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Life-cycle analysis of charging infrastructure for electric vehicles

Keisuke Nansai[a,*], Susumu Tohno[b], Motoki Kono[c], Mikio Kasahara[b], Yuichi Moriguchi[a]

[a]National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506 Japan
[b]Graduate School of Energy Science, Kyoto University, Gokasho Uji Kyoto, 611-0011, Japan
[c]Toshiba International Fuel Cells Corporation, 4-1 Ukishima-cho Kawasaki-ku Kawasaki Kanagawa, 210-0862, Japan

Abstract

Life-cycle analysis of a charging station for electric vehicles (EVs) was performed in the three phases, that is, production, transportation and installation of the charging equipment, which consists of charger, battery and stand. We chose parking lots on expressways, commercial parking lots in cities, municipal facilities, shopping centers, etc. throughout the country as the charging sites according to the EV charge program in Southern California. Air-pollutant emissions during the transportation phase were calculated based on the emission factors of vehicles, running speed and the transport distance between one factory of the charging equipment and each site. The share of transporting the charging machines in total emissions of CO_2, SO_x and CO was less than 15% and the production phase was dominant. In case of NO_x, the share of transporting them was over 20%. The relation between gasoline vehicle and gas station was applied to estimate the number of EVs using the charging stations through the country, and the contribution of the charging stations to life-cycle emissions of air pollutants from EV was presented. The share of infrastructure in total emissions of CO_2 was 16% in our model case. Thus the development of the charging infrastructure almost did not change the advantage of EV compared to gasoline vehicle (GV) in terms of CO_2, NO_x, and CO emissions. But an EV emits more life-cycle SO_x than gasoline vehicles (GVs).

Keywords: Life cycle analysis; Electric vehicle; Infrastructure; Air pollutant

1. Introduction

The potential impact of emissions generated from road transport upon the atmosphere is leading to an increase of environmental concern, both at regional and global level. The world's major car manufacturers need to not only reduce the fuel

* Corresponding author. Tel.: +81-298-50-2889; fax: +81-298-50-2880.
E-mail address: nansai.keisuke@nies.go.jp (K. Nansai).

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consumption of gasoline or diesel vehicles, but also develop zero emissions vehicles (ZEVs) like electric vehicles (EVs), hybrid cars or fuel-cell cars. If ZEVs are in common use instead of internal-combustion engine vehicles (ICVs), it is highly likely to mitigate the environmental load.

To date, the number of EVs has not increased rapidly due to their high price and immature performance, especially their limited-range drive. In order to replace ICVs with EVs, it is critical to improve the mileage per charge and provide a charging infrastructure. EV reduces tail-pipe emissions dramatically. However, a large-scale infrastructure incurs a large environmental load. Therefore, to evaluate the real effectiveness of EVs, life-cycle emissions of air pollutants from EVs including facilities, should be assessed.

In Japan there are currently about 60 public charging stations [1]. They have been constructed at gas stations in big cities like Tokyo, Aichi and Osaka, due to the usability of the existing facilities [1]. But we chose charging sites throughout the country according to the EV charge program in Southern California and performed a life-cycle inventory analysis (LCI) of charging stations for air pollutants emissions (CO_2, NO_x, SO_x and CO) [2]. The system boundary of a life-cycle includes production, transportation and installation of the charging system consisting of charger, battery and stand. Inventory data calculated by the process approach or the input–output analysis was utilized in the LCI. We compared the life-cycle emissions of an EV including the infrastructure to that of a gasoline vehicle (GV). The outline of this study is shown in Fig.1.

2. The EV charge program in Southern California [2]

The EV charge program was carried out to reduce mobile source emissions by providing public charging infrastructure to support the introduction of EVs in the

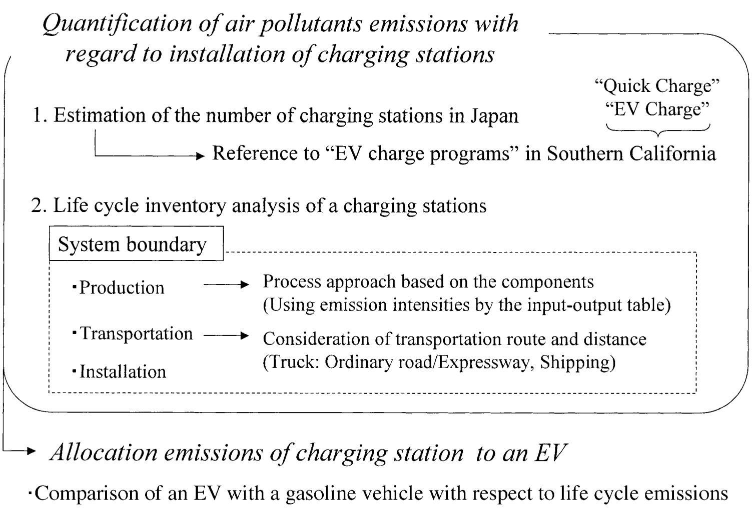

Fig. 1. Outline of this study.

South Coast Air District in Southern California. The necessity for charging stations in this region is higher than others, because in AD 2003 major automakers will be required to provide for sale a nominal 4% pure ZEVs and 6% near ZEVs. The actual number of ZEVs required in 2003 is approximately 22,000. The first EV public charging program, "Quick Charge," was initiated in 1996 and provided nearly $1.7 million for charging station installation. Quick Charge resulted in the installation of 356 chargers at 111 charging sites. Private investment has contributed to the installation of an additional 305 chargers at 117 sites. Inductive, conductive, or both chargers are available at the sites. Table 1 shows the distribution of charging sites by county in 1999.

Charging stations are Level 2 EV charging of about 3 h until completion [3]. Accordingly, the location of high usability is generally one where a driver can spend an hour or more doing something else while receiving a charge. Charger location by land use is as follows. Commercial sites show the highest occurrence at 23.7% with roughly another 20% occurring at both municipal facilities and employment sites. Other land uses where charging sites are located include airports, entertainment locations (zoos, museums, theme parks, etc.), hospitals, hotels, shopping centers, special event centers (convention centers, stadiums, arenas, etc.), transportation sites/facilities (Metrolink stations, park and ride lots, etc.), and university/college campuses.

Since 1999, a new program "EV Charge " follows the Quick Charge program for more expansion of the charging infrastructure. Charging site owners should be required to provide electricity free-of-charge during the demonstration period.

3. Estimation of eligible sites in Japan for public charging stations

According to the EV charge program in Southern California, the locations suited to the public charging stations in Japan were chosen in city areas and on expressways.

3.1. Charging sites in a city area

Charging stations in a city were chosen for the locations where a driver could spend an hour or more doing something else while charging into EV. The number of charging sites was estimated on a city basis by statistics [4] and the geographic distribution of those sites by city was used to calculate the different transport distance

Table 1
Charging sites by county in Southern California

County	No. of charging sites	No. of chargers	
		Inductive	Conductive
Los Angeles	140	276	165
Orange	40	64	39
San Bernardino	25	40	35
Riverside	23	27	15
Total	228	407	254

of the charging equipments from a factory. Since charging stations are not necessarily installed at all eligible places, the installation ratio by land use or facility scale was set.

3.1.1. Commercial

There are many free or paid parking lots for temporary use near major city facilities in Japan, and the number of them was estimated [5]. We assumed that charging stations were set up at 10% of all the parking lots in each city.

Restaurants for families in Japan are suitable for charger installation as well, because people tend to spend 1 h or more there. The number of the restaurants was obtained from the commercial census [6] and it was assumed that the charging station was installed at 10% of the restaurants.

3.1.2. Employment

A workplace with 250 or more employees is recommend as a charging place in the EV charge program. In this study, only factories with 300 or more workers were chosen as the employment site eligible for charging, because in Japan most offices located in an urban town don't have their own parking lots. The census of manufactures [7] was used to estimate the number.

3.1.3. Municipal facilities, hotel and hospital

Prefectural halls, city halls and public libraries were treated as charging location of the municipal site. Hotels with 100 or more employees and hospitals with 400 or more beds [8] were also counted as charging sites.

3.1.4. Shopping mall and entertainment

There are a lot of department stores or supermarkets with large parking lots in Japan. We chose stores having floor space of 3000 m^2 or more as the charging sites [9]. Shopping malls have higher potential for charging opportunities than other locations and the charging stations offer customers an incentive to choose the shop. Accordingly, it was assumed 20% of the stores installed charging stations.

Entertainment sites are one of the best locations a charging site. Each installation ratio of museum, art museum, amusement park, theme park, zoo and aquarium was assumed to be 10%. The number of entertainment sites was estimated by statistics [10].

3.1.5. Airport, transportation and university

The number of airports in each region was referred to the annual report of air transport [11,12]. Because an access to campus by car is allowed in few universities and colleges in Japan, we took into account no university sites.

Parking lots close to a station are eligible for transportation charging sites and the number of them was included in the commercial site.

3.2. Charging sites on expressways

In Southern California, charging sites located along major transportation corridors help ensure that EV drivers can travel to destinations throughout the region without running out of charge. A five-mile buffer is created around charging sites within half mile of a freeway. Any stretch of freeway not covered by a buffer around an EV charging site was highlighted as being a gap in service along that particular freeway corridor. Installation of charging station in a freeway corridor gap can receive an additional incentive of 10% [2].

In Japan, it would be important to set up charging stations on expressways since most of them are not free. Thus the service area offers good potential for charging opportunities. The number of service areas and their intervals are shown in Table 2. The maximum interval of 42.5 km ensures that EV drivers can easily travel to destinations throughout the region.

4. Life cycle inventory analysis of a charging station

A charging station is equipped with a charger, storage battery and stand. Each model of charging equipment was referred to the current charging station in Japan. The station, different from the California one, is equipped with a storage battery charged by midnight power. Air pollutant (CO_2, NO_x, SO_x and CO) emissions of a charging station were calculated on the three phases, that was, production, transportation and installation.

4.1. Production phase

An input–output approach was applied to estimate emissions of a charging station on the production phase. At first, we determined the weight of constituent parts of charging

Table 2
Frequency of service areas on Japanese expressways

Highway	No. of service areas	Intervals (km)		
		Maximum	Minimum	Mean
Doou	12	28.8	17.1	23.6
Tohoku	41	24.2	5.2	15.6
Joban	11	20.6	9.6	15.4
Kanetsu	16	23	7.3	14.5
Joetsu	8	26.7	17.2	21.2
Chuo	20	24.6	8.3	16.4
Hokuriku	26	27.9	7.9	18.5
Toumei	22	24.4	8.9	15.2
Meishin	12	29.8	3.3	15
Chugoku	29	24.7	8.9	17.4
Sanyo	20	42.5	9	21
Takamatu-Muatuyama	7	31.8	8.3	17
Kyusyu	19	30.1	9.8	18.4
Nagasaki	7	19.9	10.1	14.9
Oita	6	27.4	14.5	20
Miyazaki	4	27.3	11.4	20.2
Total/average	260	27.1	9.8	17.8

equipment as shown in Table 3. Next, each product price per material weight was calculated by using the attached domestic producer price table from Japan Input–Output tables [12]. Finally, the life-cycle emissions of each component were obtained by multiplying its price by the embodied emission intensities based on the tables of reference [13].

The emission from the assembly process of a storage battery was equal to 267 times that of a passenger car battery under the assumption that emission increases linearly with weight. The emission from the assembly of a car battery was obtained from statistics [14]. But emissions from the assembly process of stand and charger were not considered in this study. The total emission of charging equipment on production stage was determined by summing up the emissions of the constituent materials and those from assembly. Several emission intensities used in this study are shown in Table 4.

4.2. Transportation phase

According to the inquiry for a charger producer, a 10 tonne truck is used to deliver charging equipment from the factory to a charger location. The factory is located at Kyoto city: mapping software provided the transportation distance and route

Table 3
Weights of components of charging equipment

Component	Weight (kg)
Charging stand	
Steel	73
Copper	11
Aluminium	1
Personal computer	4.5
Card reader	1.5
Display	2.25
Others	6.75
Total	100
Storage battery	
Steel	760
Copper	20
Lead	2400
Plastic	200
Sulfuric acid	560
Glass	60
Total	100
Charger	
Steel	400
Copper	80
Aluminium	50
Breaker	30
Thyristor	20
Condenser	6
Resistor	6
Others	8
Total	600

Table 4
Emission intensity of air pollutants based on the input–output table

Sector name of the input–output table	CO_2	NO_x	SO_x	CO
	Mg-C/M-Yen[a]	kg/M-Yen	kg/M-Yen	kg/M-Yen
Steel	6.54	19.1	13.2	31.5
Copper	1.36	7.1	5.5	7
Lead	4.3	15.1	17	11.3
Aluminium	1.63	9	7.5	6
Sulfuric acid	1.31	9	7.5	6
Electric power	6.33	19.2	16.7	6.7

[a] M-Yen = 1,000,000 Yen.

(expressway, ordinary road and shipping), depending on the geographical location of the delivery point. Here, the locations of municipal offices were used as the representatives to calculate the distances to the charger sites for each city. Shipping was also utilized in the transportation to cities in the Hokkaido, Kagoshima and Okinawa prefecture.

We assumed running speeds and fuel efficiencies of the truck as follows: [15], on an expressway, the speed was 70 km/h and the consumption was 5.1 km/l. On a regular road, the speed was 32.5 km/h and the mileage was 4.8 km/l, however in the Tokyo and Osaka area, the former was 20 km/h and the latter was 4.2 km/l due to the high traffic density. Emission factors of air pollutants used in this study are shown in Tables 5 and 6 [16–18]. Loaded weight of the truck was assumed to be 10.9 tonne on the way to the site and 6.2 tonne on the way from the site. We denote the environmental load for a charging station transporting by E^{trans} hereafter.

4.3. Installation phase

Air pollutant emissions for the electric-power consumption estimated from the installation cost were allocated to those for installing charging equipment.

Table 5
Emission factors of truck and transport charging equipment

Driving road type	CO_2	NO_x	SO_x	CO
	g-C/cm^3	g/t km	g/t km	g/t km
Road in Tokyo and Osaka area	721	0.63	0.16	0.44
Highway	721	0.44	0.13	0.26
Other road	721	0.53	0.14	0.36

Table 6
Emission factors of shipping and transport charging equipment

Transport means	CO_2	NO_x	SO_x	CO
	g/t km	g/t km	g/t km	g/t km
Ship	9.69	0.275	0.195	0.273

5. Results and discussion

5.1. Environmental loads as a result of installing a charging station

Approximately 14,000 charging sites were chosen throughout the country. The categories of charging sites are shown in Fig. 2. Commercial, municipal, enterprise and entertainment categories accounted for 26, 20, 21 and 17% respectively. In terms of regions (prefectures), there were 1,300 sites in Tokyo, 900 sites in Aichi and 900 sites in Osaka.

If a charging station has three charging stands (charge ports) as implied in Table 1, CO_2, NO_x, SO_x and CO emissions of a charging station in the production and installation stages are 3.97 Mg-C, 16, 15, and 13 kg, respectively as in Fig. 3. Environmental load from a charging station in the production and installation stages is denoted by E^{prod} hereafter.

Total environmental load E from all the charging stations in a region (prefecture) j is obtained by multiplying the sum of E^{prod} and E^{trans} by the total number of the charging stations N.

$$E_j = \sum_k N_{j,k}\left(E^{\text{prod}} + E^{\text{trans}}_{j,k}\right) \tag{1}$$

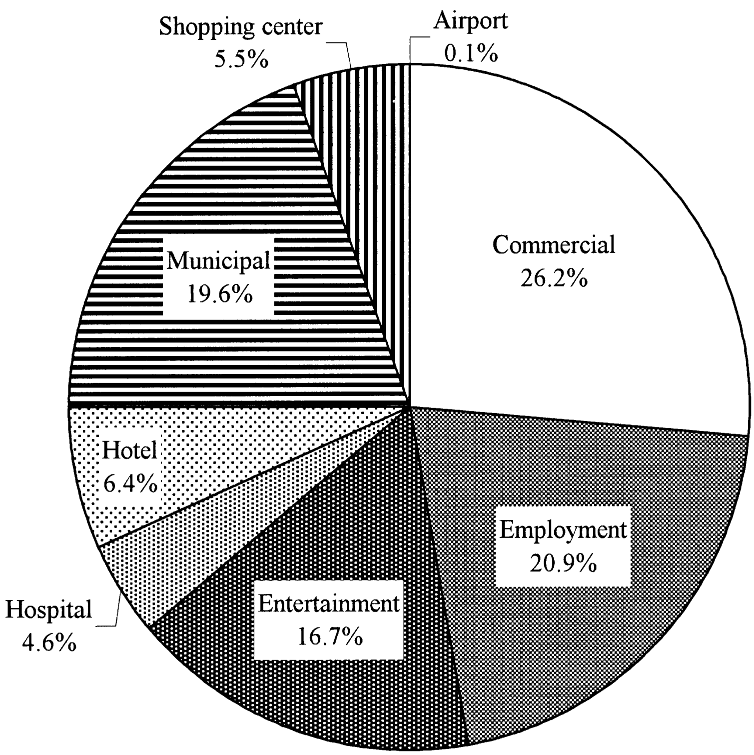

Fig. 2. Category of charging sites in Japan estimated in this study.

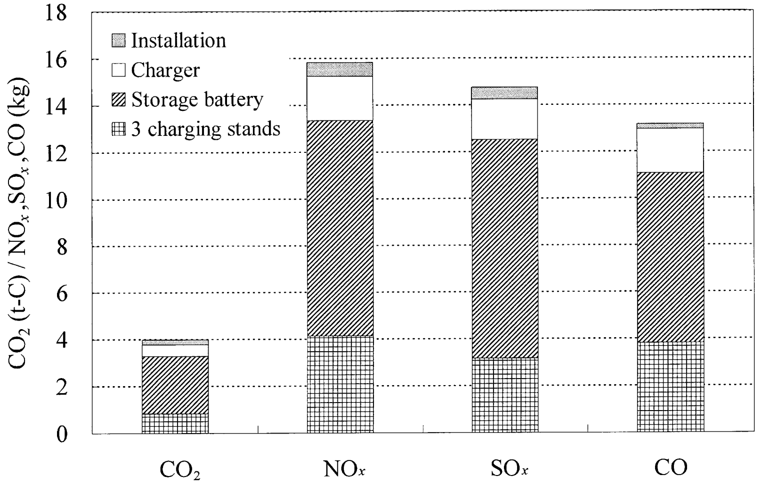

Fig. 3. Air pollutants emissions with regard to charging equipment.

where k means a city in the region j.

Figs. 4 and 5 show E_j of CO_2 and NO_x and the average emission e_j per charging station in a region j: e_j is obtained from Eq. (2)

$$e_j = E_j/N_j \tag{2}$$

The total CO_2, emission of charging stations in Japan was about 60 Gg-C. The production phase contributes 92% of the total, while the contribution of the transportation phase was only 3%. Therefore regional emissions were nearly proportional to the number of charging stations and large emissions occurred as 5.4 Gg-C emission from Tokyo, 3.7 Gg-C from Aichi and 3.5 Gg-C from Kanagawa. Total NO_x emission was roughly 273 Mg with 78 % for the production phase and 22% for the transportation phase. Contribution of transportation phase was small in the cases of SO_x and CO, and share of the production phase was 89% of 224 Mg-SO_x and 84% of 215 Mg-CO.

Variation of e_j of CO_2 ranged from −3 to 8% of the mean, while that of NO_x was in the range of −19 to 45%. This result indicates that the NO_x emission of a charging station depends highly on the delivery distance, running speed etc.

5.2. Allocation of environmental loads from charging stations to an EV

In order to perform a life-cycle analysis of an EV including the installation of charging stations, we applied a relationship between GVs and gas stations to allocate the air pollutant emissions of charging stations to an EV. Assuming that gas stations in Japan have enough injection hoses to supply GVs with gasoline, how many charging stations could supply electricity to an EV was calculated.

First the average number of injection hoses at a gas station in a region j was estimated by Eq. (3) from the design guide of a gas station utilized by Japanese oil companies.

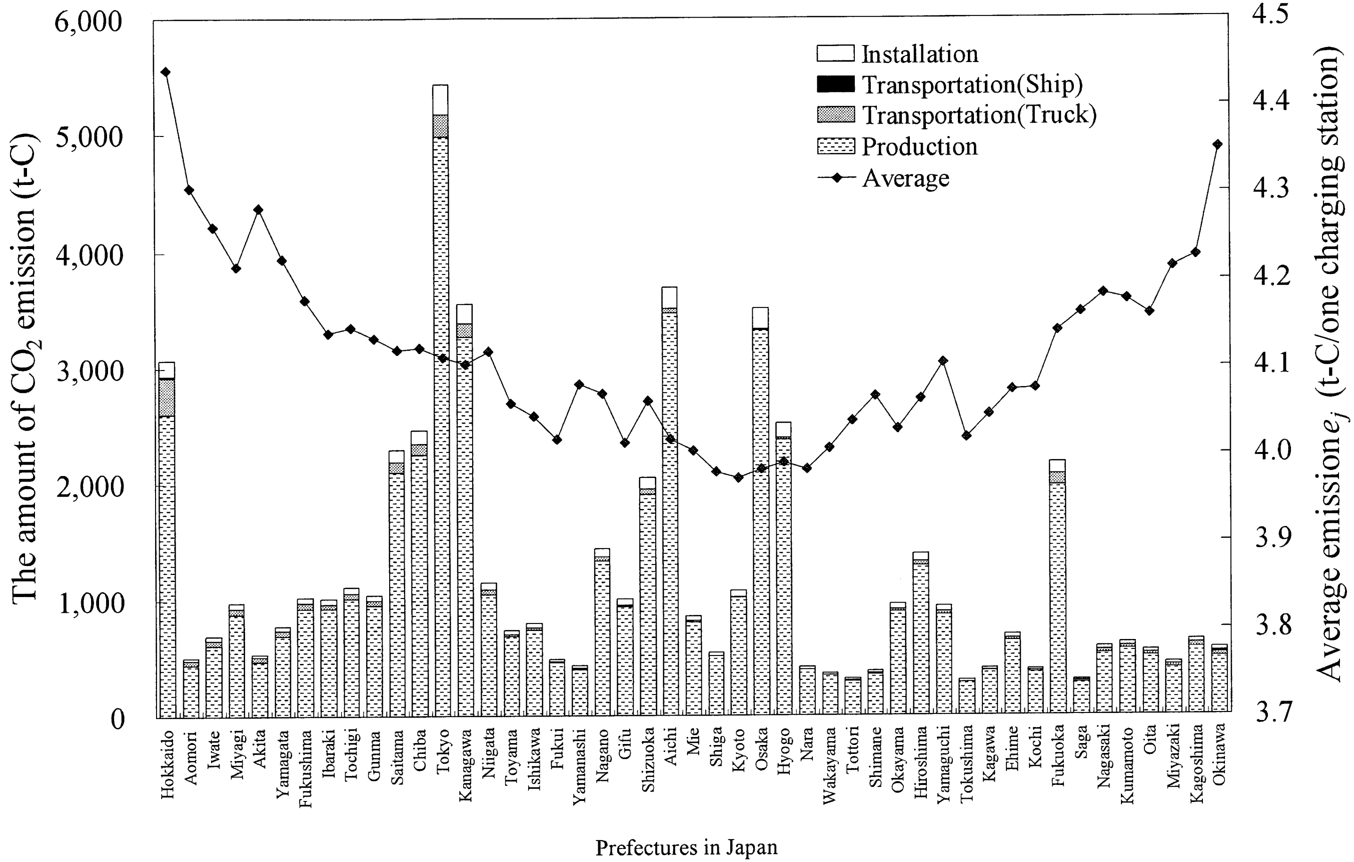

Fig. 4. Regional differences of CO_2 emissions according to location of charging station.

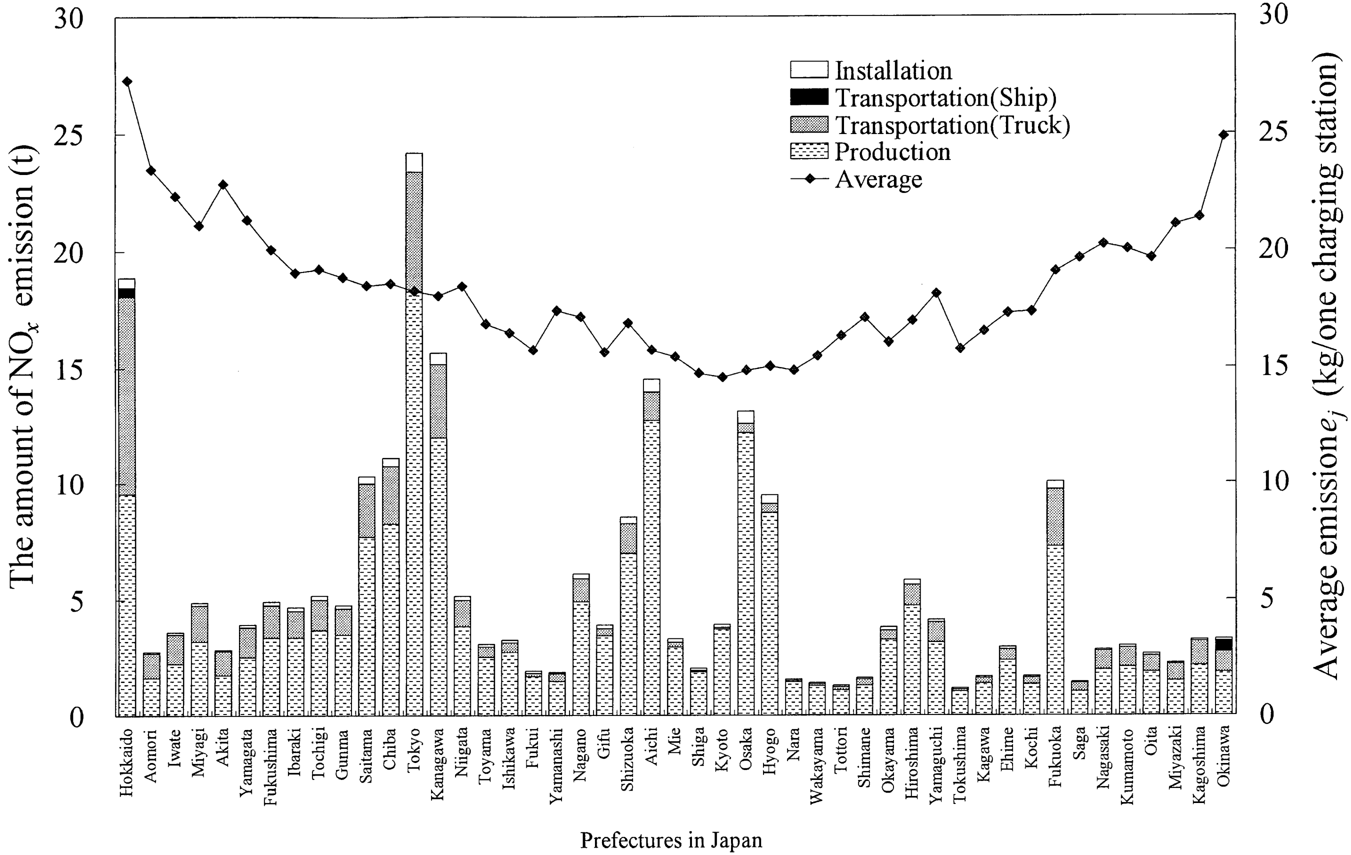

Fig. 5. Regional differences of NO_x emissions according to location of charging stations.

$$N_j = \frac{2abL_j}{l} \cdot \frac{t}{60} \tag{3}$$

where N_j represents the number of injection hoses per gas station, L_j is the daily refueling amount for gasoline cars at a gas station, l is the average amount of refueling a car, t is the average time of refueling, a is the increased rate of the number of refueled cars at the peak during a month, and b is the share of refueled cars during one hour around the peak to the total ones. We set l, t, a, and b as 25,000 cm^3, 5 min, 1.5 and 0.1, respectively according to an interview with a Japanese oil company. The total number of hoses in a region j was obtained by multiplying N_j by the number of gas stations in a region j. Then the number g_j of supported gasoline vehicles per hose in a region j was deduced by dividing the number of registered gasoline cars by the total number of hoses.

In order to calculate how many EVs can utilize a charging station, it was assumed that average charging time was 120 min and each charging station, with three stands, was utilized every day. Then the conversion factor c_j of a refueling nozzle number corresponding to a charging stand became 0.041 (=5/120). The average frequency of using a gas station is 1/4.56 a day [19]. The number of EVs per charging stand was determined by the ratio of frequency of using a charging station to a gas station, c_j and g_j. The total number of EVs throughout the country was estimated to be about 126,000. Therefore, allocating 60 Gg-C of life cycle CO_2 emission for the infrastructure to EV led to 0.45 Mg-C emission per EV. Other pollutants per EV were 2.2 kg-NO_x, 1.8 kg-SO_x and 1.7 kg-CO, respectively.

After adding the contribution of the charging infrastructure to the life-cycle emissions of the EV, a comparison of the life-cycle emissions was made between the EV and GV. Here, the model GV was a compact car size of 1 t total weight. The lifetime driving distance of the GV was 100,000 km and the consumption was 0.111/km [13]. The total weight of the EV was estimated, assuming that the batteries, a motor and other control devices were substituted for the engine and gasoline tank of the GV. Other parameters of the EV were the following: 20 lead storage batteries, 0.119 kWh/km energy consumption and 100,000 km total driving distance. Figs. 6–9 show the results of the life-cycle analyses of the EV and GV. In the case of CO_2, the share of infrastructure in the total emissions of CO_2 was 16% in our model case. For other pollutants except SO_x, similar results were obtained. Thus the development of the charging infrastructure almost did not change the advantage of EV compared to GV in terms of CO_2, NO_x, and CO emissions. But the relative superiority of EV over GV on SO_x emission was not shown under the average energy mix in Japan.

6. Conclusion and outlook

It was estimated that average life-cycle environmental loads of an electric vehicle including the infrastructure were 0.45 t-C of CO_2, 2.2 kg of NO_x, 1.8 kg of SO_x and 1.7 kg of CO. These values changed depending on the regions where charging stations were installed. A comparison of life-cycle emissions from EVs and GVs showed that

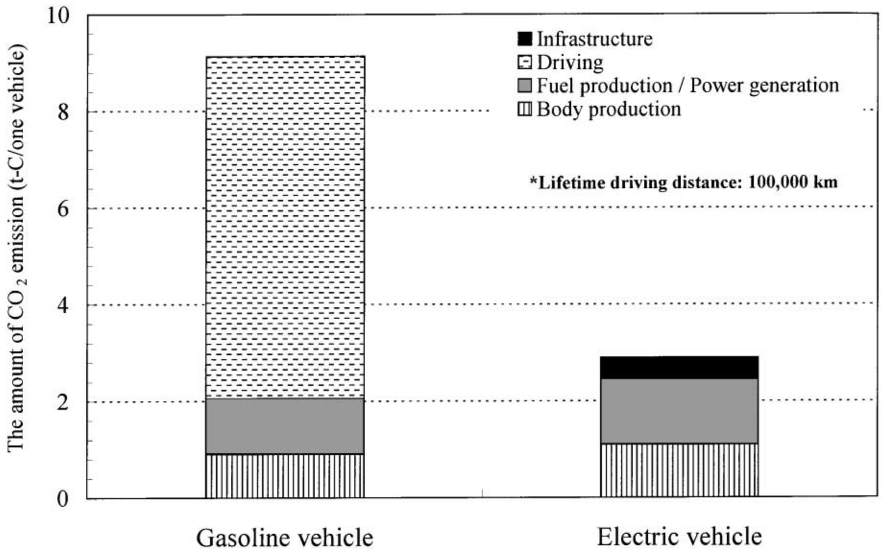

Fig. 6. Comparison of EV and GV with respect to life-cycle CO_2 emissions.

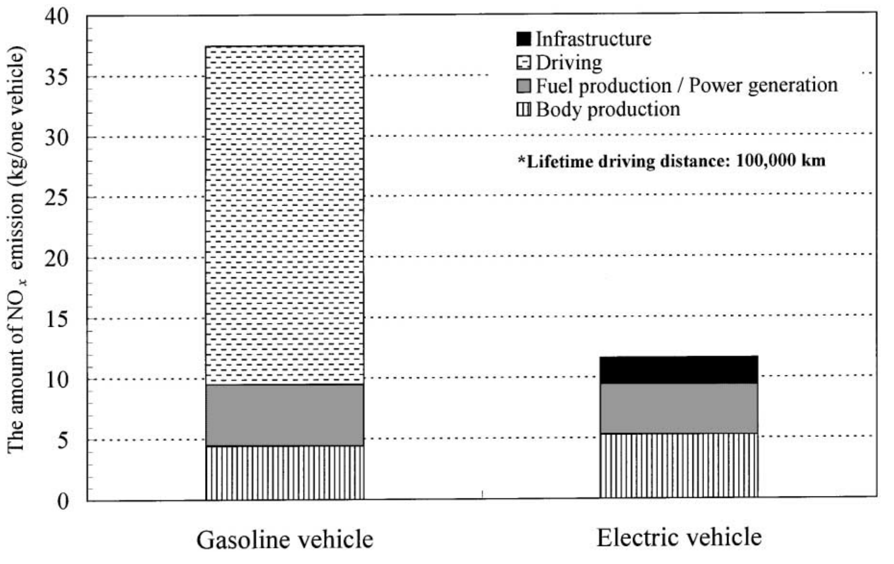

Fig. 7. Comparison of EV and GV with respect to life-cycle NO_x emissions.

manufacturing, driving and installing infrastructure of the EV resulted in less CO_2, NO_x and CO emissions than manufacturing and driving the GV. However, it was confirmed that life cycle SO_x emissions of the EV were comparable with those of its GV.

In Japan, 10 electric companies supply electricity to various regions and have their own power stations to generate electricity. Therefore, differences in the energy mix

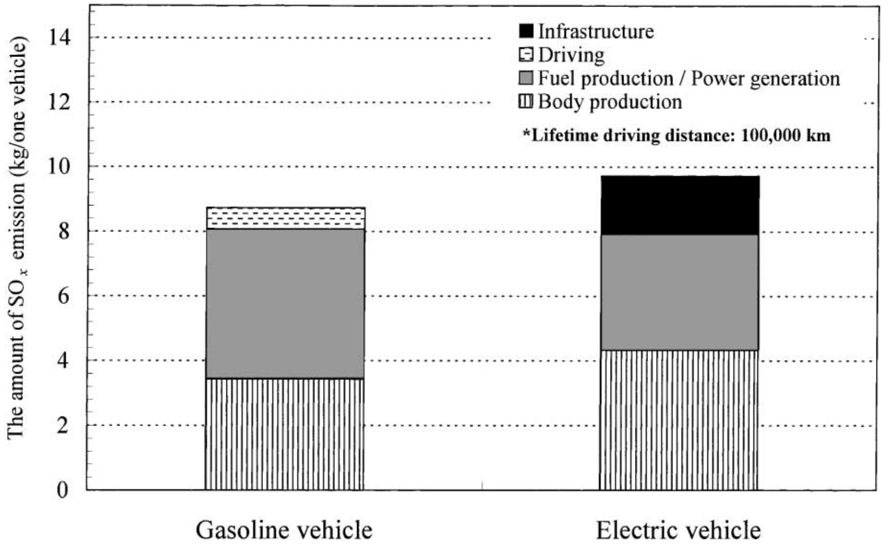

Fig. 8. Comparison of EV and GV with respect to life cycle SO_x emissions.

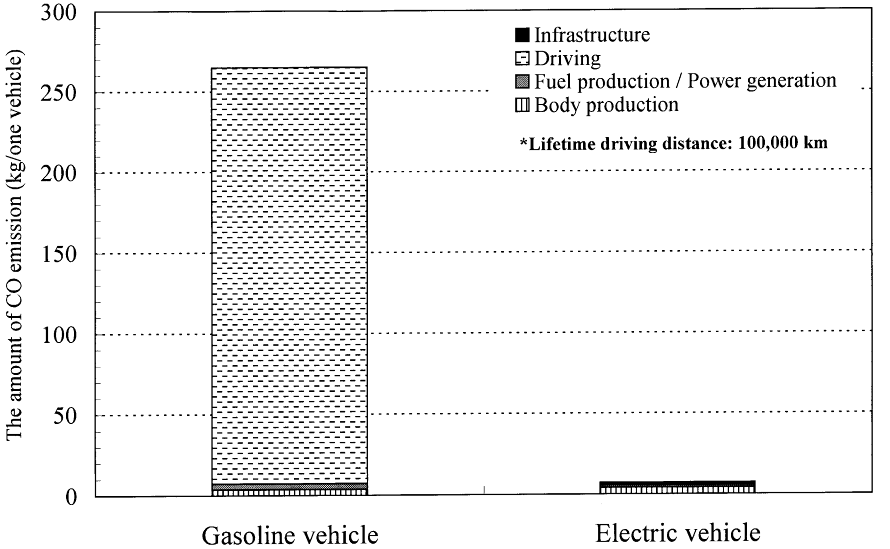

Fig. 9. Comparison of EV and GV with respect to life cycle CO emissions.

by distribution area result in regional differences of environmental loads related to electricity generation. Furthermore, the energy mix varies with time during the day even for an electric company. We used environmental loads of EV charging for the average energy mix in Japan. However, regional and temporal differences should be considered when evaluating environmental loads during the charging phase of an EV.

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