

A Development of Energy Management System with Semi-Transparent Solar Roof and Off-Cycle Credit Test Methodology for Solar Power Assisted Automobile.

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ABSTRACT

CO₂ emission is more serious in recent years and automobile manufacturers are interested in developing technologies to reduce CO₂ emissions. Among various environmental-technologies, the use of solar roof as an electric energy source has been studied extensively. For example, in order to reduce the cabin ambient temperature, automotive manufacturers offer the option of mounting a solar cell on the roof of the vehicle [1]. In this paper, we introduce the semi-transparent solar cell mounted on a curved roof glass and we propose a solar energy management system to efficiently integrate the electricity generated from the solar roof into internal combustion engine (ICE) vehicles. In order to achieve a high efficiency solar system in different driving, we improve the usable power other than peak power of solar roof. Peak power or rated power is measured power (W) in standard test condition (@ 25°C, light intensity of 1000W/m²(=1Sun)). However, improved fuel efficiency cannot be measured in the US driving test cycle. Therefore, we have to establish a new test methodology to get CO₂ credit based on off-cycle credit regulation from the Environmental Protection Agency (EPA) & the National Highway Traffic Safety Administration (NHTSA). We expect that the alternative methodology our solar power system will contribute to the automotive industry by reducing CO₂ emissions in the near future.

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INTRODUCTION

Green energy technologies including solar, wind, and other resources are promising solutions to relieve global warming. One of the main causes of global warming is CO₂ emission from automotive industry. To solve the problem, many manufacturers study how to use solar energy in vehicles. Installing a crystal silicon (c-Si) solar cell on vehicles is widely investigated and a supplemental battery is added to charge the electricity generated from solar cell [2, 3, 4]. Some manufacturers show the use of solar power to operate ventilation when a car is parked. However, the electricity productivity of c-Si solar cell is low in actual operation because its efficiency is dropped drastically in low light intensity and high temperature environment. The purpose of our research is to overcome the disadvantages of c-Si solar cell through developing the amorphous-silicon (a-Si) solar cell. We also aim to control the solar power efficiently in driving situations for achieving high CO₂ credit from EPA. We look forward to reducing CO₂ emission in the vehicles using our energy management system with a semi-transparent solar roof.

lower CO₂ emission limits recently. US EPA & NHTSA announced Corporate Average Fuel Economy (CAFE) standards and Green House Gas (GHG) emission of 2025 to global automotive manufacture companies in 2015 [5].

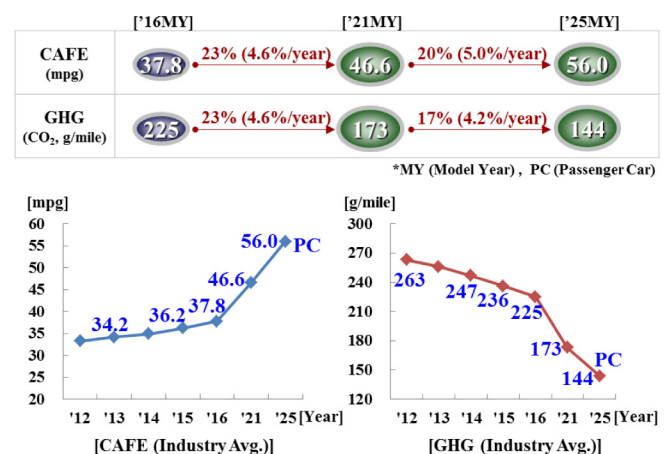


Figure 1. The CAFE and GHG standards trend for Passenger Car (PC) from 2012 to 2025 years.

CO₂ EMISSION STANDARDS IN US

CAFE/GHG Standards

CO₂ emission of transport mobility has become a big concern due to environment pollution. Because the energy consumption of the automotive sector is continuing to increase, US government trends to

According to these regulations, automotive manufacturers have to meet CO₂ 144 g/mile in the year 2025. It is as much as 36% lower than in the year 2016 and therefore manufacturers have to reduce CO₂ emissions by at least 4.5% each year up to 2025 year as shown in

Figure 1. Various types of eco-friendly vehicles such as hybrid (HV), plug-in hybrid (PHEV), electric (EV), fuel-cell (FCEV) are increasingly produced in recent years. Many eco-technologies such as Idle Stop-and-Go (ISG), Regenerative Brake System (RBS) have been applied to ICE vehicles to reduce CO₂ emission in traditional on-cycle driving test : Federal Test Procedure (FTP) & High Way Fuel Economy Test (HWFET).

Off-Cycle Credit Regulation

Challenged by CAFÉ and GHG regulations, EPA/NHTSA announced a new policy called ‘off-cycle credit’. If a manufacturer applied environmental-technology to a vehicle and manages to reduce CO₂ emission in a way that cannot be measured in traditional 2-cycle test (FTP & HWFET), carmakers can obtain CO₂ credit corresponding to the amount of reduced CO₂ emission of eco-technology through off-cycle credit regulation [6].

Table 1. Purpose of off-cycle credit and test procedure.

Off-cycle credit	
Objective	To approve CO ₂ credit for technologies not be measured in 2-Cycle
Test procedures	
Menu	Pre-approved technologies , Fixed credit value
5-Cycle	Measurable technologies in SC03, US06, Cold-FTP
Alternative	Demonstrating a different value for its unique technology

Table 2. The menu-based off-cycle credit technologies and CO₂ credit values [5, 6]

Menu-based off-cycle credit technologies	CO ₂ credit (g/mile)
High Efficiency Exterior Lighting (at 100W)	1.0
Waste Heat Recovery (at 100W; scalable)	0.7
Active Aerodynamic Improvements (scalable)	0.6
Engine Idle Start-Stop w/ heater circulation system	2.5
Engine Idle Start-Stop wo/ heater circulation system	1.5
Active Transmission Warm-Up	1.5
Active Engine Warm-Up	1.5
Passive Cabin Ventilation	1.7
Active Cabin Ventilation	2.1
Solar Roof Panels [for 75 W, battery charging only]	3.3
Solar Roof Panels [for (75 – α)W, battery charging only except for active cabin ventilation's power consumption (α)]	2.5

Three ways to acquire CO₂ credit is seen in Table 1. Many manufactures tried to employ the menu-based technologies which are pre-approved by EPA. These technologies are listed in the ‘menu’-based off-cycle technologies such as high efficiency exterior lighting, waste heat recovery and solar roof panels for P/H/EV. Test method for ‘menu’ technologies is already set up by Off-Cycle regulations. Table 2 shows the menu-based off-cycle credit technologies and CO₂ credit value. As shown in Table 2, 75 W solar roof panels for only battery charging have CO₂ credit value of 3.3 g/mile. 75W solar roof panels for combination of active cabin ventilation and battery charging has CO₂ credit value of 4.6 g/mile (The sum of 2.1 and 2.5

g/mile). As can be seen, the CO₂ credit of solar roof is higher than other menu-based off-cycle technologies. Manufacturers can demonstrate fuel consumption by comparing the standard ‘5-cycle’ test results with the 2-cycle test results. However, if automotive manufacturer applies new technology which is not listed in menu-based technologies, they should develop an ‘alternative’ test methodology to prove CO₂ emission reduction and get CO₂ credit from the EPA. We developed our own test methodology which is suitable for the HMC solar energy management system. Through it is an alternative test procedure, we will demonstrate unique characteristic of our solar system and get approval for higher CO₂ credit than menu-based solar roof panels from the EPA.

SEMI-TRANSPARENT PANORAMIC SOLAR ROOF

Fabrication Technology for Curved Solar Roof

HMC has employed panoramic sunroof extensively to many models including Genesis, Santa Fe, i30, etc. Our research group tries to achieve transparency of solar roof equal to panoramic sunroof. To maintain the transparency of a panoramic sunroof, we introduce a-Si solar cell instead of c-Si solar cell. The a-Si solar cell is transparent because its active layer has high transmittance in range of visible wavelength (390-700 nm). It is beneficial for the user to have transmittance equivalent to a normal panoramic sunroof. Large area deposition process is available to mount a-Si solar cell on a curved roof glass. Because a-Si solar cells are fabricated with several boundaries between each layer, the openness of panoramic sunroof may decline and it could make customers feel uncomfortable.

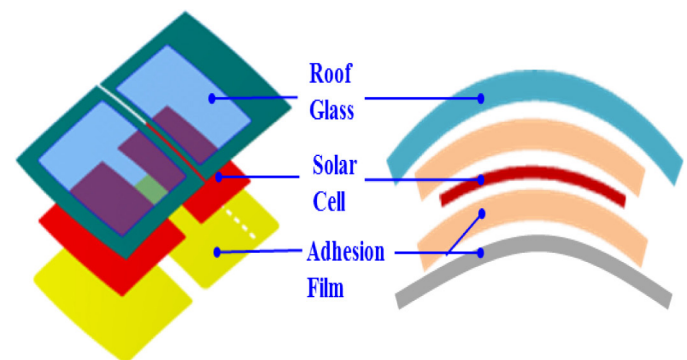


Figure 2. The layers image (left) and cross-sectional diagram (right) of a-Si solar cell laminated on the curved roof glass.

The roof curvature & area are many and various depending on vehicle design. It is important factors to determine solar cell's area and array structure on a panoramic roof. To fabricate large-scale a-Si solar cell on a curved roof glass, we have to develop a fabrication process. In order to secure the flexibility of design, we introduce lamination and auto-clave process which are appropriate to fabricate the large-size curved solar roof without defects or bubbles. Figure 2 shows the cross-sectional images of solar roof. As can be seen, a-Si solar cell is laminated with an adhesion film under the curved roof glass. We achieved the thin solar roof which is a little thicker than to panoramic sun roof. .

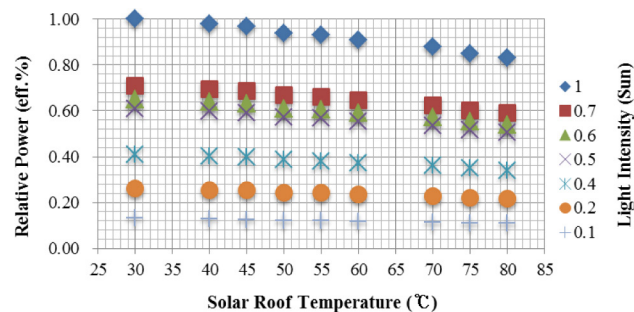


Figure 3. The photographs of (a) the semi-transparent solar roof taken from the inside vehicle, and (b) the solar power assisted automobile based on ‘Hyundai Santa Fe’w in HATCI.

Figure 3 shows photograph of the semi-transparent solar roof and the solar power assisted automobile. The solar roof is assembled into the Santa Fe Sports Utility Vehicle (SUV) and the solar power assisted SUV is on the durability test in Hyundai-Kia America Technical Center, Inc. (HATCI). As can be seen in Figure 3 (a), light scattering & distortion are not detected in a solar roof. It means that lamination & auto-clave process is effective to fabricate solar roof on the large-sized curved roof glass. Also our solar roof has high transparent characteristic enough to recognize things outside vehicle. Through this evaluation, we confirmed that lamination & auto-clave is reliable to manufacture semi-transparent curved solar roof.

The Electrical Performance of the Semi-Transparent Solar Cell

According to many reports, the peak power of a-Si solar cell measured at 25°C, 1sun still much lower than c-Si solar cell. The reason is that transparent characteristic of a-Si solar cell induce active layer to limit light concentration. Operation environment of Vehicle Integrated Photo-Voltaic (VIPV) is dissimilar to that of Building Integrated Photo-Voltaic (BIPV). VIPV usually make the electric power in medium-low light intensity because vehicle’s roof which has no sun-tracking function. So we employed the functional layer and the reflective film to improve electricity performance in medium-low light intensity and high temperature condition.



°C	30	40	45	50	55	60	70	75	80
1	100%	98%	97%	94%	93%	91%	88%	85%	83%
0.7	71%	70%	69%	67%	66%	65%	62%	60%	59%
0.6	65%	64%	63%	61%	60%	59%	57%	55%	54%
0.5	61%	60%	59%	57%	57%	56%	54%	52%	51%
0.4	41%	40%	40%	39%	38%	37%	36%	35%	34%
0.2	26%	25%	25%	24%	24%	24%	23%	22%	22%
0.1	13%	13%	13%	12%	12%	12%	11%	11%	11%

Figure 4. Effects of light intensity and temperature change on output power of a- Si semi-transparent solar cell : (a) Relative power as a function of increased temperature for light intensity (b) Numerical data assuming that the peak power measured at 30°C, 1sun is 100% .

Figure 4 shows that relative power of a-Si solar cell depending on light intensity and temperature. We assumed the peak power measured at 30°C, 1sun as 100% and we measured the change of a-Si solar roof’s electrical output power characteristics. To evaluate the effects of light intensity, we decreased light intensity from 1.0 sun to 0.1Sun at the same temperature. Whenever the light intensity is decreased by 0.1 sun, the output power is reduced by 8.7% in condition of 25°C. The output power reduction percentage is each 1.1%, 1.0%, 0.9% and 0.2% at 0.7sun, 0.6sun, 0.5sun and 0.1sun, respectively. To evaluate the effects of temperature, we increased ambient temperature at same light intensity. Whenever the temperature is increased by 5°C gradually, the output power is reduced by 1.5% in the condition of 1sun. The output power reduction percentage is each 8.5%, 8.2%, 7.9% and 7.2% at 40°C, 50°C, 60°C and 80°C, respectively. Through this experiment, we could predict the effective output power of the solar roof if we would have weather data for target areas.

$$\text{Effective Output Power (W}^{\text{for vehicle}}\text{)}$$

$$= W^{\text{Peak}} * C^{\text{Light intensity}} * C^{\text{Temperature}}$$

W^{Peak} : Peak power of solar roof (measured @25°C, 1sun)

C^{Light intensity} : Output coefficient of light intensity

C^{Temperature} : Output coefficient of temperature