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Carbon footprint effects of Japan's ban on new fossil fuel vehicles from 2035

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Abstract

Despite the increase in vehicle electrification in recent years, the transport sector is still a major contributor to the rise in global carbon dioxide (CO₂) emissions. Using dynamic product lifecycle (LC) models, our study analyzes the relationship between lifecycle CO₂ (LC-CO₂) emissions and the proportion of electric vehicle sales in Japan. We consider the contributions of fuel efficiency and vehicle lifetime to LC-CO₂ emissions in three scenarios: changes in sales, improvement in fuel efficiency, and changes in vehicles’ lifetimes. Our findings show that promoting electric vehicles and decarbonization of electricity sector will decrease CO₂ emissions from the driving phase. However, even if the energy mix follows the net zero emission target, emissions from the vehicle manufacturing phase will largely remain, and the manufacturing emissions from electric vehicle accounts for more than 50% of total emission in 2050 even in the case of the vehicle lifetime is extended by 5 years. Decarbonization of power sector is effective to reduce driving phase emissions, however it is insufficient for reducing LC-CO₂ emissions. Thus, for reducing LC-CO₂ emissions including the manufacturing phase, the Japanese government need to focus on the decarbonization of supply chain as well as reducing the driving phase emissions.
Keywords

Lifecycle assessment, Input–output analysis, Lifetime analysis, Electric vehicles, Electricity sector

1. Introduction

According to the International Energy Agency (IEA), global carbon dioxide (CO₂) emissions in 2020 amounted to 33.9 Gt: 13.5 Gt from the power sector, 8.5 Gt from the industrial sector, and 7.2 Gt from the transport sector (IEA, 2021). Electrification of the road transport sector is likely to play an increasingly important role in global decarbonization, and several governments have introduced policies and measures to support the widespread adoption of electric vehicles (EVs). The IEA has proposed that the production of passenger vehicles with internal combustion engines should be prohibited by 2035, and EVs must account for 100% of the new passenger vehicle sales by 2050, the target set for net zero emissions (IEA, 2021). Despite recent large-scale efforts for vehicle electrification, emissions from the transport sector continue to increase.

Numerous studies have analyzed the CO₂ reduction effects of introducing EVs (Bauer et al., 2015; Onat et al., 2015; Jochem et al., 2015; Woo et al., 2017; Cox et al., 2018; Knobloch et al., 2020; Milovanoff et al., 2020). While scholars have found a decrease in CO₂ emissions,
this result is highly dependent on the energy mix of the power sector, implying that introducing EVs could increase lifecycle CO$_2$ emissions (LC-CO$_2$) (Knobloch et al., 2020). The CO$_2$ reduction effects from introducing EVs also depend on the energy mix of countries; that is, to reduce CO$_2$ emissions through electrification, countries should adopt a low-emission energy mix (Wolfram and Wiedmann, 2017; Choi et al., 2018; Knobloch et al., 2020; Rietmann et al., 2020; Filote et al., 2020; Li et al., 2021; Sheng et al., 2021; Broadbent et al., 2022). In addition to the decarbonization of the energy mix, Xiong et al. (2021) showed that the improvement of fuel efficiency is a crucial factor for reducing LC-CO$_2$ emissions not only EVs but internal combustion engine vehicles.

Another important factor contributing to LC-CO$_2$ reduction is the average lifetime of vehicles (Kagawa et al., 2011; Nakamoto et al., 2019). As the emissions induced by manufacturing EVs are higher than those by conventional vehicles (Hawkins et al., 2012, 2013), the potential of EVs in reducing emissions depends on the lifetime driving distance. The longer the lifetime driving distance, the greater the reduction in LC-CO$_2$ compared to gasoline vehicles (GVs) (Hawkins et al., 2013).

Thus, governments must consider numerous factors when determining how many EVs need
to be sold to achieve the desired reduction in CO\textsubscript{2} emissions. Studies have shown that technological effects (e.g., energy mix in the power sector, fuel efficiency, and vehicle weight) as well as consumer effects (e.g., vehicle lifetime and driving distance) contribute to LC-CO\textsubscript{2} emissions (Knobloch et al., 2020; Milovanoff et al., 2020). However, these two sets of factors have not been considered concurrently in previous studies (Knobloch et al., 2020; Milovanoff et al., 2020), and thus, the hidden effects of EVs on decarbonization have not been accurately evaluated. It is therefore important to consider whether the sale of EVs should be promoted to the same extent (and time) in countries where electrification is likely to induce further CO\textsubscript{2} emissions as in countries where electrification is set to contribute positively to decarbonization.

This study focuses on sales targets for future vehicles between 1993 and 2050 in Japan to evaluate the contributions of fuel efficiency and vehicle lifetime to LC-CO\textsubscript{2}. LC-CO\textsubscript{2} emissions were estimated based on a detailed national input–output table for Japan, which included data on the direct and indirect emissions throughout the product supply chains. We show how vehicle electrification will affect LC-CO\textsubscript{2} emissions under the energy mix toward net zero emissions and propose the best approach for the government to implement vehicle electrification.
2. Methodology

2.1. Stock and flow of passenger vehicles

Based on the estimated lifetime distribution functions, this study focussed on passenger vehicles of four types of fuels: GVs, hybrid vehicles (HV), EVs, and fuel cell vehicles (FCV), newly registered between 1993 and 2050. The passenger vehicle stock for fuel type $k$ ($1 = \text{GV}; 2 = \text{HV}; 3 = \text{EV}; 4 = \text{FCV}$) in year $t$, $S_k(t)$, and the total vehicle stock, $\bar{S}(t)$, are estimated as:

$$
\begin{align*}
S_k(1) &= B_k(1) \\
S_k(2) &= B_k(2) + \varphi_{k,1}(1) + B_k(1) \\
S_k(3) &= B_k(3) + \varphi_{k,1}(2)B_k(1) + \varphi_{k,2}(1)B_k(2) \\
&\vdots \\
S_k(t) &= B_k(t) + \sum_{i=1}^{t-1} \varphi_{k,i}(t-i)B_k(i)
\end{align*}
$$

and

$$\bar{S}(t) = \sum_{k=1}^{4} S_k(t)$$

respectively, where $B_k(t)$ represents the number of newly purchased vehicles of fuel type $k$ in year $t$, and $\varphi_{k,i}(t-i)$ is the survival probability in year $t$ of the vehicles of fuel type
that were newly purchased in year $i$, when the average lifetime of the vehicles is at the baseline.

Based on Eqs. (1) and (2), the aggregate number of newly purchased passenger vehicles is estimated as:

$$
\begin{align*}
B(1) &= \tilde{S}(1) \\
B(2) &= \tilde{S}(2) - \sum_{k=1}^{4} \rho_k(1) B(1) \varphi_{k,1}(1) \\
B(3) &= \tilde{S}(3) - \left\{ \sum_{k=1}^{4} \rho_k(1) B(1) \varphi_{k,1}(2) + \sum_{k=1}^{4} \rho_k(2) B(2) \varphi_{k,2}(1) \right\} \\
\vdots & \\
B(t) &= \tilde{S}(t) - \sum_{i=1}^{t} \sum_{k=1}^{4} \rho_k(i) B(i) \varphi_{k,1}(t - i)
\end{align*}
$$

(3),

where $\rho_k(i)$ is the sales proportion for newly purchased vehicles of fuel type $k$ in year $i$, and $B(t)$ represents the total number of newly purchased vehicles in year $t$. Based on Eq. (3), the number of newly purchased passenger vehicles of fuel type $k$ in year $t$ is represented by $B_k(t)$. If the survival probability $\varphi_{k,1}(t)$ changes through a change in the average lifetime scenario, then the total vehicle stock $\tilde{S}(t)$ remains relatively constant between different scenarios described in Section 3.

In addition, the number of vehicles disposed of by fuel type $k$ in year $t$ is estimated as:
\[
\begin{align*}
D_k(1) &= 0 \\
D_k(2) &= F_{k,1}(1)B_k(1) \\
D_k(3) &= F_{k,1}(2)B_k(1) + F_{k,2}(1)B_k(2) \\
& \vdots \\
D_k(t) &= F_{k,1}(t-1)B_k(1) + F_{k,2}(t-2)B_k(2) + \cdots + F_{k,t-1}(1)B_k(t-1)
\end{align*}
\] (4).

Here, we assumed that vehicles that were newly purchased in year \( t \) remain in service throughout year \( t \), such that \( D_j(1) = 0 \).

### 2.2. LC-CO\(_2\) emissions under energy mix targets

This section formulates an analysis framework to estimate the LC-CO\(_2\) emissions for the vehicle manufacturing, driving, and disposal phases. The direct and indirect CO\(_2\) emissions in year \( t \) by vehicle of fuel type \( k \) in the manufacturing phase \( Q_k^{MN}(t) \) are calculated as:

\[
Q_k^{MN}(t) = \alpha_k B_k(t)
\] (5),

where \( \alpha_k \) represents the embodied emission intensity (i.e., CO\(_2\) emissions per vehicle) for vehicle manufacturing. The embodied CO\(_2\) emission intensity for manufacturing a vehicle of each fuel type is estimated by the environmental input–output model, formulated as \( \alpha_k = \ldots \).
\( \mathbf{e}(\mathbf{I} - \mathbf{A}(t))^{-1}\mathbf{d}_k \). Here, \( \mathbf{e} = (e_w) \) is the “direct” sectoral CO\(_2\) emission intensity row vector, \( \mathbf{I} \) is the identity matrix, \( \mathbf{A}(t) = \{a_{vw}(t)\} \) is the input coefficient matrix in year \( t \), and \( \mathbf{d}_k \) is the vehicle final demand column vector including only the inputs of the materials and parts required to produce a vehicle of each fuel type \( k \). Consequently, we obtain the following vehicle input–output lifecycle analysis framework in Eq. (6) (Hienuki et al., 2021).

\[
Q_k^{MN}(t) = \mathbf{e}(\mathbf{I} - \mathbf{A}(t))^{-1}\mathbf{d}_kB_k(t) \tag{6}
\]

Here, the CO\(_2\) emission intensity vector and the vehicle final demand column vector remain constant during the study period and the vectors are based on the inventory databases of the base year 2015.

We used the 2015 Input–Output Table for Analysis of Next-generation Energy Systems (IONGES) covering 153 commodity sectors and 7 final demand sectors (Nakano and Washizu, 2022) and disaggregated the commercial electric power generation sector into 13 power generation subsectors in the 2015 input–output table of Japan (Table S1 for the sector classification): electric power (fossil fuels), nuclear power, large-scale hydropower,
small and medium-sized hydropower, solar power for residential buildings, solar power except for residential buildings, onshore wind power, offshore wind power, large-scale geothermal power, binary geothermal power, and three type of wood-based biomass power (class A, B, and C). When considering the electricity inputs from the above-mentioned 13 power generation subsectors \((P)\) and the other sectors \((O)\) to the 153 sectors, the input coefficient sub-matrices for the electricity inputs and the other inputs over sectors can be defined as \(a^p(t) = \{a_{vEP,w}(t)\}\) and \(a^o(t) = \{a_{vEO,w}(t)\}\), respectively. Similarly, the direct \(\text{CO}_2\) emission intensity row sub-vectors for the above-mentioned 13 power generation subsectors \((P)\) and for the other sectors \((O)\) can be defined as \(e^p = (e_{wEP})\) and \(e^o = (e_{wEO})\), respectively. We finally define the input coefficient matrix and the direct \(\text{CO}_2\) emission intensity row vector as:

\[
A(t) = \begin{bmatrix}
a^p(t) \\
a^o(t)
\end{bmatrix}
\] \hspace{1cm} (7)

and

\[
e = \begin{bmatrix} e^p & e^o \end{bmatrix}
\] \hspace{1cm} (8),

respectively. Here, we assumed that the input coefficient sub-matrix for the electricity inputs
will change following the given shares of energy sources \( (P) \). Specifically, we reformulate the “future” input coefficient from electricity sector \( m \) to sector \( n \) in year \( t \) after 2015 as:

\[
a_{vEP,w}(t) = \tau_{vEP}(t) \sum_{v \in P} a_{vw}(2015) \quad (t = 2016, 2017, \ldots, 2050) \quad (9),
\]

and the “past” input coefficient from electricity sector \( v \) to sector \( w \) in year \( t \) before 2015 as:

\[
a_{vEP,w}(t) = a_{vEP,w}(2015) \quad (t = 1993, 1994, \ldots, 2015) \quad (10),
\]

where \( a_{vw}(2015) \) is the electricity input of electricity sector \( v \) required per unit of production of sector \( w \) in the base year 2015 and \( \tau_{vEP}(t) \) is the given share of a certain energy source in year \( t \). Following IEA (2021) and IEA (2020), we set the share of energy source after 2020. Notably, the input coefficient sub-matrices for the other inputs over sectors \( a^0(t) \) remains constant as the coefficients of the base year of 2015 during the study period: 1993 to 2050.
The annual fuel consumption for vintage $i$ by fuel type $k$ in year $t$ is calculated by dividing the annual driving distance for vintage $i$ by fuel type $k$ in year $t$, defined as $d_{k,i}(t)$ (km), by the fuel efficiency for vintage $i$ by fuel type $k$, defined as $FE_{k,i}(t)$ (km/L).

$$FC_{k,i}(t) = \frac{d_{k,i}(t)}{FE_{k,i}(t)}$$ \hspace{1cm} (11).

Previous studies have reported that the annual driving distance decreases as the vehicle age increases (Weymar and Finkbeiner, 2016; Kaneko and Kagawa, 2021). Following Kaneko and Kagawa (2021), this study assigned different driving distances to vintage $i$ for fuel type $k$. Kaneko and Kagawa (2021) also showed the relationship between the annual driving distance and vehicle vintage for GVs and HVs. Using the estimated parameters, we estimated the annual driving distance for vehicles of fuel type $k$ and vintage $i$.

From Eq. (7), we estimated the driving phase emissions for vintage $i$ and fuel type $k$ in year $t$ as:

$$Q_{k}^{BR}(t) = \left\{ \sum_{i=1}^{t} S_{k,i}(t)FC_{k,i}(t) \right\}(\beta_{k}(t)FP_{k} + \gamma_{k}) \quad \text{for } k=1, 2, 3 \quad (12).$$
\[ Q_{k}^{R}(t) = \sum_{i=1}^{t} \beta_k(t)d_{k,i}(t)S_{k,i}(t) \quad \text{for } k=4 \] (13),

where \( \beta_k(t) \) represents the embodied emission intensity for fuel refining, \( FP_k \) represents the price of fuel type \( k \) in year \( t \), and \( \gamma_k \) represents the direct CO\(_2\) emission intensity for fuel combustion. \( \beta_k(k=1,2,3) \) expresses CO\(_2\) emissions per million JPY of gasoline or electricity and \( \beta_k(k=4) \) expresses CO\(_2\) emissions from the production of hydrogen required per mileage. The emission intensities for fuel refining were assumed to be constant throughout the study period. The CO\(_2\) emissions from the fuel refining phase were included in the driving phase emissions. We considered only CO\(_2\) emissions from the fuel production stage, and not those from fuel transportation and supply facility operation. The system boundary of this study is shown in Figure S11.

The disposal phase emissions were estimated as:

\[ Q_{k}^{DP}(t) = \theta_kD_k(t) \] (14),

where \( \theta_k \) represents the emission intensity of a vehicle disposed, which was estimated by multiplying the recycling costs for each vehicle \( (\delta_k) \) (Xu et al., 2020; Morfeldt et al., 2021)
by the emission intensity for the disposal phase $\mu$. The recycling costs for each vehicle were obtained from Toyota (TOYOTA, 2021) and Nissan (NISSAN, 2021).

From Eqs. (6), (12), (13), and (14), the LC-CO$_2$ emissions in year $t$ were estimated as:

$$Q_{k}^{Total}(t) = Q_{k}^{MN}(t) + Q_{k}^{DR}(t) + Q_{k}^{DP}(t)$$

(15)

2.3. Scenario analysis

Three different scenarios were examined in this study: changes in fuel efficiency, sales proportion, and average lifetime (see Table 1). We analyzed the impact of these three scenarios on LC-CO$_2$ emissions between 1993 and 2050.

The Japanese government has proposed new fuel efficiency standards for passenger vehicles to be achieved by 2030 (METI, 2020). One requirement is that manufacturers will have to improve the fuel efficiency of their new vehicles by 32.4% compared to 2016 to achieve the Japanese government target in 2030 (METI, 2020). For the first time, the regulations will cover EVs, plug-in hybrid electric vehicles (PHEVs), and GVs. Japanese government target includes the fuel efficiency improvement effects by change in the sales proportion. However, the sales proportion of this study vary from sales proportion scenario,
therefor, this study assumed that all sales proportion scenarios follow the same fuel-efficiency improvement scenarios. We established three fuel-efficiency improvement scenarios: (1) a 2.0% per year improvement after 2016 (following the Japanese government target); (2) a 0.8% per year improvement after 2016; and (3) a 0% per year improvement after 2020.

In scenario (1), manufacturers will achieve the government target in 2030, after which they will continue to improve the fuel efficiency of their new vehicles by 2.0% per year by 2050. Note that manufacturers need to improve the fuel efficiency of new vehicles by 2.0% per year after 2016 to meet the standards in 2030. In scenario (2), manufacturers are unable to meet government standards in 2030, but they achieve them in 2050; it assumes that technological improvements are slow compared with scenario (1), and that fuel intensity improves by 0.8% per year after 2016. In scenario (3), the fuel efficiency of new vehicles does not improve after 2020; the fuel efficiency improvement rate is 0% per year.

Furthermore, based on the three sales proportion targets proposed by the Japanese government, Knobloch et al. (2020), and IEA (2021), we set four sales proportion scenarios depending on the diffusion rate of EVs (see Table 1). Following Alam et al. (2017), we
estimated the sales proportion of each vehicle using a logistic growth model.

In the business as usual (BAU) scenario, GVs and HVs are still mainly sold in 2050, and their sales proportions account for 90% of total sales. The sales proportion of EVs is approximately 10% by 2050. In the medium-spread scenario, HVs and EVs account for 70% and 30% of the total sales in 2050, respectively, but, in the high-spread scenario, these are 45% and 50% in 2050, respectively. Under the IEA roadmap scenario, the sales proportion of EVs is more than 90% in 2050, and the sales of new GVs and HVs, which have internal combustion engines, is prohibited after 2035. The details of each scenario are provided as Supporting Information.

Finally, we established an average lifetime-change scenario in which the average lifetime was shortened by 1–5 years or extended by 1–10 years. This analysis assumed that the lifetimes of all vehicles between 1993 and 2050 were shortened or extended regardless of their fuel intensity or fuel type.

[Insert Table 1 about here]
3. Data sources

All the variables and the data sources used in this study are presented in Table 2.

[Insert Table 2 about here]

4. Results

4.1. Lifetime distributions for GVs and HVs

Tables 3 and 4 show the estimated parameters for different lifetime distributions of GVs and HVs. Using the statistical model selection approach, we selected lifetime distribution with the smallest Akaike's information criterion (AIC) value for each vehicle's distribution. Detailed results for the distribution selections are presented in Tables S3. The most appropriate distribution for GVs in 1998 was a gamma distribution, a widely used continuous probability distribution for continuous variables, which are always positive and have skewed distributions for which the average lifetime was 13.15 years (Table 3). Similarly, the most appropriate distribution for HVs in 2003 was a normal distribution, for which the average lifetime was 14.33 years (Table 4). While most studies have assumed the same vehicle lifetime distribution for vintage vehicles, we considered that different vintages would have different lifetime distributions, with implications for LC-CO$_2$ emissions.
Considering the mechanical similarities of internal combustion engines of EVs, HVs, FCVs, and GVs, this study assumed that EVs follow the physical lifetime distribution of HVs and that FCVs follow the distribution of GVs (Nakamoto and Kagawa, 2021).

4.2. Vehicle stock in 2050

This study focused on GVs, HVs, EVs, and FCVs in Japan. We considered three scenarios (see Table 1): changes in the share of sales, changes in fuel efficiency improvement rates, and average changes in a vehicle’s lifetime. Figure 1 shows the vehicle stock in 2050 for each car sales proportion scenario (see Supporting Information), when the average lifetime was extended by 1–10 years or decreased by 1–5 years. We set this lifetime change range in this scenario analysis based on a previous study (Oguchi and Fuse, 2015). This study used the average lifetime for each vehicle estimated in Section 5.1 as the baseline lifetime (i.e., ±0 year case). The total vehicle stock in year $t$ was constant, regardless of the changes in vehicle lifetimes.
As the average lifetime was extended, the ratio of older vehicles to the total vehicle stock in 2050 increased. We assumed constant or increasing fuel efficiency for a newly purchased vehicle (see Table 3) and found that the ratio of vehicles with relatively poor fuel efficiency increases with their age. Similarly, as the average lifetime decreases, the ratio of newer vehicles to the total vehicle stock in 2050 increases, and that of vehicles with relatively good fuel efficiency increases.

In addition, as shown in Figure 1(a), we assumed that GVs would account for more than 50% of the vehicle stock in 2050. As shown in Figure 1(d), if EVs were to account for a large proportion of the vehicle stock in 2050, then GVs would account for less than 10%. In Figures 1(b) and 1(c), HVs account for approximately 70% and 50% of the vehicle stock, respectively, with the difference in sales proportion reflecting the difference in vehicle stock (Table 1).

4.3. Fuel efficiency, sales proportion, and lifetime changes

We must also account for the manufacturing phase emissions when considering changes in LC-CO₂ emissions associated with vehicle replacement, especially in the case of vehicle electrification. Figure 2 shows the sum of the three phases of emissions: manufacturing,
driving, and disposal. These phases were applied to GVs, HVs, EVs, and FCVs between 1993 and 2050, when the lifetime of all vehicles changed by -5, ±0, or +5 years. Following results are estimated under the IEA’s net zero energy mix. This study defined these three phases of emissions as LC-CO$_2$ emissions. Other lifetime change cases are presented as Supporting Information (Figure S1–S4).

As shown in Figure 2, LC-CO$_2$ emissions decreased year on year, after peaking in 2004 and 2005 because of a reduction in the sales of new cars, a declining population, and fuel efficiency improvements. Based on the demographic data, new car sales in 2050 was approximately 4.8 million in the ±0-year case, which was 56.3% less than the peak in 2004 (Supporting Information). When the fuel efficiency improvement rate was 2.0% per year the LC-CO$_2$ emissions reduced by approximately 10 Mt in 2050, compared to when the fuel efficiency improvement rate was assumed at 0% per year using average vehicle lifetimes (Figure 2(e)–(h)). Although fuel efficiency decreased gradually as the vehicle lifetime was extended, LC-CO$_2$ emissions when the fuel efficiency improvement rate was assumed to be 2.0% per year and the vehicle lifetime was extended by 5 years was reduced by approximately 7 Mt in 2050, compared with when the fuel efficiency improvement rate was assumed to be 0% per year in the same lifetime category (Figure 2(i)–(l)). The effect of fuel
efficiency improvements on LC-CO₂ emissions reduction is remarkable regardless of vehicle lifetime; thus, automakers must continuously improve fuel efficiency.

Figure 2 shows that emissions from the manufacturing phase accounted for approximately 50% of the LC-CO₂ emissions, and that the proportion of the manufacturing phase emissions was increasing when vehicle lifetime was reduced and decreasing when lifetime was extended. When the average lifetime was shortened, the number of newly purchased vehicles increased, and the emissions induced by the manufacturing phase increased. In the IEA scenario, emissions induced by the manufacture of EVs were higher than driving phase emissions.

Each row in Figure 2 represents a change in the sales proportion scenarios. For all the average lifetimes in 2050, the lowest and highest emission scenarios were the IEA and the BAU scenarios, respectively. This trend is consistent in all average lifetime change cases (see Supplementary Information). The number of fossil fuel vehicles in the BAU scenario accounted for more than 80% (GVs: 45%; HVs: 35%) of the total stock in 2050. Conversely,
the IEA scenario, which is the smallest emission scenario in 2050, accounts for 60%–92% of EVs within the total stock in 2050.

Figure 3 shows the results for the effects of changes in the average vehicle lifetime on CO$_2$ emissions between 1993 and 2050 when the fuel efficiency is assumed to improve by 2% per year. Figure 3 shows that extending the average lifetime decreased the total CO$_2$ emissions for all sales proportion scenarios, irrespective of the fuel efficiency improvement rate (see SI). The reduction effects for 58 years associated with a one-year extension in the vehicle lifetime for each sales proportion scenario were 85 Mt, 87 Mt, 88 Mt, and 89 Mt, respectively (Figure 3(a)-(d)). In contrast, shortening the average lifetime by only one year caused more than a 95 Mt increase in the LC-CO$_2$ emissions for 58 years. Even if fossil fuel vehicles account for large proportion in the scenario, increasing the average lifetime of all vehicle types could effectively reduce LC-CO$_2$ emissions.

In addition to total emissions, emissions from the manufacturing and driving phases also decrease by increasing the average lifetime. Studies have shown that lifetime extension
increases driving phase emissions because of the associated increase in the number of old and less fuel-efficient vehicles in service (Figure 1). However, following previous studies (Weymar and Finkbeiner, 2016; Kaneko and Kagawa, 2021), the annual driving distance in this study was set based on vehicle age, and it decreased as vehicle age increased. Therefore, average lifetime extension decreases not only the manufacturing phase emissions but also the driving phase emissions. Consequently, total CO$_2$ emissions decrease even if the average lifetime is extended.

5. Discussion

In 2020, fossil fuel and renewable energy sources respectively account for 76% and 20% of the total electricity generation of Japan (METI, 2019). The Japanese government’s energy mix targets for 2030 comprise 50% fossil fuels (coal and LNG) and 28% renewable energy, whereas the IEA’s net zero targets for 2030 are 25% fossil fuels (coal and LNG) and 61% renewable energy (IEA, 2020). Thus, there are significant differences between Japanese government’s target and IEA’s target for 2030. Although Japanese government has not set energy mix targets for 2050, the IEA’s targets for 2050 are 10% fossil fuels (coal and LNG) and 88% renewable energy (IEA, 2021).
In this study, we found that when the Japanese energy mix in 2030 and 2050 are at the IEA’s target levels, both LC-CO$_2$ emissions in 2050 and the cumulative LC-CO$_2$ emissions between 1993 and 2050 are the lowest under the IEA roadmap scenario (94% of EVs and 6% of FCVs in 2050) relative to other vehicle sales proportion scenarios. These results reflect that the large reduction in CO$_2$ emissions from electricity generation during the driving and manufacturing phases under the IEA’s energy mix for 2030 and 2050.

A comparison between IEA roadmap scenario based on “the Japanese government’s energy mix” and IEA roadmap scenario based on “the IEA’s net zero energy mix” showed that the promoting next-generation vehicle based on the IEA’s energy mix reduced cumulative CO$_2$ emissions from driving phase and manufacturing phase by 0.3% and 6.3%, respectively, between 1993 and 2050 (see Figure S5). It is important to decarbonize the power sector for the automotive sector, which has high emissions from manufacturing phase. Japanese automakers should try to reduce manufacturing emissions through the green power generation at the manufacturing level, in addition to changing the energy mix at the country level.

In addition to the decarbonization of power sector, this study showed that vehicles’ lifetime
extension contributed to reducing LC-CO$_2$ emissions regardless of the vehicle sales proportion. The average lifetime of Japanese vehicles is approximately 13 years, which is relatively short compared to that in other countries, so there is adequate potential for extending the vehicle lifetime. Moreover, in the vehicle manufacturing phase, CO$_2$ emissions are considerably high, especially for EVs and FCVs, which are 1.5 to 2 times higher than those of GVs. These high emissions from the EVs’ manufacturing phase are mainly caused by the production of batteries (Wolfram and Wiedmann, 2017). Even if the decarbonization of the power sector lowers the emissions from the EVs’ driving phase, the emissions from EVs’ manufacturing phase remain significant (Figure 2). To reduce LC-CO$_2$ emissions, the materials used in the vehicles must be decarbonized, and the lifetime extension should be encouraged, especially when EVs and FCVs account for large part of the total vehicle stock.

Globally, the new sales of GVs will be banned in 2035, and electrification will be promoted in the automotive sector. Japanese government has also set the target of 100% electrification (HV, EV, and FCV) of new vehicle sales by 2035, and its policies will promote the replacement of GV to HV, EV, and FCV. However, GVs' replacement and rapid electrification is likely to increase the cumulative LC-CO$_2$ emissions by increasing the emissions from the manufacturing phase. Therefore, governments should promote a gradual replacement and
lifetime extension of vehicles, especially EVs and FCVs to reduce LC-CO$_2$ emissions. Japanese government must also incentivize consumers to extend the vehicle lifetime, for example, by reviewing the vehicle inspection system (Nakamoto and Kagawa, 2018). Moreover, in terms of product lifetime extension, revitalizing the used vehicles market would be an effective measure. The COVID-19 pandemic has delayed the manufacturing of vehicle parts, which has affected the supply time of new vehicles. This delay has induced consumers to extend the vehicle lifetime or purchase a used vehicle instead. Thus, the government should draw from the opportunity presented by COVID-19 to implement policies to promote the long-term ownership of vehicles. Such a policy would enable the continuous reduction of LC-CO$_2$ emissions even in the post COVID-19 society.

6. Conclusion and Policy Implications

Lifetime extension of all types of vehicles is an effective measure for reducing LC-CO$_2$ emissions, irrespective the sales proportion of new vehicle and energy mix. Therefore, this study proposes that the Japanese government should not promote the replacement from GV to electric vehicles immediately, but encourage the lifetime extension of currently owned vehicles. Moreover, before promoting the electrification of vehicles, the electricity sector should be first be decarbonized. Japanese government should change the energy mix target in 2030 to incorporate a larger share of renewable energy. Finally, although electrifying
vehicles and decarbonizing power sector simultaneously will reduce the driving phase emissions, it cannot address the increase of manufacturing phase emissions under the current manufacturing processes, even if the energy mix follows the net zero target. Thus, for reducing LC-CO$_2$ emissions, decarbonization of the electricity sector is insufficient, and it is important to decarbonize the supply chain. Therefore, the government need to focus on the reduction of emissions under the vehicle manufacturing phase as well as reducing the driving phase emissions.

**Code availability**

The MATLAB code that was used for estimating the results of this study is available upon reasonable request and can be used to reproduce the results of this study.
References


(4) Automobile Inspection and Registration Information Association of Japan., 2021, *Vehicle Stock in Japan*.


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### Table 1. Summary of the scenarios used in this study

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GV</th>
<th>HV</th>
<th>EV and FCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales proportion in 2050</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Business as usual (BAU) scenario</td>
<td>49%</td>
<td>40%</td>
<td>11%</td>
</tr>
<tr>
<td>Medium spread scenario</td>
<td>0%</td>
<td>70%</td>
<td>30%</td>
</tr>
<tr>
<td>High spread scenario</td>
<td>0%</td>
<td>44%</td>
<td>56%</td>
</tr>
<tr>
<td>IEA roadmap scenario</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Fuel efficiency improvement rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improvement of 2.0% per year after 2016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improvement of 0.8% per year after 2016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improvement of 0% per year after 2020</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime change between 1993 and 2050</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average lifetime decreased by 1–5 years or extended by 1–10 years.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Data sources in this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho_k(i))</td>
<td>Sales proportion for newly purchased vehicles of fuel type (k) in year (i)</td>
<td>Table S5</td>
<td>Knobloch et al. (2020), IEA (2021)</td>
</tr>
<tr>
<td>(e)</td>
<td>Direct sectoral CO(_2) emission intensity row vector</td>
<td><a href="http://www.f.waseda.jp/washizu/table.html">http://www.f.waseda.jp/washizu/table.html</a></td>
<td>Washizu and Nakano (2021)</td>
</tr>
<tr>
<td>(d)</td>
<td>Vehicle final demand column vector</td>
<td>Table S3</td>
<td>Hienuki et al. (2021)</td>
</tr>
<tr>
<td>(\tau_{m\in P}(t))</td>
<td>Share of a certain energy source in year (t)</td>
<td>Figure S6</td>
<td>IEA (2020), IEA (2021)</td>
</tr>
<tr>
<td>(F_{E,k,i}(t))</td>
<td>Fuel efficiency for vintage (i) by fuel type (k)</td>
<td>Table S6</td>
<td>METI (2020)</td>
</tr>
<tr>
<td>(d_{k,i}(t))</td>
<td>Annual driving distance for vehicles of fuel type (k) and vintage (i)</td>
<td>Table S2</td>
<td>Own calculation</td>
</tr>
<tr>
<td>(\mu)</td>
<td>Emission intensity of the disposal phase</td>
<td>0.605 t-CO(_2)/million JPY</td>
<td>Washizu and Nakano (2021)</td>
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<td>(\alpha_k)</td>
<td>Embodied CO(_2) emission intensity per vehicle of fuel type (k) in the manufacturing</td>
<td>Table S7</td>
<td>Own calculation</td>
</tr>
<tr>
<td>(\beta_k)</td>
<td>Embodied CO(_2) emission intensity for fuel refining</td>
<td>Table S8</td>
<td>Washizu and Nakano (2021), Hienuki et al. (2021)</td>
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<tr>
<td>(\gamma_k)</td>
<td>Direct CO(_2) emission intensity for gasoline combustion</td>
<td>(\gamma_k = 2.32 \text{ kg-CO}_2/\text{L} \ (k = 1,2,3))</td>
<td>Ministry of the Environment (2017)</td>
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<tr>
<td>(\delta_k)</td>
<td>Recycling cost of a vehicle disposed</td>
<td>(\delta_1 = 7500) JPY, (\delta_2 = 10645) JPY, (\delta_3 = 9470) JPY, (\delta_4 = 13565) JPY</td>
<td>Toyota (2021), Nissan (2021), Toyota (2021)</td>
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<tr>
<td>(FP_k)</td>
<td>Price of fuel type (k)</td>
<td>(FP_k = 127.52) JPY/L ((k = 1,2)), (FP_3 = 22.65) JPY/kWh</td>
<td>Agency for Natural Resources and Energy (2021), Ministry of Internal Affairs and Communications (2019)</td>
</tr>
</tbody>
</table>

Note: Tables and Figures are provided in Supporting Information.
<table>
<thead>
<tr>
<th>Vintage</th>
<th>No. of observations</th>
<th>Distribution</th>
<th>Parameter</th>
<th>Average</th>
<th>S.D.</th>
<th>AIC</th>
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<tr>
<td>1998</td>
<td>1,272,841</td>
<td>Gamma</td>
<td>$k=4.16$</td>
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<td>$\theta=3.16$</td>
<td>(3.15,</td>
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<td></td>
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<td>$\mu=12.80$</td>
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<td>3.17)</td>
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<td>1999</td>
<td>1,166,747</td>
<td>Normal</td>
<td>$\mu=12.79$</td>
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<td>$\sigma=5.10$</td>
<td>(5.11,</td>
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<td></td>
<td>$\sigma=5.11$</td>
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<td>5.12)</td>
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<td>1,260,003</td>
<td>Normal</td>
<td>$\mu=12.96$</td>
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<td>$\sigma=5.11$</td>
<td>(5.12,</td>
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<td>5.12)</td>
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<td>5.13)</td>
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<td>2001</td>
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<td>Weibull</td>
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<td>2.47)</td>
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<td>Weibull</td>
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<td>$m=2.44$</td>
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<td>2.44)</td>
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<td>2.44)</td>
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<td>2003</td>
<td>1,183,923</td>
<td>Normal</td>
<td>$\mu=13.01$</td>
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<td>5.62)</td>
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<td>2004</td>
<td>1,273,381</td>
<td>Normal</td>
<td>$\mu=13.34$</td>
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<td>5.63)</td>
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<td>2006</td>
<td>1,124,827</td>
<td>Weibull</td>
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<td>2.15)</td>
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<td>2007</td>
<td>1,183,667</td>
<td>Weibull</td>
<td>$\eta=17.32$</td>
<td>(2.05,</td>
<td>$m=2.05$</td>
<td>(2.06)</td>
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<td>2.06)</td>
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<td>2.07)</td>
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</table>

Note: Confidence intervals for estimated parameters are in parentheses.
**Table 4. Lifetime distributions for HVs**

<table>
<thead>
<tr>
<th>Vintage</th>
<th>No. of observations</th>
<th>Distribution</th>
<th>Parameter</th>
<th>Average</th>
<th>S.D.</th>
<th>AIC</th>
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<tbody>
<tr>
<td>2003</td>
<td>23,861</td>
<td>Normal</td>
<td>$\mu=14.33$</td>
<td>14.33</td>
<td>4.91</td>
<td>108,539</td>
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<td></td>
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<td></td>
<td>$\sigma=4.91$</td>
<td>(14.26, 14.40)</td>
<td>(4.86, 4.97)</td>
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<tr>
<td>2004</td>
<td>67,637</td>
<td>Normal</td>
<td>$\mu=14.35$</td>
<td>14.35</td>
<td>4.97</td>
<td>280,818</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$\sigma=4.97$</td>
<td>(14.31, 14.39)</td>
<td>(4.93, 5.02)</td>
<td></td>
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<tr>
<td>2005</td>
<td>59,200</td>
<td>Weibull</td>
<td>$\eta=15.91$</td>
<td>14.14</td>
<td>5.78</td>
<td>237,621</td>
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<td></td>
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<td></td>
<td>$m=2.63$</td>
<td>(15.94, 15.98)</td>
<td>(2.61, 2.66)</td>
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</tr>
<tr>
<td>2006</td>
<td>79,139</td>
<td>Weibull</td>
<td>$\eta=16.19$</td>
<td>14.38</td>
<td>5.96</td>
<td>281,540</td>
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<td>$m=2.59$</td>
<td>(16.12, 16.26)</td>
<td>(2.56, 2.61)</td>
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<td>2007</td>
<td>84,229</td>
<td>Weibull</td>
<td>$\eta=17.19$</td>
<td>15.22</td>
<td>7.74</td>
<td>274,958</td>
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<td></td>
<td>$m=2.06$</td>
<td>(17.08, 17.30)</td>
<td>(2.04, 2.08)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Confidence intervals for estimated parameters are in parentheses.
Figures

(a) BAU scenario

(b) Medium spread scenario

(c) High spread scenario

(d) IEA roadmap scenario

Figure 1. Vehicle stock in 2050 when the average lifetime was changed (million cars).
Figure 2. Lifecycle CO$_2$ emissions from 1993 to 2050.

Note: Areas under the charts show a 2% improvement in the fuel efficiency per year after 2016.
Figure 3. Effects of changes in the average lifetime of vehicles registered between 1993 and 2050 on CO$_2$ emissions.