Solar Energy 146 (2017) 523–531

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Static concentrator photovoltaics for automotive applications

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ARTICLE INFO

Article history:
Received 20 December 2016
Received in revised form 6 February 2017
Accepted 9 March 2017

Keywords:
Solar powered vehicle
Static concentrator
III–V on Si
CO_2 emission

ABSTRACT

This research investigated the benefits of utilizing solar power as an energy source for future passenger vehicles and an innovative static concentrator photovoltaic module for practical automotive applications. Due to strict emissions standards, alternative energy sources must be found for vehicles in the future. It was estimated that replacing all passenger vehicles with hybrid vehicles (HVs) equipped with an 800 W rated-power solar module that generates an average output of 1.8 kW h/day would reduce CO_2 emissions by 63% in Japan. To confirm the validity of this estimation, a test vehicle was created by installing a 6.8 m^2 solar module onto a commercially available plug-in HV. An average power generation of 2.1 kW h/day was obtained by this solar module over 100 days under real-world conditions, which was larger than the power required to achieve the estimated CO_2 emissions reduction. In addition, an innovative static low-concentrator with III–V cells was studied to help reduce the installation area of the solar module on the vehicles, which is essential for practical passenger vehicles. A new concentrator design method was proposed that can be easily integrated into a standard vehicle design procedure by utilizing numerical optimization in a CAD-friendly environment. Both design equations and a design example are discussed in this paper. The proposed lens design (asymmetric-aspheric type) can expand the acceptance incident angle of solar light and increase the annual energy yield of a solar panel, while maintaining the essential thin structure for automotive applications. In spite of the wide range of sun positions, this asymmetric-aspherical lens can maintaining stable illumination on the cell while suppressing the maximum spot intensity to 20×.

1. Introduction

In 2012, the U.S. Environmental Protection Agency and National Highway Traffic Safety Administration adopted standards for CO_2 emissions and improved fuel economy for light-duty vehicles covering the model years (MYs) 2017–2025 (EPA report, 2015). The new emissions rules require an average fuel economy of 23.2 km/L (equivalent to CO_2 emissions of 100 g/km) for these vehicles by MY 2025. Similar rules have been developed by the EU, Japan, and other countries and regions. Accordingly, automakers have been developing various types of environmentally friendly vehicles (EFVs) such as hybrid vehicles (HVs), plug-in hybrid vehicles (PHVs), electric vehicles (EVs), and fuel cell vehicles (FCVs) to help reduce CO_2 emissions. Although more than 20% of MY 2015 vehicle production already meets the MY 2018 CO_2 targets, or can meet the targets with the addition of expected air conditioning improvements, less than 5% of 2015 production, comprising solely of HVs, PHVs, and EVs, can meet the MY 2025 targets (EPA report, 2015). Therefore it is necessary to develop other technologies that use renewable energy as driving power to achieve further reductions in CO_2 emissions. Power generation by solar cells is a promising renewable energy candidate because most EFVs are equipped with large capacity batteries that can be charged by electricity generated by these cells. Since the passenger vehicles, which account for approximately 50% CO_2 emission in the transport sector, has much smaller energy consumption rate and shorter driving distance per day compare to heavy vehicles (trucks, buses, and trains), a larger CO_2 emission reduction can be expected for the passenger vehicles compare to heavy vehicles by the solar cells.

This paper investigates the benefits of utilizing solar power as an energy source for future passenger vehicles from the viewpoint of CO_2 emissions reduction. Analysis results showed that replacing all passenger vehicles with HVs equipped with an 800 W rated-power solar module (SM) would reduce CO_2 emissions by 63% in Japan. In addition, an innovative static low-concentrator with

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http://dx.doi.org/10.1016/j.solener.2017.03.028
0038-092X/

III–V cells was studied to reduce the installation area of the SM on a vehicle which is essential for practical automotive applications. This paper shows that the proposed asymmetric-aspheric design can expand the acceptance incident angle and increase the annual energy yield compared with a conventional spherical design, while maintaining the essential thin structure for automotive applications.

2. Benefit of solar power for vehicles

2.1. Estimation of CO_2 emissions reduction

First, the benefit of utilizing solar power for vehicles was investigated by estimating the electricity generation of an SM installed on a PHV. The current plug-in Prius is equipped with 4.4 kW h lithium-ion batteries and has an electric power consumption rate of 8.8 km/kW h based on the JC08 Japanese test cycle and verified by the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT). However, it is estimated that this rate can be improved to 17.0 km/kW h mainly by reducing the weight of the vehicle from 1410 kg to 600 kg in the future. Table 1 shows the assumed efficiencies of the charging system. To protect the battery and avoid errors, an additional battery control system is required for charging from the SM. The power consumption and hours of operation of the control system were assumed to be 30 W and 12 h/day, respectively. A solar irradiation of 3.7 kW h/m^2/day (the average from 1961 to 2012 in Nagoya, Japan) obtained from a report by the Japan Meteorological Agency was used.

When an SM with a rated power of 800 W (e.g., a module with efficiency of 22% and a surface area of 3.4 m^2) is installed on the PHV, an average output power of 1.8 kW h/day can be obtained, which is equivalent to a drive range of 31 km/day based on a rate of 17.0 km/kW h. The average daily driving distance of passenger vehicles in Japan is 24 km/day, and approximately 70% drive less than 30 km/day as shown in Fig. 1 (Japanese Ministry of Land, Infrastructure, Transport and Tourism, 2015). The fuel consumption ratio of passenger vehicles that drive less than 30 km/day is estimated to be 32%, while 31% out of the remaining 68% (fuel consumed by passenger vehicles that drive more than 30 km/day) can be saved by the electricity generated by a 800 W SM. These calculations were performing using the road traffic census carried out by MLIT (Japanese Ministry of Land, Infrastructure, Transport and Tourism, 2015). Therefore, replacing all passenger vehicles with HVs equipped with an 800 W SM would reduce energy consumption or CO_2 emissions from these vehicles by 63%. Since passenger vehicles account for 51% of energy consumed in the transport sector, this 63% reduction would be equivalent to 32% of the total energy consumed by this sector in Japan (Agency for Natural Resources and Energy, 2014). These calculations show that utilizing solar power from automotive SMs has a great potential to reduce CO_2 emissions.

2.2. Verification of the estimated power generation by SM on a vehicle

After identifying the benefit of SMs for automotive applications, the actual power generation of an SM installed on a PHV was investigated under real-world conditions to confirm the validity of the estimation. A Prius PHV was equipped with 16 SMs, consisting of 422 back-contact monocrystalline Si solar cells with a conversion efficiency at AM1.5G and dimensions of ~22% and 125 × 125 mm^2, respectively, as shown in Fig. 2. The calculated total rated output power of the modules was ~1308 W, but the actual value is much lower because 218 out of the 422 cells were installed on vertical planes such as side doors. The solar irradiation of the horizontal plane was measured by a pyranometer installed on the hatch (Fig. 2(b)). Since commercially available c-Si solar cells were used for the test vehicle, the total surface area of the SMs was large. As a result, half of the SMs needed to be installed on vertical planes (side doors) of the car.

The measurements were conducted over the course of 100 days, over seven months between July 1, 2014 and January 30, 2015 in Susono, Japan. The measured average solar irradiation was 3.0 kW h/m^2/day, which was lower than the assumed value in the previous section.

Fig. 3(a) shows that although the solar radiation measured by the pyranometer fell by nearly 60% between July (4.2 kW h/m^2/day) and December (1.9 kW h/m^2/day), the total power generation decreased by nearly 40% from 2.8 kW h/day to 1.6 kW h/day. The smaller reduction is due to increasing power generation by the SMs installed on the vertical planes as the incident angle of the

Table 1
Summary of efficiencies.

Cell temperature correction	0.91
MPPT	0.95
DC/DC conversion	0.90
DC charging	0.95

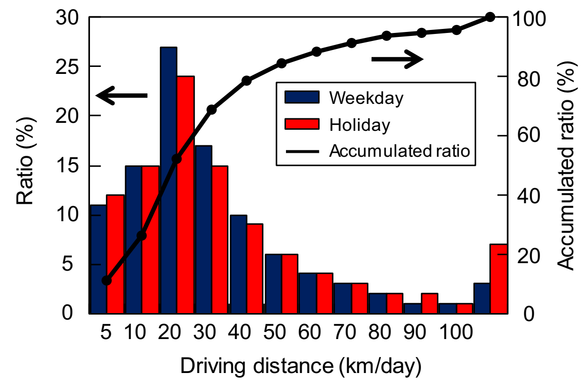

Fig. 1. Daily trip distance distribution in Japan for passenger vehicles.

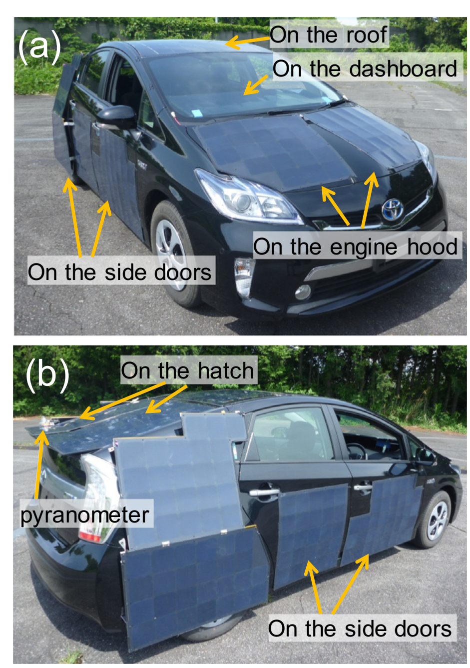

Fig. 2. Test vehicle (Prius PHV) with SMs.