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Development of low-CO_2-emission vehicles and utilization of local renewable energy for the vitalization of rural areas in Japan

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ABSTRACT

Most of Japan's energy supply depends on imports from foreign countries, making the independence ratio of energy in Japan very low. The Fukushima nuclear power plant accident triggered by the Great East Japan Earthquake and Tsunami led to a mass shutdown of all the nuclear plants in Japan, a stoppage that is still in effect. In this paper, we review the energy supply situation and some social problems faced by rural areas in Japan. Given that lifestyles in rural Japan are reliant on automobiles, there is significant demand for the establishment of a sustainable mobility society. Furthermore, Japan is now entering an aging society ahead of other countries. In order to enhance the vitalization of rural areas and accelerate the establishment of sustainable society, our project developed low-CO_2-emission vehicles (i.e., a single-driver EV [micro-EV] and a low-speed E-bus) for elderly people and tourists through the cooperation of regional industries, a local university, and a city office. This paper also reports some trial test results on renewable energy utilization as the driving energy supply for these low-emission vehicles.

Contents

1. Introduction

Energy is a fundamental element in sustaining society, the quality of people's lives, and economic development. A steady supply of energy is an important responsibility for national governments. Before 1800, the world's energy consisted largely of renewable energy, including biomass and a small amount of waterwheel, windmill, and animal energies, which were used for agricultural production and daily life. On the other hand, transportation was mainly dependent on animal energy. After around 1850, the main energy source changed to coal, which was used for industrial production. Later, the primary source of energy shifted from coal to liquid and gas fuels in the 1900s. In 2012, fossil fuels accounted for over 89% of the world's total energy [1]. P. Moriarty

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and D. Honnery [2] reported that the global energy consumption from 1950 to 2010 increased from 86 EJ (85×10^{18} J) to 503 EJ and that global energy usage in 2050 would reach roughly 1000 EJ if the global GDP continued to increase at the same rate. They also showed that the concentration level of atmospheric CO_2 has increased from 310 ppm (1950) to 390 ppm (2010). The crisis of climate change has become a serious problem, but the world is unfortunately still in need of more fossil energy.

Various types of new fossil energy have now been developed in many countries [3]. These new resources are called “unconventional resources” to contrast the “conventional resources” of coal, oil, and natural gas. Shale gas, developed in United States, has the potential to be one of these unconventional gas resources. Shale gas is natural gas found in the fine-grained sedimentary rock called shale [4]. As the gas is trapped in the rock, “hydraulic fracturing” technology is required to enhance gas production. The United States is set to become an exporter of shale gas in the near future.

Moreover, “tight gas” and “coal bet methane (CBM)” have been the subjects of aggressive development as unconventional gas resources. Tight gas is gas trapped in hard rock that has lower impermeability levels than the sedimentary rock of shale gas. On the other hand, CBM is gas stored in the coal seams, consisting mostly of methane and a small amount of heavier hydrocarbons, hydrogen, and so on. Some papers have suggested that there are abundant CBM reserves in China and that the resource will play an important role as the future energy of China [5,6].

Methane hydrate also has huge potential to become an alternative resource of conventional gas. An ice-like material that consists of water and methane or a mixture of light natural gas components, methane hydrate exists stably under the high-pressure and low-temperature conditions found in the world's deep seas [7,8]. Experts believe that the total volume of methane hydrate reservoirs is several times larger than the currently known reserves of conventional natural gas. Ensuring a stable supply of methane hydrate, however, requires economically practicable technology. Considering that methane is a greenhouse gas with a larger global warming potential (GWP) than CO_2, there is also a need for technology that helps prevent gas leakage into the atmosphere. As explained above, the world energy situation is in a state of major change.

As for Japan, most of the energy supply depends on foreign resources. The independence ratio of energy in Japan is very low [9]. Furthermore, the Fukushima nuclear power plant accident that occurred in the aftermath of the Great East Japan Earthquake and Tsunami on March 11, 2011, has exacerbated the energy shortage by prompting plant shutdowns that remain in effect [10]. After the Fukushima nuclear power plant accident, officials implemented a planned blackout—a rotational electric power shutdown in the area covered by the Tokyo Electric Power Company—that affected several railway operations. Simultaneously, the earthquake also triggered a gasoline shortage; long lines of cars waited, sometimes for days, at gas stations to fill up. Therefore, the problem of energy security is directly related to the transportation system. In rural Japan, people rely on their automobiles. Thus, the demand for the establishment of a sustainable mobility society is just as strong in rural areas as it is in urban areas [11–13]. However, marked depopulation and aging in rural areas have impeded efforts to construct a sustainable transportation system through public transportation.

In this paper, we review the energy supply situations and social problems of rural areas in Japan. We also discuss the development of renewable energy-based low-CO_2-emission vehicles for the vitalization of rural communities.

2. The energy and social situations of Japan

Most of Japan's energy supply depends on imports. Fig. 1 illustrates trends in the energy independence and oil dependence ratios of Japan. The independence ratio for energy from foreign countries decreased steadily and sank below 10% in 1980, eventually reaching a level of 4.8% in 2011 [9]. Furthermore, the proportion of oil dependence on the Middle East is higher than 80% today. Clearly, the energy supply of Japan is in a very vulnerable situation.

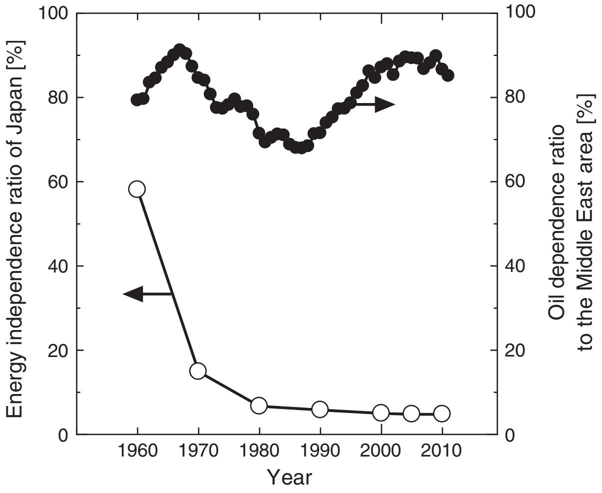

Fig. 1. Energy independence and oil dependence ratios of Japan.

The Fukushima nuclear power plant accident on March 11, 2011, altered Japan's energy supply situation significantly. Fig. 2 shows the primary energy distribution of Japan in 2010 and 2011. As a result of the Fukushima nuclear power plant accident, the proportion of energy created via nuclear power fell by 64.5%. In order to compensate for this power shortage, thermal power stations driven by natural gas have increased their energy production levels [14]. This heavier operational load on these power stations raised overall CO_2 emission levels by 4.1% from 2011 to 2012. In order to reduce CO_2 emissions and avoid accelerating climate change, we need to take a proactive approach to using more renewable energy.

Fig. 3 shows the sources of direct CO_2 emissions in Japan. Total CO_2 emissions in 2011 were 1241 Mt [15]. 37.1% of that total came from the energy power industry, while 27.3% came from the industrial fields. Transportation accounted for a share of 17.9%, equivalent to 222 Mt of CO_2. This represents a substantial quantity that cannot be ignored. The pie charts in Fig. 4 provide more detail on the CO_2 emissions from transportation, showing the indirect CO_2 emissions from various forms of transportation. In 2011, the total indirect CO_2 emissions from the transportation sector were 230 Mt. The ratios of freight and passenger transportation were 38% and 62%, respectively. Passenger transportation was thus responsible for 143 Mt of CO_2 emissions. The largest source of CO_2

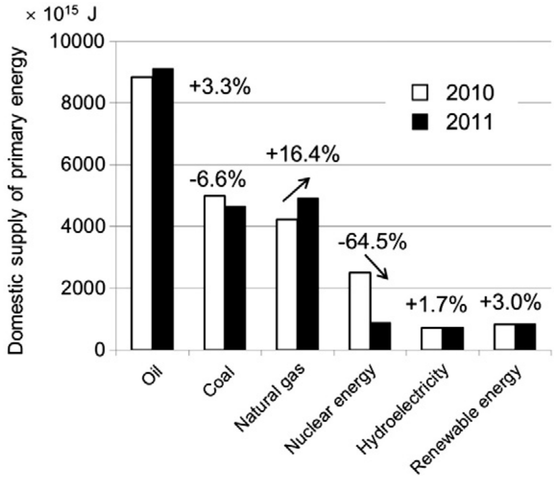

Fig. 2. Domestic supply of primary energy in Japan at 2010 and 2011.

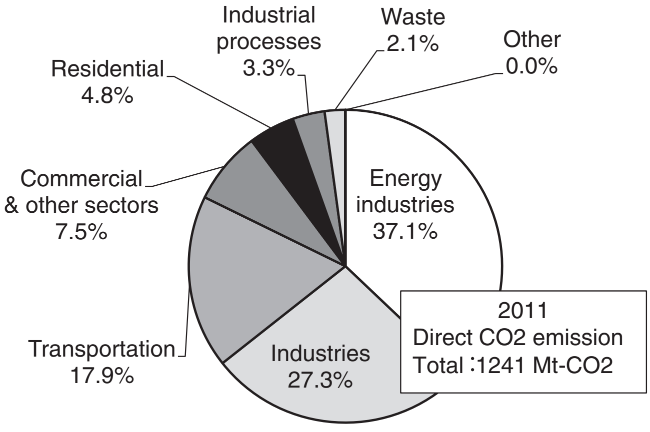

Fig. 3. Direct CO_2 emission in Japan.

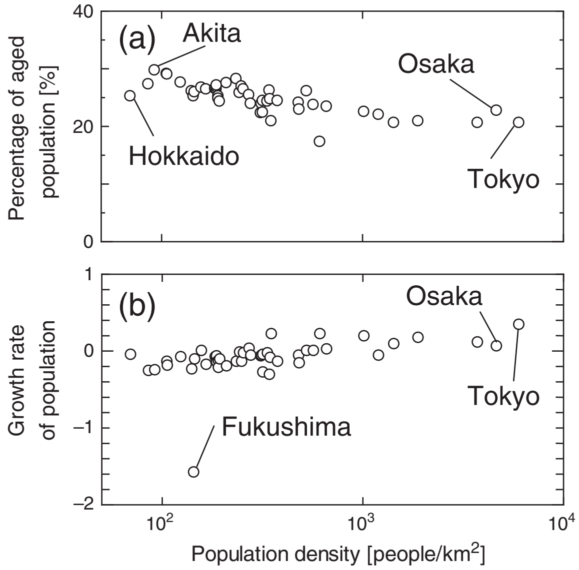

Fig. 5. Social situations of each prefecture plotted against population density.

emissions in the passenger transportation area was private vehicles, which produced about 81% of the corresponding total [16]. Next was railway at 6%, and third was civil aviation at 5%. From the perspective of reducing CO_2 emissions from transportation, private vehicles are the most effective targets.

Various technologies have been developed in recent years to curtail CO_2 emissions from each sector. Carbon capture and storage (CCS) at point sources such as large fossil fuel power plants is one such technology for reducing CO_2 in the energy industry and may be actually deployed in the near future [17,18]. However, it is difficult to capture CO_2 from vehicles because they are non-point sources. Therefore, the shift from conventional engine vehicles to electric vehicles (EV) may be effective in limiting CO_2 output from transportation. Still, EVs and hybrid electric vehicles (HEVs) accounted for only about 3.5% of all vehicles in 2013 [19].

Japan is now experiencing an aging society phenomenon ahead of other countries [20]. The proportion of people over the age of 65 in the total population of Japan was about 23.3% in 2012, the highest ratio in the world. The development of this aging society is a serious problem in Japan and most prevalent in rural areas.

Fig. 5(a) indicates the relation between the percentages of aged populations in prefectural populations as a function of population density [21]. In this paper, we use population density as an index of urbanization. Tokyo and Osaka are the most urbanized prefectures in Japan, while Hokkaido has the lowest population density. Sapporo, the capital of Hokkaido, has a high population density of about 1700 persons per km^2 and is very urbanized. As Hokkaido has a much larger land area than other prefectures, however, the total prefectural population density is low. The prefecture with the highest ratio of aged population to total population is Akita Prefecture. This figure shows that the aging of society is most prominent in low-population-density prefectures.

Fig. 5(b) shows population growth in Japan by prefecture. The growth rate was defined as the difference between the inflow and outflow of populations per total prefectural population. A negative value indicates that, over the given period, more people moved out of the prefecture than to the prefecture. This graph illustrates the migration from low-population-density prefectures to high-population-density prefectures. The vitalization of rural area requires a return of the population from urban areas to rural areas; however, Japan is currently

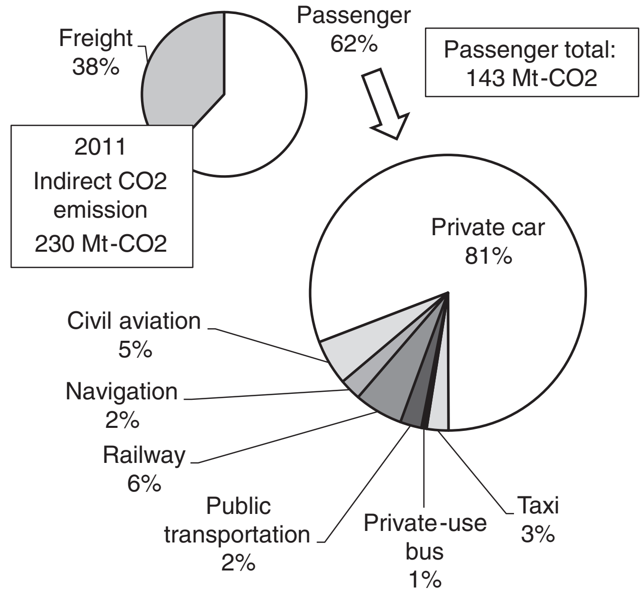

Fig. 4. Indirect CO_2 emissions from transformation sector.

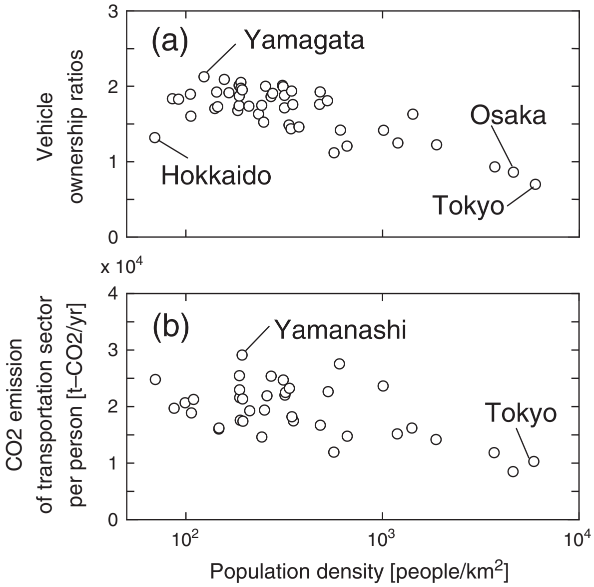

Fig. 6. Number of vehicles and CO_2 emissions from transportation sector plotted against prefectural population density.

experiencing the opposite phenomenon. The data also shows a conspicuously negative value for Fukushima Prefecture, a change that relates directly to the Fukushima nuclear power plant accident.

Fig. 6(a) is a graph of vehicle ownership ratios. Here, the ownership ratio is defined as the number of vehicles per household. The ratio in Tokyo is less than 1.0, while the value in Yamagata Prefecture comes in at over 2.0. This graph implies that ownership ratio increases as population density decreases. Put together, the data from Figs. 5(a) and 6(a) suggest that not only is the aging of rural populations progressing rapidly, but the number of elderly drivers is also growing.

Fig. 6(b) plots CO_2 emissions per person and year from the transportation sector against population density. The plotted data were collected from the websites of prefectures that published values from 2008 to 2010. From this perspective, CO_2 emissions from the transportation sector in high-population-density prefectures such as Tokyo and Osaka were lower than those of low-population-density prefectures. The values for Yamanashi Prefecture were three times larger than of the values for Tokyo, suggesting that a person does not necessarily need a private car to live a regular daily life in a highly urbanized area. On the contrary, residents of rural prefectures rely on private cars, dependence premised on a stable supply of fossil fuel. As described below, however, many rural areas have more renewable energy resources than urbanized areas.

Fig. 7(a) and (b) illustrates the potential for micro and small hydro power as a form of local renewable energy [22]. These graphs suggest that rural areas have a high potential for small hydro power, a well-established and popular technology. Recently, small, micro, and pico hydro power have been developed as key technologies for the utilization of local renewable energy. Hydro power is usually classified by power level [23]: “large” hydro power is over 100 MW, and “small” hydro power is under 25 MW. The “mini” and “micro” hydro power generation levels are below 1 MW and several hundred kW, respectively. Hydro power of several kW is called as “pico” hydro power—a technology that has been applied to rural areas in developing countries without access to sufficient electric power [24]. In Japan, the electrical grid is set up to cover the entire rural area nationwide. However, the utilization of pico hydro power presents an attractive option because of the large numbers of suitable points in rural Japan, as shown in Fig. 7(a). If such renewable energy were to be connected to vehicles, it could unlock new value for rural areas in terms of both vitalization and maintaining energy security.

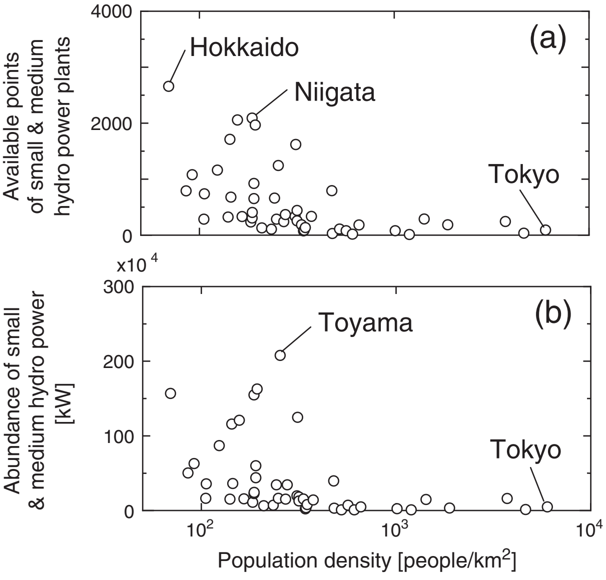

Fig. 7. Potentials of hydro power plotted against prefectural population density.

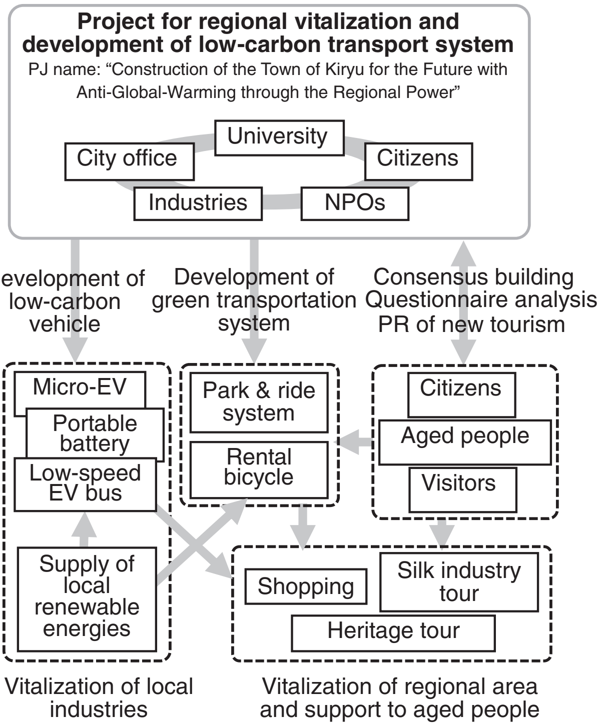

Fig. 8. Overview of the low-carbon transportation system tested in Kiryu, Gunma Prefecture.

3. The development of low-carbon vehicles and utilization of renewable energy

Fig. 8 outlines a project that was implemented to help achieve a sustainable transportation system and vitalize a rural area. The project was a social experiment in Kiryu, Gunma Prefecture, a city of around 120,000 in the northern region of the Kanto plain and roughly 60 km from Tokyo. A thriving hub for silk textile products, Kiryu also boasts many historical industrial heritage sites. The project created a collaboration system integrating universities, city offices, NPOs, industries, and citizens for planning, evaluations, and analysis of tested data. Titled “Construction of the Town of Kiryu for the Future with Anti-Global-Warming through the Regional Power,” the project received support from the Research Institute of Science and Technology for Society (RISTEX) of the Japan Science and Technology Agency (JST).

The project tested the utilization of renewable energy for a small electric vehicle (called a “micro-EV”) to help reduce CO_2 emissions from vehicles. The micro-EV was developed with the assistance of Gunma University and regional industrial companies. Another development initiative produced a low-speed electric community bus called eCOM-8®, which features solar panels that provide additional driving power. The project conducted road tests to evaluate the utilization of solar energy as an assisted power source for buses. Additionally, the project aimed to enliven regional industry through the development and production of these new motilities and create a fully low-carbon transportation system that encompasses public trains, buses, and bicycles. Walking tours for industrial heritage sites and traditional silk goods stores were also created to vitalize the community as a whole.

3.1. The development of a micro-EV

Fig. 9 is a photograph of the micro-EV developed for the course of the project, while Table 1 summarizes the vehicle's specifications. In most cases, the micro-EV was charged using a household 100-V power source. The vehicle's solar panel and battery system, shown in

Fig. 9. Micro-EV and solar power system.

the figure, was also developed for the project. The size and weight of the vehicle, a single-passenger mode of transportation, are much smaller than those of ordinary EVs. Developed for usage exclusively within the city area, the vehicle has a cruising distance of less than 30 km but, given its compact body size, is easy to drive on the characteristically narrow streets of older towns. The battery capacity of this micro-EV is about 1.6 kWh and the maximum cruising distance is about 30 km by using 80% of battery capacity. It may be estimated that the performance of micro-EV is 1.28 kWh/km. If we use 0.465 kg-CO_2/kWh which is CO_2 emission factor of electric power in Tokyo Electric Power Company area at 2012, the micro-EV's CO_2 emissions were estimated at about 19.9 g-CO_2/km, or about 1/6 of a regular gasoline-fueled car with a fuel efficiency of 18 km/L. Where, 18 km/L is a mean fuel efficiency of the regular car at 2010 measured by ten-fifteen mode test of Japan. And the value of 2.32 kg-CO_2/L is used as the CO_2 emission factor of gasoline.

Nowadays, some motor companies developed a small car such as micro-EV. It is expected that the price of micro-EV becomes less than 1 million yen. On the other hand, the price of regular car is usually around 1.5 million yen. The regular car needs an automobile inspection cost of about 40,000 yen and an automobile tax of about 35,000 yen per year. In the case of micro-EV, automobile tax is 2500 yen per year and there is no automobile inspection. Moreover the fuel cost of regular car is higher than the electricity charge of micro-EV. Usually, the cruising distance of regular car is about 10,000 km per year at rural area. Then the fuel cost is estimated about 78,000 yen per year for the gasoline-fueled car of 18 km/L. Here, the gasoline price is assumed as 140 yen/L. In the case of micro-EV, the electricity charge is about 30,000 yen. Here, we assumed that the electricity charge is 21.3 yen/kWh. Therefore, if we use the regular car in 10 years, the total cost is about 3.03 million yen. This cost is higher than micro-EV, because the total cost of micro-EV is estimated as 1.325 million yen per 10 years.

Table 1
Specifications of the micro-EV developed by local industries and a university in Gunma Prefecture.

Passenger capacity		1
Size	Length	2495 mm
	Width	1295 mm
	Height	1365 mm
	Wheelbase	1810 mm
Weight		295 kg
Performance	Max. speed	30 km/h
	Battery (Li-ion)	52 V–31 Ah
	Cruising distance	30 km/full charge
Consumption		2.96 JPY/km
CO_2 emission		19.9 g-CO_2/km

Our project investigated the usage of private cars in Kiryu through a questionnaire [25] sent to 10,000 households randomly selected from the city total of 50,163 households. There were 2269 returned questionnaires; the recovery rate was thus 22.7%, or 4.52% of the total households in Kiryu. Using the questionnaire, we obtained data on trip distance and number of trips per month by private car, public transportation, and walking/bicycle. A summary of the results appears in Table 2. The data showed that most people used private cars in their daily lives. Mean distance per trip was 2.43 km; this distance is considerably shorter than the cruising distance of a fully charged micro-EV, which would be enough for a trip 10 times longer than the mean distance of 2.43 km.

In Kiryu, the number of private cars per householder is approximately 2.0. Therefore, if a household were to change one of its two private cars from a gasoline car to a micro-EV, it would be possible to make a sizable reduction in CO_2 emissions. The ordinary car could be mainly used for longer-distance trips, while the micro-EV could act as the vehicle for regular daily use. Micro-EV utilization might also be an effective measure in cutting down on traffic jams during commuting hours and saving parking space. These sorts of CO_2-reduction scenarios may apply to the rural areas of not only Japan but many other countries, as well. Lifestyles that take advantage of micro-EV technology could potentially become defining features of rural life in the future.

3.2. The development of a low-speed electric-community bus

Our project also developed a low-speed electric-community bus using the same technology as that applied in the micro-EV. For example, a similar in-wheel motor was used for the driving system. Fig. 10 and Table 3 are a photograph of and the specifications for the bus, named "eCOM-8®." The bus has eight wheels, each of which has an in-wheel motor. Passenger capacity (including the driver) is ten. The bus has no windows besides the front and rear windows; on rainy days, however, clear plastic sheets are used for side windows. The battery is a lithium polymer-type device, and the solar panels installed on the roof of the bus provide driving power assistance. Fully charged, the bus has a cruising distance of around 40 km on flat roads. The exchangeable-type battery was developed to elongate cruising distance. Weighing approximately 50 kg, the battery can be lifted by two people. The seats inside the bus are wooden benches, as shown in Fig. 10. The most notable attribute of the bus is its maximum speed of 19 km/h. In recent years, researchers have explored several low-speed transportation systems. For instance, the concept of the "30 zone"—a stretch of road where the speed limit is 30 km/h—has made an impact in many areas [26]. The bus from our project is a new slow-mobility vehicle type that demonstrates effectiveness in reducing traffic accidents. CO_2 emissions from the bus were estimated at about 64.5 g of CO_2 per km, assuming the no solar power assist. With nine passengers on board, the bus's emission per person comes out to about 6.45 g of CO_2 per km, which is lower than the emission

Table 2
Vehicle trip distance data for Kiryu, Gunma Prefecture, based on questionnaire data from Kiryu residents.

Number of people			1618
Total number of trips			25,324
Total trip distance		km/month	61,556
Mean distance		km/trip	2.43
Trip distance per person	Walk/bicycle	km/month	5.77
	Public	km/month	0.45
	Vehicle	km/month	31.82
	Vehicle	km/day	1.27
	Total	km/month	38.04

Fig. 10. Photographs of low-speed E-bus during a road test.

levels of micro-EV vehicles. The key design concepts behind the bus were:

- The bus gives passengers a comfortable view of the surroundings because of the low-speed cruising.
- The bus allows passengers seated on opposite sides of the bus to communicate because of the bench-type seating and low operating noise; in other words, the bus is a communication-enhancing tool for the local community.
- Given its simple design with minimum function, the bus ensures low-cost production.

The target users of the bus are citizens of the local community, including the elderly and tourists. A survey on the effective use of the bus was conducted via questionnaire, which was sampled on July 15 and 16, 2012. The maximum atmospheric temperatures of the two sampling days were approximately 32 and 35° centigrade, respectively. One question was, “How comfortable did you feel riding the bus?” Respondents could answer “Comfortable,” “Normal,” or “Uncomfortable.” Fig. 11 summarizes the results. Out of 92 respondents, 82% answered “Comfortable,” while only 2% were “Uncomfortable.”

Table 3
Specifications of the low-speed E-bus.

Passenger capacity		10
Size	Length	4405 mm
	Width	1900 mm
	Height	2455 mm
	Wheelbase	700 mm × 3
Weight		1160 kg
Performance	Max. speed	19 km/h
	Battery (Li-poly.)	52 V–100 Ah
	Cruising distance	30 km/full charge
	Gradeability	8° at 5 km/h
Solar panel		140 W × 4
Consumption without solar assist		4.0 JPY/km
CO_2 emission		48.5 g-CO_2/km

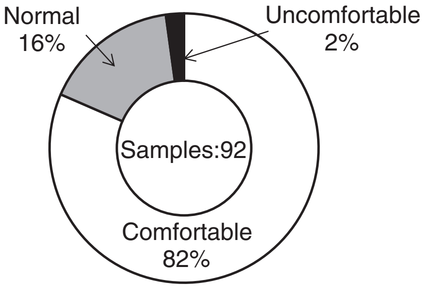

Fig. 11. Questionnaire results: low-speed E-bus comfort.

The questionnaire also inquired about the lack of side windows on the bus, asking respondents to gauge their comfort on the bus in light of the windowless design. Respondents could answer “Comfortable,” “Normal,” or “Uncomfortable.” As shown in Fig. 12, “Comfortable” accounted for 86% of all respondents, and no respondent chose “Uncomfortable.” These results confirmed that many people felt good and comfortable riding the bus. The questionnaire also asked, “What would be the ideal application of the E-bus?” Fig. 13 shows the corresponding data. Most respondents said that the bus would be suited for applications at amusement parks, but many people also noted the possibilities of using the E-bus for sightseeing, in place of fixed-route buses, and for transporting elderly people. These findings suggested that the people see considerable applicability and effectiveness in the low-speed E-bus.

3.3. The utilization of local renewable energy for low-CO_2-emission vehicles

Some trial tests on the utilization of renewable energy were performed using low-CO_2-emission vehicles. Solar energy was used for the micro-EV, as shown in Fig. 14. The tests evaluated whether the micro-EV could, on solar power alone (130 W × 4 panels) complete a 15-km daily driving regimen during the winter season. The results show that solar energy was sufficient to drive the micro-EV for daily use. The cost of solar power system for micro-EV could be estimated as 1 million yen. As mentioned above, it is calculated that the total cost of micro-EV in 10 years is lower than 1.325 million yen compared to ordinary car. Therefore, it is an advantage in cost for the utilization of micro-EV. Another portion of the test examined using solar energy for the low-speed E-bus. On sunny days, the solar assist was equivalent to a 50% increase in cruising distance.

A test on the utilization of hydro power, as shown in Fig. 15, was also conducted through the cooperation of Kiryu city office and Gunma University supported by the Ministry of the Environment in Japan. The test used pico hydro power, whose output was approximately 1.5 kW and whose electricity was stored in light, portable lithium ion batteries with a capacity of about 1 kWh. As hydro power can supply electricity

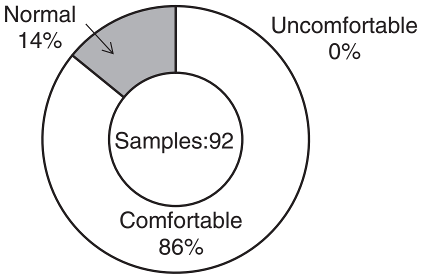

Fig. 12. Questionnaire results: windowless design comfort.

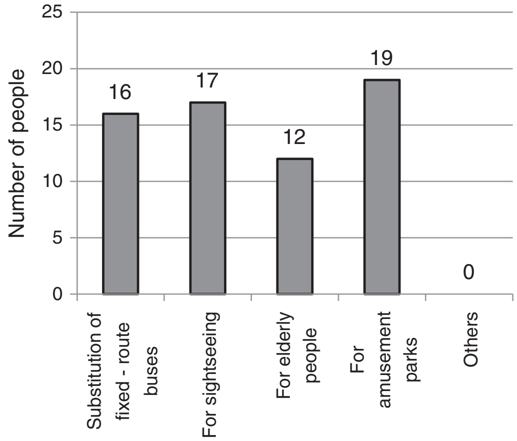

Fig. 13. Questionnaire result about application of low speed E-bus.

day and night, the test system provided about 34 kWh per day. We used 40 batteries for electric power storage. The experiments involved 50 electrically assisted bicycles (20 for monitoring purposes and 30 for rental bicycle applications), two micro-EVs, and an ordinary EV. Most of the stored energy was consumed by the rental bicycles. In the end, the test demonstrated that electricity generated by pico hydro power was sufficient to operate the system.

4. Conclusions

We reviewed the problems of energy security and social situations in Japan using statistical data. We also discussed the utilization of renewable energy, such as solar power and hydro power, in mobility applications and the contributions of said utilization to the sustainability and vitalization of rural areas. Our project developed a micro-EV and a low-speed E-bus as examples of low-CO_2-emission vehicles. Finally, we also reported some test data on the actual use of the developed vehicles. Questionnaires confirmed public receptiveness to the low-speed E-bus.

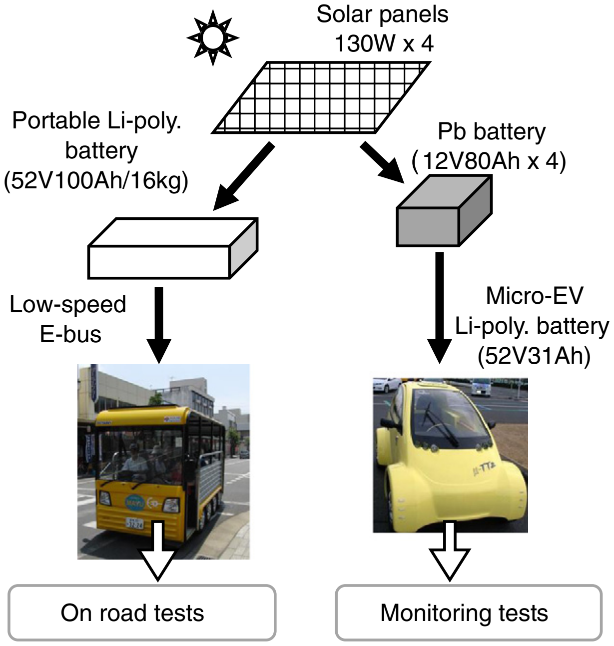

Fig. 14. Solar power utilization systems of low-carbon vehicles.

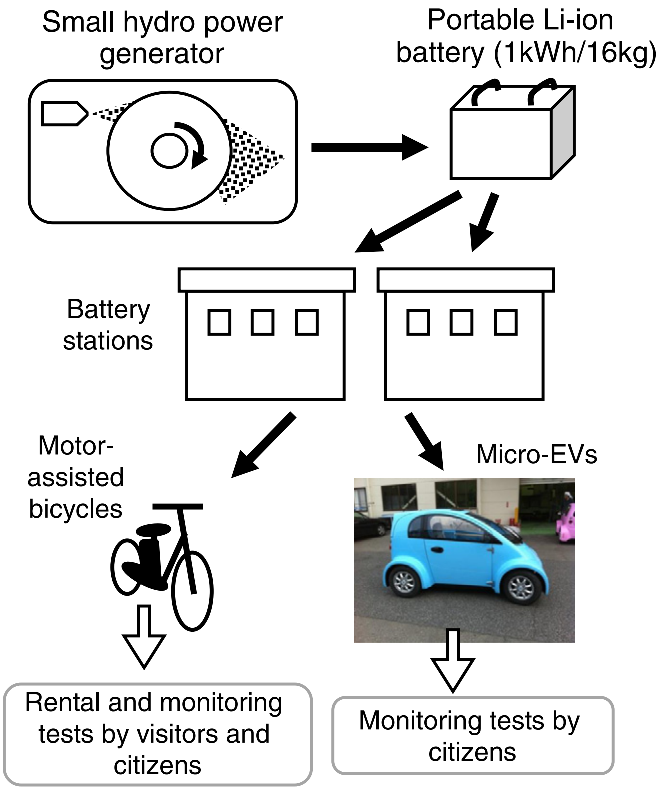

Fig. 15. Hydro power utilization systems for low-carbon vehicles.

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