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Design, Manufacture, and Environmental Sustainability Evaluations of Advanced Electric Medium Duty Bus "WEB for Suntory"

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Abstract

This paper describes the design and manufacture of a highly practical electric medium duty bus called the WEB for Suntory (WEB: Waseda electric bus). The new electric medium duty bus has a 55-passenger capacity, which is significantly greater than the other vehicles in the WEB series. This project prioritized weight reduction and maximization of the passenger compartment space to develop a bus that meets the requirements for short distance transportation and very frequent charging. A new compact powertrain system incorporating the minimum number of lithium-ion batteries was developed. The intended purpose of the bus is to convey passengers on a plant tour along a steep and low-velocity route located at the foot of a mountainous region. The merits of an electric bus make it particularly suited to this usage scenario and route, which require environmentally sustainable transportation. The dynamic performance and environmental sustainability of the bus were evaluated based on long-term actual driving data. The results found that adopting this bus on this route greatly reduced energy consumption and CO_2 emissions due to its efficient dynamic performance and energy regeneration system. The bus was charged from the solar power generation system installed at the plant, thereby further reducing CO_2 emissions and running costs.

Keywords: bus, EV (electric vehicle), photovoltaic

1 Introduction

Our research and development to enhance the environmental sustainability and practicality of electric buses was started in 2002 as part of efforts to respond to environmental and energy issues.[1] Potentially, electric buses have excellent environmental sustainability because EVs emit no CO_2 or other gases that affect the environment and because EVs run virtually silently and with little vibration. However, the widespread adoption of electric buses as a practical form of transportation depends on the improvement of battery performance and the development of a more convenient charging system. To resolve these issues, a concept was formulated to develop buses that meet the requirements for short distance transportation and very frequent charging. Under this approach, the project studied methods of greatly reducing the number of large, heavy, and expensive batteries required by an electric bus while addressing the issues of cruising range and charging.[2] In addition, a non-contact inductive power supply (IPS) system was developed as a way of improving

charging convenience. Subsequently, strong progress was made in the development of a line of highly practical electric buses called the Waseda electric micro bus (WEB) series.[3] The developed buses have significant commercial potential and are particularly suitable as small or medium duty buses that run along fixed routes.
This paper describes the design and manufacture of the WEB for Suntory, a new electric medium duty bus with a 55-passenger capacity, which is significantly greater than the other vehicles in the WEB series. [4] This paper also describes the environmental sustainability evaluations of using solar power to charge the bus.

2 Design and Manufacture of the WEB for Suntory Electric Bus

2.1 Design

Figure 1 shows a photograph of the newly developed bus and Table 1 lists its main specifications. The base vehicle, a medium-sized Melpha bus produced by Hino Motors, was modified into an electric bus that meets the requirements for short distance transportation and very frequent charging. A short cruising range requires fewer batteries, thereby reducing initial costs and weight, and allowing maximization of the passenger compartment space.

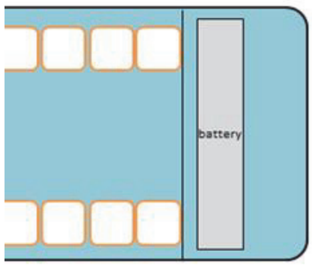
Figure1: WEB for Suntory

The diesel engine of the base vehicle was replaced with a brushless DC motor and lithium-ion batteries were installed. The brushless DC motor is manufactured by UQM Technologies Inc. and has a maximum output of 200 kW and a maximum torque of 900 Nm. A manganese lithium-ion battery manufactured by GS Yuasa Corporation with a proven track record of use in electric buses was selected. This is a prismatic lithium-ion battery with a nominal voltage of 355 V and a capacity of 35.5 kWh. The interior of the bus is heated by a 4 kW electric hot water heater and cooled by an 3.7 kW electric compressor cooler (cooling capacity:15.7 kW).

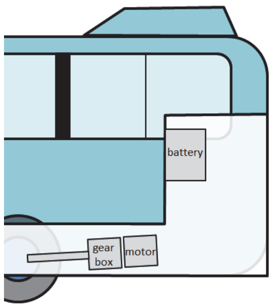
Table 1: Specifications of the Base Vehicle and the WEB for Suntory

		Base Vehicle: Hino “Melpha”	WEB for Suntory
Capacity		60 persons	55 persons
Weight		6890 kg	6780 kg
Engine/ motor	Type	Diesel Engine	Brushless DC Motor
	Manufacturer	Hino Motors	UQM Technologies
	Max. Output	165 kW	200 kW
	Max. Torque	600 Nm	900 Nm

Figure 2 shows the powertrain components and battery layout. The passenger compartment space was maximized by reducing the size of the components and optimizing the layout. The drive motor is directly connected to the differential gear through a newly designed compact and lightweight gear box integrated with the motor. The inverter was installed inside the engine compartment and the battery was located inside the rear of the passenger compartment. The electric compressor for the air conditioning system and the hot water heater were also installed in the engine compartment.



(a)Top View



(b)Side View
Figure2: Component Layout

This component and system development resulted in a powertrain that achieves virtually the same-sized passenger compartment as the base vehicle. The design concept of this bus emphasized weight reduction and maximization of the passenger compartment space compared to the base vehicle. Consequently, non-essential components such as flywheels, clutches, transmissions, and the like were eliminated, providing that this did not lead to substantial increases in costs. As a result, the weight of the developed electric bus is 6,780 kg, 110 kg lighter than the base vehicle.
In addition, a portion of the dividing wall between the battery storage and passenger compartments was made from a transparent plastic panel. This allows the passengers to watch the electric drive system and increases the appeal of the bus. Other key features of the bus include a foldable wheelchair lift, the adoption of an AC 100 V inverter as a backup power source for the main battery (Fig. 3), and the like.

Figure3: AC100V Output

2.2 Charging System

To reduce costs, this bus uses a conventional rapid charging system instead of the non-contact rapid charging inductive power supply system adopted on the other buses developed by Waseda University. Although the short cruising range of this bus increases the required number of charges, this issue was resolved by adopting the proven and user-friendly CHAdeMO rapid charging system (Fig. 4). This system delivers 50 kW of power and is capable of charging the battery in the bus to 80% of its full capacity in approximately 40 minutes. Unlike the non-contact rapid charging inductive power supply system, a conventional system is also easily visible, which makes it easier for people to appreciate the environmental activities of the company operating the bus.

Figure4: CHAdeMO (Rapid Charging System)

3 Environmental Sustainability Evaluation by Actual Driving

3.1 Driving Route and Current Operational State

Figure 5 shows the route of the plant tour bus at the Suntory Minami Alps Hakushu Water Plant, which is located at the foot of a mountain range in Yamanashi prefecture, Japan. The length of the route is 0.8 km in one direction and links the still house and natural mineral water plant.

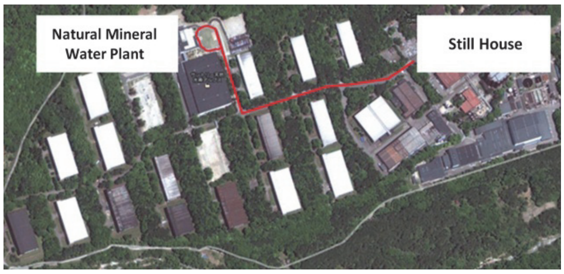


Figure5: Route

As shown in Fig. 6, this route features a 35-meter change in altitude. In the direction starting from the still house and heading toward the natural mineral water plant, the route is all uphill. Conversely, the return journey is downhill.

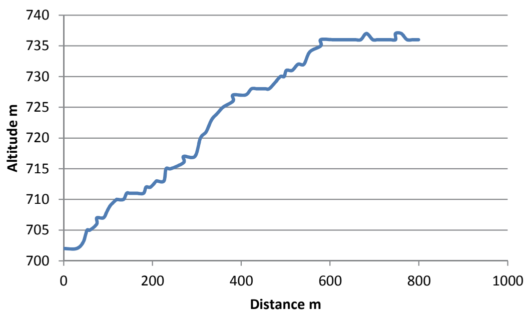


Figure6: Altitude

Detailed driving data of the WEB for Suntory bus was obtained. Figures 7 and 8 show the results obtained for the velocity and state of charge (SOC) of the bus for June 30, 2012. This data was selected since it is unaffected by the energy consumption of the air conditioning and the like. The velocity data indicates that the maximum velocity of the bus is only approximately 25 km/h and that the bus only decelerates greatly when turning right or left. The SOC data shows that the battery charge decreases when the bus travels uphill, but virtually no energy is consumed when the bus travels downhill. Observation of the battery discharge current while driving confirmed that the battery was being charged by the regeneration system during the downhill section. This result indicates that power required for driving downhill is virtually the same as the amount of energy regeneration. Since this is a steep and low-velocity driving route, an electric bus is more efficient than a diesel-powered bus. Therefore, the merits of an electric bus make it particularly suited to this route.

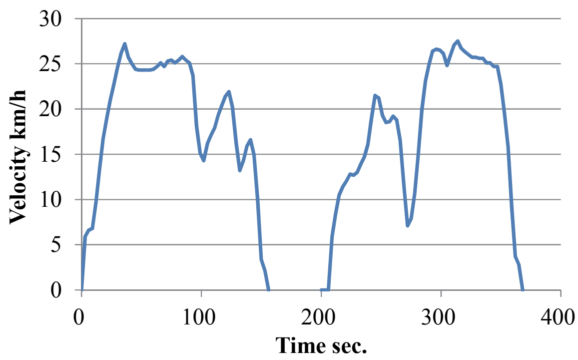


Figure7: Velocity

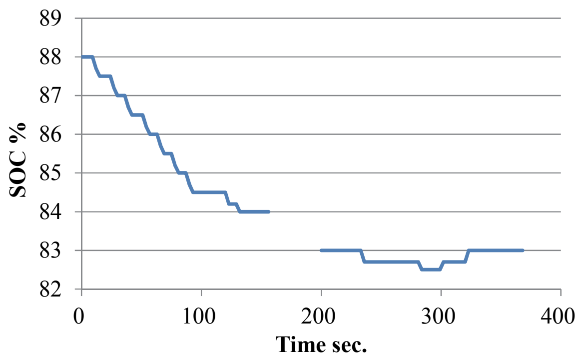


Figure8: SOC

3.2 Evaluation of Impact of Air Conditioning by Monthly Energy Consumption Comparison

Table 2 and Fig. 9 show the average monthly test results for driving distance, energy consumption, and mileage (energy efficiency) per day. Between April and July and in September and October, the bus achieved mileage between 0.9 and 0.95 km/kWh. However, this fell substantially to 0.5 km/kWh between December and February. Mileage also fell slightly to 0.77 km/kWh in August. In these periods, energy consumed by the heating and cooling systems adversely affected mileage. The reduction in mileage is greater in winter than summer. This is because Hakushu has relatively cool summers and the bus requires more energy to heat in winter than to cool in summer. It also reflects the effects of the use of snow tires with a higher rolling resistance in winter.

Table2: Monthly Test Results (Average)

Month	Distance km/day	Energy Consumption kWh/day	Mileage km/kWh
2012.1	8.0	16.1	0.50
2012.2	9.7	16.8	0.58
2012.3	10.4	12.1	0.86
2012.4	11.1	11.7	0.95
2012.5	11.7	12.2	0.96
2012.6	10.8	11.1	0.97
2012.7	12.5	13.4	0.93
2012.8	15.1	19.6	0.77
2012.9	11.4	13.1	0.87
2012.10	11.3	12.4	0.91
2012.11	11.5	17	0.68
2012.12	8.3	16.3	0.51

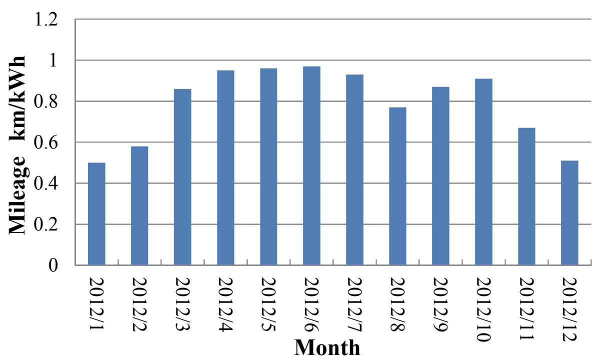


Figure9: Monthly Test Results (Average)

3.3 Battery Temperature Trends

Since lithium-ion battery performance degrades faster under high-temperature conditions, battery temperature management while the electric bus is operating is important. This bus is particularly susceptible to rises in battery temperature due to its high charge/discharge current density. This is a side effect of the low battery capacity, which was selected in line with the development concept of short distance transportation and frequent charging.
The battery temperature was measured during driving and during charging. Table 3 shows an extract of the monthly battery temperature results for one bus. The results indicate that the system controls increases in battery temperature in every month. Although the energy consumption while driving uphill at 25 km/h is large (approximately 50 kW), the short driving time means that the heat generated by the battery discharge can be absorbed by the thermal capacity of the battery, thereby preventing an increase in temperature.

Table3: Battery Temperature

		Dec.	May	Jun.	Jul.	Aug.
Distance	km	0.82	0.82	0.82	0.82	0.82
Energy Consumption	kWh	1.6	1.4	1.2	1.4	1.5
Mileage	km /kWh	0.51	0.59	0.68	0.59	0.54
Battery Temp. ini.	℃	10.5	15.5	20.5	28.5	27.5
Battery Temp. fin.	℃	10.5	15.5	20.5	29.0	27.5
Battery ΔTemp.	℃	0.0	0.0	0.0	0.5	0.0

Figure 10 shows the battery temperature and SOC during charging for the summer day with the hottest forecast (the afternoon of August 9, 2012). The temperature increased by 4 degrees during rapid charging of approximately 50 kW in the SOC range from roughly 30% to just under 90%. Lithium ion batteries generate large amounts of heat while charging and this large temperature increase is caused by the length rapid charge (approximately 40 minutes). Previous research has found that performance degrades more significantly once the battery temperature reaches 45 degrees or higher. Therefore, it was confirmed that this battery bus does not reach a temperature that would result in drastic performance degradation under the current operational conditions.

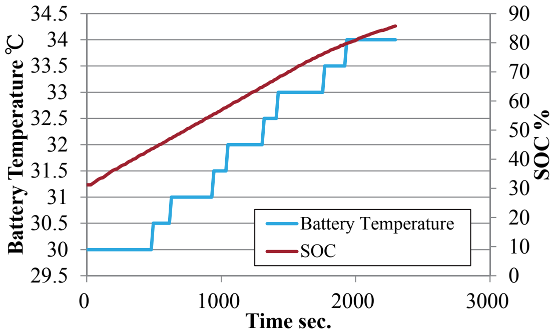


Figure10: Battery Temperature and SOC

4 Environmental Sustainability Evaluation of Electric Bus Adopting Solar Power for Charging

4.1 Solar Power Generation Performance

The Suntory Minami Alps Hakushu Water Plant is provided with 490 kW photovoltaic (PV) panels (Fig. 11).

Figure11: 490kW PV System

This development aimed to further reduce environmental load by charging the electric bus with energy generated by these panels. Table 4 shows the specifications of the PV panels, which utilize 180 W polycrystalline silicon solar cells.

Table4: Specification of PV Panels

Type		Polycrystalline Si
Maximum Output	W	180
Maximum Operating Voltage	V	23.6
Maximum Operating Current	A	7.68
Open Circuit Voltage	V	29.5
Short Circuit Voltage	A	8.35
Dimension(W)	mm	1341
Dimension(L)	mm	990
Dimension(H)	mm	36

Figure 12 shows the amount of solar irradiation and electricity generated by the PV panels. The solar irradiation was measured by a pyrheliometer located close to the PV panels and the generated electricity was calculated in terms of the total generation of the system and per 1 m^2 of the total area of the PV panels. The amount of solar irradiation was high between July and September and low in winter. Similarly, more electricity was generated in the summer and less in winter.

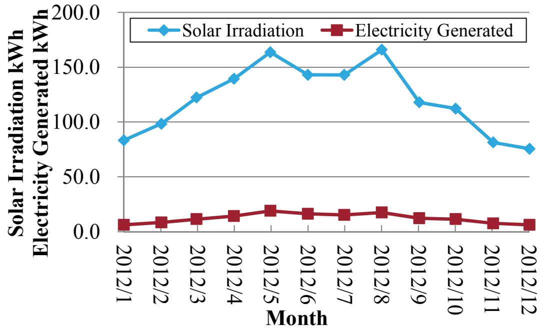


Figure12: Solar Irradiation and Electricity Generated

Figure 13 shows the actual efficiency of the PV panels (i.e., the ratio of electricity generated compared to the amount of irradiation) and the outside temperature. In the case of polycrystalline silicon panels, electricity generation efficiency falls as the temperature of the panel increases. However, the results in Fig. 13 indicate that the efficiency was lower in cold winter temperatures than in summer.

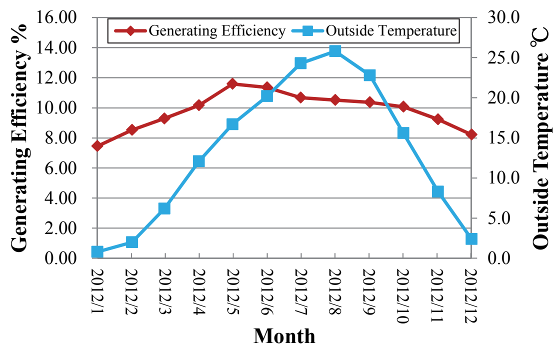


Figure13: Generating Efficiency and Outside Temperature

In addition, the total capacity factor of the solar power generation system over the whole year was 12%. The number of sunlight hours[5] in Yamanashi prefecture is 2,183 per year, higher than the national average of 1,897 hours, which suggests that this region is particularly suited to solar power generation. Figure 14 shows the optimum tilt angle of the PV panels around the plant. Since the angle of the sum changes depending on the season, the optimum tilt angle[6] also changes. It was confirmed that the PV panels were installed to maximize the total amount of electricity generation by utilizing the maximum roof area of the plant, rather than to increase efficiency by changing the installation angle. Therefore, it was confirmed that the system was operating as intended.

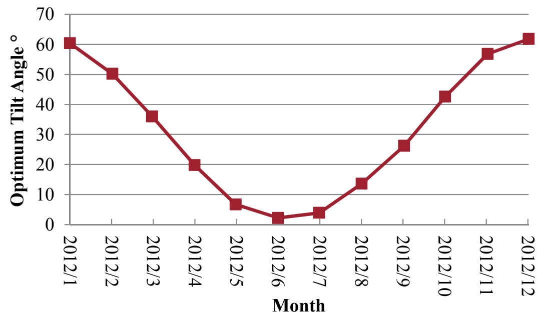


Figure14: Optimum Tilt Angle

4.2 Comparisons of CO_2 and Cost

Since the electricity generated from solar power is used to power the plant as well as the bus, it is not possible to identify exactly how much the use of solar power reduces the CO_2 emissions of the bus. Therefore, this research calculated the reduction in CO_2 emissions compared to a diesel-powered bus also used for touring the same plant. These calculations used the rate of solar power used to charge the electric bus as a variable. The CO_2 emissions of the electric and diesel buses were calculated by Equations (1) and (2), respectively.

$$CO_2 \text{ emissions} = \text{Basic unit of } CO_2 \text{ emissions} / (\text{Vehicle energy efficiency} \times \text{Battery charging efficiency}) \quad (1)$$

Basic unit of CO_2 emissions: 0.463 kg-CO_2/kWh[7]

$$CO_2 \text{ emissions} = (\text{diesel } CO_2 \text{ emissions factor (WTW)}) / \text{fuel efficiency} \quad (2)$$

Diesel CO_2 emissions factor (WTW): 2.83 kg-CO_2/L[8]
*WTW: well-to-wheel (the emissions generated in the process from oil extraction to driving)

Figure 15 shows the relationship between the CO_2 emissions of each bus obtained using Equations (1) and (2). The WTW CO_2 emissions were compared based on the fuel efficiency of the diesel-powered bus and the energy efficiency of the electric bus. If the CO_2 emissions of the diesel-powered bus at the plant are considered to be the baseline of 100%,

CO_2 emissions would fall to 15% by replacing the diesel bus with the electric bus, a reduction of 85%. Previous research using the WEB-3 electric micro bus calculated a 54% reduction in CO_2 emissions compared to the base vehicle.

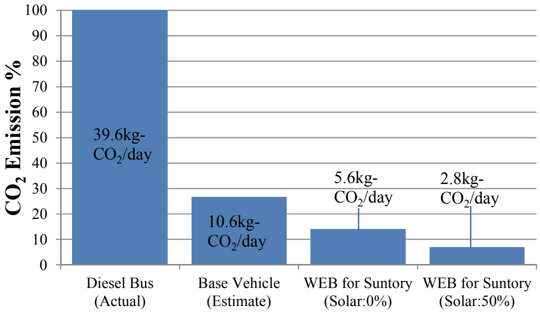


Figure15: Relationship between Rate of Solar Power and Rate of CO_2 Emissions

The reduction effect of the WEB for Suntory bus is much greater. This is probably because the diesel-powered bus used for comparison in this paper has worse fuel efficiency than the WEB-3 base vehicle due to the following factors: (1) higher weight and larger passenger capacity, (2) differences in the driving route, (3) a larger proportion of low-velocity driving, and (4) longer idling periods while waiting for passengers.

Diesel-powered buses with the same specifications as the developed electric bus have test cycle fuel efficiency values between 3 to 5 km/L (the value differs depending on the model and equipment). Under the driving conditions in the plant, the fuel efficiency of the diesel-powered bus was estimated to be 3 km/L. Estimating the rate of reduction in CO_2 emissions using this value indicates that the CO_2 emissions of the electric bus would be 47% of the diesel-powered bus.

The high energy conversion efficiency of the electric bus motor helps to reduce the CO_2 emissions of the bus. Furthermore, the 35-meter change in altitude over the 800-meter driving route and the unique capability of the electric bus to regenerate energy due to the average gradient of 4% also increases the ability of the electric bus to reduce CO_2 emissions. Another reason for the larger CO_2 emissions-reduction effect achieved by this bus is the reduction in weight compared to the base vehicle, which was achieved by minimizing the number of batteries and eliminating unnecessary components in the conversion process. Consequently, this electric bus has a substantial CO_2 emissions-reduction effect on this steep, low-velocity, and short-distance driving route.

The output of the solar power generation system installed at the plant is 490 kW with an average daily electricity generation capacity of 1.4 MWh. Since the electric bus uses the power grid at the plant, the rate of solar power used to charge the bus is not necessarily particularly high. It should be possible to further expand the CO_2 emissions-reduction effect of the bus by increasing the rate of solar power used for charging. If the rate of solar power is 50%, the estimated CO_2 reduction rate of the electric bus compared to the base vehicle (estimated fuel efficiency: 3 km/L) is 74%.

The following section compares the electricity and fuel costs for running the buses. The electricity and fuel costs of the electric and diesel buses were calculated by Equations (3) and (4), respectively.

$$\begin{aligned}\text{Electricity costs} = {} & \text{Electricity price rate} \\ & / \text{ Vehicle energy efficiency} \\ & \times \text{ Driving distance} \\ & \times \text{ Number of days} \\ & \times \text{ Battery charging efficiency}\end{aligned} \tag{3}$$

Electricity price rate: 9.76 yen/kWh[9]
Vehicle energy efficiency: 0.964 km/kWh (results from April to June)
Driving distance: 11.2 km/day
Battery charging efficiency: 96.5%

$$\begin{aligned}\text{Diesel costs} = {} & \text{Diesel price rate} \\ & / \text{ Fuel efficiency} \\ & \times \text{ Driving distance} \\ & \times \text{ Number of days}\end{aligned} \tag{4}$$

Diesel price rate: 111.1 yen[10]
Fuel efficiency: 0.8 km/l (results from April to June)

Using Equations (3) and (4), Fig. 16 shows the relationship between the rate of solar power used for charging and the difference between diesel and electricity costs. According to Fig. 16, if the fuel efficiency of the diesel-powered bus at the plant is used for the calculation, the monthly energy costs of the electric bus can be reduced by approximately 43,000 yen even when the rate of solar power is 0%. In the same way as the CO_2 emissions reduction evaluation, the reduction in energy costs was also provisionally calculated using the estimated fuel efficiency of the base vehicle. In this case, even when the rate of solar power is 0%, the minimum reduction in monthly costs was approximately 9,000 yen. When the rate of solar power is 50%, the reduction increases to at least 10,000 yen (Ignoring the initial cost of the PV). These calculations were made based on the current daily driving distance of the WEB for Suntory bus (11.2 km). However, CO_2 emissions and costs can be further reduced by improving the utilization rate of the electric bus.

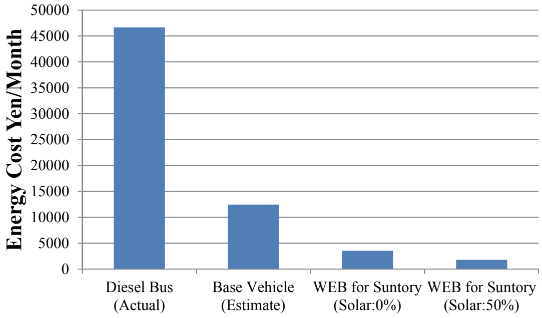


Figure16: Relationship between Rate of Solar Power and Difference of Energy Cost

5 Conclusion

This paper has described the environmental sustainability evaluations of the newly designed and manufactured WEB for Suntory electric medium duty bus. The following results were obtained in this project.

(1) Design and manufacture of WEB for Suntory bus

This project aimed to develop a bus with low initial costs and the potential for widespread adoption. For this reason, the WEB for Suntory bus was designed and manufactured with the minimum amount of batteries to meet the requirements for short distance transportation and very frequent charging. In the conversion process from the base vehicle, non-essential components such as clutches, flywheels, transmissions, and the like, were eliminated to reduce weight and maximize the passenger compartment space.

(2) Environmental sustainability evaluation by actual driving

The dynamic performance of the WEB for Suntory bus was evaluated in actual driving. The results confirmed that this electric bus has substantially lower energy consumption and CO_2 emissions than a diesel-powered bus. In particular, the steepness and low-velocity of the circular route allow for high efficiency due to energy regeneration during the downhill section. As a result, the merits of an electric bus make it particularly suited to this route. It was also confirmed that the electricity costs of the WEB for Suntory bus were much lower than the fuel costs of a diesel-powered bus.

(3) Environmental Sustainability Evaluation Adopting Solar Power for Charging

The power generation performance of PV panels was evaluated and the seasonal differences in electricity generation were confirmed. Subsequently, the environmental sustainability of the electric bus was evaluated using solar power for charging. It was found that this combination further reduces CO_2 emissions and running costs.

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