fig. 8)

The calculation was conducted using the following formulas:

$$\text{Additional\_energy} = 80.4\ \text{Wh} * 8\ \text{hours} = 643.2\ \text{Wh} \tag{5}$$

$$\text{Total}_{\text{range}} = 100\text{km} + \frac{643.2\ Wh}{150\ Wh/km} \approx 104.88\ km \tag{6}$$

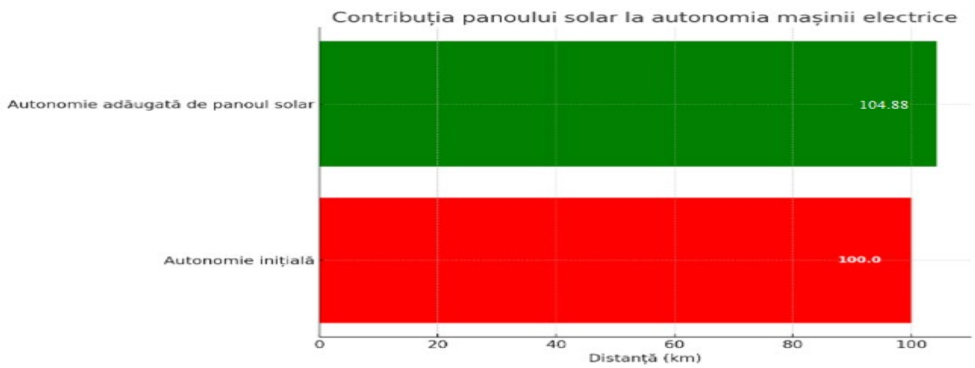

Fig.8 The impact of the solar panel on the electric car's autonomy

This experiment demonstrates that even a relatively small solar panel can bring significant benefits in terms of extending the autonomy of an electric car (Figure 5.). In addition to the immediate benefits, this can have positive long-term implications, such as reducing the frequency of charging and, consequently, operating costs.

It is important to note that the results may vary depending on several factors, including the efficiency of the solar panel, the weather conditions, the state of the vehicle's battery, and the driving style.

4. Conclusion

The incorporation of renewable energy sources, particularly solar energy, into automotive applications has shown great promise in improving vehicle efficiency and reducing dependence on fossil fuels. A flexible 100Wp solar panel demonstrated adaptability to varying sunlight conditions and its ability to positively impact a vehicle's performance. This technology's tangible benefits were evident in the Toyota Auris, leading to a reduction in fuel consumption and an extended range for the electric vehicle.

Concluding from the series of experiments conducted with the 100Wp solar panel, several significant insights emerge regarding its practical applications:

- Variation in energy output: experiment 1 highlighted the direct correlation between solar light intensity and energy output of the solar panel over a 10-day period. This fluctuation in energy production emphasizes the importance of understanding daily variations in solar irradiance for optimizing efficiency.
- Impact on hybrid vehicle fuel consumption: Experiment 3 showcased a tangible reduction in fuel consumption (18%) in a hybrid car when equipped with the solar panel. This suggests that integrating solar panels into automotive designs can significantly contribute to energy efficiency and reduce reliance on traditional fuel sources.
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Moreover, the integration of solar panels can yield long-term operational benefits, such as reduced charging frequencies for electric vehicles and cost savings. The findings from these experiments indicate the potential for scaling these solutions across various vehicle types and sizes.

In essence, merging renewable energy sources with modern vehicles represents a substantial step toward a sustainable and efficient future for transportation. As technology continues to advance, the integration of these energy sources is expected to become even more complex, solidifying the role of renewable energy in the automotive.

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