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Potential for reducing CO_2 emissions from passenger cars in Japan by 2030 to achieve carbon neutrality

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ABSTRACT

For Japan to achieve its targets for carbon neutrality and reduction of carbon dioxide (CO_2) emissions, decarbonization of road transport is essential. Japan regards next-generation vehicles, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell vehicles, as a key means of reducing carbon emissions from road transport. Four scenarios were proposed to predict the potential carbon emissions reduction of passenger car use in 2030: baseline, business-as-usual, government's target-based, and aggressive scenarios. Economic input–output life cycle assessment was used to evaluate potential CO_2 emissions, acidification, eutrophication, human toxicity, and photochemical oxidation associated with passenger cars. In this study, all environmental impacts were calculated using the multi-regional environmentally extended supply and use/input–output database by applying the CML 2001 impact assessment method. The findings indicate that PHEVs have the lowest CO_2 emissions per km traveled, followed by HEVs and BEVs. The prediction for carbon emissions from passenger cars shows that adopting electrified vehicles, such as HEVs, PHEVs, and BEVs could help decarbonize the passenger car sector. The population of vehicles, vehicle manufacturing, well-to-wheel cycle of fuel, and fuel economy will significantly contribute to CO_2 emissions. Finally, this study recommends policies to steer Japan into achieving its goal of carbon neutrality.

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1. Introduction

The transportation sector produces one-fourth of worldwide carbon dioxide (CO_2) emissions from direct fossil fuel burning. According to the International Energy Agency (IEA), road vehicles, which include automobiles, trucks, buses, and two- and three-wheelers, contributed to approximately 75% of all transport-related global CO_2 emissions in 2020 [1]. The CO_2 emissions of Japan totaled 1.11 billion tons in 2020, of which approximately 19% was generated by the transportation sector.

Electric vehicles are one possible solution for decarbonization of the transportation sector. Electricity production is decarbonized if fossil fuels are replaced with renewable energy sources [2,3]. Japan regards next-generation vehicles, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell vehicles (FCVs), as a key means of reducing CO_2 emissions from road transport, enhancing energy security, and boosting the competitiveness of the automotive industry. The Japanese government aims at achieving carbon neutrality by 2050 [4]. To reach this target, one objective is to increase the proportion of electrified (i.e., electric or partially electric) vehicles in yearly sales of new passenger cars on the domestic market to 100% by 2035. Numerous initiatives are being undertaken to achieve this objective [5]. Next-generation vehicles are gradually being introduced into the market, and the share of next-generation vehicles in new passenger car registrations in 2019 and 2020 exceeded 39% [6].

Generally, BEVs and FCVs do not release CO_2 when operating, in contrast to internal combustion engine vehicles (ICEVs); however, the primary energy sources of the electricity used to charge BEV batteries or to produce hydrogen must be considered when comparing total CO_2 emissions. Accurate evaluation of the environmental impact of such vehicles demands a comprehensive life cycle assessment (LCA) considering all stages of vehicle production and consumption, including the associated fuel use and CO_2 emissions.

The environmental impacts of individual of various vehicles have been extensively assessed by previous studies. In order to enhance

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policy-making, many researchers have moved their attention to assessing large-scale CO_2 emissions from a nation's vehicle fleet. Bandivadekar et al [7] evaluated full life cycle of ICEVs, HEVs, PHEVs, BEVs and FCVs individually, then assessed CO_2 emissions from vehicle fleet in the United States (US) and major European countries by considering ICEVs, diesel vehicles, HEVs and PHEVs. Garcia and Freire [8] conducted a literature review on studies evaluating the environmental effects of adopting electrified vehicles into fleets of light-duty vehicles. This review found that most research omitted vehicle manufacturing on the system boundaries and that most of the geographic coverage was restricted to the US. Wolfram and Wiedmann [9] applied a multi-regional input-output (MRIO) based hybrid approach to evaluate the total carbon footprint of adopting ICEVs, HEVs, PHEVs, and BEVs into vehicle fleets in Australia. Moreover, Guo et al [10] estimated China's total CO2 emissions from the passenger vehicle sector by considering ICEVs and BEVs. Nevertheless, previous studies in other countries contexts could not reflect Japan's case since assumptions and results are highly reliant on national factors. This study also considers FCVs for fleet vehicles together with ICEVs, HEVs, PHEVs, and BEVs. Therefore, the main objective of the present study was to predict the total greenhouse gas (GHG) emissions by passenger cars in 2030 under various scenarios. The subsequent sections of this paper have been organized as follows. Section 2 explains the methodology, data sources, and scenarios. Results and discussion are presented in Section 3. Finally, conclusions are presented in Section 4.

2. Methodology

2.1. LCA

LCA is a technique used to examine the environmental impacts of a product, process, or activity across its entire life cycle, from extracting and processing raw materials to the production, transportation, and distribution of the finished product/process/activity, as well as its end-of-life [11]. The benefit of LCA is its comprehensive assessment of an entire product, thereby preventing any sub-optimization that may result from only concentrating on a few stages. LCA enables a comparison of the potential environmental impacts of multiple alternatives [12].

There are several approaches in the LCA methodology, including process-based LCA, economic input–output (EIO) LCA, and hybrid LCA [13]. Process-based LCA is a bottom-up approach which focuses on scientifically analyzing the step-by-step process involved in producing, transporting, using, and disposing of a product. In this approach, the life cycle is modeled as a series of unit processes, calculating the environmental impacts of the inputs and outputs for each unit process. However, the main disadvantage of process-based LCA is that analyzing a complicated product or service, such as automotive manufacturing, requires a massive amount of data that is difficult to obtain, as well as clearly defined analysis boundaries [14]. Despite being a recognized standard framework, it has drawn criticisms for having incomplete system boundary [15], difficulties in allocation, and double counting [16]. Process-based techniques for compiling life cycle inventories suffer from a truncation error caused by the exclusion of resource requirements or pollutant emissions of higher-order upstream stages of the production process. The magnitude of truncation error varies with the product type and can be high [17]. These drawbacks can be addressed by EIO–LCA since it theoretically covers the whole economy and interactions among all sectors. EIO–LCA is a relatively straightforward approach to LCA that uses historical data on various economic transactions to trace a readily available supply chain from which the environmental impacts can be calculated accordingly. The key benefits of the EIO–LCA method are that it accounts for the complete supply chain of economic activity required to manufacture any good or service in the economy [18,19] without the need to define a particular analysis boundary. And a combination of EIO–LCA and process-based LCA is called hybrid LCA, taking advantage of both methods. The result from EIO–LCA or hybrid LCA may contain errors due to sector-level aggregation, homogeneity, and proportionality problems. The aggregation problem comes from the fact that all currently existing input-output models aggregate potentially considerably varied industrial sectors into a single sector. The homogeneity problem implies that all sector items are considered to have the same environmental impacts per monetary transaction. The proportionality problem arises from the assumption that the relationship between the price of one sector and its environmental burdens is linear. The three errors inherent in EIO–LCA are claimed to be significantly smaller than the truncation error of a process-based [17]. Advantages and drawbacks of each method are summarized in Table 1.

Despite the widespread use of single-region EIO models in previous electric car-related LCA studies [20–22], MRIO models reflect the latest developments to assess environmental impact on a worldwide scale [23–25]. In an MRIO framework, the flows reflect the import and export value by nation and economic sector. MRIO analysis can link environmental data to integrate environmental accounting into an economy using an extension known as environmentally extended input–output (EEIO) analysis, which can more realistically quantify environmental impacts within a whole economy from a life cycle perspective. Currently, several projects are producing global MRIO tables, such as the externality data and input–output tools for policy analysis (EXIOPOL), the global resource accounting model, the global trade analysis project, the world input–output database (WIOD), the multi-regional environmentally extended supply and use/input–output database (EXIOBASE), and Eora [26,27].

In this study, EIO–LCA was applied to evaluate environmental impacts of passenger cars in Japan. All environmental impact categories were calculated using the EEIO database EXIOBASE [28] and openLCA software [29]. OpenLCA makes it possible to perform simple EEIO-based calculations using EXIOBASE, such as global warming potential (GWP), without the need for manual calculations and EEIO handling. EXIOBASE is a set of multi-region, environmentally extended supply-use and input–output tables created for EEIO analyses [28]. EXIOBASE supply-use tables are monetary, i.e., inputs are expressed as financial units, although the newest hybrid version of the database also includes physical units. EXIOBASE version 3 covers 44 countries, 200 products, 662 material and resource categories, and 417 emissions categories [28]. EXIOBASE 3 includes data from 1995 to 2011.

A LCA is comprised of four phases: (i) goal and scope definition, (ii) inputs and outputs inventory, (iii) impact assessment, and (iv) interpretation of results [30]. This study will address the four stages as established in the standards set by the International Organization for Standardization (ISO).

2.2. Goal and scope

System boundaries include vehicle and fuel life cycles. The vehicle life cycle refers to the CO_2 emissions generated through vehicle production, whereas the fuel life cycle refers to CO_2 emissions generated through fuel consumption during vehicle use. In this study, the five previously introduced types of vehicles are considered to be passenger vehicles, including gasoline ICEVs, HEVs, PHEVs, BEVs, and FCVs. The total driving mileage in the life cycle is set as 150,000 km as the functional unit.

2.3. Life cycle inventory

2.3.1. Vehicle characteristic and data

For vehicle composition, including main body, power train, chassis, electrical system, and other miscellaneous parts, the gasoline ICEV was considered as the baseline. HEVs and PHEVs have added batteries and motors when compared to gasoline ICEVs. The BEV has the engine and fuel tank removed when compared to a gasoline car and is equipped with a motor and a large capacity battery. The FCV is equipped with

Table 1
Characteristics of different LCA approaches based on Suh et al [13] and Lenzen [17].

Element	Process-based LCA	EIO–LCA	Hybrid LCA
Life cycle inventory	Process analysis	Input-output analysis	Combining process and input-output analysis
Advantage	Provide detailed information on the process	Includes the entire economy	Includes a complete system boundary
Drawback	Tend to be time intensive and costly	High sector-level aggregation	High sector-level aggregation
	Usually has high truncation errors	Homogeneity and proportionality problems	Homogeneity and proportionality problems
			Relatively complex to use

an FC stack and hydrogen tank, a battery, and a motor. Reflecting the latest technological trends, HEVs, EVs, PHEVs, and FCVs are considered to be equipped with lithium-ion batteries. Estimations of the vehicles manufacturing producer costs were obtained from Washizu and Nakano [31]. Vehicles' lifetimes are assumed to be 15 years with a 150,000-km driving mileage.

2.3.2. Fuel life cycle

The fuel life cycle, also known as well-to-wheel (WTW), can be divided into two groups of processes: well-to-tank (WTT) and tank-to-wheel (TTW). WTT includes fuel production, fuel storage, distribution to fueling stations and refueling, whereas TTW includes the use of fuel in the vehicle [32]. In this study, three types of fuel-related to vehicles were taken into consideration, namely, gasoline, electricity, and hydrogen.

The electricity mix for 2030 was assumed based on power source composition for the energy supply, and the projected demand outlook for 2030 of thermal power (41.0%), nuclear power (20%–22%), and renewable energy (36%–38%) can be seen in Fig. 1. Inventory data for electricity mix were obtained from Washizu and Nakano [31]. Japan's electricity mix in 2015 was also considered for showing changes in environmental impact due to different composition ratios of power generation.

In this study, only one pathway for the hydrogen supply chain was considered, in which hydrogen is produced overseas by electrolysis using wind power and stored through the hydrogenation of toluene-methylcyclohexane (MCH) [33,34]. The MCH is then transported to Japan via sea tanker. In the landing port, the MCH is then dehydrogenated to produce toluene and hydrogen. The released hydrogen from MCH must be purified, as highly pure hydrogen is required for fuel cell use. Finally, the hydrogen is transported by truck to the hydrogen refueling station, and the toluene is shipped back to the origin countries for repeat use as a raw material in MCH production. Inventory data of hydrogen were obtained from Nakano and Washizu [35].

Emissions in the TTW cycle mainly depend on type of fuel and fuel consumption. Fuel economy is important to estimate fuel consumption during the operation phase of passenger cars. Fuel economy of each passenger car was found from literature, where the worldwide harmonized light duty driving test cycle (WLTC) mode was used in vehicles' driving cycle [31], as shown in Table 2.

2.4. Impact assessment

The CML 2001 approach was used in this study to categorize and characterize the environmental impacts of the system. The categories considered in this study are briefly described in the following subsections:

- GWP: The release of GHG into the atmosphere is linked to climate change. Climate change can have negative implications on ecological and human health and planetary well-being. The GHG emissions of vehicle/fuel options are calculated in terms of equivalent CO_2 (CO_2 eq), which is used to express the GWP for a time horizon of 100 years (GWP100).
- Human toxicity: Toxic substances on the human environment are the primary concerns of this category. 1,4-Dichlorobenzene equivalents/kg emission is used to express each toxic substance.
- Acidification potential: It measures the changes in acidity level. Acidification potential is accounted for in terms of equivalent sulfur dioxide (SO_2 eq).
- Photochemical oxidation potential: It is measured in terms of equivalent ethylene.

2.5. Scenarios

This study intended to examine the possibility for reducing CO_2 emissions and to evaluate the additional environmental impacts of the passenger car subsector in 2030. Subsequently, alternative scenarios, including baseline, business-as-usual (BAU), government's target-based (GOV), and aggressive, have been defined based on the primary

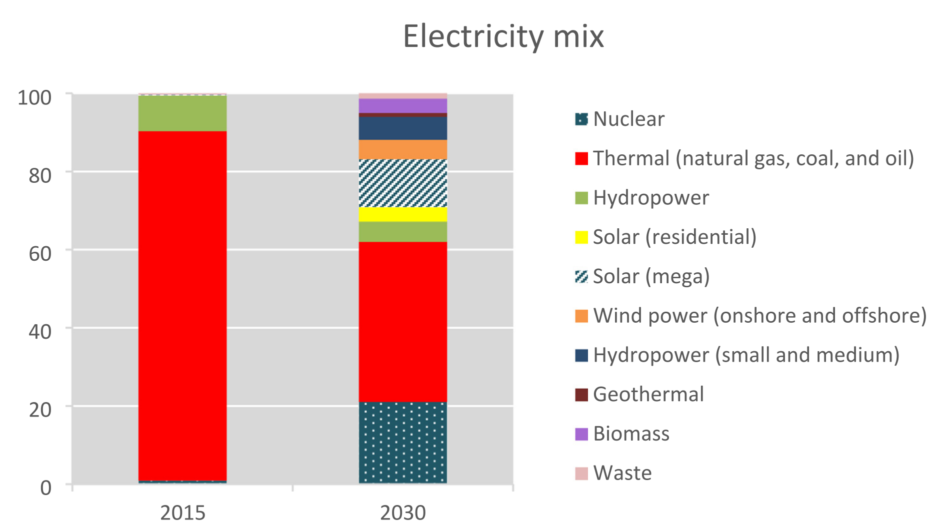

Fig. 1. Composition ratio of Japan's electricity mix in 2015 and 2030.

Table 2
Assumed fuel economy in WLTC mode (based on Washizu and Nakano [31]).

Vehicles	Gasoline car	HEV	BEV	PHEV*	FCV
Fuel economy	16.4 km/L	27.2 km/L	155.0 Wh/km	30.3 km/L 107.0 Wh/km	135.0 km/kg

* Use of both gasoline and electricity is assumed to equal 50%.

variables impacting CO_2 emissions from passenger cars. The data and settings of these scenarios are detailed below.

2.5.1. In-use passenger car population

According to the Japanese Automobile Manufacturers Association (JAMA), there were 62.19 million units of in-use passenger cars, including 49.92 million gasoline ICEVs, 10.87 million HEVs, 141 thousand PHEVs, 152 thousand BEVs, 3.6 thousand FCVs, and 1.02 million clean diesel vehicles (CDVs), in Japan in 2019. The proportions of each vehicle type to the total in-use passenger cars were 80%, 17.5%, 0.23%, 0.24%, 0.006%, and 1.6% respectively [6].

2.5.2. Newly registered passenger cars

In 2019 and 2020, the share of next-generation vehicles among all newly registered passenger cars in Japan exceeded 39%. In 2019, 4.3 million cars were sold, including 2.3 million gasoline ICEVs, 1.3 million HEVs, 14.3 thousand PHEVs, 700 FCVs, and 147,000 CDVs (JAMA, 2021). The shares of each vehicle type in the total in-use passenger cars were 60.8%, 34.2%, 0.41%, 0.49%, 0.02%, and 4%, respectively [6]. The number of newly registered passenger cars in 2030 is expected to reach 4 million.

2.5.3. Future passenger car population trends in 2030

The Japan passenger car population prediction used in this study was obtained from Gendai Mobility Research [36], which predicts that the total number of in-use passenger cars in Japan will decline to 55.55 million in 2030, owing to ownership saturation and diminishing population.

2.5.4. Building scenarios

Four scenarios are considered in this study, based on the share of each vehicle type in the total predicted passenger car population and newly registered cars in 2030. The expected percentages of in-use passenger cars and newly registered cars for each scenario is shown in Table 3. Due to a lack of data on CDV manufacturing, this study cannot consider CDVs in the analysis.

- Baseline scenario

In this scenario all passenger cars are gasoline ICEVs.

Table 3
Shares of expected number of in-use passenger cars and newly registered cars for each scenario.

Expected shares of vehicles in 2030		Scenario			
		Baseline	BAU	GOV	Aggressive
In-use passenger cars (%)	ICEVs	100	58.09	53.28	52.08
	HEVs	0	39.75	28.80	30.21
	PHEVs	0	0.95	8.24	8.30
	BEVs	0	1.15	8.24	8.37
	FCVs	0	0.06	1.44	1.04
Newly registered passenger cars (%)	ICEVs	100	50.00	30.00	18.60
	HEVs	0	47.00	38.70	51.30
	PHEVs	0	1.27	14.10	14.10
	BEVs	0	1.63	14.20	14.20
	FCVs	0	0.10	3.00	1.80

Total of expected number of in-use passenger cars in 2030 is 55.55 million unit.
Total of expected number of newly registered cars in 2030 is 4 million unit.

- BAU scenario

This scenario is constructed based on the assumption of a linear trend in the proportions of each type of vehicle in the total newly registered passenger cars and in the total number of in-use passenger cars.

- GOV scenario

This scenario is constructed based on the Japanese government's targeted roadmap. For 2030, the Japanese government has established a target of 50–70% of new passenger car sales being next-generation vehicles, of which 30%–40% are HEVs, 20%–30% are PHEVs and BEVs, approximately 3% are FCVs, and 5%–10% are CDVs. The market share of gasoline ICEVs is expected to decrease to 30%–50% in 2030. The government also targeted the number of FCVs to reach 800,000 in 2030.

- Aggressive scenario

The aggressive scenario is constructed referencing Washizu and Nakano [31]. The “Green Growth Strategy for 2050 Carbon Neutral”, announced in June 2021, set a goal of reducing the number of gasoline vehicles sold to 0% by 2035; thus, if the ratio of gasoline vehicle sales decreases linearly from 2020 to 2035, the number of gasoline ICEVs in 2030 is estimated to be 18.6%.

2.6. Calculation

Emissions of vehicle manufacturing for each car were calculated based on the EIO–LCA approach, as well as WTT of each fuel type. The TTW CO_2 emissions of gasoline is assumed to be 2.323 kg/L, which is converted from direct CO_2 emission per calorific value in literature [37]. Since electricity and hydrogen have no emissions during operation, TTW emissions of electricity and hydrogen are assumed to be zero. Furthermore, WTW environmental impacts of each fuel are calculated using eq. 1.

$$E_{WTW_j} = E_{WTT_j} + E_{TTW_j} \tag{1}$$

Here, j refers to fuel type (i.e., gasoline, electricity, and hydrogen), E_{WTW_j} is WTW environmental impacts of fuel type j, E_{WTT_j} is WTT environmental impacts of fuel type j, and E_{TTW_j} is TTW environmental impacts of fuel type j. Environmental impact of fuel use per km traveled for each vehicle (E_{WTW/km_i}) are counted based on eq. 2.

$$E_{WTW/km_i} = \sum_{j=1}^{3} \frac{Q_{ij} E_{WTW_j}}{F_{ij}} \tag{2}$$

Here, $i = 1, 2, 3, 4, 5$ refers to passenger cars' type (i.e., ICEV, HEV, PHEV, BEV and FCV, respectively), $j = 1, 2, 3$ refers to fuel type (i.e., gasoline, electricity, and hydrogen, respectively), Q_{ij} is the proportion of utilization of fuel type j for passenger cars type i, and F_{ij} is fuel economy of passenger cars type i with fuel type j. Total life cycle environmental impacts per km distance traveled are calculated based on eq. 3.

Table 4
Global warming potential per unit of vehicle manufacturing (kg CO_2 eq), according to CML 2001.

	Gasoline ICEV	HEV	PHEV	BEV	FCV
Vehicle (without battery and fuel stack)	2410	3048	3325	2345	8183
Lithium-ion batteries	–	313	1728	6807	3185
Fuel cell stack	–	–	–	–	14,040
Total	2410	3361	5053	9151	25,408

$$E_i = \frac{E_{V_i}}{VKT_i} + E_{WTW/km_i} \qquad (3)$$

Here, E_i is total life cycle environmental impacts of passenger cars type i per km distance traveled, E_{Vi} is environmental impact per manufactured passenger cars type i, and VKT_i is vehicle distance traveled of driving mileage of passenger cars type i during their lifetime. Estimation of passenger cars' life cycle environmental impact in 2030 are calculated based on four scenarios using eq. 4. Annual vehicle travel distance is assumed to be 10,000 km for all of passenger cars.

$$C_r = \sum_{i=1}^{5}\sum_{j=1}^{3} TS_iK_iQ_{ij}F_{ij}E_{WTW_j} + \sum_{i=1}^{5} NP_iE_{V_i} \qquad (4)$$

Here, C_r is total environmental impact of passenger cars in 2030,T is total number of in-use passenger cars in 2030, S_i is proportion of in-use passenger cars of type i in 2030, K_i is annual vehicle distance traveled of passenger car type i, N is total number of newly registered passenger cars in 2030, and P_i is proportion of newly registered passenger cars of type i in 2030.

3. Results and discussion

3.1. Life cycle impact assessment results

3.1.1. Vehicle manufacturing

Table 4 presents the GWP in vehicle manufacturing for each type of vehicle, revealing that FCV manufacturing emits more than 10 times that of ICEV manufacturing, wherein the largest contributor is the fuel cell stack. The fuel stack, and battery account for 55% and 12.5% of GHG emissions in FCV manufacturing, respectively. The GWP of BEV manufacturing is almost four times that of ICEV manufacturing, in which lithium-ion batteries have the highest share of GHG emissions. Battery production accounts for 74% of the GHG emissions in BEV manufacturing, whereas engine production only accounts for 5% of the GHG emissions in the life cycle of an ICEV vehicle.

Table 5 shows other midpoint impacts per km of vehicle travel for different vehicles, demonstrating that the FCV has the highest impacts in all categories, including acidification, eutrophication, human toxicity, and photochemical oxidation potential.

3.1.2. Environmental impacts of fuel use in each vehicle

Table 6 shows GWP and other impact categories of the different fuel use required in each vehicle per km traveled. The fuel use of the gasoline ICEV has the highest GWP among the five vehicle types, owing to high direct CO_2 emissions from gasoline when driving. In gasoline ICEVs, the combustion reaction produces environmentally hazardous emissions, primarily CO_2 and carbon monoxide (CO). FCVs produce no emissions in fuel operations, only water. Although FCVs do not emit CO_2 when operational, the GWP of hydrogen use, caused by high GHG emissions in upstream processes of hydrogen production, storage, transportation, and dispensing, is higher than that of BEVs, HEVs, and PHEVs. Fig. 2 presents the contributions of each stage of the hydrogen WTT process to environmental impact per km of distance traveled, indicating that environmental impact is primarily generated by the hydrogenation process, followed by the dehydrogenation process.

Regarding fuel life cycle, the gasoline ICEV is inferior to the BEV and FCV, in contrast to vehicle manufacturing; therefore, to assess the sustainable effects of all vehicles, a total LCA comprising both vehicle and fuel life cycles is required.

3.1.3. Total life cycle impacts

Fig. 3 presents the total life cycle GHG emissions for vehicle manufacturing and WTW per km distance traveled for gasoline ICEVs, HEVs, PHEVs, BEVs, and FCVs, indicating that the GWPs of HEVs, PHEVs, and BEVs are lower than gasoline ICEVs. Despite the GWP related to HEV, PHEV, and BEV manufacturing being higher than gasoline ICEVs, these vehicles cannot dominate the GWP, based on the WTW of gasoline in ICEVs. The GWP of FCVs related to vehicle manufacturing and WTW is the highest among the five vehicle types. FCV manufacturing contributes 56% of total GWP per km distance traveled, which is 10 times that of gasoline ICEVs.

3.1.4. GWP of passenger cars in different scenarios

The GWPs of all passenger cars in Japan in 2030 under all four scenarios are presented in Fig. 4. The GWP of baseline, BAU, GOV, and aggressive scenarios are 103, 89.9, 91.2, and 91.8 million tons, respectively, with the latter three being lower than the GWP of passenger cars in the baseline scenario. In the BAU scenario, the GWP from fuel use and newly registered vehicle manufacturing are 76.9 and 12.1 million tons, respectively. The GWP of the GOV and aggressive scenarios

Table 5
Other impact categories per unit of vehicle manufacturing, according to CML 2001.

Impact categories	Unit	Gasoline ICEV	HEV	PHEV	BEV	FCV
Acidification	kg SO2 eq	13.5	19.3	27.6	44.6	123.5
Eutrophication	kg PO4 eq	1.2	1.6	2.1	3.3	11.4
Human toxicity	kg 1,4-dichlorobenzene eq	6536.3	9142.6	12,431.7	18,084.3	52,906.4
Photochemical oxidation	kg ethylene eq	1.9	2.4	3.0	3.5	9.9

Table 6
Global warming potential, acidification, eutrophication, human toxicity, and photochemical oxidation potential per km of vehicle distance traveled, according to CML 2001.

Impact categories	Unit	Gasoline ICEV	HEV	PHEV	BEV	FCV
GWP	g CO_2 eq/ km	168	101	72	76	134
Acidification	g SO2 eq./ km	0.11	0.12	0.17	0.29	2.28
Eutrophication	g PO4 eq./ km	0.01	0.01	0.01	0.02	0.14
Human toxicity	g 1,4-dichlorobenzene eq./ km	41.22	50.86	72.14	112.65	979.51
Photochemical oxidation	g ethylene eq./ km	0.01	0.02	0.02	0.02	0.18

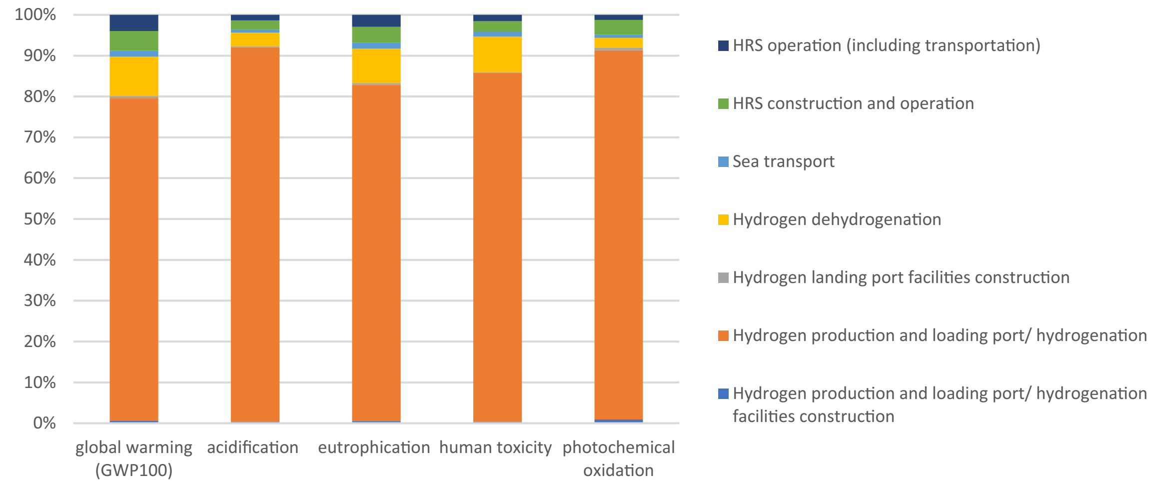

Fig. 2. Contribution of each stage of hydrogen WTT to environmental impact per km traveled.

are slightly higher than the BAU scenario. In the GOV scenario, fuel use contributes 71.4 million tons and newly registered vehicle manufacturing contributes as high as 19.2 million tons. Contribution of fuel use and newly registered vehicle manufacturing in the aggressive scenario are 73.2 and 18.6 million tons, respectively.

The GWP of electricity use changes with different electricity mix as shown in Fig. 5. In electricity generation mix 2015, thermal power generation accounted for around 89% of the electricity supply composition ratio. Meanwhile, composition ratio of nuclear and renewable energies in electricity mix 2030 is targeted to increase to around 60%. It can be seen that by using electricity mix 2030, emission intensity will be lower than electricity mix 2015.

3.1.5. Other impacts of passenger cars from different scenarios in 2030

Fig. 6 presents other impacts of passenger cars, including acidification potential (a), eutrophication potential (b), human toxicity potential (c), and photochemical oxidation potential (d). These impacts reveal similar patterns, in which the baseline scenario elicits the lowest results among scenarios and the GOV scenario has the highest results, with a slight difference from results of the aggressive scenario. Manufacturing of newly registered cars in baseline, BAU, GOV, and aggressive scenarios will contribute 68%, 72%, 74%, and 75% of total acidification potential; 71%, 76%, 77%, and 77% of total eutrophication potential; 84%, 84%, 81%, and 83% of total human toxicity potential; and 75%, 76%, 77%, and 78% of total photochemical oxidation potential in 2030, respectively. The contribution of fuel use to the impact categories from each scenario is no more than 32%. The fuel cell stack and hydrogen tank in the manufacturing of FCVs have large contributions to acidification, eutrophication, human toxicity, and photochemical oxidation potential; battery production for BEVs also accounts for a large contribution toward acidification, eutrophication, human toxicity, and photochemical oxidation potentials. Different from the GWP, which has global effects, acidification, eutrophication, and human toxicity potential will have regional impacts depending on the emission location and the exposed population [38,39]. In order to mitigate acidification potential, desulfurization of emitted gas could be a favorable choice to control SO_2 emissions [40].

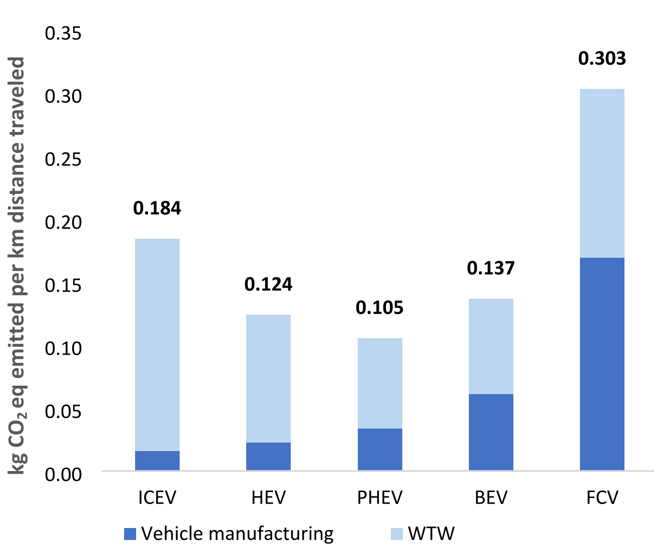

Fig. 3. Total GWP per km distance traveled for five vehicle types.

3.2. Discussion

In terms of emissions related to vehicle manufacturing, the FCV produced the highest GHG emissions. This result is concordant with those of previous studies evaluating LCA of passenger cars. Desantes et al [41] and Burkhardt et al [42] used a process-based LCA to investigate GHG emissions of vehicles, finding that emissions resulting from manufacturing of FCVs are higher than those for ICEVs. These emissions occur mainly due to production of hydrogen tanks and fuel cell stacks [41]. Another study using hybrid EIO–LCA also showed that FCVs emit more GHGs, compared to ICEVs, during manufacturing phase [43]. However, in this study, GHG emission data for FCV manufacturing do not concur with the findings of other studies. This study shows that FCV manufacturing emits more than 10 times the GHGs emitted during ICEV manufacturing, while other studies suggest that GHG emissions of FCV manufacturing are nearly twice as high as those of ICEV manufacturing. Regarding the discrepancy of GHG emissions of manufacturing FCV between our study and process-based LCA, we find considerably higher emission intensity due to the EIO–LCA approach, which facilitates an extended system boundary. The difference seems to be similar to a hybrid LCA study that evaluated BEVs, which found that its GHG emission was nearly five times higher than the process-based LCA study [9].

In this study, we found that BEVs and PHEVs offer substantial carbon reduction potential in Japan. This result is similar to a previous study in the US or European context [7] but has a different result compared to the Australian context [9]. On the other hand, FCV has lower GHG emission intensity in the US or in Europe [7], this is not the case for Japan due to differences in hydrogen pathway and LCA method. We assumed that hydrogen fuel in Japan is extracted from electrolysis using wind power

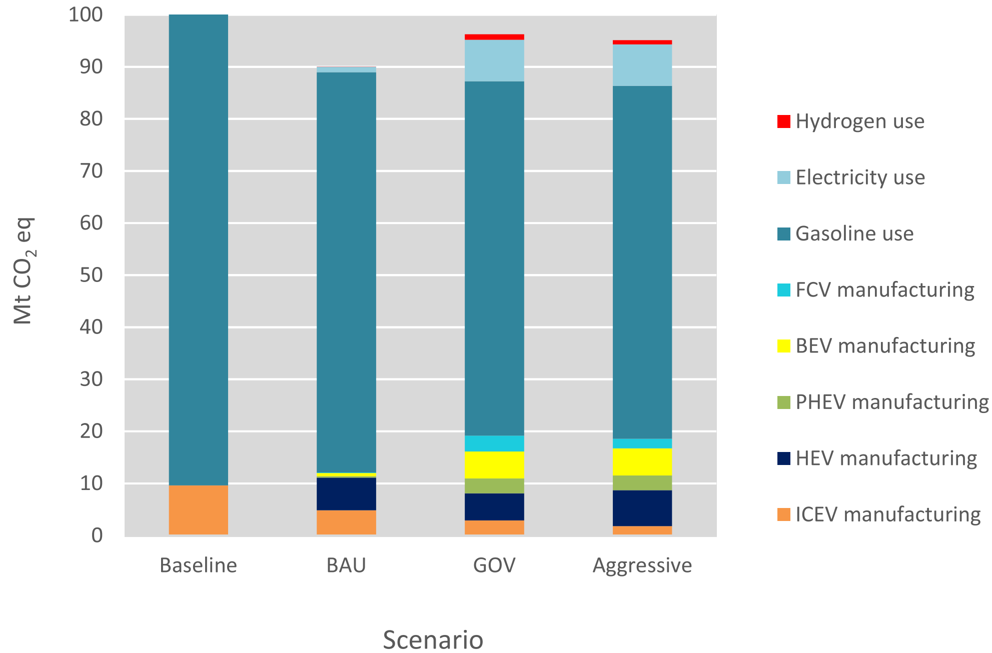

Fig. 4. Projected GWP of passenger cars in 2030 for each scenario.

in another country, stored through the hydrogenation of toluene-methylcyclohexane (MCH), and transported to Japan via sea tanker. Meanwhile, Bandivadekar et al. [7] assumed that hydrogen fuel is produced with steam-reforming from natural gas at distributed locations and compressed to 10,000 psi.

Fig. 4 presents the projected trend of total GHG emissions from the four scenarios. Without the adoption of any next-generation vehicles, GHG emissions are expected to reach 103 million tons, as demonstrated in the baseline scenario. Widespread adoption of electrified vehicles (HEVs, PHEVs, BEVs, and FCVs) could help reduce GHG emissions depending on the share of newly registered vehicles, as well as the number of in-use passenger cars for each type of fuel. GHG emissions in the BAU scenario are slightly lower than the GOV and aggressive scenarios. Despite GHG emissions from fuel use in the BAU scenario being higher than the GOV and aggressive scenarios, GHG emissions from manufacturing newly registered vehicles are lower than others due to a smaller number of FCVs and BEVs, which directly offsets the GHG emissions of fuel use in the BAU scenario.

The contribution of FCV manufacturing to GHG emissions is relatively high. An effort to reduce GHG emissions from FCV manufacturing, which are mainly generated by fuel cell stacks and hydrogen tanks, is required. GHG emissions of hydrogen use in FCVs are also relatively high. An effort to reduce the GHG emissions from hydrogen use, primarily through hydrogen storage, is essential to decrease the negative impact of FCVs on the environment. In contrast, with growth in the proportion of HEVs, PHEVs, and BEVs, the emissions of fuel use factor will become

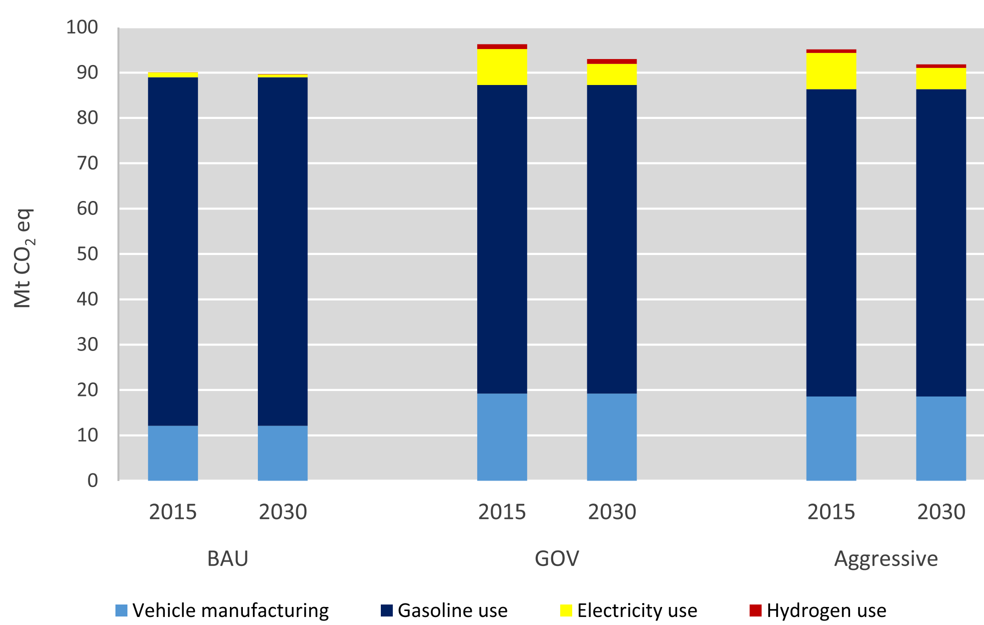

Fig. 5. Projected GWP of passenger cars in 2030 for each scenario with different electricity mix (2015 and 2030).

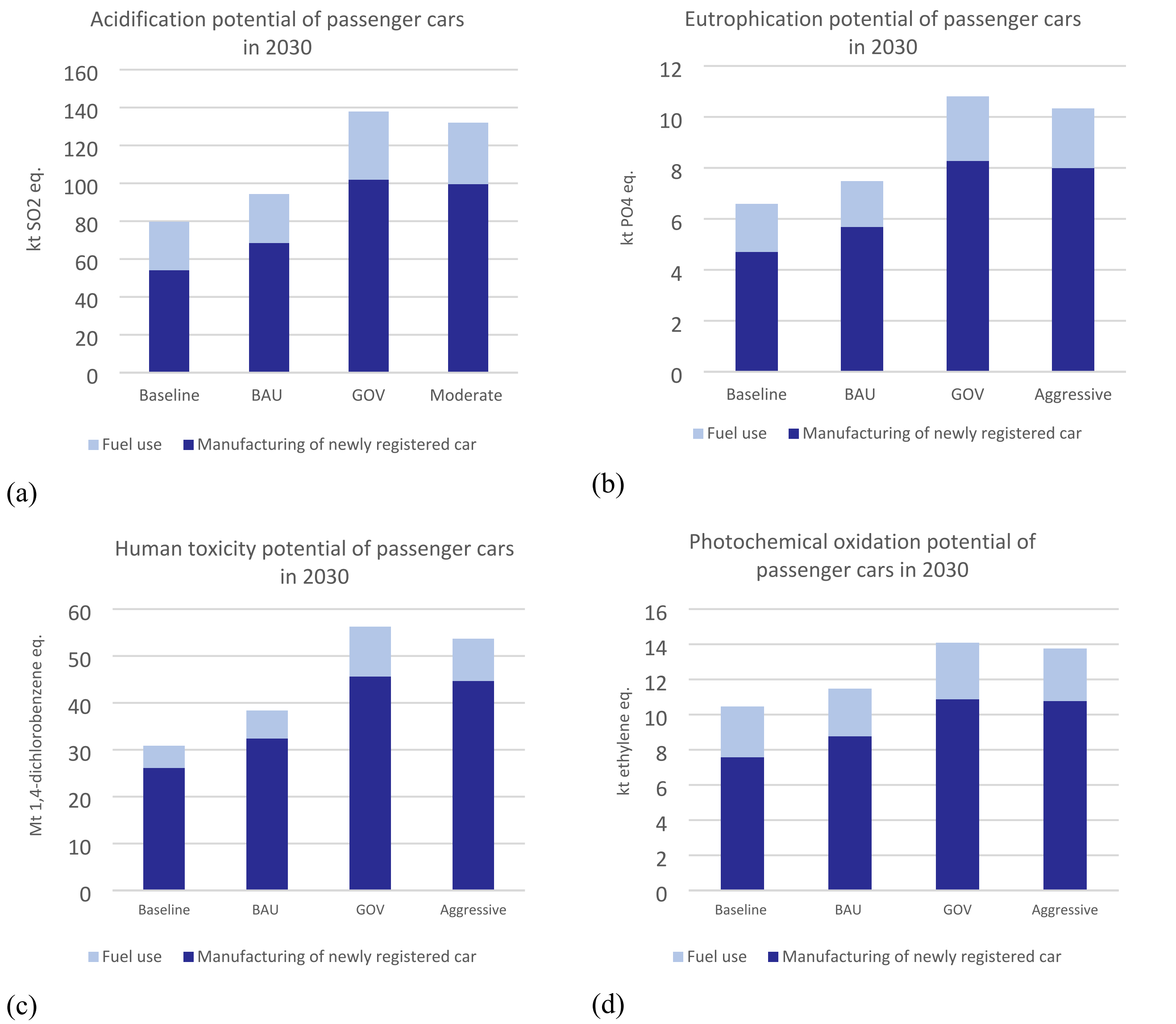

Fig. 6. Other impacts of passenger cars from different scenarios in 2030; (a) acidification potential, (b) eutrophication potential, (c) human toxicity potential, and (d) photochemical oxidation potential.

significant and non-negligible in the long run. Reducing the impact of BEV manufacturing, which are mainly generated by batteries production, is also important to decrease the negative impacts on the environment.

3.3. Sensitivity analysis

In addition to analyzing the total life cycle impact of different scenarios, we also conducted a sensitivity analysis of GHG emissions to the gasoline fuel economy. The fuel economy parameter setting for sensitivity analysis is detailed below.

- Base setting refers to a fuel economy in the current assumption of gasoline consumption per km driven, including gasoline ICEVs, HEVs, and PHEVs.
- The 10% setting refers to 10% increased fuel efficiency from the current gasoline fuel economy.
- The 20% setting refers to 20% increased fuel efficiency from the current gasoline fuel economy.
- The 30% setting refers to 30% increased fuel efficiency from the current gasoline fuel economy.

The fuel economy sensitivity analysis is illustrated in Fig. 7, demonstrating that by increasing fuel efficiency to 20% and 30%, the GWP of future passenger cars in 2030 will be lower than other scenarios with a base setting of the fuel economy. By increasing fuel efficiency to 10%, 20%, and 30% in the BAU scenario, the GWP will reduce by 8%, 14%, and 20%, respectively. In the GOV scenario, increasing fuel efficiency to 10%, 20%, and 30% will reduce the GWP by 7%, 12%, and 17%, respectively. For the aggressive scenario, by increasing efficiency 10%, 20%, and 30%, the GWP will decrease by 7%, 15%, and 17%, respectively.

Since monetary values are supposed to have a significant impact on the total life cycle impacts, a sensitivity analysis of producer price is provided. The price parameter setting for sensitivity analysis is detailed below.

- Base setting refers to referenced producer price.
- The 10% setting refers to 10% price reduction of lithium batteries of HEVs, PHEVs, BEVs, and FCVs, and 10% price reduction of fuel cell stack and hydrogen tank.
- The 20% setting refers to 20% price reduction of lithium batteries of HEVs, PHEVs, BEVs, and FCVs, and 20% price reduction of fuel cell stack and hydrogen tank.

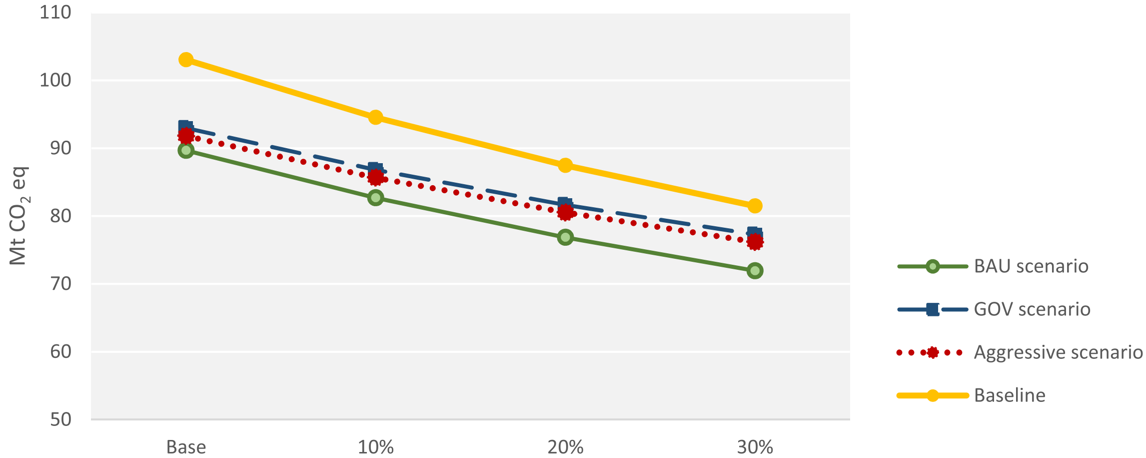

Fig. 7. Sensitivity analysis of the gasoline fuel economy to global warming potential in 2030.

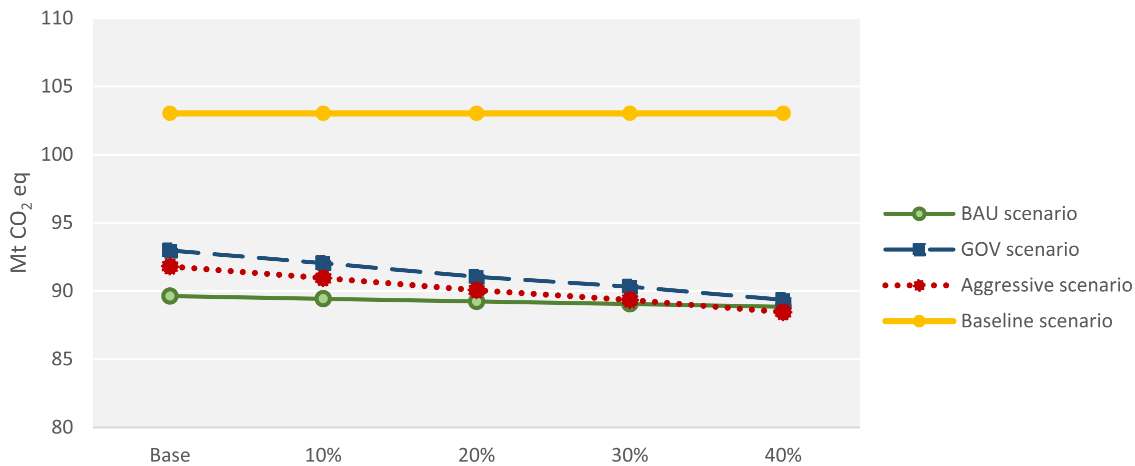

Fig. 8. Sensitivity analysis of the monetary values to total GWP in 2030.

- The 30% setting refers to 30% price reduction of lithium batteries of HEVs, PHEVs, BEVs, and FCVs, and 30% price reduction of fuel cell stack and hydrogen tank.
- The 40% setting refers to 40% price reduction in lithium batteries of HEVs, PHEVs, BEVs, and FCVs, and 40% price reduction in fuel cell stack and hydrogen tank.

The monetary values sensitivity analysis is illustrated in Fig. 8, which shows that a decrease in producer price of next-generation vehicles will bring only minor changes to total GWP. In the BAU scenario, each 10% decrease in price will reduce around 0.2% of the total GWP. Decreasing by 10% in producer price, total GWP will reduce by around 1% for both GOV and aggressive scenarios. In the GOV scenario, falling producer price to 10%, 20%, 30%, and 40% will reduce the GWP by 1.0%, 2.0%, 2.9% dan 3.9%, respectively. For the aggressive scenario, decreasing producer price to 10%, 20%, 30%, and 40% will reduce the GWP by 0.9%, 1.8%, 2.7% dan 3.6%, respectively. Even if producer prices fall by up to 40%, the reduction in total emissions is no more than 4%. In addition, it can also be seen that at a producer price reduction of 40%, the total emission from the aggressive scenario is smaller than the BAU scenario.

4. Conclusions

We conducted an LCA study to predict the future of passenger cars in Japan by 2030, considering gasoline ICEVs, HEVs, PHEVs, BEVs, and FCVs in different scenarios. The main findings can be summarized as follows:

1. Considering both vehicle manufacturing and fuel life cycles, the PHEV has the lowest GHG emissions when the 2030 electricity generation mix is considered, followed by PHEVs and BEVs.
2. WTW cycle is the major contributing life cycle phase to the total life cycle impacts of any given passenger cars for all fuel types.
3. The results of this study showed that FCV did not demonstrate any improvement in terms of emissions, as large quantities of GHG emissions are emitted during the production of fuel cell stacks and hydrogen tanks. Moreover, a substantial quantity of GHG emissions is released in the WTW cycle of hydrogen, even when green hydrogen pathway is utilized. The GHG emissions of hydrogen use in FCVs is relatively high due to hydrogenation and dehydrogenation processes that are carbon intensive.
4. The adoption of electrified vehicles, such as HEVs, PHEVs, and BEVs, could help decarbonize the passenger car sector to achieve carbon neutrality.
5. Increasing fuel efficiency also makes a significant contribution to reducing GHG emissions and can further benefit the attainment of carbon neutrality.

Under Japan's carbon neutrality objective, the findings of this study also have policy implications for the government's construction of a pathway toward low-carbon road transportation. The particular policy recommendations are as follows:

1. The power sector must focus on an extensive expansion of the amount of clean energy in power generation, including solar power, hydropower, wind power, and nuclear energy, to significantly cut CO_2 emissions from electric cars, as planned in the 2030 electricity generation mix.
2. The government should strategically formulate relevant policies to encourage vehicle manufacturers to enhance the fuel economies of both conventional ICEVs and new generation vehicles to cut the overall GHG emissions of passenger cars.
3. The government should formulate relevant policies to encourage vehicle manufacturers to reduce the GHG emissions generated in BEV battery production and improve fuel stacks and hydrogen tanks in FCVs to reduce the overall GHG emissions of passenger cars.

This study also has some limitations, which are mentioned as follows:

1. The maintenance and end-of life stages of vehicle life cycles were not considered in the analysis due to a lack of data.
2. The prices of HEV, PHEV, BEV, and FCV are expected to decline by 2030, but the inventory data for HEV, PHEV, BEV, and FCV manufacturing was assumed from data in 2015 due to lack of data for future prices.
3. There are currently several hydrogen supply chain projects in Japan, but we only considered green hydrogen from a wind power source with MCH storage, owing to limited access to data.
4. In terms of the other synthetic fueled vehicles, the future development of such vehicles is uncertain and exceedingly difficult to predict. In addition, the proportions of such vehicles are currently negligible.
5. Acidification, eutrophication, and human toxicity potential should have different impacts depending on the emission location and the exposed population. However, we cannot provide a detailed analysis for these three impact categories due to a lack of data on manufacturer locations and the exposed population.
6. Carbon capture utilization and storage (CCUS) could reduce CO_2 emissions, and desulfurizing emitted gas could help control SO_2 emissions. However, we did not consider the adoption of these technologies in this study.

Further research can be performed to address the limitations of this study.

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Declaration of Competing Interest

Authors declare that there is no conflict of interest.

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