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Pathways toward Achieving Carbon Neutrality in the Commercial and Residential Sectors of Tokyo with a Focus on Electrification and Energy Saving

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In addition to improving energy efficiency, increasing the electrification rate in the commercial and residential sectors is regarded as an important CO_2 emission reduction measure to achieve carbon neutrality in Japan's capital city, Tokyo, by 2050. Here, the AIM/Enduse energy model was used to examine the pathways available for achieving carbon neutrality in the commercial and residential sectors of Tokyo by introducing both electrification and high-efficiency equipment. It was found that in order to reduce CO_2 emissions to zero, it is necessary not only to reduce the CO_2 emission factor for electricity to zero, but also to make electrification mandatory for both new and existing buildings and residences after 2030. In contrast, if the electrification mandate is limited to only newly constructed buildings and residences, consumption of fossil fuels such as city gas will remain, resulting in CO_2 emissions of about 5.0 Mt CO_2 in 2050. The results indicate the importance of making electrification mandatory to achieve carbon neutrality.

1. Introduction

In October 2021, Japan's Cabinet approved the Plan for Global Warming Countermeasures, the goal of which is to achieve carbon neutrality by 2050 (Ministry of the Environment, 2021). To achieve this goal, it will be essential to evaluate what CO_2 emission reduction measures can be implemented and then to quantify the effects of those measures. Various studies have been conducted as part of efforts to achieve carbon neutrality by 2050, such as those targeting Japan (Ministry of Economy, Trade and Industry, 2021), the EU (Potrc et al., 2021), Brazil, etc (Alves et al., 2023). These studies show that achieving carbon neutrality requires a significant introduction of renewable energy, improving energy efficiency, electrification of equipment and hydrogen-based systems, etc. In particular, the study, which focuses on Japan, indicates that increasing the electrification rate (the share of electricity consumption among the total energy consumption) within the commercial and residential sectors will be important CO_2 emission reduction measures to achieve carbon neutrality.

In this situation, mandatory electrification is attracting attention as a measure to strongly promote electrification.

In Europe and the U.S., some municipalities have taken major steps toward increasing the electrification rate, such as by making electrification mandatory for new buildings in order to decarbonize buildings (Nakano and Nishio, 2023). Although some positive policy interventions have begun, little study has been done to evaluate the extent to which mandatory electrification will reduce CO_2 emissions.

The aim of the present study was to show what pathways exist for achieving carbon neutrality in the commercial and residential sectors of Tokyo. Of particular interest was the effects mandatory electrification of commercial and residential buildings would have on reducing CO_2 emissions. In Japan's capital city, Tokyo, the commercial and residential sectors account for about 70 % of the total CO_2 emissions of Tokyo (Tokyo Metropolitan Government, 2021), meaning increasing the electrification rate of those sectors will be essential for reducing CO_2 emissions. Nevertheless, the Tokyo Metropolitan Government has yet to mention any specific electrification policy, even in the Tokyo Metropolitan Government's Basic Environmental Plan (Tokyo Metropolitan Government, 2022). This study clarifies the impact of mandatory electrification on CO_2 emission reductions, and provides important insights for future climate policies.

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2. Methodology for estimating CO_2 emissions in 2050

2.1 Overview of the AIM/Enduse model

In this study, we examined the effects of installing high-efficiency equipment and increasing the rate of electrification in order to achieve zero CO_2 emissions in the commercial and residential sectors of Tokyo. For this purpose, the AIM/Enduse model (Kainuma et al., 2002), a bottom-up energy model that allows detailed analysis at the equipment level, was used to estimate final energy consumption and CO_2 emissions in the commercial and residential sectors of Tokyo. In this model, the least-cost energy technologies, considering both annualized initial cost and running cost, are selected year by year to meet energy service demands exogenously defined in advance (Eq(1)). Based on the results of the technology selection, energy consumption and CO_2 emissions are calculated. In the present analysis, the year 2013 was used as the base year, and CO_2 emissions were estimated for each year from 2013 to 2050. Table 1 shows the data on which the analysis is based.

$$TC = \sum_i \left[\sum_l \left\{ \left(c_{l,i} \times r_{l,i} \right) + \sum_k \left(g_{k,i} \times E_{k,l,i} \right) \right\} + tax \times Q_i \right] \quad (1)$$

TC – total annual cost
r_l – annual new installations of equipment l
$E_{k,l}$ – annual consumption of energy type k of equipment l
Q – annual emissions of CO_2
C_l – initial cost of equipment l (annualized)
g_k – price of energy species k
tax – carbon tax
i – sector classification

Table 1: List of the data on which the analysis is based.

Related section	Data
2.3	Equipment efficiency, initial cost, durable life
3.1	Energy consumption and equipment penetration rate in the base year, the total floor area, the number of households, population, the number of workers by industry, past construction starts
3.2	Energy prices, CO_2 emission factor

The above data used in this study are publicly available on GitHub (github.com/Hiroaki-0/CET-data.git). However, this data is not commonly used in AIM/Enduse, but only in this study.

2.2 Sector classification

This study focused on the commercial and residential sectors of Tokyo. Based on Tokyo Metropolitan Government (2021) and The Institute of Energy Economics, Japan (2020), the commercial sector was classified into eight industry categories: offices/buildings, department stores/supermarkets, wholesale/retail, restaurants, schools, hotels/inns, hospitals, and others. Based on Ministry of Internal Affairs and Communications (2013a), the residential sector was classified into eight categories based on a combination of region (urban area or suburb), housing construction type (detached or collective), and household composition (single or multiple).

2.3 Energy, energy service types and energy technology

Based on Tokyo Metropolitan Government (2021), five energy types were set as consumed: electricity, city gas, LPG, kerosene, and heavy oil (no heavy oil is consumed in the residential sector). Based on various reports such as The Institute of Energy Economics, Japan (2020) and Imaeda and Yanagi (2004), seven energy service types were defined: cooling, heating, hot water, cooking, lighting, refrigeration/freezing, and other power.
Table 2 lists the energy technologies targeted for implementation in the present study. Equipment efficiency, initial cost, and durable life were set based on several reports including Ministry of the Environment (2012), Kanamori (2017), Takahashi and Asano (2008), and Ministry of Internal Affairs and Communications (2013b).

Table 2: List of targeted energy technologies

Energy service	Energy technology
Cooling/heating	Packaged air conditioners, air-cooled heat pumps, gas heat pumps, turbo chillers, absorption hot and chilled water generators, absorption chillers, boilers
Hot water	Gas water heaters and boilers, oil water heaters and boilers, heat pump water heaters, electric water heaters
Cooking	Gas kitchen, electrified kitchen
Lighting	LED lighting, fluorescent lamps, incandescent lamps
Refrigeration/freezing	Refrigerators/freezers
Other	Power equipment

3. Analysis scenarios

3.1 Future energy service demand

The following method was used to calculate future energy service demand in the commercial sector. First, energy consumption was estimated for the base year (2013) by energy type and energy service. Energy consumption and equipment penetration rate in the base year were estimated based on several reports including Tokyo Metropolitan Government (2015), Ministry of the Environment (2012, 2013), Imaeda and Yanagi (2004), and Tonooka et al. (2008). Second, the base-year energy service demand was calculated by multiplying the base-year energy consumption by the equipment efficiency of the energy technology. Finally, the future energy service demand was calculated by multiplying the base-year energy service demand by the future growth rate of the total floor area of the commercial sector. The future total floor area of the commercial sector was calculated by multiple regression analysis using the number of workers by industry and population as explanatory variables. For the detailed calculation method, refer to Katano and Masui (2023).

In the residential sector, as in the commercial sector, the base-year energy service demand was calculated first. Future energy service demand was calculated by multiplying the base-year energy service demand by the future growth rate of the number of households. The future number of households was prorated by household composition and house construction based on the Tokyo Metropolitan Government's future projections (Tokyo Metropolitan Government, 2019) and another survey (Ministry of Internal Affairs and Communications, 2013a). To distinguish between buildings and houses built up to 2030 and new buildings and houses built after 2030, the total floor area of new and existing buildings and houses were calculated each year. The energy service demand was prorated by the ratio of the total floor area of existing construction to the total floor area of new construction in each year. For the total floor area of buildings and houses, the total floor area of new buildings and houses was calculated for each future year by assuming that the total floor area of buildings and houses decreases each year based on the Weibull distribution, referring to the method in Adachi et al. (2004). For past construction starts, we used statistics from the Ministry of Land, Infrastructure, Transport and Tourism (2023). The shape parameters of the Weibull distribution were also determined based on a previous study (Hasegawa et al., 2014). As a result, as of 2050, the commercial and residential sectors accounted for 51.2 % and 40.9 % of the total floor area of buildings constructed after 2030.

3.2 Case setup

Energy prices for 2013 were set based on actual values (The Institute of Energy Economics, Japan, 2020). Electricity prices until 2050 were defined using Ministry of Economy, Trade and Industry (2021). Fossil fuel prices for 2050 were changed according to the Stated Policies scenario in the World Energy Outlook 2020 (IEA, 2020). In this analysis we combined several CO_2 emission reduction measures, set up a case setting, and estimated CO_2 emissions in 2050 to evaluate what measures would bring CO_2 emissions closer to zero. The CO_2 emission reduction measures assumed in this analysis are shown in Table 3, and the case settings are shown in Table 4.

Table 3: CO_2 emission reduction measures considered in this analysis

CO_2 emission reduction measure		Contents
Mandatory electrification	Not mandated	No electrification is mandatory.
	Mandatory only for new construction	After 2030, electrification of equipment is required when buildings are newly constructed.
	Mandated	After 2030, electrification of equipment is mandatory for both new and existing buildings.
Reduction of emission factor for electricity	Constant	Assume that the emission factor for electricity does not change from the emission factor as of 2013.
	Zero	Assume that the emission factor for electricity is zero in 2050 and that it decreases linearly from 2013.
Introduction of carbon tax and subsidies	Not introduced	No carbon tax and subsidies
	Introduced	Introduce a carbon tax of 10,000 JPY/t CO_2 after 2025. 33.3 % of the initial cost will be subsidized for high-efficiency electrical equipment after 2025.

Table 4: Cases for which estimates were made

Case	Mandatory electrification	Reduction of emission factor for electricity	Introduction of carbon tax and subsidies
No-ELE + Const	No	Constant	No
No-ELE + Zero	No	Zero	No
Part-ELE + Zero	Yes, only for new construction	Zero	No
Part-ELE + Zero + Tax	Yes, only for new construction	Zero	Yes
All-ELE + Zero	Yes	Zero	No
All-ELE + Zero + Tax	Yes	Zero	Yes

4. Simulation results

4.1 Final energy consumption by energy type

Figure 1a shows the estimated final energy consumption by energy type for the base year and for 2050. In the commercial sector, if electrification is mandated only for new buildings constructed after 2030 (case: Part-ELE + Zero), the electrification rate will increase from 65.0 % in the base year to 83.8 % in 2050, and electricity consumption will also increase by 2.6 % from the base year. Along with electrification, city gas consumption in 2050 will have decreased by 63.7 % from that in the base year. If electrification of all buildings after 2030 is made mandatory (case: All-ELE + Zero), the electrification rate in 2050 will rise to 99.6 %, and electricity consumption will increase by 12.7 % from the base year. With a significant increase in electrification, city gas consumption would decrease by 99.2 % from that in the base year.

In the residential sector, if electrification is mandated only for new houses after 2030, the electrification rate in 2050 will increase from 50.2 % in the base year to 64.2 %, and electricity consumption will also increase by 3.5 % from the base year. Consumption of city gas would decrease by 41.6 % from that in the base year. If electrification of all residences, including existing houses after 2030, is also made mandatory, the electrification rate in 2050 will rise to 99.6 %, and electricity consumption in 2050 will increase by 22.7 % compared to that in the base year. A significant increase in electrification would result in a 99.5 % decrease in city gas consumption compared to that in the base year.

If all buildings and residences are subject to mandatory electrification after 2030, the electrification rate in 2050 will be approximately 100 %. By contrast, if the electrification mandate is applied only to newly constructed buildings and residences, a considerable amount of city gas consumption will remain in 2050, so it will be necessary to replace city gas with synthetic fuels or take other measures. Introduction of a carbon tax and subsidies will promote the use of highly efficient equipment and result in a further 6–9 % reduction in electricity consumption in the commercial sector and a further 1 % reduction in electricity consumption in the residential sector compared to the case in which the carbon tax and subsidies are not introduced. These results indicate that measures to reduce electricity consumption will be important for achieving carbon neutrality, especially since renewable energy and other resources are currently limited in Tokyo.

4.2 CO_2 emissions

Figure 1b shows the results for CO_2 emissions. In the commercial sector, if the CO_2 emission factor of electricity is left unchanged until 2050, CO_2 emissions in 2050 will be reduced by 10.9 % compared with that in 2013. Even if the CO_2 emission factor for electricity is zero in 2050, CO_2 emissions will be reduced by 87.7 % in the absence of mandatory electrification. If electrification is mandated for new buildings after 2030, the reduction will be 94.0 %. Furthermore, if electrification is made mandatory for all buildings after 2030, the reduction will be 99.9 %, resulting in almost zero CO_2 emissions.

Similarly, in the residential sector, if the CO_2 emission factor for electricity remains at the same level as in 2013, CO_2 emissions in 2050 will be reduced by 7.7 % compared to that in 2013; even if the CO_2 emission factor for electricity is zero in 2050, CO_2 emissions will be reduced by 73.7 % in the absence of mandatory electrification. If electrification is mandated for new homes after 2030, the reduction will be 84.4 %; if electrification is mandated for all homes after 2030, the reduction will be 99.9 % and CO_2 emissions will be almost zero.

These results show that it is extremely important to reduce the CO_2 emission factor for electricity. However, to bring emissions close to zero, it will also be necessary to promote electrification of all buildings after 2030. Note that the effect of introducing a carbon tax and subsidies on reducing CO_2 emissions in 2050 was negligible, with a less than 1 % decrease in emissions compared to that for cases in which they were not implemented.

4.3 Cost of measures

Table 5 shows the estimated cumulative costs from 2013 to 2050 for energy and initial investment costs. Note that the cumulative costs are additional costs based on case No-ELE + Zero. In the commercial sector, the additional initial investment costs associated with the electrification mandate amounted to approximately 0.5 to 2.6 trillion JPY. Energy costs associated with the electrification mandate increased by about 0.5 to 1.4 trillion JPY without a carbon tax and subsidies, while they were decreased by about 0.5 trillion JPY with a carbon tax and subsidies. Similarly, in the residential sector, the additional initial investment costs associated with the electrification mandate were 2.3 to 7.0 trillion JPY. By contrast, energy costs decreased by approximately 10 billion to 0.4 trillion JPY.

The findings for both the commercial and residential sectors show that the introduction of a carbon tax and subsidies could reduce cumulative costs. However, the costs in Table 5 do not include carbon tax payments and subsidy receipts. The results also show that in each case, cumulative carbon tax payments ranged from 2.1 to 2.7 trillion JPY and cumulative subsidy receipts ranged from 0.7 to 1.5 trillion JPY.

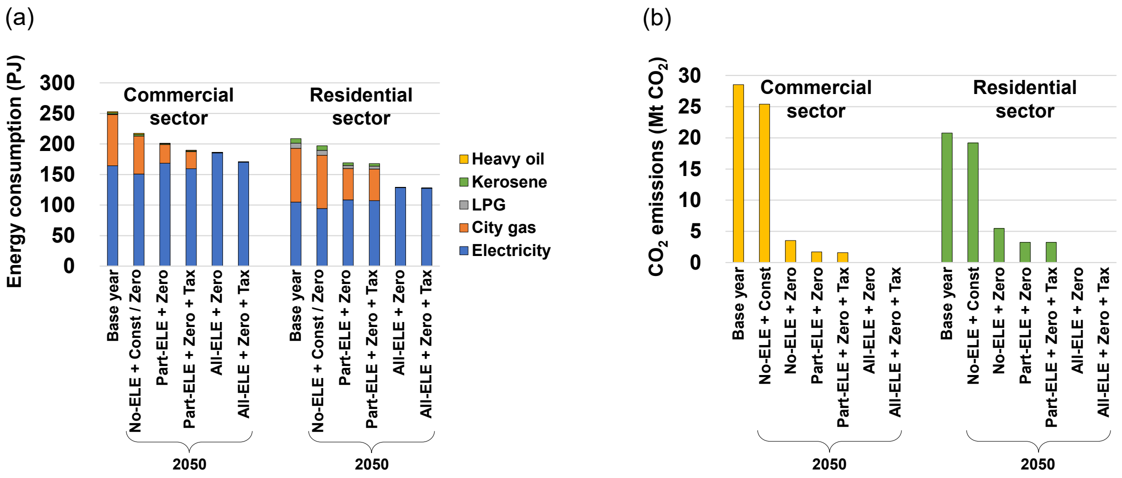

Figure 1: Simulation results of (a) final energy consumption, and (b) CO2 emissions

Table 5: Cost of measures

Case	Commercial sector			Residential sector		
	Energy cost (billion JPY)	Initial investment cost (billion JPY)	Total cost (billion JPY)	Energy cost (billion JPY)	Initial investment cost (billion JPY)	Total cost (billion JPY)
No-ELE + Zero	0	0	0	0	0	0
Part-ELE + Zero	510	540	1,040	-10	2,250	2,230
Part-ELE + Zero + Tax	-540	1,390	850	-210	2,380	2,180
All-ELE + Zero	1,380	1,200	2,580	-200	6,790	6,590
All-ELE + Zero + Tax	-480	2,620	2,130	-440	6,950	6,520

5. Conclusion

Here, AIM/Enduse was used to analyze the commercial and residential sectors of Tokyo in order to identify the measures necessary to achieve zero CO_2 emissions.

The results indicate that efforts to reduce the CO_2 emission factor for electricity to near zero are extremely important because of the high CO_2 emissions from electricity in the commercial and residential sectors of Tokyo. Currently, many countries, including Japan, are mainly dependent on natural gas and coal as fuels for power generation. Those countries are required to switch to power sources with lower CO_2 emission factor. However, simply bringing the CO_2 emission factor of electricity closer to zero will not reduce CO_2 emissions to zero. To achieve zero CO_2 emissions, electrification of all new and existing buildings and homes needs to be mandatory after 2030. Several issues exist when electrifying existing buildings and residences, such as securing installation space for heat pump water heaters and other equipment. If it is difficult to mandate electrification of existing buildings and residences, city gas consumption in the commercial sector and residential sector will remain at around 36.3 % and 58.5 % of the 2013 level, respectively. CO_2 emissions from city gas consumption in 2050 will be around 5.0 Mt CO_2, which would be equivalent to 10.0 % of the CO_2 emissions in 2013. Therefore, it will be necessary to replace these fossil fuels with synthetic fuels or other technologies that do not emit CO_2. Since this study did not analyze the availability and acquisition cost of synthetic fuels to replace the remaining fossil fuels, it is needed to be addressed in future studies.

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