International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0251

A NOVEL RAILWAY ENERGY SYSTEM INTEGRATED WITH PHOTOVOLTAIC POWER GENERATION

Hideyuki Chisaka[1], Naoki Shiraga[2], Nobusuke Kobayashi[3], Yoshinori Itaya[1,3], Tsuguhiko Nakagawa[1,3*]

1 Renewable Energy System Research Center, Gifu University, 1-1 Yanagido, Gifu-shi, Gifu, Japan (Corresponding Author)
2 Aisin Seiki Co., Ltd., 2-1 Asahi-machi, Kariya, Aichi, Japan
3 Department of Mechanical Engineering, Gifu University, Gifu University, 1-1 Yanagido, Gifu-shi, Gifu, Japan

ABSTRACT

In order to reduce CO_2 emissions, PV & BEC railway system which is combined with Photovoltaic Power Generation (hereinafter referred to as PV) and Battery-powered Electric Railway Car (hereinafter referred to as BEC) has been proposed. However, the air-conditioning energy consumption is about 30% of the whole of railway car energy consumption. Therefore, it is important to improve the energy efficiency of the air-conditioner for railway cars. In this paper, a novel railway system which is integrated BEC, air-conditioners and PV has been proposed. In this system, Air-conditioner Integrated Electric Vehicle (hereinafter referred to as AI-EV) system which is combined air-conditioner with a power generator driven by a small engine is applied as an air-conditioning system for BEC. The effects of the novel railway system have been evaluated based on a theoretical simulation when a novel system is applied to the non-electrified sections of the Kibi line in Okayama prefecture.

Keywords: Photovoltaic power generation, Electric railway car, Railway system

1. INTRODUCTION

In Japan, diesel cars are used with the local railway lines of non-electrification. In order to reduce CO_2 emissions, it is necessary that those diesel cars are replaced by BECs, and the batteries installed on BECs are directly charged by PV in the same way as a solar powered electric vehicle charging station [1,2].

However, BEC has a limit of traveling distance because an installed battery capacity has a limit. As one of solutions, it is important to reduce the energy consumption of air-conditioning which is 30% of the whole electricity consumption of BEC.

In this paper, a novel railway system which is integrated BEC, air-conditioners and PV has been proposed. In this system, the AI-EV system which is combined air-conditioner with a power generator driven by a small engine is applied as an air-conditioning system for BEC [3]. The effects of the novel railway system have been evaluated based on a theoretical simulation when a novel system is applied to the non-electrified sections of the Kibi line in Okayama prefecture.

2. OUTLINE OF A NOVEL SYSTEM

2.1 INTEGRATION with PV, Air-conditioner and BEC

A PV & BEC railway system is shown in Figure 1.

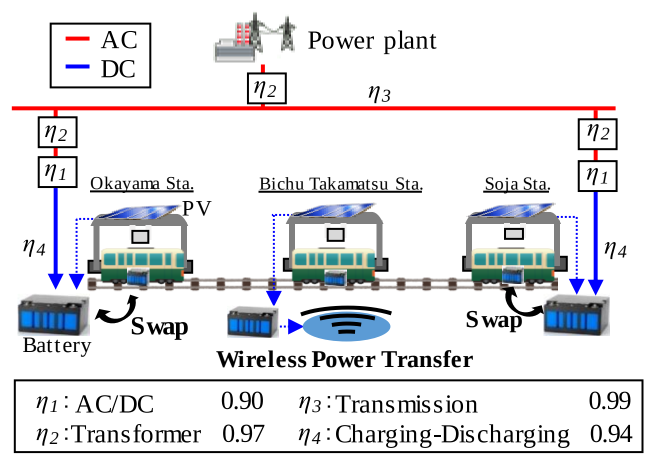

Fig 1 Image of PV & BEC railway system

In Figure 1, the batteries installed on the railway cars are exchanged when the railway cars arrived at the terminal stations. The exchanged empty batteries are charged by PV which is installed at the terminal stations. While PV cannot generate electricity during the night or rainy day, batteries are charged from the conventional power system. Additionally, in order to manage the PV

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

power, the Wireless Power Transfer system (hereinafter referred to as WPTS) [3] is installed in BicchuTakamatu station which is the intermediate station of the Kibi line.

2.2 AI-BEC

In order to reduce the air-conditioning energy consumption which is about 30% of the whole of railway car energy consumption, AI-BEC (Air-conditioner Integrated Battery-powered Electric railway Car) has been proposed.

The structure and operation image of AI-BEC are shown in Figure 2 and Figure 3.

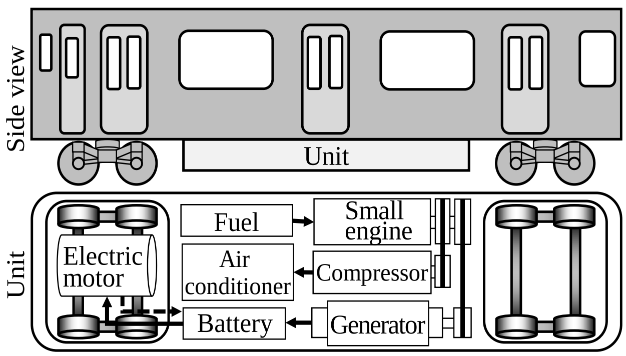

Fig 2 Structure of AI-BEC

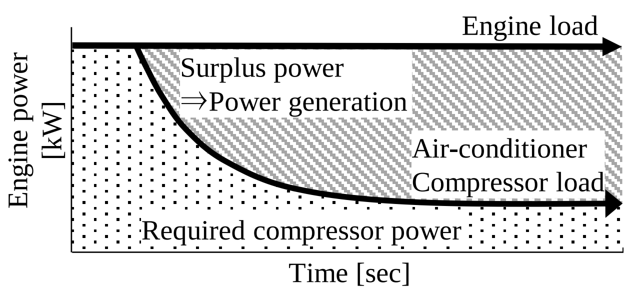

Fig 3 Operation image of AI-BEC

The AI-BEC uses a small engine which is operated with constant rotation for air-conditioner compressor load. The surplus engine power which is caused by changing air-conditioning load is used for power generation.

There are four features of AI-BEC as follows,

(a) The energy efficiency of the air-conditioner compressor is higher than the electric motor system powered by the power system.

(b) The required engine displacement to drive the air conditioner is less than 1/10 of the conventional diesel car. Therefore, it means a possibility that this system can be driven by only biofuels, such as the countries which achieved Ethanol 10 (E10).

(c) The battery utilization efficiency is increased, so the installed battery capacity can be reduced.

(d) Waste heat from the small engine can be recovered as a heat source for heating.

3. EVALUATION MODELS

The energy consumption of the railway car is calculated based on the theoretical model which is evaluated as the electricity balance of the battery, the energy consumption of the traveling and the air-conditioning.

3.1 Battery Balance Model

The electricity balance can be calculated using Equations (1) and (2).

<The electricity balance of the AI-BEC battery>

$$BE_{i,j}(t+1) = BE_{i,j}(t) + \sum_{k=1}^{3} S_k(t)\Delta t - \sum_{l=1}^{2} C_l(t)\Delta t \qquad (1)$$

<The electricity balance of the BEC battery>

$$BE_{i,j}(t+1) = BE_{i,j}(t) + \sum_{k=1}^{2} S_k(t)\Delta t - \sum_{l=1}^{3} C_l(t)\Delta t \qquad (2)$$

Where, t : time (t=0-8760) [h], BE : battery level [kWh], i : number of batteries[-], j : state of battery (j=1: batteries installed on railway car, 2: batteries at station)[-], S : electricity supply to battery [kW], k : power source to charge (k=1: PV, 2: power system, 3: power generation of engines) [-], C : electricity consumption to battery[kW], l : electricity consumption factor (l=1: traveling, 2: equipment, 3: air-conditioning) [-].

3.2 Traveling Model

The driving force F required for traveling the railway car is obtained from each resistance force by Equation (3). The energy required for traveling the railway car and the regenerative energy obtained by braking are calculated by Equations (4) and (5) respectively.

All of conversion efficiencies were obtained by the results of experiments.

$$F = Fr + Fw + Fs + Fa \qquad (3)$$

$$C_1 = F \cdot \frac{\partial x}{\partial t} \cdot \frac{1}{\eta_{BAT}} \cdot \frac{1}{\eta_{INV}} \cdot \frac{1}{\eta_{MOT}} \cdot \frac{1}{\eta_{MEC}} \qquad (4)$$

$$C_{rg} = F \cdot \frac{\partial x}{\partial t} \cdot \eta_{REG} \qquad (5)$$

Where, F : driving force [N], Fr : rolling resistance [N], Fw : air resistance [N], Fs : slope resistance [N], Fa : acceleration resistance [N], x : traveling distance [m], C_1 : traveling consumption energy [W], C_{rg} : regenerative energy [W], η_{BAT} : charge and discharge efficiency [-], η_{INV} :

inverter efficiency [-], η_{MOT} : motor efficiency [-], η_{MEC} : mechanical efficiency [-], η_{REG} : regeneration efficiency [-]

3.3 Verification of the Traveling Model

The calculation accuracy of the traveling model is verified by the actual energy consumption trend of traveling which was examined by the Railway Technical Research Institute of JR Kyusyu Railway Company [5]. Additionally, the energy consumption results calculated under the same conditions as the experiment car specifications and driving conditions.

A comparison between the calculated results and the experiment results is shown in Figure 4. From this, the trend changes of the calculated power consumptions are well agreed with the trend changes of the measured power consumptions in the experiment.

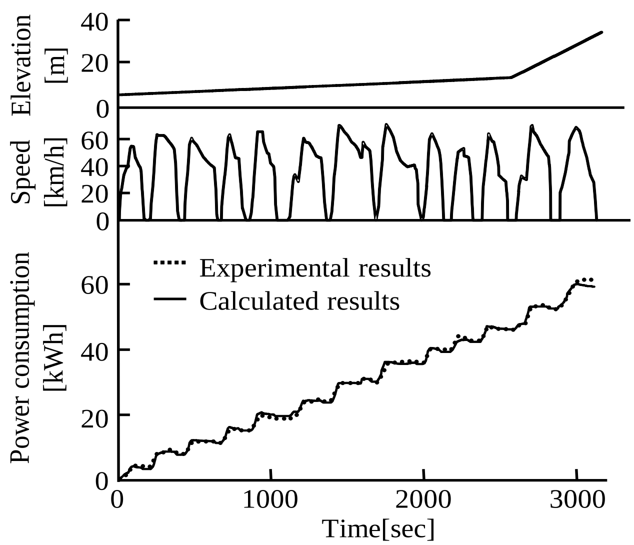

Fig 4 A comparison between experiment results and calculated results

3.4 Air-Conditioning Model

A necessary ability for the railway car air-conditioning is calculated by the heat load of outside such as air temperature, the number of passengers, solar radiation and ventilation flow rate as shown in Figure 5 by using Equation (6). The energy consumption of an air-conditioner is determined by Equation (7).

$$Q = q_1(T_1(t)) + q_2(t) + q_3(t) + q_4(t) \tag{6}$$

$$C_3 = \frac{\partial Q}{\partial t} \cdot \frac{1}{COP} \cdot \frac{1}{\eta_{BAT}} \cdot \frac{1}{\eta_{INV}} \cdot \frac{1}{\eta_{MOT}} \cdot \frac{1}{\eta_{MEC}} \tag{7}$$

Where, Q : air conditioning consumption [kWh], T_1 : A difference in temperature between inside and outside of railway car [℃], C_3 : required air conditioning load [kW], COP : the coefficient of performance [-].

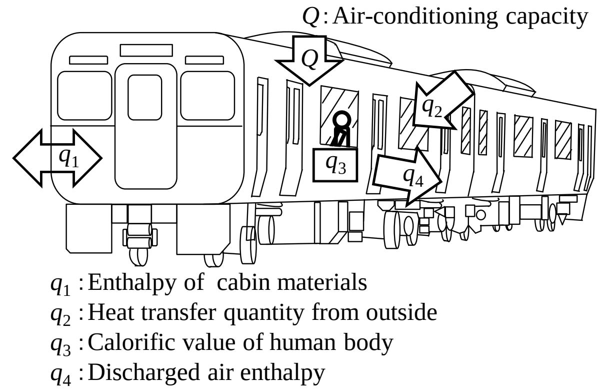

Fig 5 Theoretical model of air-conditioning energy Consumption

3.5 Calculated Conditions

The energy consumption and CO_2 emissions which are compared with the reference values of the conventional diesel car are evaluated when BEC and AI-BEC are introduced into the Kibi line. In the calculation, the route conditions, such as the slope and the train schedule, are considered.

Table 1 shows the specifications of each railway car used in the study and the performance conditions of the equipment to be installed.

Table 1 Calculated conditions

Type		Diesel	BEC		AI-BEC
PV Power	Okayama St. [kW]	-	280	262	194
	BichuTakamatsu St. [kW]	-	-	67	67
	Soja St. [kW]	-	180	191	175
Train	The number of composed coaches	2cars/train × 5			
Battery	Capacity [kWh]	-	10		
	The number Train	-	14	12	8
	The number Station	-	56	66	66
Wireless Power Transfer [kW]		-	-	11kW/unit × 21	
Engine	Power [kW]	195	-	-	20
	Displacement [cc]	11,040	-	-	750
	Fuel	Light fuel	-	-	LNG
Motor	Power [kW]	-	300		
Air-conditioner	Capacity [kW]	50			
	COP	3.0			
Heater	Power [kW]	15			

In this study, the PV area was determined so that the rate of the generated surplus PV power (= surplus PV power / all of the generated PV power) was 10% or less in the entire system. The energy balances of each model, such as charging & discharging of the battery, generated

PV power and consumed energy are calculated by continuously and hourly for one year by using changes of atmosphere temperature, the amount of solar radiation and the number of passengers, etc.

4. RESULTS

The electric power remaining in the batteries which is a difference between charging and discharging of the batteries is shown in Figure 6.

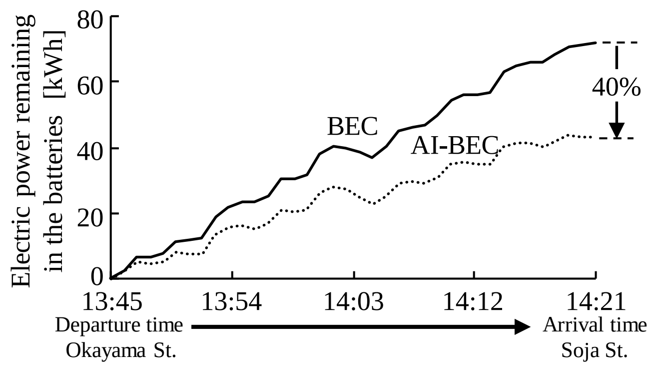

Fig 6 A comparison of electric power remaining in the batteries

From Figure 6, AI-BEC is able to reduce the battery capacity by 40% compared with BEC. The reason for this is that the battery on AI-BEC is charged by electric power which is generated by the AI-BEC system while air-conditioning is used.

Additionally, calculated annual CO_2 emissions of diesel car system, PV & BEC system and PV & AI-BEC system are shown in Figure 7.

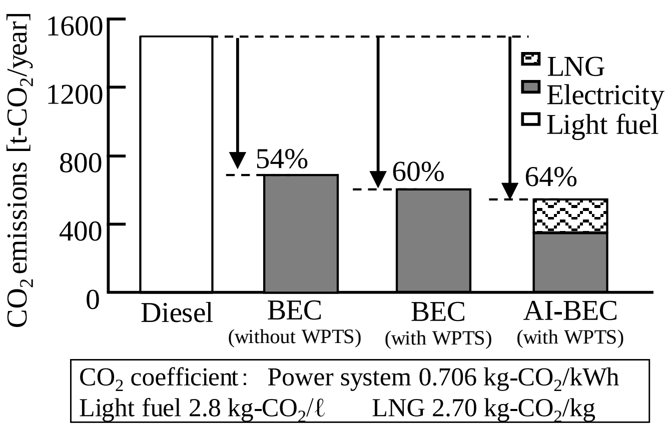

Fig 7 A comparison of CO_2 emissions

From this Figure, the PV & BEC system is able to reduce more than 54% of CO_2 emissions compared with the conventional diesel car system. As for using WPTS, CO_2 emissions is reduced 11% {= (60-54)/54*100} in comparison with BEC system. Additionally, a novel PV & AI-BEC system is able to reduce CO_2 emissions by grand total 7% {= (64-60)/60*100} compared with PV & BEC system using WPTS. As the reason for this, it is considered that the power generation efficiency of the AI-BEC system is higher than the efficiency as the whole system from the power plant to the motor-driven air conditioner.

In Figure 7, the CO_2 emissions from the engines of AI-BEC system using fuel are less than 13% of the conventional diesel car. Therefore, if this system can be driven by only biofuels in the future such as the countries which achieved Ethanol 10 (E10), the future AI-BEC system using WPTS can reduce more than 77% of CO_2 emissions compared with the conventional diesel car.

Furthermore, the air conditioners which are used in this study are COP=3, so fuel consumption can be reduced by the improvement of this COP which has room for improvement.

5. CONCLUSION

In this paper, a novel railway system which is integrated BEC, air-conditioners and PV has been proposed. In this system, the AI-EV system which is combined air-conditioner with a power generator driven by a small engine is applied as an air-conditioning system for BEC. The effects of the novel railway system have been evaluated based on a theoretical simulation when a novel system is applied to the non-electrified sections of the Kibi line in Okayama prefecture.

PV & AI-BEC system using WPTS is able to reduce CO_2 emissions by 64% compared with the conventional diesel car. Additionally, this system using WPTS is able to reduce the battery capacity by 40% compared with the conventional BEC.

REFERENCE

[1]S. Shibata, et al., ”A Novel Concept of AI-EV (Air-Conditioner Integrated Electric Vehicle) for the Advanced Smart Community”, Journal of Energy and Power Engineering, 8, 1933-1941, (2014).

[2]G.R. Chandra Mouli, et al., ”System design for a solar powered electric vehicle charging station for workplaces”, Applied Energy, 168, 434-443, (2016).

[3]T. Nakagawa, et al., “A Novel Concept of Air-conditioner–Integrated Electric Vehicle for the Future Smart Community”, Heat Transfer Engineering, 37, 1498-1506, (2016).

[4]DAIHEN Corporation,”D-Broad EV”, Available online: https://www.daihen.co.jp/en/products/wireless/

[5]Y. Taguchi, et al., ”Development of a Traction Circuit for Battery-powered and AC-fed Dual Source EMU and Running Test Evaluation of the On-board Battery Performance”, Quarterly Report of RTRI, 56, 98-104, (2014).