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DEVELOPMENT OF THE MODERN AUTOMOTIVE INDUSTRY BASED ON THE SOLAR TECHNOLOGY APPLICATION

Natalija Aleksić [1], Danijela Nikolić [2], Vanja Šušteršič [3], Saša Jovanović [4]*

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RESEARCH ARTICLE

ABSTRACT: In the past decades, the automotive industry is growing proportionally with the rapid population increase. On the other hand, increasing energy consumption and the use of fossil fuels have led to increased environmental pollution. A new trend in the automotive industry in the last twenty years is the development of new types of vehicles that are powered by renewable energy and the solar-powered vehicle is very popular among them. Solar photovoltaic technologies are very convenient for electric and hybrid vehicles, due to the direct conversion of solar energy to electricity, the low cost of photovoltaic panels, and their positive environmental impact. There are various types of solar cars developed by different companies, which have remarkable development in terms of materials, energy management systems, and used mechanical and electrical components. This paper represents an overview of solar energy applications in the automotive industry and the development of solar and hybrid cars. Also, a comparative analysis of different solar vehicles is presented, with the possibilities for further investigation and development of solar energy applications in the automotive industry.

KEY WORDS: *automotive industry, photovoltaics, solar vehicle, hybrid solar vehicle*

[1] *Natalija Aleksić, University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia, natalija94u@gmail.com,* ORCID ID: - *(*Corresponding author)*
[2] *Danijela Nikolić, University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia, danijelan@kg.ac.rs,* ORCID ID: 0000-0003-3267-3974
[3] *Vanja Šušteršič, University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia, vanjas@kg.ac.rs,* ORCID ID: 0000-0001-7773-4991
[4] *Saša Jovanović, University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia, dviks@kg.ac.rs,* ORCID ID: 0000-0001-5916-2483

RAZVOJ MODERNE AUTOMOBILSKE INDUSTRIJE ZASNOVANE NA PRIMENI SOLARNE TEHNOLOGIJE

REZIME: Poslednjih decenija razvoj automobilske industrije je rastao proporcionalno sa naglim porastom stanovništva. S druge strane, povećana potrošnja energije i upotreba fosilnih goriva doveli su do povećanog zagađenja životne sredine. Novi trend u automobilskoj industriji u poslednjih dvadesetak godina je razvoj novih tipova vozila koja za pogon koriste obnovljivu energiju i među njima su veoma popoularna solarna vozila. Solarne fotonaponske tehnologije su veoma pogodne za električna i hibridna vozila, zbog direktne konverzije solarne energije u električnu energiju, niske cene fotonaponskih panela i njihovog pozitivnog uticaja na životnu sredinu. Postoje različiti tipovi solarnih automobila koje su razvile različite kompanije, koji imaju značajan razvoj u pogledu materijala, sistema upravljanja i korišćenih mehaničkih i električnih komponenti. Ovaj rad predstavlja pregled primene solarne energije u automobilskoj industriji i razvoj solarnih i hibridnih automobila. Takođe, prikazana je komparativna analiza različitih tipova solarnih vozila, sa mogućnostima daljeg razvoja primene solarne energije u automobilskoj industriji.

KLJUČNE REČI: *automobilska industrija, fotonaponski paneli, solarna vozila, hibridna solarna vozila*

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INTRODUCTION

The idea of an electric vehicle has a history longer than 100 years. More than a decade ago, the search for the development of Zero-Emission Vehicles (ZEV), Electric Vehicles (EV), and Hybrid Electric Vehicles (HEV) [1-3] had taken a new influence. The interest in these vehicles has grown, mainly because of their characteristics that reduce pollution. Over the past 10 years, the significant development of electric and hybrid vehicles was noted. Also, over the last few years, there are more and more discussions about the development and production of solar cars and hybrid solar cars. Solar cars use solar energy by photovoltaicls, rechargeable batteries, and use that energy to power the vehicle's electric motor. However, to apply solar energy to vehicles, it is necessary to carefully analyse critical points, such as the efficiency and cost of photovoltaic panels, as well as to consider how to maximize solar radiation and how to manage and to control obtained energy [4, 5].
Today, there are three types of solar cars in the literature, which include:

- Solar operated cars – A solar car is driven by solar energy, obtained from solar panels placed on the surface of the car, or integrated solar cells into its body. The term solar cars mean that solar energy is used to power all or a part of a propulsion vehicle.
- Hybrid solar energy and electric operated cars – A hybrid car is a vehicle that uses two or more power sources to initiate the car. The term most commonly refers to HEVs, which combine solar energy and electric energy. Instead of using energy from solar panels, electric cars get their energy from batteries.
- Hybrid solar energy and internal combustion engine (ICE) operated car – Hybrid solar cars use a combination of the ICE and solar panels. The stored battery system powers the electric motor. A car is driven by a specified petrol engine and by solar energy obtained from solar panels [6].

In most of the solar cars, solar panels are located and fixed at almost a horizontal position. This solution, although it is the most practical, does not allow the maximization of net power from the sun. A moving panel would increase the solar contribution from about 46%, at low latitudes, up to 78%, at high latitudes. Also, to maximize the solar contribution, solar panels could be integrated into windows and to the lateral surface of a car [7]. Therefore, it seems that the installation of a movable solar roof and the use of solar panels on windows, side doors, and other accessible surfaces would allow a significant yield of solar energy. In the continued paper, they will be presented a various prototypes of solar cars and solar hybrids developed and made by well-known automobile companies, as well as prototypes of start-up companies whose primary goal is the mass production of solar cars.

1. DEVELOPMENT OF SOLAR VEHICLES

The development of solar cars in terms of the appearance of vehicles, weight, speed, and energy management in the last 20 years is astonishing. An Australian adventurer from Denmark Hans Tholstrup, in 1982, drove the world's first solar car. His passion for motorsport and the experience he gained during his travels inspired him to organize an event known as the World Solar Challenge or the Bridgestone World Solar Challenge (BWSC) from 2013. For more than 30 years, the world's largest solar event has been urging the greatest minds from around the world to come to Australia to push the boundaries of technological innovation and test their solar-powered vehicle to travel 3,000 km from Darwin to Adelaide. In 2017, this event celebrated its 30th anniversary. The teams consist of high school and university students from over 30 countries. At the first event in 1987, 23 teams from seven countries were attending, and the winner was General Motors 'solar car, Figure 1 [7]. In 2019, 44 teams from 21 countries took part in the race, and the winner was the Belgian team The Agoria Solar Team with their solar vehicle BluePoint, Figure 2 [8, 9]. Over the last 20 years, the technological development of solar cars, which participated in BWSC, has shown that the aerodynamic shape of the vehicle and its weight are the two most important factors that influence the speed. These two areas made enormous progress. From the first organized event until today, the materials used to build solar cars have changed dramatically and evolved. The usage of composite materials, found in the aerospace industry, is common because these materials are extremely strong, and at the same time very light. The shape and appearance of solar cars have changed quite completely as the aerodynamic factor becomes a very strong influencing factor.

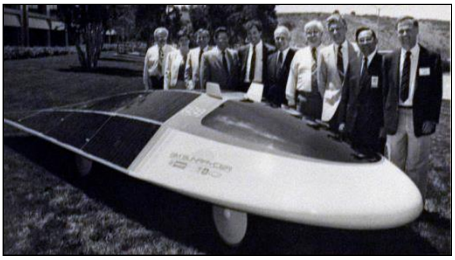

Figure 1 General Motors' team (1987) [7]

Figure 2 Agoria Solar Team (2019) [9]

To ensure that solar cars increase their practicality, event organizers are constantly introducing new regulations. So, present solar cars should have the appearance of "normal cars" with characteristics such as more upright seating, unobstructed entry and exit from the vehicle, lamps on the front and rear of the vehicle, etc. [10]. The organizers' idea is to build a solar car for everyday use.

2. CURRENT STATUS OF THE SOLAR TECHNOLOGY IN AUTOMOTIVE INDUSTRY

Automotive regulatory frameworks around the world were key for creating a sustainable environment in the automotive industry. In December 2018, the EU set new regulations for carbon dioxide emissions for new passenger cars and commercial vehicles. Regulation (EU) 2019/631 sets new EU fleet-wide CO_2 emission targets are set for the years 2025 and 2030, for newly registered passenger cars. These targets are defined as a percentage of car emission reduction starting from the 2021: 15% reduction until 2025 on and 37.5% reduction until 2030 [11]. Great expertise is needed in various fields, such as photovoltaics, electrical engineering and vehicle design, to install and to integrate solar photovoltaic panels and cells in a car. The Solar Vehicle Market is a comprehensive survey that provides information on the size, trends, growth, cost structure, capacity, revenue, and forecast of solar vehicles until 2026. The Global Solar Vehicle Market Report is available for international markets as well as development trends, competitive landscape analysis, and key development status of the region. It considers development policies and plans, as well as production processes and cost structures. The Global Solar Vehicle Market is segmented based on vehicle type, electric vehicle type, battery type, solar panel type, and geography,

Table 1 [12]. Main players in this field are Lightyear, Volkswagen, Toyota, Nissan, Ford, General Motors, Mahindra and Mahindra, Sono Motors, Hyndai, etc. Also, the report, "Solar Cars, Buses, Trucks, Trains 2020-2030" shows why a rapidly increasing number of car companies are incorporating solar bodywork that significantly increases range or reduces battery size [13].

Table 1 *Scope of the Global Solar Powered Vehicles Market*

Vehicle Type	Passenger Cars; Commercial Vehicles
Electric Vehicle Type	Battery Electric Vehicle; Hybrid Electric Vehicle
Battery Type	Lithium Ion; Lean Acid; Others
Solar Panel Type	Mono-Crystalline; Poly-Crystalline
Geography	North America (US, Canada, Rest of North America); Europe (Germany, UK, France, Spain, Rest of Europe); Asia Pacific (China, Japan, India, Rest of Asia-Pacific); Rest of the World (Brazil, UAE..)

2.1 Stella

Solar Team Eindhoven, a group of students from the Technical University of Eindhoven in the Netherlands, designed, constructed and built Stella Era [14].

The Stella Era is an experimental, solar car capable of traveling a distance of 1 800 km through more efficient use of solar energy, Figure 3. Equipped with Ericsson’s Solar Smart parking, Stella Era car drives autonomously to a parking spot with the most sunshine to recharge its batteries [15]. In this way, it is enabled the maximum use of the available solar energy. It is also possible to share the energy with other electric vehicles parked next to it. In the morning, a car can transmit energy to the house to satisfy the energy needs of the users. The car also monitors the daily routines to make sure that the user had enough energy. The advantage lies in the aerodynamics, electrical efficiency, and weight of the car. Electrical efficiency has been significantly improved by developing a complete powertrain.

Figure 3 Stella Era [15]

Figure 4 Stella Era – energy exchange [15]

The most important parts are the two independent motors which reaching an efficiency of 98.5%. Energy exchange is possible only when solar energy collection is maximized, Figure 4 [15].

The Stella Lux is an energy-positive family car. Throughout the year, it generates more energy than it consumes. Aerodynamic design plays an important role in this fact. Namely, it seems that the tunnel passes through the car center, Figure 5. Besides, Stella Lux has an extended roof on both sides of the car, Figure 6. This made it possible to install another series of solar panels on the car, which increases the energy yield. Stella Lux is extremely light. To accomplish this characteristic it was used material such as carbon fibres and aluminium. Solar cells are the most important component in powering a vehicle. A total of 381 monocrystalline silicon cells were combined to form a highly efficient solar array (module) (1.5 kW) with a total area of 5.84 m^2.

Figure 5 Stella Lux [16]

Figure 6 Extended roof [15]

Even when it is cloudy, the capture of sunlight is maximized by using a non-reflective surface made up of tiny prisms. These prisms bend the diffracted light to ensure that it arrives perpendicular to the solar cells, increasing the solar yield under all conditions. The solar array has demonstrated a maximum efficiency of up to 23.9%, which is very high in comparison with standard solar panels [16]. The custom-designed battery pack contains 1224 Lithium-Ion 3450 mAh battery cells, giving a total storage capacity of 15.2 kWh. The battery pack uses intelligent load balancing technologies to ensure an extremely efficient conversion of the stored energy. The battery monitoring system continuously checks the state of charge. With the combination of direct solar energy and the battery pack, the maximum daily range of the car is up to 1000 km in summer but varies with the time of the year. Placing the motors directly in the wheels means that no transmission or gearbox is needed, resulting in an energy efficiency of 96%. The total powertrain – consisting of the battery and motor – has a measured efficiency of 92% [17]. Stella Lux is a fully functional prototype.
During 2017, the students involved in making these vehicles started their own start-up company to make a commercially viable version of the car, called the Lightyear One.

2.2 Lightyear One

The Lightyear one is a vehicle that the Times magazine announced as one of the top 100 inventions for 2019. The Dutch company for solar cars, Lightyear, has designed the body of its vehicle to be as aerodynamic as possible at the same time, as well as to increase the space for installing solar cells. The Lightyear One is a lightweight car that has all-wheel drive, four doors, and that offers an exceptional range of 725 km on a relatively small battery, Figure 7.

Figure 7 Lightyear One [19]

According to the co-founder of the start-up company Lex Hoefslot, this car should be able to stay completely on solar energy for two months in the summer. The car has a unique design. There are about 1000 individual photovoltaic cells placed on the body of the car. Together, the roof and cover offer a stunning 5 m^2 of integrated solar cells in safety glass so strong that a fully grown adult can walk on them without causing dents. Lightyear One charges itself whenever the roof absorbs daylight. No matter whether you're driving or parked, the solar cells add up to 12 km of range per hour. If this car stays in the sun, it can reach an average of about 32 km of additional electric range per day. Conservative driving style, which includes slower acceleration, proper regenerative braking, and limited top speed, allows the car to have an even longer range. Due to the improved energy efficiency of the powertrain, it is required less energy for the same range. This improves the charging time by almost a factor of three. With power outlets available worldwide, the Lightyear One can be charged 440 km overnight (12 hours), anywhere [18]. The company predicted that there would be situations where the solar roof would be in the shade, so they included a 30% shadow factor to compensate for these losses. The Lightyear Platform uses a combination of aluminium and carbon fibre. One of the advantages of our architecture is there is no engine at the front of the car. Lightyear One has four in-wheel motors, providing power when and where needed. Working independently, they improve traction control on various surfaces and maximize efficiency. They have been able to increase the efficiency of the whole powertrain, making the Lightyear One the most efficient production car. One of the biggest achievements of this car is the low value of the aerodynamic drag. Current simulations show that this car will become the most aerodynamic production car [19]. Recent tests showed that the value of the drug coefficient (Cw), a measure of air resistance, will be below 0.20. Good aerodynamic performance ensures the reduced energy consumption. This is particularly advantageous when used frequently on motorways, especially when driving long distances or high speeds. Due to the lower energy consumption, the car has a greater range [20]. One of the key contributions to this achievement is the removal of physical side mirrors, which have been replaced by cameras.
At Lightyear one, the focus is on clear design, futuristic technology, and intuitive interaction. The first handmade production model will cost 149990 €. The start of production is in 2021 [21].

2.3 SionSono

Sono Motors is a new innovative car manufacturer founded in 2016, and has a vision of sustainable mobility that is not dependent on fossil fuels. Sono Motors is developing an advanced self-charging electric car with integrated solar cells, Figure 8 [22]. The CO_2 emission that cannot be avoided or reduced during the production and construction of the vehicle will be fully compensated. This company developed Sion 2017 prototypes. Solar cells are integrated on car entire surface, which completely redefines its appearance. The roof, side roof cover, fenders, and rear of the vehicle contain integrated solar cells, Figure 9.

Figure 8 Sion [23]

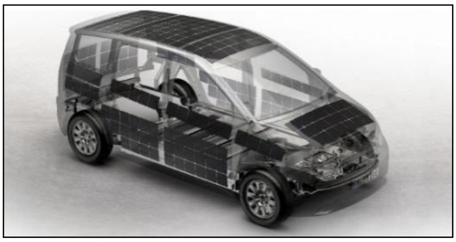

Figure 9 Integrated cells [24]

Sion thus becomes a solar electric vehicle (SEV), whose battery can be additionally charged by the power of the Sun. The cells are made of monocrystalline silicon and can produce energy even under clear skies or in the shade. In terms of top performance, integrated cells can generate up to 1.2 kW. The system is protected by a robust scratch-resistant polymer [23]. With solar cells integrated into the entire body of the car, Sion can easily charge the battery with the help of the Sun. So, in ideal conditions, up to 34 km of additional range per day can be achieved with pure solar energy, Figure 10.

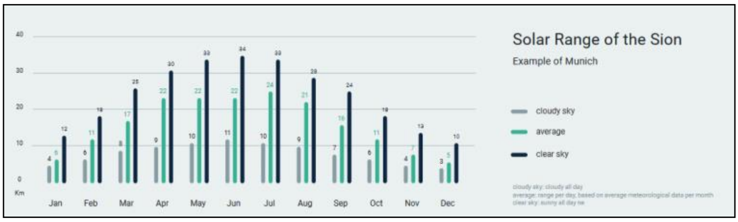

Figure 10 Solar range [24]

Sion solar panels are not unique just because of their lightweight. Innovative solar cell technology provides maximum efficiency and higher energy yield in small areas. The car has a lithium-ion battery, with a capacity of 35 kWh, which has water cooling. The battery capacity is sufficient for a range of 255 km. This car has a single-speed gearbox with a three-phase 120 kW synchronous motor. The speed of this car can easily reach 140 km/h. Sion can be charged at almost any charging station in Europe using any of three different charging modes: SchuKo (13 h), Type 2 (3.2 h), and CCS (fast-charging station 40 min).
Thanks to two-way charging technology, Sion can draw and store energy, and share it as well. Together with its partners, this company has developed a not only completely new technology for cell integration but also a device that enables the use of solar energy. The company calls this device "MPPT Central Unit". MPPT is a term for tracking maximum power commonly used in photovoltaic conditions. It is a process that adjusts the electrical load of the solar module so that the cells can give optimal performance. The prototype device developed by Sono Motors was tested earlier this year. Production will begin in the second half of 2021 and Zion will be produced in the former cult plant of the SAAB brand in Sweden. Sono Motors plans to produce 260,000 Sion over eight years [24].

2.4 Hyundai

Korean carmaker Hyundai has also applied solar energy to its cars. July 22, 2019 - Hyundai launches the Sonata Hybrid equipped with the world’s first Active Shift Control (ASC) technology and solar roof system [25], Figure 11. This generation of models has a classic Sonata exterior design, but additionally includes an updated grille, a more precisely defined spoiler and, in particular, a solar roof.


Figure 11 Hyundai Sonata Hybrid [25]

The new 2020 Hyundai Sonata Hybrid has an eco-friendly solar roof system which charges car’s battery using solar panels even while driving. The solar roof system improves fuel efficiency while preventing battery discharge and reducing CO_2 emissions. With this technology, 30 to 60 % of a car’s battery can be charged via solar energy [26]. The solar roof system consists of the structure of silicon solar cells. The annual range can be increased up to 1300 km if the car is charged 6 hours per day [27]. The system consists of a solar panel and a regulator. After processing through various control mechanisms to increase efficiency, electricity is stored in both the starter battery and the drive battery, Figure 12. This electricity in the drive battery works to extend the driving distance, while that in the starting battery reduces the time required for the alternator to charge the starter, thus reducing the engine load and improving fuel efficiency [28].

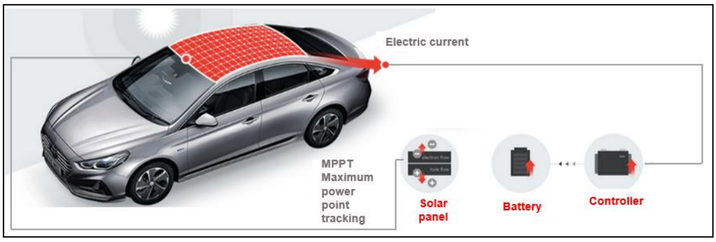

Figure 12 Hyundai Sonata Hybrid [25]

So far, Hyundai has only revealed the powertrain specifications of a model designed for the Korean market that consists of a 4-cylinder 2.0-liter internal combustion engine that produces 110 kW paired with an electric motor that produces 37 kW power. When working together, the total power of 145 kW is sent to all four wheels via a six-speed hybrid automatic transmission. ASC applies new control logic software to the hybrid control unit, which then controls the electric motor to match engine rotation and transmission speeds, ultimately reducing gear transmission time by 30%.

2.5 Toyota

Toyota does not currently produce purely electric vehicles (except Mirai with hydrogen), so these solar roofs are currently intended for plug-in hybrids. Toyota has positioned plug-in hybrid cars (PHVs) as the “pillars of next-generation of eco-friendly vehicles” alongside hybrid vehicles and has made significant efforts to strengthen its products [29]. Toyota, along with NEDO and Sharp, is leading an interesting research project on an electric car that uses a plug-in, equipped with a solar charging system, Figure 13. The idea is to assess how much energy can be provided by using highly efficient photovoltaic cells and how this corresponds to economic viability. The Japanese manufacturer decided to use Sharp's triple couplings solar cells in the form of a thin film (about 0.03 mm thick) with a conversion efficiency of up to 34%. A new Prius PHV model was used for this research, which has greatly developed environmental performance. Namely, this model has enough flexibility, not only on the roof of the car but also on the hood and its rear part, Figure 14. Toyota said that these panels have achieved conversion efficiencies of 34% or more and they are capable of delivering 860 W of power, which is roughly 4.8 times more than the commercially available Prius [30].

Figure 13 Toyota Prius [31]

Toyota will test the vehicle in different driving conditions to verify data such as the amount of solar panel electricity and the amount of charge of the drive battery, and the future charging of the solar devices in the vehicle.

Figure 14 Solar cells [31]

The demonstration vehicle was shown at the NEDO stand on “14. World Renewable Energy Exhibition” held in Pacific Yokohama in 2019. Prius PHV has solar battery cell conversion efficiency about 22.5% while demonstration vehicle has cell conversion efficiency about 34% [32].

2.6 Ford

It’s been more than six years since Ford introduced its C-Max Solar Energy concept, Figure 15. The C-Max Solar Energy concept uses solar energy to directly charge the hybrid battery. In 2014, Ford introduced a rooftop solar system that tracks the movement of the sun and uses a Fresnel lens [33].

Figure 15 C-Max Solar Energy concept [35]

The car has a special concentrator that acts like a magnifying glass (Fresnel lens), which intensively directs the rays to the solar panels on the roof of the car [34]. This design helps increase the efficiency of the solar cells on the roof, which can also move to follow the sun as it moves across the sky. The Figure 16 represents how Ford's Solar Energy system works.

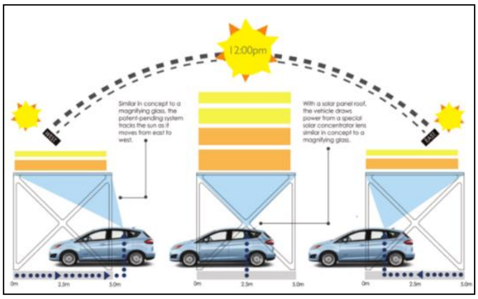

Figure 16 Ford's Solar Energy system [35]

Ford filed the patent application on November 8, 2019, and it was published on May 14, 2020. In this patent application, the roof-mounted shape of the switch stands out: a fabric with automatic covering with flexible solar cells with a thin layer that is controlled by a central shaft mounted on the rear bumper or in the trunk. The patent describes the concept as a flexible shield that unfolds using an inflatable pump and is powered by stored solar energy. The cover consists of flexible, thin-film solar cells that, once deployed, maintain shape using a memory polymer [36].

2.7 Tesla

So far, there has been no application of solar technology on Tesla cars. Elon Musk initially rejected the application of solar panels directly on cars. However, in November 2019, Musk announced that the new Tesla Cybertruck would be the company’s first car which offers solar panels as an option to expand the range, Figure 17. The Tesla Cybertruck is an upcoming all-electric light commercial vehicle. There will be 3 models available with a range of 400 to 800 km and with the acceleration from 0-60 mph (0-97 km/h) of 6.5 to 2.9 seconds, depending on the model [37].

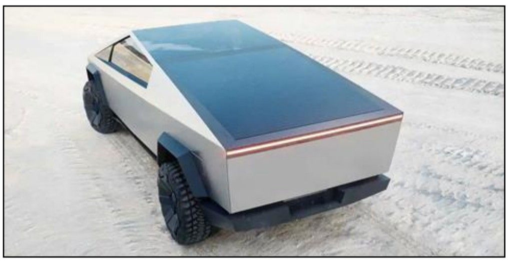

Figure 17 Tesla Cybertruck [38]

So far, there is no other information, except that production should start at the end of 2021.

3. COMPARATIVE ANALYSIS OF SOLAR VEHICLES

Fig. 18 shows driving ranges of solar vehicles: Stella Era, Lightyear One, and Sion.

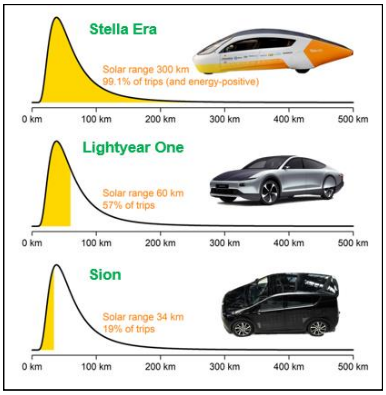

Figure 18 Solar range [39]

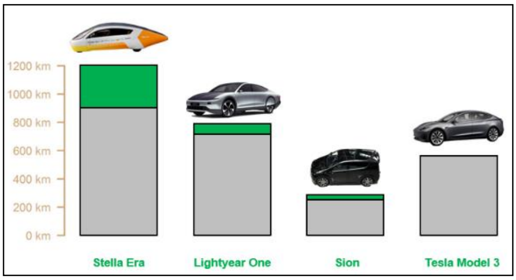

Figure 19 Driving ranges [39]

The Stella Era has a solar-only range for about 300 km (more than 4 times the mean 70 km driven). On more than 99% of trips, Stella Era can operate solar-only, and, on average, its solar panel produces substantial excess electricity which can be donated to other vehicles. Lightyear One has a solar-only range for about 60 km (less than the mean 70 km) but is still able to operate solar-only on 57% of trips. And Sion as a solar-only range for about 34 km, but Sion is able to operate solar-only on 19% of trips, and has a useful solar boost to its battery the rest of the time.

Figure 19 represents the driving ranges for four electric vehicles (grey for battery range, green for amplification due to the existence of solar panels). The four cars are Stella Era, Lightyear one, Zion, and non-solar model Tesla Model S. The Stella Era, in spite of having a much smaller battery pack, has almost double the range of the Tesla. This is due to the Dutch racing car's extremely aerodynamic shape and light carbon-fiber construction. Lightyear One comes about as close to the performance of Stella Era.

Fig. 20 and 21 represents a diagram which compares parameters and price of cars.

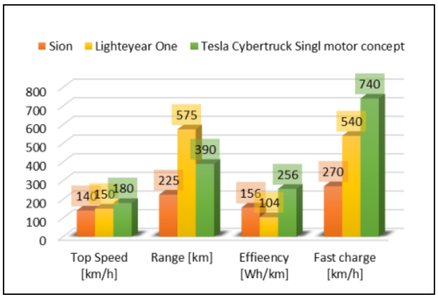

Figure 20 Parameters comparsion

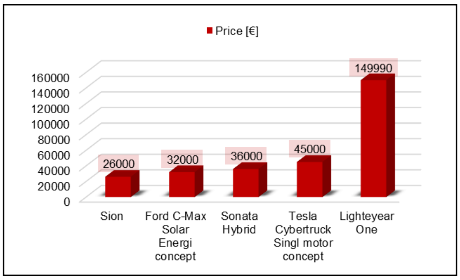

Figure 21 Price of cars

Figure 21 shows that the characteristics of the car differ significantly. For example, Lightyear One has a long-range, but also has a lower top speed, compared with other cars and alike. Also, figure 21 gives a comparison between cars for its price. Sion is the most affordable car, and Lightyear One is the most expensive car [39]. In the end, it is the buyer who determines which car to choose. The Sonata Hybrid solar roof has improved panel output and made the regulator more efficient, increasing the daily distance by 20% compared to the Toyota Prius. The one-day sonata ride is 3.6 km, which is more than the distance of 2.9 km announced by Toyota. Besides, the cost of a solar roof for the Sonata Hybrid is about 970 €, while the Prius is approximately 2250 €. Sonata's system is, in other words, more powerful, but twice economical as Prius'.

4. CONCLUSIONS

Our future clearly depends on our ability to utilize solar and other renewable sources of energy. Solar energy is a major renewable energy source with the potential to meet many of the challenges facing the world. The automotive industry has seen increased application of solar power. Many automobile manufacturers have attempted to use photovoltaic panels as an energy source for its cars. The application of solar energy on vehicles is becoming more feasible, that is why solar vehicles and hybrid solar vehicles may, therefore, represent a valuable solution to face both energy-saving and environmental issues. Although the development of these cars is based on well-known technologies, it is necessary to redesign and optimize the entire drive system to maximize its benefits. Also, it is necessary to pay special attention to maximizing the net power of solar panels and managing the obtained energy. In addition to the fact that the potential benefits of solar energy are clear, its limitations are also clear, which are occasional and which arise due to the influence of the relative movement between the Earth and the Sun and due to changes in weather conditions.

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