Review Paper

Integration of solar energy in electrical, hybrid, autonomous vehicles: a technological review

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Abstract
Conventional energy resources are depleting very fast and to meet the global energy demand, the scarcity of these resources is the most crucial factor in the present era. One of the major contributors to carbon emissions is transportation sector which survives mostly on conventional energy resources. In the Indian context, the transportation sector contributes about 18% of CO_2 emissions of total emissions. To decarbonize this sector, the vehicles utilizing renewable resources such as solar PV technology would be a sustainable step. Solar energy which is abundant in nature and present everywhere can prove to be a great alternative to conventional resources. In the present study, solar PV technology is integrated with electric and hybrid vehicles. Additional literature review of solar electric vehicles including three-wheeled as well as four-wheeled is carried out. Autonomous vehicles and robots utilizing PV technology are also studied and presented. Finally, the foremost barriers and challenges to adopting PV technology in electric and autonomous vehicles are identified and presented.

Keywords Internal combustion engine vehicles · Electric vehicles · Solar electric vehicles · Autonomous ground vehicles · Photovoltaic

1 Introduction

The conventional resources of energy are the primary pillar for the survival of human beings in the current era. Coal, oil and natural gas are the essential sources of conventional energy and globally 74% of the total population's fuel consumption depends on these sources [1, 2]. The conventional energy sources are depleting day-by-day simultaneously the rate of proliferating is also high which has resulted in an imbalance between the supply and demand for global energy [3–6]. Hence, there is a scarcity of conventional resources to meet the present energy demand and additional energy is needed to keep the present mankind development [7]. Solar, wind, biomass and geothermal are the renewable energy resources and can fulfil the present energy requirement. Additionally, these resources have meritorious characteristics such as clean-environment and non-polluting nature [8].

Internal combustion engine (ICE) is the most widely used technology in the existing transportation sector that utilizes oil and natural gas as fuel [9–14]. Greenhouse gas emissions, depletion of the ozone layer, global warming, air, land, and water etc. are the several environmental as well as pollution issues associated with conventional vehicles [15–17]. Therefore, alternate engine technology is required to mitigate these problems associated with conventional vehicles. Electric vehicles (EVs) and hybrid electric vehicles (HEVs) are the alternate solutions to decarbonize the transportation sector. Additionally, these vehicles are less polluting and have the potential to mitigate greenhouse gas emissions of conventional vehicles [15–17, 18, 20–22].

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Among the available renewable resources of energy, solar energy is considered as one of the promising resources to meet the present and future energy demand [23]. Solar energy has the exclusive potential to generate electricity through Photovoltaic (PV) panels technology [24–26]. The capability of electricity generation from solar PV technology is versatile from milliwatt to gigawatt [27–29]. Additionally, solar PV technology can also be used with electric, hybrid and autonomous vehicles either directly integrating PV panel with these vehicles or indirectly through PV power station to recharge these vehicles. In the present study, integration of solar PV technology either directly or indirectly with electric, hybrid and autonomous vehicles is carried out to meet the sustainable development goals.

Several studies related to the ICE, electric and autonomous vehicles are reported in the literature. However, no efforts have been made to compile and update the work related to vehicles utilizing PV technology. From the literature survey, it has been established that the number of research documents on this subject has increased considerably over the previous decade. A comprehensive status report on the state-of-the-art technology of how renewable energy systems are being employed in the ICE, electric and autonomous vehicles is very acute. This makes the case for the present literature review to motivates on this important issue. In this paper, an effort has been made to showcase the major studies with a focus on the electric, hybrid and autonomous vehicles utilizing non-conventional solar energy.

The discussion begins with a brief overview of electric and hybrid vehicles. Further, the integration of PV technology with electric and hybrid vehicles is presented. This is followed by studies of solar powered assisted electrical and hybrid vehicles including three and four-wheel-drive structure. Next, the study of solar powered assisted autonomous vehicles and robots are presented. Thereafter, the overall discussion and limitation of relevant studies are outlined.

2 Overview of electric and hybrid vehicles

India contributes around 18% of CO_2 emissions in the transportation sector and imports 70% of crude oil to fulfil the demand [30]. Maximum numbers of existing vehicles such as two-wheeler, three-wheeler and four-wheeler including private and commercial vehicles in Indian cities are based on ICE drive technology. These ICE vehicles utilize conventional energy resources such as crude oil, compressed natural gas and petrol [30, 31]. According to the Society of Indian Automotive Manufacturers (SIAM), the Indian auto industry is one of the largest in the world

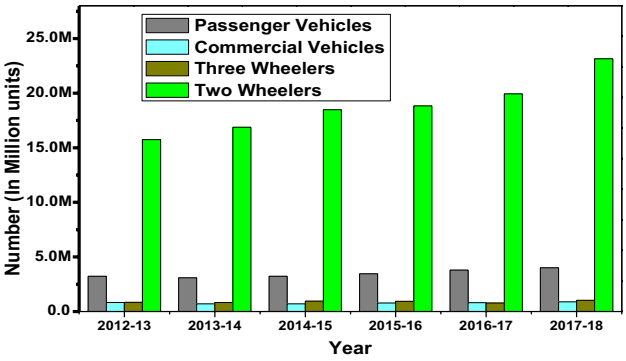

Fig. 1 Total Indian automobile production trends

with a production rate of 29.07 Million vehicles in the year 2017–2018. The total production rate of passenger, commercial, three and two-wheelers vehicles for the financial year 2012–2013 to 2017–2018 is shown in Fig. 1 [32]. Hence, there is a need to utilize alternative power system technology for the road transportation sector. Electric vehicles (EVs) including battery electric vehicles (BEVs), Hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) are the appropriate solution offering a clean mode of mobility. Overview of electric vehicles in place of the conventional engine vehicles reported in the literature is discussed below.

The merits of the electric vehicles for a better future and demerits of conventional fuel powered vehicles are presented [33, 34]. Designing, fabrication, testing and conversion of conventional fuel engine vehicle into a hybrid electric vehicle are proposed [35]. Light hybrid electric vehicles have better fuel economy and efficiency than conventional ICE vehicles is verified experimentally [36]. A compact size electric vehicle is developed and analysed in MATLAB tool to reduce carbon emissions of internal combustion engine vehicle [37].

Van Keulen et al. [38] propose a supervisory energy management control strategy for electric drive vehicle to reduce fuel consumption and enhance the vehicle's dynamic performance. An attempt is being made to utilize waste energy during the braking in hybrid electric vehicles. A controller is being employed to converts mechanical energy into electrical power [39]. The optimized charging along with drive management methodologies are proposed for an electric vehicle to decrease EV energy consumption, improve battery life, and to reduce electricity consumption [40].

Designing of an electrical propulsion system based on a synchronous machine for a hybrid electric vehicle is proposed [41]. An electric drive machine is used in conjugation with an IC engine to make hybrid electric powered vehicle [42, 43]. Electrical components such

as a compact size efficient motor, battery and electrical power system are used with conventional engine vehicle to make an advanced hybrid electric vehicle [44].

Lithium Iron Phosphate ($LiFePO_4$) battery system, arranged in a parallel configuration is proposed for an electric vehicle [45]. Another, parallel-series combination arrangement of the battery packs are employed in electric vehicles to improve efficiency [46]. Lithium-ion battery banks are proposed for electric vehicles [47]. A hybrid energy storage system consisting of polymer fuel cells and supercapacitors are suggested for an electric vehicle [48].

The electric and hybrid-electric vehicles have been introduced in Prague (Czech Republic) for urban areas with remarks that vehicles are technically as well as economically befitted for human health [49]. According to a study carried out in the U.S.A., BEVs are preferred by the customer due to environmental appeal while PHEVs are preferred due to less maintenance and range anxiety factors [50]. A case study related to the application of electric vehicle in comparison to petrol and diesel engine vehicles is conducted on the island of Barbados [51]. This study highlights the estimation of cost per km for electric, petrol and diesel vehicles as shown in Fig. 2.

Several electrical propulsion systems are tested with a conventional vehicle to reduce carbon emissions. These modified vehicles are popularly known as electric vehicles (EVs), battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs). Most of the automotive industries have initiated research and development towards these vehicles to decarbonize the transportation sector.

3 Integration of photovoltaic technology with EVs

Solar energy is available free of cost in the most continental areas of the world and can be converted into useful electrical energy through Photovoltaic (PV) technology.

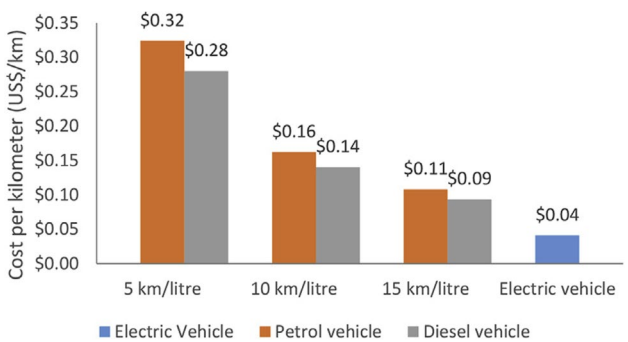

Fig. 2 A comparison of cost per km for electric vehicles (Nissan Leaf), petrol and diesel vehicles in Barbados [51]

Photovoltaic technology is getting more attention towards the 'Green' and 'Clean' environment. Semi-conductor materials of PV cells absorb photons of light and generate electric current to perform the desired task.

PV technology with electrical and hybrid vehicles can be used through two different modes. The first mode is the installation of solar PV station to recharge electric and hybrid vehicles and the second one is directly integrating PV panels with these vehicles. Integration of solar PV technology and different solar charging infrastructure schemes for electric and hybrid vehicles are discussed below.

A hybrid electric vehicle that utilizes the human effort and solar PV technology to drive the vehicle is designed [52]. The solar powered electric vehicle is designed to overcome the future crisis of non-renewable energy resources [53]. The feasibility of low budget electric vehicle utilizing efficient PV array system is proposed [54, 55]. A conversion scheme of the conventional vehicle into the solar vehicle is proposed as shown in Fig. 3. Further, the effect of this conversion scheme is analysed in MATLAB simulation environment [56]. A prototype of the solar hybrid vehicle is developed from the conventional car by employing several electrical components such as in-wheel motor, photovoltaic panels and Li-Ion batteries [57]. The Control and Applications Research Centre (CARC), designed and implemented a running vehicle model using the PV panel to modernize the traditional tri-wheeler vehicles and efficient use of renewable energy in Bangladesh. A solar charging station is also proposed to make the system completely independent from the national grid [58].

Solar PV station based on inductive power transfer methodology to recharge the electric vehicle is proposed [59]. Another, solar PV station to recharge the electric tricycle vehicles is proposed in Bangladesh [60]. A PV charging station having a capacity of 6.62 kW power is designed to recharge four electric vehicles simultaneously in Ireland as shown in Fig. 4 [61]. The concept of the solar power station to charge plug-in electric vehicles is proposed in

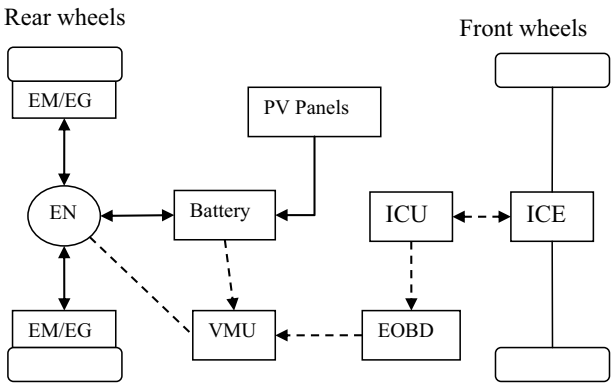

Fig. 3 The conversion scheme of the conventional car into the hybrid solar vehicle, adopted and modified [56]

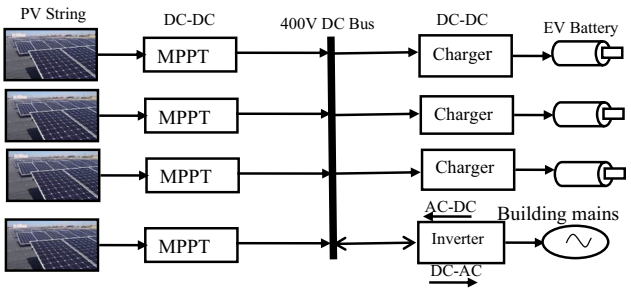

Fig. 4 PV-MPPT charging layouts system adopted and modified [61]

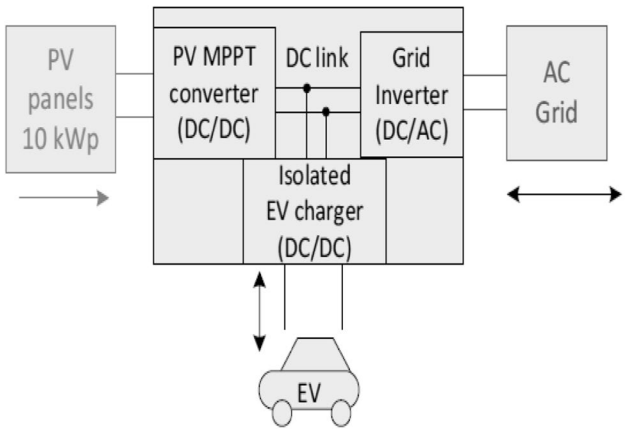

Fig. 5 Architecture scheme of PV-grid and EV charging [64]

developing countries like India and further this stored energy in batteries enhances backup power for home loads [62]. A conversion scheme of ICE vehicles into EVs in conjunction with home PV system to achieve the goal of greenhouse gases reduction in the transportation sector is proposed [63].

The PV-grid charging infrastructure scheme to recharge electric vehicles is presented [64]. Apart from this, several PV-grid charging schemes are proposed in the literature for electric vehicles [65–71]. Figure 5 shows the possible arrangement of the integration of PV-grid with electric and hybrid vehicles.

Several authors in the literature have proposed the concept of PV parking lots to recharge electric vehicles during parking hours [64, 72–74]. Additional advantages of PV parking lots such as shading and simultaneously recharging of electric vehicles are presented [74–76]. Design of optimized PV parking model structures to charge the parking EVs is proposed [75, 77].

A combined methodology consisting of solar and wind renewable energy to charge the electric vehicles is proposed [78]. Possible complementarities of renewable wind and solar energy to recharge the EVs for Portugal 2050 project is discussed [79]. The integration impact of renewable energy resources based charging infrastructure with plug-in electric vehicles (PEVs) is presented to meet the sustainable development goal in California [80, 81]. A power station utilizing renewable solar PV energy is developed to recharge electric taxis in Daejeon city [82]. A premium and green method to recharge electric vehicles from renewable energy resources is shown in Fig. 6 [83, 84]. Renewable solar and wind energy based recharging mechanism for electric vehicles are proposed to reduce carbon emissions [85].

An intelligent transportation system having a solar based ad-hoc networking technique for sensing, harvesting, estimating and communication characteristics is presented [86]. Renewable solar and battery bank based control strategy for a light solar electric vehicle is proposed [87]. Adoption of PV dispersion with electric vehicles on the basis of several geographical, economic and political factors towards clean energy in New York city is evaluated [88]. Mobile multi-pyranometer array-based methodology to estimate the solar energy generation accurately from car roof PV system is proposed [89].

4 Studies of solar powered assisted electrical and hybrid vehicles

Globally fossil fuel-based engine vehicles are the key mode of transportation, causing unexpected outcomes such as climate change, deficiency in natural visibility, air, land and water pollution. These factors are responsible for different pollution and global warming issues. Numerous works have been published in the literature on electric vehicles using a renewable resource such as solar energy. The review of three-wheeled and four-wheeled solar electric vehicles utilizing renewable solar energy is discussed in the following subsections.

4.1 Studies of solar powered assisted three-wheeled vehicles

Designing a hybrid tricycle rickshaw as a sustainable substitute to revamp energy consumption is proposed [90]. The power and dimensions of the hybrid tricycle are evaluated and analysed based on aerodynamic, rolling force, the desired load, moving speed and solar irradiation. Finally, the life cycle analysis approach is employed to find out the environmental and economic impacts of the solar vehicle with the help of SolidWorks sustainability software. Various mechanical, electrical and electronic components of tri-cycle are shown in Fig. 7.

Mulhall et al. [91], developed a solar powered assisted three-wheeler electric auto rickshaw to overcome the

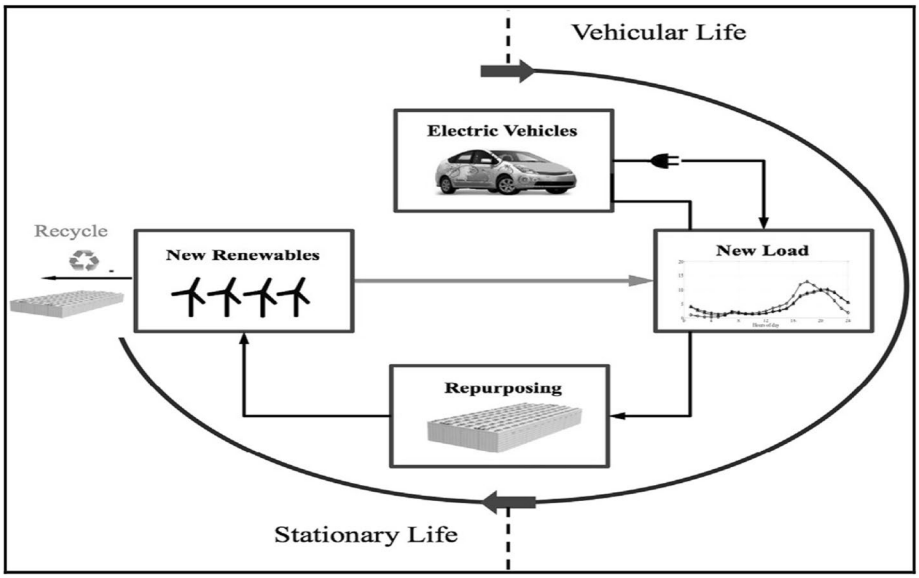

Fig. 6 A concept of the renewable energy based charging system [84]

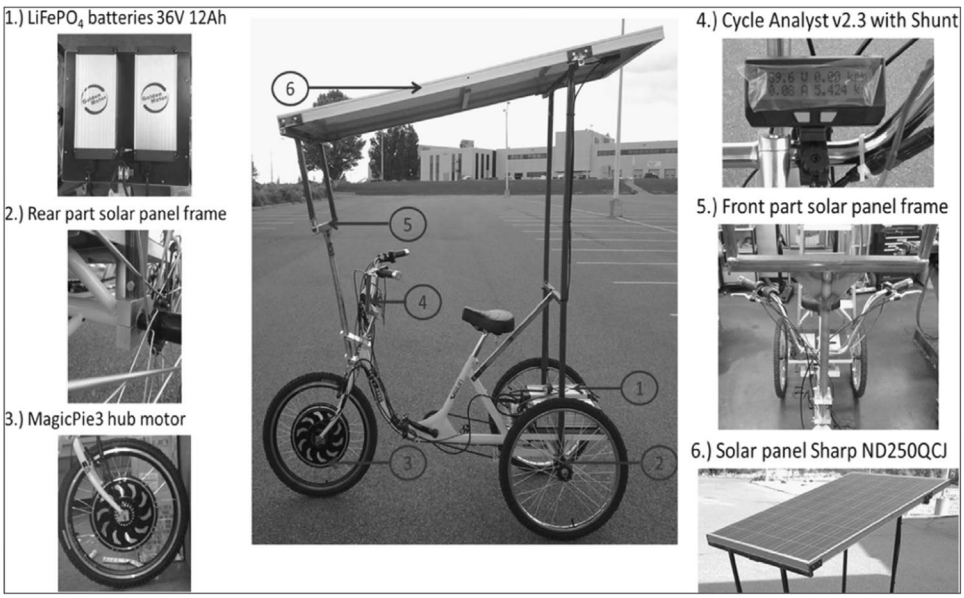

Fig. 7 Different components of solar power assisted tricycle [90]

pollution issues and scarcity of fossil fuel resources for developing country like India. The results show that the performance of the proposed electric auto rickshaw is far better than a conventional rickshaw. Solar assisted drive-train configuration of this three-wheeled is shown in Fig. 8 [91].

There is a scarcity of natural resources to produce adequate electricity as per demand in Bangladesh, even there is no electricity supply for the rural areas. Pollution and traffic jam are common problems due to the excessive quantity of conventional vehicles i.e. auto rickshaws. Therefore, BRAC University Dhaka, Bangladesh has implemented renewable solar energy based power station to charge the batteries of three-wheeler rickshaws to resolve these issues [92, 93].

Solar powered three-wheeler autorickshaw along with a control drive scheme is proposed to resolve pollution problems arising from conventional rickshaws. Various components such as monocrystalline structure PV panels, battery charge controller and DC sequence motor have been employed for the solar rickshaw as shown in Fig. 9 [94, 95].

A three-wheeler electric auto rickshaw utilizing renewable solar PV source is developed. The proposed model has a better driving range, speed, lifetime and travelling capability. The battery bank of the vehicle model can be charged in two distinct modes: through plug-in charging

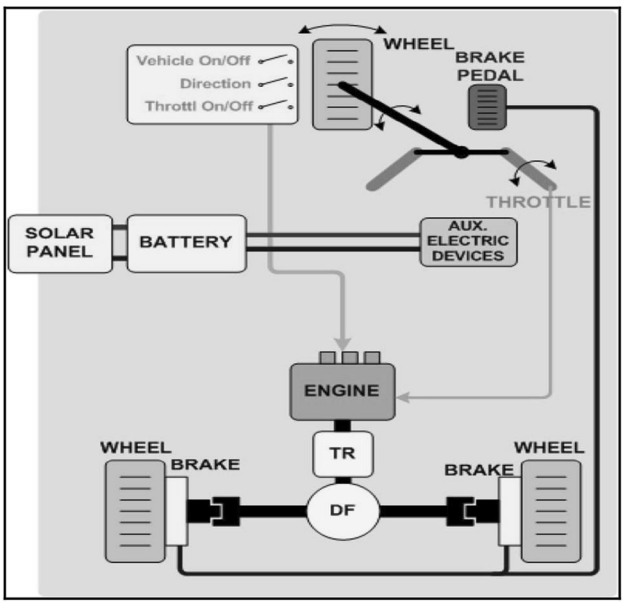

Fig. 8 Conventional rickshaw with the solar assisted unit [91]

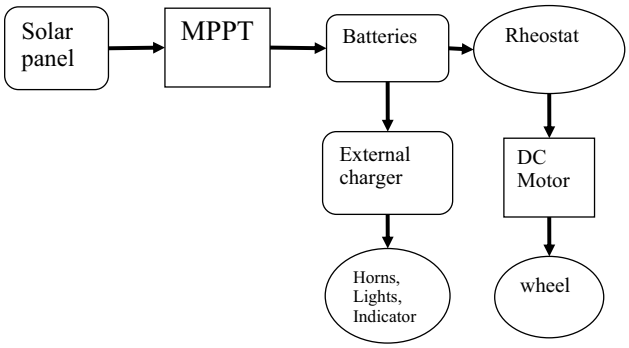

Fig. 9 Control scheme configuration for solar rickshaw model, adopted and modified [95]

method and through solar PV panels during motion [96]. Another, environmentally friendly electric rickshaws are proposed in Bangladesh to find out the PV array impact on rickshaw system as shown in Fig. 10 [97, 98].

A three-wheeler solar electric rickshaw is developed to minimize the driver pulled efforts. An electrical motor is used with the model that utilizes the electrical energy of the PV panels [99, 100]. A three-wheeler solar ambulance van utilizing renewable PV panels technology is proposed for the patient's transportation facility in the rural area of Bangladesh [101]. Two models of three-wheeler solar vehicle powered by split and conventional solar source architecture to increase the driving range performance are designed and compared [102].

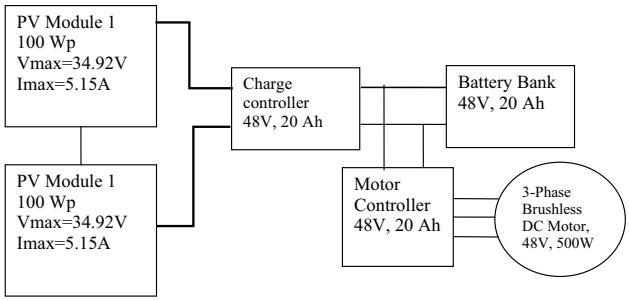

Fig. 10 The layout of the solar system concept [98]

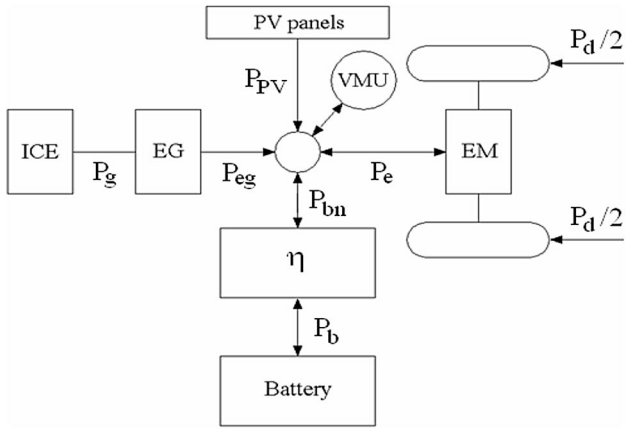

Fig. 11 Block diagram of a solar hybrid vehicle [103]

4.2 Studies of solar powered assisted four-wheeler vehicles

Application and implementation of solar PV energy are not limited to three-wheeler vehicles. Four-wheeler vehicles such as commercial and private are also getting attention toward the use of solar energy. Various four-wheeler vehicles that utilize solar photovoltaic technology are presented below.

Preitl Z et al. [103], proposed a four-wheeled solar hybrid vehicle (SHV) model that utilizes renewable solar PV technology. Various components such as electric motor, management unit, PV panels, and power batteries are used for the proposed vehicle model as shown in Fig. 11 [103]. Another, four-wheeler solar electric vehicle that utilizes the solar insolation, directly and indirectly, is presented [104]. A four-wheeler solar electric vehicle having one person seating capacity is developed [105]. Design and development of an eco-friendly solar electric car are proposed [106].

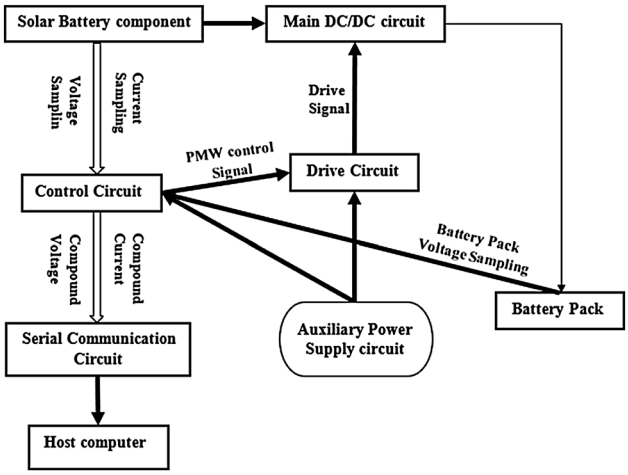

Fig. 12 Charging circuit diagram for solar hybrid midibus [118]

An axial flux permanent magnet brushless DC motor with a four-wheeler solar vehicle is tested to provide traction power [107]. An advanced approach to convert a conventional vehicle into a solar powered car by replacing the ICE with a 4-kW electric motor is proposed [108]. A four-wheeler solar electric vehicle with 850 W brushless DC-motor, 12 V 90AH lead-acid battery system and having the seating capacity of four passengers is developed [109]. Several important electrical components such as a lead acid battery, electronically commutated motors, solar panels and charge controller are employed in a solar powered four-wheeler electric vehicle [110]. Switched reluctance motors with a solar powered four-wheeled vehicle are employed [111]. Designing of a single phase as well as three phase induction motor drive for a four-wheeler solar electric vehicles is presented. The proposed induction motor has the advantage of soft phase conversion skill without changing the system hardware [112].

Optimal solar tracking and electrical power system are designed for a four-wheeler solar electric vehicle [113, 114]. A bi-directional DC converter is employed for a solar powered four-wheeled vehicle that utilizes regenerative braking energy to recharge battery storage systems [115, 116]. Designing and development of an electrical power system that utilizes the PV panels to extract solar energy and converts into useful electricity for a solar vehicle are presented [7, 117]. The charging control strategy for a solar powered hybrid midibus is shown in Fig. 12 [118].

A sustainable training centre to harness renewable resources such as solar, wind, and biomass for the transportation facility is proposed [119, 120]. Availability of solar energy in the different cities of Bangladesh throughout the year to support the construction of four-wheeler solar vehicles are surveyed. Additionally, the effect of solar photovoltaic technology with the plug-in electric vehicle on corporate fuel economy standards in 2025 is analysed [121]. Global System for Mobile communication (GSM) network technique is employed for an electric vehicle with 5 watts photovoltaic panel [122]. Renewable solar PV technology is integrated with an electric vehicle to cool the cabin space [123].

5 Studies of solar powered autonomous vehicles/robots

Autonomous ground vehicles (AGVs) are mobile robots or innovative electric vehicles that produce zero emission at tail point [124–127]. The most promising technology to improve efficiency and safety in future is autonomy [128, 129]. Various AGVs and robots that utilize renewable solar power to perform different tasks are discussed below.

The concept of satellite solar power station (SSPS) to meet the future energy demand in space based on photovoltaic technology is presented [130]. Designing and performance analysis of Mars exploration rovers with solar array technology to accumulate excessive dust is presented [131]. Design and construction of a power management system for robotic exploration vehicle (VANTER) are proposed as shown in Fig. 13 [132]. The construction of an optimized battery charging system for solar powered exploration robots is presented [133, 134]. Apart from this, numerous exploration robots such as *spirit, Tumbleweed, Hyperion, Cool* are presented in the literature [135–139].

A solar powered robot with an inductive sensor, video camera and ATmega32 microprocessor is designed to help the humanitarian effort in landmine detection [140]. Solar powered E- BOT robot is designed and developed for agriculture use [141]. A solar powered lawn mower directed by vision sensors to cut the grass is designed [142]. A four-wheeled solar robot that has 32 small 8-Watt power PV panels is designed [143]. The design and fabrication of automated mobile vehicle i.e. wheelchair with retractable solar panels to help handicap persons is proposed [144, 145]. The energy storage system to store intermittent solar energy as an alternate source for mobile robots is designed as shown in Fig. 14 [146].

The prototype of an autonomous surface vehicle which utilizes solar energy to check the ocean physical parameters such as temperature, wind speed and salinity of the water is designed [147]. Another, solar powered underwater vehicle which has an intelligent navigation system to measure the physical and chemical parameters of water is developed [148]. Another, the prototype of an unmanned surface vehicle that utilizes renewable solar and wind energy is designed [149].

A model of unmanned solar powered air vehicle is designed [150]. The concept of solar energy inclusion in

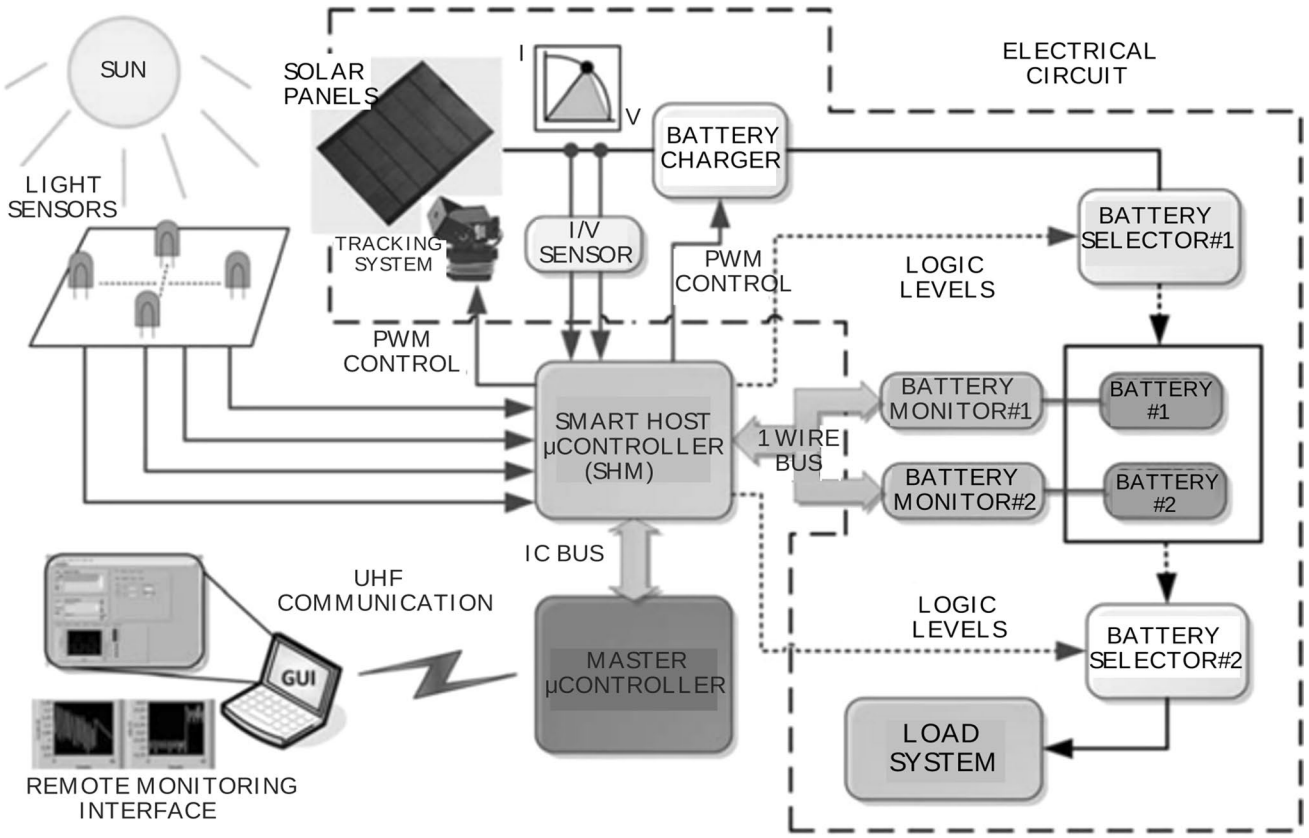

Fig. 13 The design scheme of the power management system for VANTER [132]

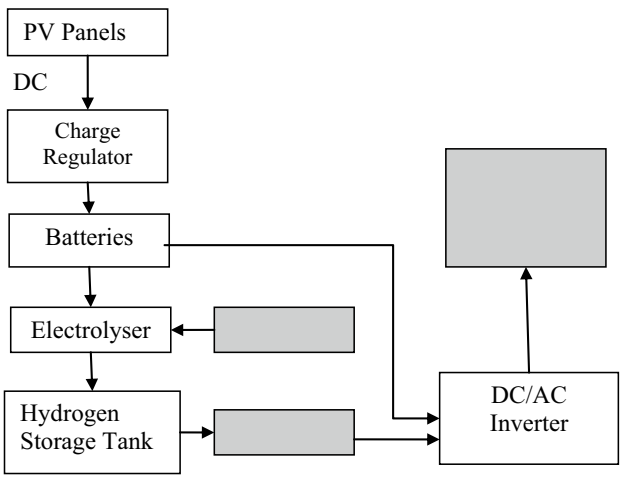

Fig. 14 Hydrogen fuel cell block diagram adopted and modified [146]

place of conventional fuel without increasing mass as well as the size of the fuel system for an unmanned aerial vehicle is analysed and verified experimentally [151]. The path time of flight for a solar powered unmanned aerial vehicle is optimized using battery energy concepts [152]. A model of solar powered UAV is developed to design the capacity of the battery system as per flight time and availability of solar insolation [153]. Designing and analysis of an intelligent drone are presented to monitor PV power plants [154].

An optimal Gaussian regression algorithm for solar energy operated mobile robot is validated [155]. Solar powered mobile charging stations that utilize the visual-spectrum image of solar insolation to charge unmanned ground vehicles are experimentally tested and constructed [156]. Apart from this, several AGVs that use vision-assisted hybrid navigation system are proposed in the literature [157–163].

The solar insolation at different regions of Minneapolis USA for solar robots is tested with the help of satellite [164]. Two robotic systems are applied to design a two axis sun tracking mechanism, one for adjusting the automatic orientation of the PV module and second for providing reference trajectory [165, 166].

6 Discussion and limitations

Conventional ICE vehicles consume too much fossil fuel that is 'finite' and 'non-invertible' in nature. People are considering electric vehicles as an alternate solution to replace ICE vehicles. The discussion begins with reviews of various electric and hybrid vehicles to convert ICE vehicles into eco-friendly vehicles. Further, the integration of solar PV technology with electric and hybrid vehicles is presented. Thereafter, studies of three-wheeler and four-wheeler vehicles that utilize renewable solar source are carried out. Finally, studies of solar powered autonomous vehicles, robots, unmanned aerial vehicles and unmanned surface vehicles are carried out.

The following limitations are outlined based on the studies of solar power assisted vehicles carried out in this article to achieve future sustainable development goals as follows.

a. Solar powered EVs and HEVs which mostly rely on sustainable solar energy are free of charging limitations, but the range anxiety problem is more severe due to the unavailability of sunlight.
b. Despite numerous research on PV-grid charging scheme, it is admitted that PV is an intermittent source of energy due to the volatility of solar irradiance.
c. Non-uniformity of solar irradiation and variation in atmospheric temperature is a serious concern to utilize of PV system with EVs and HEVs efficiently.
d. To store the output of sustainable energy in solar powered vehicles is a huge concern due to the much lower specific energy of batteries compared to fossil fuel.
e. According to the IESS 2047 plan, solar energy will be the largest contributor among the all renewable and clean energy sources in India. However, the overall penetration of solar energy with electric vehicles is negligible.
f. In the developing countries like India, the unavailability of charging station is also a considerable concern for the society to adopt solar electric vehicles.
g. From the studies of solar powered autonomous vehicles and robots, it is found that robots utilizing solar energy are designed and developed exploration purposes only.

7 Conclusions

Electric vehicles are the appropriate solution to mitigate pollution and environmental issues of conventional ICE vehicles. Solar energy is considered as the most promising renewable energy resource of the twenty-first century. In the present study, electric, hybrid, autonomous vehicles and robots utilizing the solar PV technology are reviewed. Overview of electric and hybrid vehicles suggests that in a developing country like India, there is a huge demand for green-powered electric vehicles for the transportation sector. Further, integration of renewable PV technology with electric, hybrid and autonomous vehicles would be a green and sustainable step to decarbonize the road transportation sector. Studies of solar powered electric vehicles suggest that a very little effort has been made to implement and design solar powered vehicles by the Indian government. Automation industries and research organization should focus on the innovative design and implementations of PV technology with AGVs for greener production towards sustainable development goals.

It is evident from the studies of solar powered electric, hybrid, and autonomous vehicles that there is a need to increase the number of innovative and sustainable solar charging stations to improve the range anxiety problem of EVs in India. The government of India should focus on public awareness policies and strategies to increase the penetration of EVs which will help to achieve the National Electric Mobility Mission Plan 2020. Next, an efficient and high specific energy storage system must be incorporated with the electric and hybrid vehicles to enhance the driving range. Further, government agencies should start various projects and schemes related to renewable solar energy to meet the sustainable development goals of developing countries like India.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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