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The State of Solar-Powered Automobiles: A Review of Technological Progress and Commercialization Challenges

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ABSTRACT. *Solar energy stands as a cornerstone of renewable and clean power, with applications scaling from portable devices to grid-level power generation. Its utilization in off-grid and standalone systems, including vehicles, has been a long-standing goal. However, despite this potential, the development of the Solar Car (SC) has not kept pace with other alternative fuel vehicles. Unlike the Hydrogen Car (HC) and the Pure Electric Vehicle (PEV), both of which have seen successful commercialization strategies involving supportive policies, tax incentives, and significant private sector investment, the SC remains largely a non-commercialized concept. A typical SC comprises five key subsystems: the chassis/body, photovoltaic (PV) array, battery pack, electric motor, and a power management unit. The fundamental challenge for any SC is reconciling the vehicle's energy demand with the limited and variable energy supply from its solar array. While researchers are exploring multifaceted solutions, development has been predominantly driven by academic institutions, with over thirty distinct prototypes created primarily for solar racing competitions. This review examines the technological hurdles and strategic deficits that have hindered the commercial viability of SCs, drawing lessons from the successful market entry of HCs and PEVs to identify a potential path forward.*

KEYWORDS. Solar car; Electric vehicle; Solar energy, Standalone photovoltaic.

INTRODUCTION

Solar energy consists of Solar Photovoltaic (PV), solar thermal (Hamid *et al*., 2019) and solar photovoltaic-thermal (Ibrahim *et al*., 2011). Solar photovoltaic system can be divided into two categories: grid connected and off grid (standalone) system. Grid connected system usually used by solar farm and small system without battery bank as its energy storage. The electricity produced was supplied into the grid attached. The net metering is one of the examples used in grid connected system. The second system was isolated from the grid and require battery bank as energy storage. This system is suitable at remote area and for vehicles. Usually the capacity and load are small, and simpler compared to grid connected system. Several issues related to environment awareness and modernization of automobile industry contribute to emerging of Solar Car (SC). Transportation emitted the highest greenhouse gas emission by Internal Combustion Engine (ICE). **Figure 1** shows amount of carbon dioxide release approximately 1800 million metric tons.

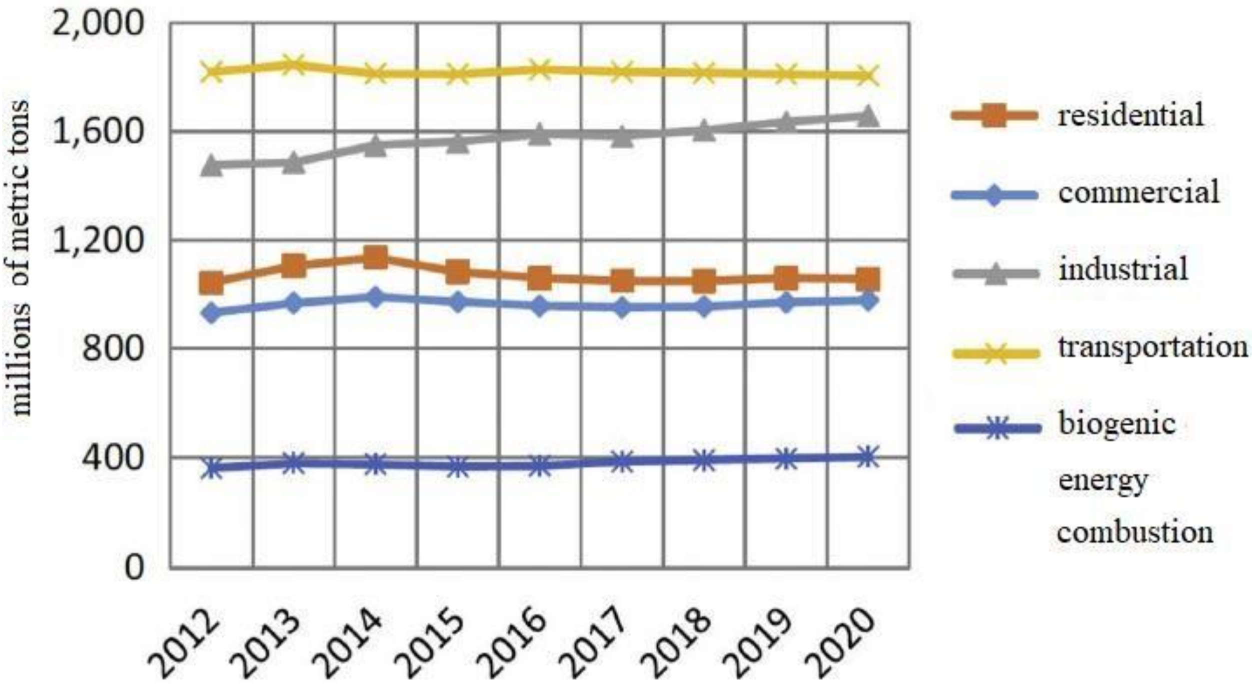

Figure 1 Survey and prediction of carbon dioxide for various sectors between 2012 – 2020 (Das *et al*., 2017).

Research shows by just installing PV module on conventional car, CO_2 emission can be reduced by 1-3%. The module estimated received 58% of solar irradiance available (Lodi *et al*., 2018). The hope from the implementation of SC can reduce even more and significant amount of pollutant by replacing the Internal Combustion Engine (ICE) with clean and renewable transportation vehicle.

It was estimated there are more than 900 million vehicles today and 1.1 billion by 2020. A review report divided electric car under three categories: battery powered car, fuel cell car and hybrid electric car (Wilberforce *et al*., 2017). However, authors would like to introduce the characterization of vehicle (car) based on the energy source (fuel) and type of engine as shown in **Figure 2**. The description of **Figure 2** is shown in **Table 1**.

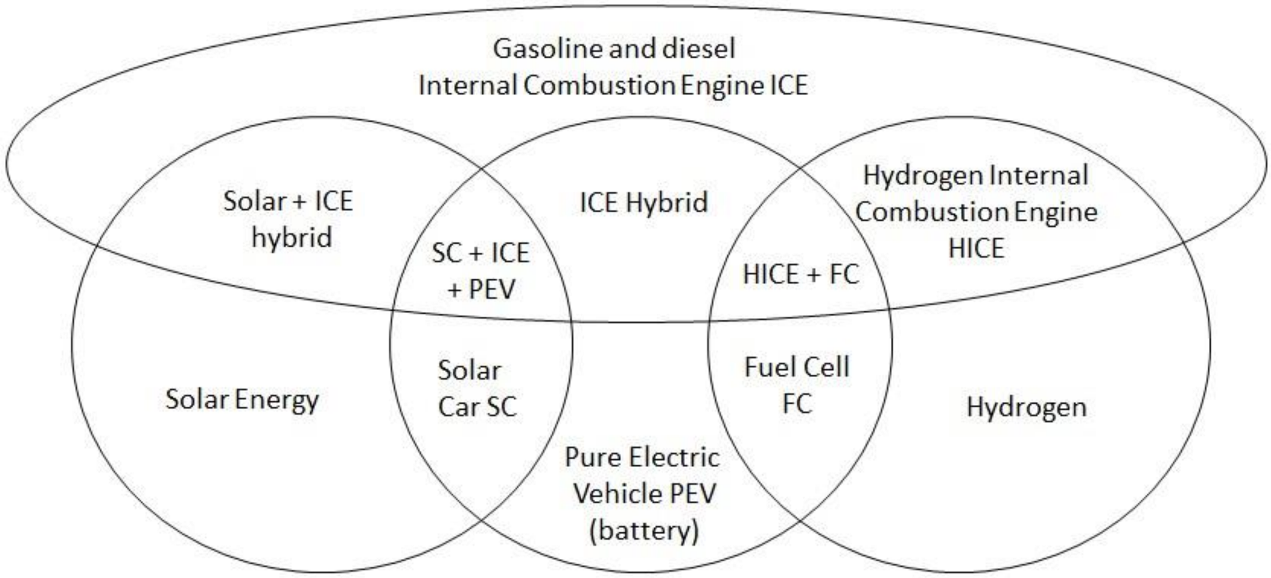

Figure 2 The characterization of car based on the fuel and type of engine.

Table 1 Description of car characterization based on fuel and engine technology.

	Type	Description
1	Internal Combustion Engine (ICE)	conventional (gasoline and diesel)
2	Hydrogen Internal Combustion Engine (HICE)	used hydrogen as mixture in ICE
3	Pure Electric Vehicle (PEV)	using battery + electric motor. Charge by electric grid
4	Fuel Cell (FC)	utilize FC technology
5	HICE + FC	the car is on dual mechanism (mechanical from HICE and electric motor from FC). The hydrogen divides to ICE and FC.
6	ICE hybrid	dual mechanism. Charging battery from grid
7	Solar Car (SC)	electric car. Charging battery from solar energy
8	SC + ICE + PEV	dual mechanism and the battery charged by solar energy
9	Solar + ICE hybrid	dual mechanism without battery

THE SOLAR CAR

Solar car basically use PV technology to convert sunlight spectrum to electricity. The electricity then used to power motor to create movement. Battery acts as energy storage to maintain power supply especially during low level or absence of sunlight. Power management unit will configurate charge and discharge process. **Figure 3** shows the diagram and components of SC.

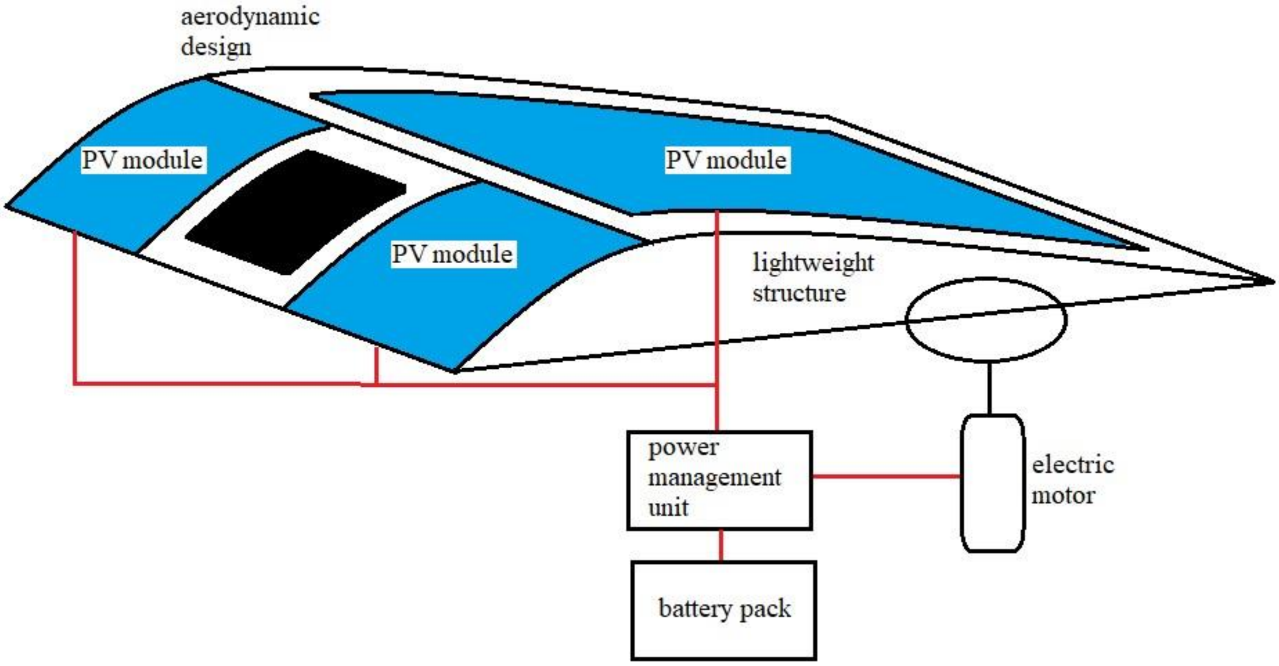

Figure 3 Solar car diagram and components.

To achieve pure solar car or self-powered solar car, the car should be able to generate its own energy from the sun. However, in practical so far almost all prototype SC need electric socket from grid for (plug-in) charging. The energy converted is insufficient due to small PV area and high energy require by the car.

1. Solar Photovoltaic PV Module

Energy conversion from direct sunlight spectrum into electric energy was done by using PV technology. The main characteristic of PV output can be referred to its voltage and current. These values can be manipulated into various parameters such as I-V (current-voltage) curve and P-V (powervoltage) curve. Shading will reduce PV module output. Unlike stationary PV installation, SC will experience inconsistence sunlight due to shading effect from tree, building and other terrestrial structures. Study estimates PV mounted car expose to only 58% of solar radiation available (Lodi *et al*., 2018). Choosing travelling path and parking spot are important for SC in order to reach direct sunlight as much as possible. This situation has already been studied by using Solar Car optimized Rout Estimation SCORE scheme (Hasicic *et al*., 2017). The SCORE gathered weather information (historical and forecast) and configurated the best path and spot for the car. Sunlight exposure will create temperature effect. Higher temperature will reduce module output. Research found that low temperature by using surface laminar H_2O method performed better than standard module. The improvement of power output and efficiency achieved are 9.74 W and 3.7 % respectively (Sukarno *et al*., 2017). The latest invention of flexible solar module enables designer of SC to create aerodynamic shape. The advantages of flexi solar are light weight, can be manufactured in roll, higher yield production, capable to bend and can be used as textile (Idris *et al*., 2018). Amorphous silicon and other thin film photovoltaic are capable to flex. However, poor bending radius and cost limited the potential (Schubert and Werner, 2006). Flexible solar cell based in carbon nanomaterial including dye sensitized, organic and perovskite solar cells have also been investigated. Several factors contribute to use carbon nanomaterials as flexible solar cell such as transparency, conductivity, durability, bendability and adjustable energy level (Fu *et al*., 2018). Research on fabrication, mechanical tolerant and stability of flexible perovskite solar was done at different condition. The result from the test successfully achieved 17.3 % efficiency of flexible perovskite solar cell (Idris *et al*., 2018).

2. Structure and Design

Solar car structure is important as body to attach all the component together. The structure must be light weight and strong for energy saving and safety purposes. Most of SC prototype aerodynamically designed to create less friction and smooth airflow all over the body. Light weight composite such as fiberglass and carbon fiber have advantages and potential to replace aluminum and steel in the automobile sector. Various supercars used increasing percentage of the composite such as Lamborghini, Ford GT, McLaren, Koenigsegg, Ferrari and Corvette (Howell *et al*., 2018). Teijin Group and Toho Tenax developed material and technology for SC. The ultra-light carbon fiber can be fabricated as thin as 0.06 mm and used as the cars body layer and the windows made from panlite polycarbonate resin. The fiber is 5 times lighter and has 8 times strength (tensile strength) of steel (Teijin 2018). **Figure 4** shows SC from Japan developed by Kogakuin University. The material was supplied by Teijin Group.

Figure 4 Solar car developed by Kogakuin University Japan for the Bridgestone World Solar Challenge race in Australia.
Source: Teijin 2018

The aerodynamic design of solar car not only reduces the air drag but also increases PV module output. Better module performance is the result of heat removal by the airflow (Vinnichenko *et al*., 2014).

3. Energy Storage

Energy generated must be stored in order to sustained energy supply during low radiation or at night. Three type of rechargeable battery available for SC which are lithium-ion battery (li-ion), nickel metal hydride battery (NiMH) and lead-acid battery. Brief comparison shows specific energy for li-ion, NiMH and lead-acid are 100-265 Wh/kg, 60-120 Wh/kg and 33-42 Wh/kg respectively. Average energy density also estimated as 471.5 Wh/L, 220 Wh/L and 85 Wh/L respectively. The lowest specific power is lead-acid 180 W/kg, followed by li-ion 250-340 W/kg and NiMH 250-1000 W/kg. Charging and discharging efficiency also identified for li-ion ranging between 80-90 %, NiMH 66-90 % and lead-acid 50-95 % (Kim *et al*., 2019; Morris and Tosunoglu, 2012; Bukhari *et al*., 2015).

The battery suitable for SC has the same criteria with battery that use in standalone PV system and electric car. Researchers are focusing on li-ion battery and are trying to optimize the performance in many aspects. The temperature of the battery increases drastically during discharge. Cooling process was investigated by applying several configuration of phase changes material PCM round the battery. Result showed two PCM configurations reduced maximum temperature by 20.9 K and 23.2 K (Moraga *et al*., 2016). Investigation on battery requirement concluded that the possibility of using home and public charger station, battery technology is the bottleneck to electric car implementation and the relevant of charging infrastructure service to reduce the required battery range (Shi *et al*., 2019). Lithium ion battery supply chain is also important. A study has proposed a strategy from development and remanufacturing aspects related to li-ion battery to maximize the profit. Outcome from the study estimated 9.81 % higher profit can be achieved by considering several selected key factors (Li *et al*., 2018). Another study experimented on load optimization to reduce the cost. The result showed 12.7 % cost reduction compared to original battery pack setup from the factory (Cardenas *et al*., 2018).

4. Power Management Unit

The process of charging from PV to battery and discharging from battery to motor must be in optimized condition. Generally, in PV system, power management configurated by charge controller. Charge controller divided into maximum power point tracker and pulse width modulation. In solar or electric car, the configuration is more complex due to variation of charge and load condition. Some features such as additional load for computation and brake-charging push the need for more dynamic controlling capabilities. Power management unit or battery management system BMS act like charge controller in PV system. The function of BMS for SC is illustrated in **Figure 5** (Hoquea *et al*., 2017).

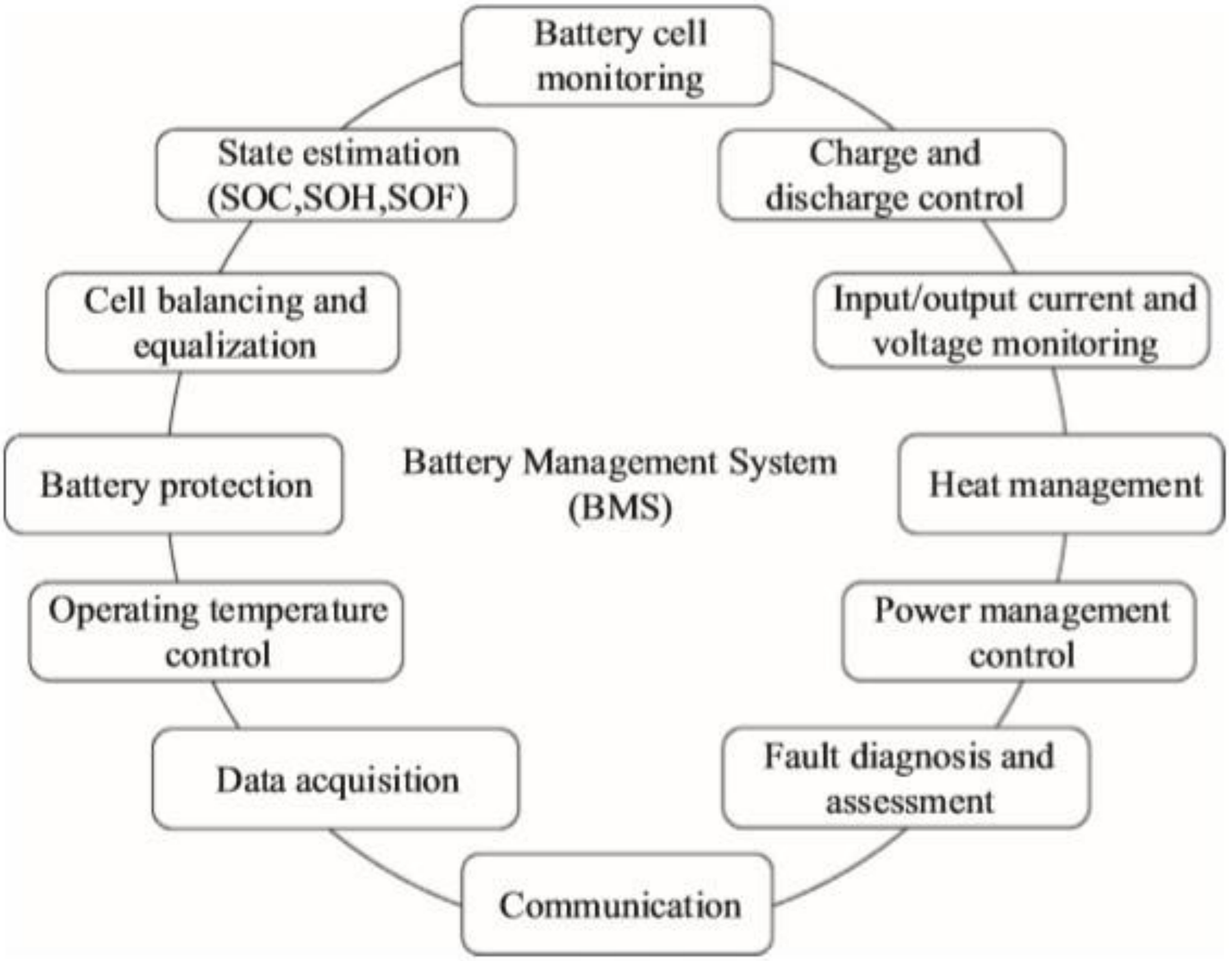

Figure 5 The functions of battery management unit in solar car (Hoquea *et al*., 2017).

5. The Electric Motor

Solar car movement is created by electric motor. Efficient motor is crucial to minimize energy loss from the battery. Type of electric motor available are Permanent Magnet Synchronous Motor (PMSM), direct current motor and induction motor. The main issues related to electric motor for vehicle are inconsistent drive cycle, high torque and power, some main component failure in backup system, durability and wide range of speed control (Chi-lan *et al*., 2011). For PMSM, motor needs to match the requirements of the external characteristics as shown in **Figure 6**, such as start-stop, climbing and acceleration maneuver which require constant torque at low-speed. Another maneuver is for high speed which requires constant power at low torque (Wang *et al*., 2018).

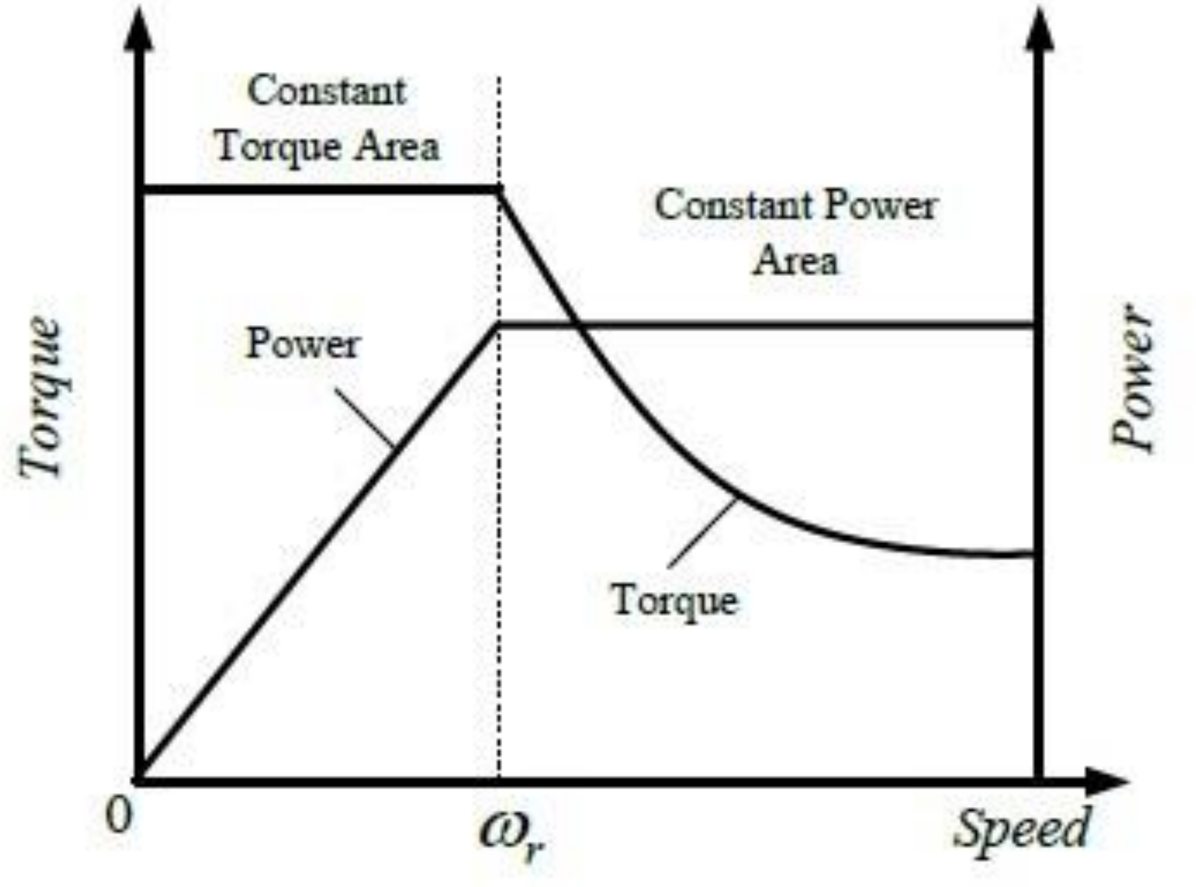

Figure 6 The external characteristic of PMSM (Wang *et al*., 2018).

The application of electric motor for solar car becomes interesting by discovering more concepts such as in-wheel component, using multiple motor and charge-braking features. In-wheel motored vehicle was tested and simulated, focusing on yaw stability control. Results simulated the advantages of control methodology during maneuver on slippery road (Ren *et al*., 2016). A comparison between single and dual motor input was also discussed. The outcome shows dual motor powertrain produced higher overall efficiency compared to single motor (Wu *et al*., 2018). The capability of charging by braking was also discovered and discussed. Regeneration charge was produced by several method such as DC-DC converter, ultracapacitors and electronic gearshift technology. The testing on brushless DC motor was analyzed from simulation and experimental data (Godfrey and Sangkaranarayanan, 2018).

RECENT PROGRESS AND CHALLENGES

The achievement of SC can be measured by the number of cars commercialize in the market. So far, not a single SC marketed yet. In comparison, hydrogen car has already launched 5 models: two hydrogen internal combustion engine models (BMW hydrogen 7 and Aston Martin Rapid S) and three fuel cell models (Honda clarity, Hyundei Nexo and Toyota Mirai).

The current status of SC remains as prototype. Various parties already come out with their SC concept. However, none of them successfully achieve market commercialization. The prototype list is shown in **Table 3**. Most of them were produced by universities or academic body and involved in solar car racing. Meaning that SC is still under R&D and heavily funded.

Table 3 The model, developer and origin of the SC prototype.

No	Solar car model	Developer	Origin
1	Sunswift V (eVe)	University of New South Wales	Australia
2	Solar Spirit 3	TAFE institute	
3	e.coTech Solar version	HiTech Electric	Brazil
4	Schulich Delta	University of Calgary	Canada
5	"Chen Shungui"	-	China
6	Hochschule Bochum: Open World	Hochschule Bochum	Germany
7	PowerCore SunCruiser	Hochschule Bochum	
8	Sion	Sono Motors	
9	SolarWorld GT	Hochschule Bochum	
10	ThyssenKrupp SunRiser	Hochschule Bochum	
11	SolarMobil	Manipal University	India
12	P-Mob	Fiat	Italy
13	Emilia 4	University of Bologna	
14	Kaiton II	Goko High School	Japan
15	OWL	Kogakuin University	
16	Venturi Astrolab	Venturi Automobiles	Monaco
17	Venturi Eclectic	Venturi Automobiles	
18	Stella	Eindhoven University	The Netherlands
19	Stella Lux	Eindhoven University	
20	Stella Vie	Eindhoven University	
21	Twente One	University of Twente and Saxion University	
22	UltraCommuter	University of Waikato	New Zealand
23	ECO1, ECO1GL and ECO3GL	Muhammad Aslam Azaad	Pakistan
24	Metron 7	Andrej Pecjak and his Metron team	Slovenia
25	Superpiki	Yuneec & Metron	
26	Icare	Icare	Switzerland
27	Solar Taxi	Lucerne University and University of Applied Sciences Northwestern Switzerland	
28	Apollo Solar Cruiser Car	National Kaohsiung University of Applied Sciences	Taiwan
29	Daedalus	University of Minnesota	USA
30	Eos	University of Minnesota	

Most significant SC race is Bridgestone World Solar Challenge held in Australia. The racetrack between Darwin and Adelaide is estimated to be 3000 km. The racing class is divided into three: challenger, cruiser and adventure class. The main hurdle to implement self-powered SC is insufficient power generated to tackle energy demand for the motor and other appliances. The fundamental problem emerged from several aspects such as power supply, weight and PV area. To achieve full charge for average typical battery vehicle, 4.5 peak sun hour with 7.5 kW array required. Meaning that 7500 m^2 PV and additional of 800 kg weight needed which is not practical for SC. In comparison, the car must be able to overcome 6.25 times PV power, 4 times weight and 1250 times PV area. Other issues are PV efficiency, shading and cost. Flexible solar cell only achieved 17.3 % (Idris *et al*., 2018), exposed to 58 % (Lodi *et al*., 2018) sunlight available and cost is extremely high (4 times electric car and 15 times conventional car). A case study (Sukarno *et al*., 2015) determined the limitation of solar source estimated that the average and maximum irradiance intensity were 500 W/m^2 and 1000 W/m^2 respectively. These factors will add even more challenges to construct practical SC in term of SC energy balance and structure design.

In order to overcome the deficit energy. Main solar array can be off set from the car and construction of solar charging station might be helpful. Applying wireless charging road enables SC to maintain travelling without stopping while charging its battery. Many strategies can be learned from hydrogen car and electric vehicle. Japan as leading country in hydrogen development has invested great effort in many sectors such as facilities, economy, R&D and public involvement program. Japan provides many hydrogen stations for hydrogen car. In economy, 12.3 billion USD was invested in hydrogen development. The country also patented around 25 000 patents on fuel cell and selected several cities to implement hydrogen energy as their main energy source (Behling *et al*., 2015).

CONCLUSION

This report briefly concludes the importance to revolutionize transportation sector and applying SC as part of transportation mode. The basic of SC and its components were also discussed. As far as technological concern, fundamental hurdle and other technology aspect contribute to slow progress of SC compared to hydrogen car and battery electric vehicle. Not a single commercial self-powered solar car yet to be marketed indicates that many more must be done and there is a need for government and private support. However, it is optimistic that SC can be implemented in the future by proceeding to discover solution for current issues.

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