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Scenario input–output analysis on the diffusion of fuel cell vehicles and alternative hydrogen supply systems

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Abstract

Ratifying the Paris Climate Change Agreement of 2015, which is the new framework for global environmental measures for change after 2020 onward, Japan is proposing to reduce its greenhouse gas emissions by 26% by 2030 from 2013 levels. To achieve this target, it is indispensable to transcend the current fossil-fuel-based technologies (petroleum, coal, and natural gas) and shift to renewable energy systems. Neutral fuels or fuels free of carbon dioxide emissions must become the predominant source of energy, in addition to introducing energy conservation technologies in manufacturing, transportation, business, and households. Amid these developments, fuel cell vehicles and hydrogen production technologies are gaining much attention. Our research group is developing a new hydrogen-generating system that directly decomposes hydrogen from methane and separates carbon as a solid substance with zero carbon dioxide emissions. We estimate the carbon dioxide reduction effect of our new hydrogen-generating system and compare it with the current steam reforming method by applying scenario input–output analysis. Our new system is expected to lower carbon dioxide emissions to 14.1% of the conventional system in the industrial sector. With the replacement effect of gasoline vehicles to fuel cell vehicles, carbon dioxide emissions are expected to reduce for both hydrogen production technologies. The new system is more efficient and saves carbon dioxide emissions by 21.7% more than the conventional system, under the assumption that 800 thousand fuel cell vehicles will be available in Japan before 2030.

Keywords: Scenario input–output analysis, Fuel cell vehicles, Hydrogen production technology, Carbon dioxide emissions, Direct decomposition of methane, Methane steam reforming

JEL Classification: C67, L62, P18, Q55

1 Introduction

Ratifying the Paris Agreement[1] of 2015, which is a new framework for global environmental measures for change after 2020 onward, Japan is proposing to reduce its greenhouse gas emissions by 26% by 2030 from 2013 level. To achieve this target, it is into transcend the current fossil-fuel-based (petroleum, coal, and natural gas) technologies

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[1] According to this agreement, each country sets an individual greenhouse gas (GHG) emission targets called nationally determined contributions (NDC).

and shift to renewable energy systems. Neutral fuels or fuels free of carbon dioxide (CO_2) emissions must become the predominant source of energy, in addition to introducing energy conservation technologies in each sector of manufacturing, transportation, business, and households. Amid these developments, fuel cell vehicles and hydrogen production technologies[2] are gaining much attention.

The engineering team of our research group is developing a new hydrogen-generating system that directly decomposes hydrogen from methane and separates carbon as a solid substance with zero CO_2 emissions. We evaluate the potential economic and environmental effects of reducing CO_2 on the broader economy when the new system is introduced. Our simulation analysis estimates the impact of reducing CO_2 in our new hydrogen production system and compares it with the current steam reforming method by applying scenario input–output analysis. In implementing this simulation analysis, we assume a certain volume of diffusion of fuel cell vehicles in the future and use it as a reference case for the simulation analysis.

Broadly, several extended input–output models have been applied in the energy and environmental fields. According to Miller and Blair (2009), since the late 1960s, researchers theorized that the input–output framework could be extended to account for environmental pollution generation and abatement processes associated with inter-industry activity. Leontief (1970) provided a key methodological extension that has since been applied widely and extended further. In relation to CO_2 emissions, there is accumulation of carbon footprints as Nansai et al. (2009), Wiebe et al. (2012), and Usubiaga and Acosta-Fernandez (2015).

Cantono et al. (2008) present an assessment of the benefits of public transportation using hydrogen and fuel cell buses using environmental input–output analysis. The authors show that the process of producing hydrogen by steam reforming of methane does not reduce CO_2 emissions completely, even though fuel cell buses do not emit CO_2 during operation. They suggested the use of hydrogen in fuel cell buses as it is environmentally desirable, especially if accompanied by renewable sources, CO_2 capture, or both. In contrast, using a framework of life cycle assessment (LCA), Bohnes et al. (2017) evaluated the environmental impact of passenger car fleet development in the City of Copenhagen for the years 2016–2030 and showed the relative environmental benefits from range-extended electric vehicles and fuel cell vehicles (FCVs) over conventional vehicles and battery electric vehicles (BEVs). Miotti et al. (2017) conducted a detailed LCA of the environmental impact of FCVs and other vehicles. They concluded that if fuel is sourced from renewable energy sources, as is the case of BEVs, FCVs have the advantage of lower greenhouse gas emissions over conventional vehicles.

There are several methods to produce hydrogen.[3] Dincer and Acar (2015) examined various potential methods of producing hydrogen using renewable and non-renewable sources, and compared the environmental impact, cost, and energy efficiency. Photonic

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[2] Hydrogen, a source of energy for fuel cells, can be generated in various ways. Representative examples include extraction from fossil fuels or electrolysis of water. Currently, there are two practical ways to generate hydrogen: steam reforming of natural gas during petroleum refining and gasification of coal. These methods, however, are at a disadvantage as they emit CO_2 during the process of generating hydrogen.

[3] Valente et al. (2017) conduct a literature review of the methodological choices made in LCA studies of hydrogen energy systems.

energy-based hydrogen production is environmentally more beneficial compared to other methods in terms of emissions, although costs and efficiency are not attractive. On the other hand, fossil fuel reforming and biomass gasification produce cheaper hydrogen efficiently. They concluded that hybrid-energy-based hydrogen production methods, in which the energy sources are electrothermal, photo-biochemical, and electro-photonic, have higher rankings on average.

Keipi et al. (2018) compared the costs of producing hydrogen using thermal decomposition of methane to steam reforming and water electrolysis in the current and potential future market environments. They estimated costs from engineering-based information and not from input–output tables. They found that thermal decomposition of methane is suitable for on-site demand-driven hydrogen production in small- and medium-scale operations and economically competitive with steam reforming. Thermal decomposition of methane has the advantage of feedstock availability via the current natural gas infrastructure, whereas electrolysis is highly dependent on the cost and availability of renewable electricity.

Our study is an environmental input–output analysis, focusing on the economic effects of new hydrogen production technologies. As reference, we consider hydrogen demand from fuel cell passenger cars bought by consumers and not fuel cell buses for public passenger transport. Further, we compare the new hydrogen production technology from methane decomposition to steam reforming. Electrolysis and other production methods are beyond the scope of this research because they have little advantage in production costs compared to reforming fossil fuels using current technologies.

Our input–output model comprises a wide range of technologies to produce hydrogen for a single commodity of hydrogen so that the row number differs from the column number of the input coefficient matrix, which requires certain arrangement to obtain the Leontief inverse matrix. Here, we introduce a weighted average of the plural technologies. The weights, which are given exogenously as a scenario, indicate the choice of technology. Such studies appear in Ikeda et al. (1996), Yoshioka and Suga (1997), Wang (2016), and Fujikawa and Wang (2017).

In some studies, we find the same characteristic of input–output models based on a rectangular matrix in which the row–column sizes differ. Nakamura and Kondo (2002a, b, 2009) and Kondo and Nakamura (2004) developed waste input–output model that was extended to the conventional input–output model by including waste generation sectors in the rows and waste treatment sectors in the columns. Since the number of waste generation sectors (rows) is larger than waste treatment sectors (columns) in the waste industry input–output table, a suitable method was proposed and implemented to obtain a squared input coefficient matrix for calculating the Leontief inverse matrix.

Klein (1983, 2003) proposed a flow-of-funds model that is similar to Leontief's input–output model. The flow-of-funds model describes that each economic agent owns several financial assets and liabilities. Tsujimura and Mizoshita (2003) and Nishiyama (2008) extended the scope of Klein's flow-of-funds model by developing new approaches that convert a rectangular table to a square table for analysis.

In engineering studies, we found another type of application for the rectangular input–output model. Tsunoka et al. (2011, 2012) investigated environmental burdens associated with a complex production system with some feedback flows. They described

Table 1 Greenhouse gas emissions and sectoral CO_2 emissions (Unit: Million t-CO_2 equivalent) *Source*: Ministry of Environment (2017)

Fiscal year	2005	2013	2016 (P)	Growth rate (%, 2016/2005)	Growth rate (%, 2016/2013)
GHG	1386	1409	1322	−4.6	−6.2
Carbon dioxide (CO_2)	1297	1316	1222	−5.8	−7.1
Methane and others	89	93	100	12.4	7.5
Carbon dioxide, total	1297	1316	1222	−5.8	−7.1
Energy origin	1206	1235	1144	−5.1	−7.4
Industrial sector	468	463	418	−10.7	−9.7
Transportation sector	245	224	215	−12.2	−4.0
Business and other sectors	217	244	219	0.9	−10.2
Household sector	175	205	179	2.3	−12.7
Energy conversion sector	100	100	113	13.0	13.0
Non-energy origin	91.8	80.9	78	−15.0	−3.6
		Share (%)			
GHG	100.0%	100.0%	100.0%		
Carbon dioxide (CO_2)	93.6%	93.4%	92.4%		
Methane and others	6.4%	6.6%	7.6%		
Carbon dioxide, total	100.0%	100.0%	100.0%		
Energy origin	93.0%	93.8%	93.6%		
Industrial sector	36.1%	35.2%	34.2%		
Transportation sector	18.9%	17.0%	17.6%		
Business and other sectors	16.7%	18.5%	17.9%		
Household sector	13.5%	15.6%	14.6%		
Energy conversion sector	7.7%	7.6%	9.2%		
Non-energy origin	7.1%	6.1%	6.4%		

process activities with material input–output in the system as a rectangular matrix, in which one technique was presented to obtain the matrix inversion. Fukuhara and Hondo (2011) proposed a generalized method to describe a production system as a geometrical figure and construct a regular coefficient matrix using graph theory.

This paper is organized as follows. In the next section, we describe the study background. Section 3 outlines the input–output scenario analysis model, and Sect. 4 discusses the assumptions and analytical results of the scenario input–output analysis. The analysis results are summarized in Sect. 5.

2 Background research

2.1 Changes in carbon dioxide emissions

Table 1 shows the trends in Japan's recent greenhouse gas (GHG) and sectoral CO_2 emissions. In FY2016 (preliminary figures), GHG emissions were 1322 million tons of CO_2 equivalent, down 4.6% from FY2005 and 6.2% from FY2013, with CO_2 emissions accounting for 1.222 million tons, or 92.4% of overall GHG emissions. Of the CO_2 emissions, 93.4%, or 1.144 million tons, originated from energy sources, while the remaining 78 million tons had non-energy origins. The industrial sector (energy origin) accounts for 34.2% of total CO_2 emissions, while business and other sectors 17.9%, transport sector 17.6%, household sector 14.6%, and energy conversion 9.2%.

Table 2 Number of next-generation vehicles and number of units sold. *Source*: Japan Next Generation Automobile Promotion Center (2018), Japan Automobile Manufacturers' Association (2018), and Automobile Inspection & Registration Information Association (2018)

Fiscal year	2011	2015	2016
Number of units owned (units)			
EV	22,262	80,511	89,844
PHV	4132	57,130	70,323
FCV		630	1807
HV	2,029,009	5,764,401	6,971,035
Next-generation vehicles, total	2,055,403	5,902,672	7,133,009
All vehicles (except motorcycle)	75,609,883	77,301,798	77,657,517
Share of next-generation vehicles (%)	2.72	7.64	9.19
Units sold (units)			
EV	13,256	14,733	13,817
PHV	3753	14,997	13,847
FCV		494	1204
HV	633,708	1,146,164	1,337,497
Next-generation vehicles, total	652,799	1,176,388	1,366,365
All vehicles (except motorcycle)	4,753,273	4,937,734	5,077,903
Share of next-generation vehicles (%)	13.73	23.82	26.91

2.2 Diffusion of next-generation vehicles

Table 2 shows the number of vehicles owned and unit sales of next-generation vehicles sold in Japan after FY2011. Number of vehicles owned in FY2016 was 7.133 million units, accounting for 9.19% of total ownership of all vehicles. In addition, unit sales stood at 1.366 million, accounting for 26.91% of total sales of all vehicles. Next-generation vehicles include electric vehicles (EVs), plug-in hybrid vehicles (PHVs), fuel cell vehicles (FCVs), and hybrid vehicles (HVs).

Hybrid vehicles are overwhelmingly large, both in number of vehicles owned and in sales volume. Nearly 1.337 million units of hybrid vehicles were sold in FY2016, while number of vehicles owned stood at 6.971 million units at the end of FY2016. Sales units of electric vehicles and plug-in hybrid vehicles were 13,800 units each, number of electric vehicles owned was 89,800 units, and number of plug-in hybrid vehicles stood at 70,323 units. Sales of FCVs started in 2014 and 1807 units were sold by the end of FY2016, and these vehicles are gaining popularity.

2.3 Basic structure of next-generation vehicles

Table 3 shows the basic structure of an FCV compared to hybrid and electric vehicles. A hybrid vehicle adds a motor and an auxiliary battery to an engine-driven conventional vehicle to increase energy efficiency by assisting the engine power. Conversely, an electric vehicle has a simple structure that does not have an engine/fuel tank, charges a large-capacity battery, and is driven by a motor, but needs to seek electric power from other sources. Fuel cell vehicles are driven by motors as well as electric vehicles, but power is generated by the process of reacting hydrogen atoms with oxygen atoms using a fuel cell stack. Therefore, the battery does not need to have a large capacity; however, in addition to the FC stack, a hydrogen tank is required. For these next-generation vehicles, expensive parts such as

Table 3 Basic structure of next-generation vehicles. ***Source*****: Influence of Next Generation Mobility Promotion on the Chubu Region Industries, CRISER (2015)**

	Engine fuel tank	Motor	Auxiliary battery	FC stack	Hydrogen tank	Large-capacity battery
Conventional vehicle	○					
Hybrid vehicle (HEV)	○	○	○			
Fuel cell vehicle (FCV)		○	○	○	○	
Electric Vehicle (EV)		○				○

high-performance motors, high-power density batteries, FC stacks, and hydrogen tanks are required, whereas major automotive parts such as engines, fuel tanks, and transmissions are no longer needed.

Figure 1 represents well-to-wheels-based CO_2 emissions for each vehicle. For gasoline vehicles, it is 147 g-CO_2/km, diesel vehicles are slightly lower at 132 g-CO_2/km, and hybrid vehicles are at 95 g-CO_2/km. Gasoline refueling emissions from PHVs are almost equal to that of a hybrid vehicle, 102 g-CO_2/km, and drop to 55 g-CO_2/km when charging. In electric vehicles, refueling emissions depend on the mix of power sources, which was 55 g-CO_2/km in 2009 and 77 g-CO_2/km in 2012 when nuclear power plants were shut down due to the Great East Japan Earthquake in March of 2011. In contrast, when electricity generated from photovoltaic power is used almost no CO_2 is generated as 1 g-CO_2/km.

Further, FCVs depend on hydrogen production technologies. It is 79 g-CO_2/km when hydrogen is used by on-site reforming of gas, and 78 g-CO_2/km for off-site reforming of natural gas. These amounts are not different from that of EVs depending on a mix of power sources in 2012. Gas-reforming technologies are currently established to produce hydrogen. In on-site alkaline water electrolysis with solar power, it is considerably lower at 14 g-CO_2/km.

The chemical formula for steam reforming of methane, primary component of city gas and natural gas in Japan, for producing hydrogen is given by:

$$\mathrm{CH_4 + 2H_2O \rightarrow CO_2 + 4H_2} \tag{1}$$

It generates CO_2 in the hydrogen production process. If hydrogen is produced without generating CO_2 from the same gas, CO_2 emissions from FCVs can be significantly reduced. This is possible through an alternative hydrogen production technology, namely direct decomposition. Similarly, when using methane, the chemical formula is given by:

$$\mathrm{CH_4 \rightarrow 2H_2 + C} \tag{2}$$

In this case, instead of CO_2, solid carbon (C) is generated. Once this technology is established, there is a possibility that FCVs will approach the same amount of CO_2 emissions as on-site alkaline water electrolysis with solar power.

3 Method: Scenario input–output analysis model

When there is more than one activity (production technologies) for one product in the input–output analysis, there is difficulty in handling technology selection among the several activities. One approach is solving the equation with additional constraints on

Fig. 1 Comparison of CO_2 emissions (well-to-wheels JC08 mode). *Source*: "Report on overall efficiency and GHG emissions by type of vehicles," Japan Automobile Research Institute, March, 2011. "The roadmap of the hydrogen and fuel cell strategy, Revised," Hydrogen and fuel cell council, METI, March, 2016. *Note* The CO_2 emission of EV (the power source mix in FY2012) is estimated suitable to the power source mix in FY2012 by the Hydrogen and fuel cell council, METI

the input coefficient matrix.[4] The electric power generation sector is a typical example, but is just one product. However, in Japan's input–output table, there are three activities: (a) nuclear power, (b) fire power, and (c) hydro power and other activities. Figure 2 shows the input–output table.

If we change the composition of these activities, the environmental load and the economic effect also change. In our study, the technology for hydrogen production consists of two methods: conventional and direct decomposition of methane. If the input structure and energy utilization structure differ for each hydrogen production technology, the environmental load and economic effect will also change by altering the composition.

This input–output model is expressed as follows.

$$\begin{aligned} \mathbf{A_{11}x_1} + \mathbf{A_{12}z} + \mathbf{f_1} &= \mathbf{x_1} \\ \mathbf{A_{21}x_1} + \mathbf{A_{22}z} + \mathbf{f_2} &= \mathbf{x_2} \end{aligned} \tag{3}$$

Here, $\mathbf{x_i}$ is the product vector, $\mathbf{f_i}$ is the final demand vector, and $\mathbf{A_{ij}}$ is the input coefficient matrix. Suffix 1 denotes the usual sectors, and suffix 2 shows a sector with plural

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[4] Input–output analysis with a single product produced by multiple activities appears in Yoshioka and Suga (1997), Wang (2016), and Fujikawa and Wang (2017).

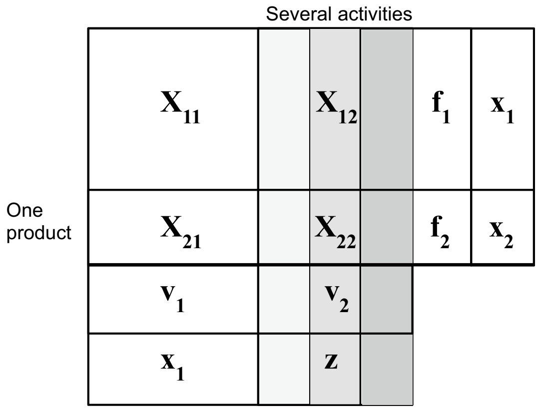

Fig. 2 Input–output table with non-square input transaction matrix *Source*: Illustrated by Authors

activities of hydrogen. Since there are plural activities, $\mathbf{z}$, and one product, $\mathbf{x}_2$, the input coefficient matrix,$\mathbf{A}_{22}$, does not become a square, and it is difficult to obtain the conventional Leontief inverse matrix. Therefore, the following scenario (restriction) is added.

$$\begin{aligned} &\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ 1-\alpha_1 \end{bmatrix} \mathbf{x}_2 \\ &\mathbf{z} = \mathbf{c}\,\mathbf{x}_2 \end{aligned} \tag{4}$$

Here, vector "$\mathbf{c}$" on the right-hand side represents the scenario. This ratio will be given exogenously. Typically, if vector "$\mathbf{c}$" changes, the required production volume also changes. Substituting Eq. (4) into Eq. (3), we obtain

$$\begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12}\mathbf{c} \\ \mathbf{A}_{21} & \mathbf{A}_{22}\mathbf{c} \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} + \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} \tag{5}$$

The input coefficient matrix becomes a square, and, with the identity matrix $\mathbf{I}$ for appropriate orders, the Leontief inverse matrix can be obtained as follows.

$$\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{I}-\mathbf{A}_{11} & -\mathbf{A}_{12}\mathbf{c} \\ -\mathbf{A}_{21} & \mathbf{I}-\mathbf{A}_{22}\mathbf{c} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_2 \end{bmatrix} \tag{6}$$

In the hydrogen sector, vector "$\mathbf{c}$" represents the composition of hydrogen supply for two different technologies. By changing the proportion of the conventional method for direct decomposition of methane, it is possible to see the influence exerted in CO_2 emissions. In addition, it is also possible to simulate how CO_2 emissions differ at the same final demand level (i.e., with the same GDP).

4 Assumptions and results of analysis

We examine the impact of the following three aspects.

1. By introducing FCVs, there is fuel substitution effect from gasoline to hydrogen.

2. Conventional vehicles and FCVs have different economic consequences in the automobile production process because the input structure for manufacturing each automobile is different.
3. By considering two hydrogen production technologies, that is, methane steam reforming and direct decomposition of methane, different economic and environmental effects are expected because these technologies have different input structures.

For the hydrogen production sector, there are different activities for one product, and it is necessary to generate the composition ratios externally as a scenario.[5]

According to The Strategic Road Map for Hydrogen and Fuel Cells, released in March 2016 by the hydrogen-fuel cell strategy council of Japan's Ministry of Economy, Trade and Industry (METI), fuel cell vehicles (stock base) are projected at 800 thousand units in 2030. The price of FCVs to be realized would be equivalent to the price of a hybrid vehicle by 2025. In addition, the Japanese government plans to establish 900 hydrogen fueling stations by 2030. The price of hydrogen is equal to or less than the fuel cost for hybrid vehicles.

4.1 Input structure of the automobile sector

According to the Strategic Road Map for Hydrogen and Fuel Cells mentioned above, we assume that the spread of FCVs will proceed at a pace of 53,333 vehicles per year (cumulative total of 800,000 vehicles over 15 years).

Table 4 shows the estimated decline in the price of components used in FCVs, based on the research on next-generation vehicles by the Chubu Region Institute for Social and Economic Research. The cost of hydrogen tanks, fuel cell stacks, and batteries, which currently increase the price of FCVs, are expected to drop by 2030 due to advances in manufacturing technology and mass production effects. By 2025, the goal is to fix FCV prices as high as hybrid vehicles. We assume that the prices for major FCV components shown in Table 4 are realized and the purchaser's price of an FCV[6] declines to 3.696 million yen (51.1% of the current price, 7.236 million yen in the case of the Toyota Mirai hydrogen fuel cell vehicle).

As shown in Table 5, from the 2011 input–output table, it can be seen that the average price of an ordinary size car is 2.942 million yen (purchaser's price), and the producer's price is 2.022 million yen, excluding the commercial and transport margins, although the average prices in the automobile sector are 2.406 million yen and 1.653 million yen for purchaser's price and producer's price, respectively. Compared to these prices, the FCV purchaser's price of 7.236 million yen in 2014 is exorbitant, which is one reason that FCVs are not accepted in the market. Therefore, as shown in Table 4, we assume that the price of FCVs is reduced to 3.696 million yen, replacing gasoline vehicles sold at the same price.[7]

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[5] Substitution from conventional vehicles to FCVs can be regarded as having two activities for one automobile sector, although we treat these sectors as two independent entities because the automobile, which is the final good, has no intermediate demand. This calculation results in the same values as the case with the given composition of vehicles.

[6] Purchasing an FCV has a subsidy of 2 million yen, but the high manufacturing costs impede market diffusion. Low accessibility to hydrogen fueling stations is another obstacle.

[7] We assume that gasoline vehicle has the same price of FCV, 3.696 million yen. This is regarded as the condition that any user of the conventional vehicle replaces it easily to an FCV. However, in the 2011 input–output table, the purchaser's price of the normal-size car with more than 2000 cc engine capacity was 2.942 million yen, which might be another option for the price of a gasoline car. The choice of expensive but fuel-efficient FCVs and cheaper but fuel-inefficient conventional vehicles is one of the important issues. We would like to examine this issue as a future challenge, although conclusions in our paper are at least quantitatively invariant against the variation of vehicle prices.

Table 4 Costs of FCV components (Unit: Yen). ***Source*****: Influence of Next Generation Mobility Promotion on Chubu Region Industries, CRISER (2015)**

Sectors	2013	2030	Ratio	Parts name
Other ceramics and non-mineral products	2,000,000	549,250	0.275	Hydrogen tank
Industrial electric machine	116,100	48,549	0.418	Driving motor, generator motor, motor inverter (for driving), inverter (for generator), inverter, DC–DC converter, reactor
Electronic appliances and electric measuring instruments	9388	6398	0.682	Battery management unit, electric current sensor for inverter, electric current center for battery
Other electrical equipment	1,330,764	408,229	0.307	Nickel metal hydride battery, lithium ion battery, fuel cell stack
Electronic parts	3667	2591	0.707	Electric current sensor (for inverter)
Auto parts	− 241,294	− 241,294	1.000	Engine, fuel tank, transmission, etc.
Total	3,459,919	1,015,017	0.293	
Producer's price	4,984,800	2,546,398	0.511	
Purchaser's price	7,236,000	3,696,384	0.511	

Year "2013" is set as an estimation year in the original table of CRISER (2015), though FCV "Mirai" of Toyota Motor Co. released in 2014

Table 5 Relationship between car purchaser price and producer price. ***Source*****: Authors' calculation**

	Automobile sector average	Ordinary size vehicle	FCVs (2014)	Gasoline vehicle	FCVs (2030)
	Unit price (Yen)	Unit price (Yen)	Unit price (Yen)	Unit price (Yen)	Unit price (Yen)
Producer's price base	1,653,468	2,021,748	5,995,755	2,539,753	2,539,753
Wholesale margins	48,407	59,188	79,728	74,353	74,353
Retail margins	665,039	813,164	1,095,356	1,021,510	1,021,510
Railway freights	26	32	43	41	41
Road freights	30,646	37,472	50,476	47,073	47,073
Coastal and inland water freights	1242	1519	2046	1908	1908
Port service fees	4266	5216	7026	6552	6552
Domestic air freights	0	0	0	0	0
Handling service fees	1651	2018	2719	2536	2536
Warehouse fees	1731	2116	2850	2658	2658
Purchaser's price base	2,406,475	2,942,474	7,236,000	3,696,384	3,696,384

We estimate the input structure of FCVs as follows. First, we obtain the input values for the gasoline vehicle with a purchasing price of 3.696 million yen, after conversion to the producer's price of 2.540 million yen, by multiplying the input coefficient of the automobile sector. To obtain input values for the FCV, we modify the costs of the gasoline vehicle. We break the total cost down into major input expenses and indirect expenses and obtain each sectoral cost for the indirect expenses by multiplying their total value by the input coefficient of headquarters' activity sector.[8] The sectoral costs for the major inputs are obtained by subtracting the indirect costs from the originally estimated costs. Thus, major material costs to produce FCVs are modified, based on the costs of parts in Table 4. The difference in the total input cost between the two types of vehicle is absorbed in the value-added sectors of the FCV not to change the price.[9]

We finally estimate sectoral inputs by adding two estimated costs: major costs and indirect costs. We refer to a gasoline vehicle at the same price in comparison with an FCV. The difference between them is as follows. Table 6 partly shows the estimated input coefficients of gasoline vehicles and FCVs in the input–output table, which is integrated into 38 sectors to make it easier to see the characteristics.[10] In FCVs, inputs for ceramic, stone and clay products, electric machinery, and electronic components have increased, while input for transportation machines (automobile parts) is decreasing. Total input ratio in FCVs is larger than that in gasoline vehicles, so that the value-added ratio for each stands in opposite relation.

Table 7 shows the overall estimates of fuel purchases for gasoline vehicles and FCVs in the market. The number of units purchased is 53,333 units per year, assuming that the target number of FCVs is 800,000 units over 15 years. The price is 3.696 million yen for each, and the annual purchase amount is 197.14 billion yen. Since it is assumed that the price of conventional vehicles, replaced by FCVs, is the same, sales value is 197.14 billion yen.

If the average mileage[11] of one vehicle is 8000 km/year and fuel efficiency[12] is 10 km/l, then annual gasoline consumption for a vehicle will be 800.0 l/year. If gasoline price[13] is 137.8 yen/l, then annual gasoline consumption value is projected at 5.878 billion yen.

On the other hand, since the tank capacity of an FCV is 5 kg of hydrogen and its cruising distance is 650 km, then hydrogen fuel efficiency is 130 km/kg, assuming the same average mileage of 8000 km/year. Hydrogen consumption is 61.54 kg/year. Therefore, if the price of hydrogen is 1080 yen/kg,[14] hydrogen consumption value is estimated at 3.545 billion yen.

Total gasoline consumption for 800,000 units is 640,000 kl, and consumption value is 88.173 billion yen. Hydrogen consumption is 49,230,769 kg, and consumption value is 53.169 billion yen. Thus, CO_2 emissions due to gasoline consumption are 1,486,080 t-CO_2[15] and CO_2 emissions coefficient is estimated as 23.591 t-CO_2/million yen, considering the commercial margin and transport cost.

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[8] The input coefficient of headquarters' activity sector is obtained from the 2011 Tokyo metropolitan input–output table.

[9] In estimation of the input structure of FCV, we set the future costs of major parts, by referring the report on the next-generation mobility (CRISER 2015). However, the future costs of the other parts and services are indirectly estimated by multiplying the future price of FCV by the current input coefficients of the corresponding sector. In that sense, our estimation includes partly some kind of errors, which is one of the remaining issues.

[10] Input coefficient is estimated based on the input–output table of 188 sectors, as described later.

[11] The average mileage of conventional vehicles is obtained from a report by Next Generation Vehicle Promotion Center on the diffusion of clean-energy vehicles in 2017.

[12] Fuel efficiency of gasoline vehicles in 2015 is calculated from the Fuel Consumption Statistics of Japan's Ministry of Land, Infrastructure and Transport.

[13] Value as given by Ministry of Resources and Energy, 2015.

[14] JX Nippon Oil and Energy Corporation started to sell hydrogen for 1000 yen/kg (excluding consumption tax), according to a newspaper article from Nikkei Inc. dated December 26, 2014.

[15] Gasoline CO_2 emission coefficient is 2.322 kg-CO_2/l, which is calculated by using the 2005 revised data of Resource and Energy Agency, Japan.

Table 6 Estimated input coefficients in gasoline vehicles and FCVs. *Source*: Authors' calculation

No.	Name of sector	Gasoline vehicles	FCVs
1	Transportation equipment	0.5373	0.3327
2	Ceramic, stone, and clay products	0.0198	0.2303
3	Electrical machinery	0.0417	0.1824
4	Iron and steel	0.0475	0.0378
5	Plastic and rubber products	0.0416	0.0331
6	Education and research	0.0408	0.0325
7	Commerce	0.0287	0.0229
8	Business services	0.0281	0.0224
9	Information and communication electronics equipment	0.0208	0.0166
10	Transport and postal services	0.0192	0.0153
11	Nonferrous metals	0.0074	0.0059
12	Electricity, gas, and heat supply	0.0062	0.0050
13	Chemical products	0.0060	0.0048
14	Finance and insurance	0.0043	0.0034
15	Metal products	0.0041	0.0032
16	Textile products	0.0030	0.0024
17	Information and communications	0.0026	0.0021
18	Miscellaneous manufacturing products	0.0023	0.0018
19	Real estate	0.0014	0.0011
20	Electronic components	0.0000	0.0010
	Other inputs	0.0043	0.0034
	Total input ratio	0.8670	0.9599
	Value-added ratio	0.1330	0.0401

4.2 Hydrogen production and input structure

We compare the two hydrogen production technologies: steam reforming and direct decomposition of methane. The upper half of Table 8 shows the amount of material methane, heating methane, CO_2 generated, and carbon in mol when producing 1000 mol of hydrogen.

In steam reforming of methane, according to Eq. (1), 250 mol of material methane and 46.213 mol of heating methane (in total 296.213 mol) are required for producing 1000 mol of hydrogen with 296.213 mol of CO_2 as emissions. By contrast, in direct decomposition of methane, according to Eq. (2), 500 mol of material methane and 41.951 mol of methane for heating (in total 541.951 mol) are required for producing 1000 mol of hydrogen.[16] In this process, 41.951 mol of CO_2 is generated due to combustion of methane for heating, and 500 mol of (solid) carbon is generated. For producing the same hydrogen, in direct decomposition of methane, methane required for material and heating is 1.83 times compared with steam reforming of methane, but the amount of CO_2 generated is only 14.2%. The lower half of Table 8 shows the relationship on a mass kg basis.

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[16] It requires 41.2 kJ/mol-H_2 for steam reforming of methane and 37.4 kJ/mol-H_2 for direct decomposition of methane. Methane calorific value is 39.8 MJ/Nm^3 and the molar volume is 22.4 l and the volume of heating methane is calculated. To evaluate the constant pressure specific heat of each species, thermodynamic data were cited from JANAF Table (see Stull and Prophet (1971)).

Table 7 Comparison of gasoline vehicles and FCVs. ***Source*****: Authors' calculation**

	Gasoline vehicles	FCVs	Unit	Year
Stock of FCV	800,000	800,000	unit	2030
Sales per year	53,333	53,333	unit/year	
Unit price	3.696	3.696	mil. Yen	
Annual purchase amount	197,140	197,140	mil. Yen	
Average mileage	8000	8000	km/year	2017
Fuel efficiency	10.0		km/l	2015
Gasoline consumption per year unit	800.0		l/year unit	
Gas price	137.8		Yen/l	2015
Gasoline consumption amount	5878		mil. Yen	
Tank capacity of FCV		5	kg	
Cruising distance of FCV		650	km	
Hydrogen fuel efficiency		130	km/kg	
Hydrogen consumption per year unit		61.54	kg/year unit	
Hydrogen price		1080	Yen/kg	
Hydrogen consumption amount		3545	mil. Yen	
Gasoline for 800 thousand vehicles	640,000		kl	
Hydrogen for 800 thousand FCV		49,230,769	kg	
Fuel consumption amount for 800 thousand vehicles	88,173	53,169	mil. Yen	
CO_2 emissions	1,486,080		t-CO_2	
CO_2 emissions coefficient	23.591		t-CO_2/mil. Yen	

Table 8 Material balance of hydrogen production (by technology). ***Source*****: Authors' calculation**

	Steam reforming of methane	Direct decomposition of methane	Unit
Methane for material	250.000	500.000	mol
Methane for heating	46.213	41.951	mol
Methane, total	296.213	541.951	mol
CO_2 emissions	296.213	41.951	mol
Carbon	0.000	500.000	mol
Hydrogen	1000.000	1000.000	mol
Methane for material	4.000	8.000	kg
Methane for heating	0.739	0.671	kg
Methane, total	4.739	8.671	kg
CO_2 emissions	13.033	1.846	kg
Carbon	0.000	6.000	kg
Hydrogen	2.000	2.000	kg

Table 9 Input structure of hydrogen production (by technology). ***Source*****: Authors' calculation**

	Steam reforming of methane	Direct decomposition of methane	Unit
Methane input	6694	15,879	mil. Yen
Indirect expenses	18,000	18,000	mil. Yen
Transport costs	539	539	mil. Yen
Other	5976	− 3210	mil. Yen
Capital depreciation allowance	22,500	22,500	mil. Yen
Hydrogen production	53,169	53,169	mil. Yen
CO_2 emission coefficient	6.034	0.855	t-CO_2/mil. Yen
Carbon (by-product)		59,062	mil. Yen
Methane input	0.1259	0.2987	–
Indirect expenses	0.3385	0.3385	–
Transport costs	0.0101	0.0101	–
Other	0.1124	− 0.0604	–
Capital depreciation allowance	0.4232	0.4232	–
Hydrogen production	1.0000	1.0000	–

Table 9 shows the input structure for both manufacturing methods.[17,18] Hydrogen production amounts to 53.169 billion yen, a value obtained from annual consumption of hydrogen at 49,230.8 t for 800 thousand units of FCVs and hydrogen price of 1080 yen/kg (see Table 7). Methane material costs can be calculated from the relationship in Table 8. Capital depreciation is calculated assuming the establishment of 900 hydrogen stations, at a construction cost of 500 million yen per site, with a service life of 20 years. Indirect expenses were obtained from the annual expenses of 20 million yen per station, which is a METI estimate. In both the technologies, transportation margin for hydrogen is required in the case of off-site production but not for on-site production. This transport margin is set as 1% of the total costs, considering the corresponding value for gasoline production.

Input ratio is shown in the lower half of Table 9. The coefficient of CO_2 emissions is 0.855 t-CO_2/million yen for direct decomposition of methane and 6.034 t-CO_2/million yen for the methane steam reforming method.

Based on this, the input structure of hydrogen production was estimated. First, total cost is divided into direct expenses such as methane for materials and other indirect expenses. The former is estimated from Table 9, and the latter is introduced by referring to the input structure of the headquarters sector as in the case of FCV in 4.1. Finally, we summed up both and fixed them as sectoral inputs for hydrogen production. The main difference in the input structure of both technologies is the amount of methane used as the raw material and source of heat. Direct decomposition of methane needs approximately double the methane input as in the methane steam reforming method. However,

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[17] In our analysis, we adopted the simplest input structure for hydrogen production and used methane as an input, as a preliminary approach. Methane is a dominant input, although other materials can be used as the energy source of energy.

[18] In Table 9, the value of the by-produced carbon in the methane direct decomposition method is calculated as reference by using the price of carbon rods, 399.9 yen/kg, which is the lowest price among carbon products in the 2011 input–output table of Japan. The by-product carbon is not used in the following simulations.

the former has a bigger advantage when CO_2 emissions are lower than the latter. The presence or absence of a transport margin also depends on whether production is on-site or off-site.

4.3 Simulation results

Simulation is conducted for the following cases.

1. Purchase of gasoline vehicle: Purchase of 53,333 gasoline vehicles per year, at the same price as FCVs
2. Purchase of FCVs: 53,333 FCVs per year
3. Gasoline purchase: Annual purchase of gasoline for gasoline vehicles in case 1
4. Hydrogen purchase: Annual purchase of fuel hydrogen for FCVs in case 2
5. Substitute gasoline vehicles by FCVs (subtract case 2 from case 1)
6. Substitute gasoline with hydrogen (subtract case 4 from case 3)

In the analysis below, we used an input–output table aggregated into 188 sectors based on the 2011 national input–output table (benchmark table) and the employment table. As for CO_2 emissions, we obtained the sectoral CO_2 emissions given by the National Institute for Environmental Studies (3EID) corresponding to the 2011 input–output table.[19]

Table 10 shows the final demand, induced production amount, gross added value, number of workers, and CO_2 emissions for cases 1 to 6, when hydrogen is produced by the methane steam reforming method. Further, CO_2 emissions indicate these industries (endogenous sectors) and household sectors.

Although final demand for gasoline vehicles and FCVs is the same, the economic ripple effect of FCVs is relatively small compared to gasoline vehicles. Production of gasoline vehicles requires more automobile parts, and the sector has a greater ripple effect. On the other hand, FCVs use more electrical components, such as electric machinery, electronic parts, and industrial machinery. For this reason, the effect of substitution from gasoline vehicles to FCVs, in case 5, is negative for production, added value, although a positive effect is obtained for employment. It has the impact of increasing CO_2 emissions by 17,288 t-CO_2.

Gasoline consumption value in using the vehicle is higher than hydrogen consumption, under the assumed prices. Therefore, replacing energy from gasoline with hydrogen reduces final demand, resulting in a negative impact on production and employment, even though the effect on value-added is positive. However, in this case, hydrogen production induces more CO_2 emissions than gasoline production; thus, CO_2 emissions increase in the industrial sector by 7899 t-CO_2. Additionally, in the household sector, gasoline consumption directly results in 99,072 t-CO_2 emissions, but if replaced with hydrogen, the same amount of CO_2 reduction is achieved. Overall, these amounts are reduced by 91,183 t-CO_2.

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[19] National Institute for Environmental Studies (2018). In our analysis, we apply a domestic input–output model to evaluate domestically economic and environmental effects of the choice of hydrogen production technologies in the production, though footprint and global allocation of the hydrogen production are another important issues.

Table 10 Hydrogen production by steam reforming of methane method. *Source*: Authors' calculation

	(1) Gasoline vehicle purchase	(2) FCV purchase	(3) Gasoline purchase	(4) Hydrogen purchase	(5) Vehicle substitution (2)–(1)	(6) Fuel substitution (4)–(3)	Unit
Final demand	197,140	197,140	5878	3545	0	− 2334	mil. Yen
Production	509,121	497,773	7384	4742	− 11,347	− 2642	mil. Yen
Gross added value	165,861	156,998	2788	3288	− 8863	500	mil. Yen
Employment	25,374	25,743	339	110	369	− 229	Persons
CO_2 emissions	509,445	685,733	114,074	22,891	176,288	− 91,183	t-CO_2
Industrial sector	509,445	685,733	15,002	22,891	176,288	7889	t-CO_2
Household sector	0	0	99,072	0	0	− 99,072	t-CO_2

Table 11 shows similar simulation results when hydrogen is produced by direct decomposition of methane. The direction of the effect in each case is almost the same as in Table 10, except CO_2 emissions in the fuel substitution of the industrial sector. Carbon dioxide emissions increase by 176,288 t-CO_2 when the impact of vehicle substitution decreases by 9372 t-CO_2 in the industrial sector due to fuel substitution, and by 99,072 t-CO_2 in the household sector, resulting in total reduction of 108,444 t-CO_2. Compared with Table 10, even though the effect of the household sector remains dominant, additional reduction is achieved in the industrial sector.

In Tables 10 and 11, we evaluate the production effect of replacing gasoline vehicles by FCVs and the changing effect of fuel purchase per year required for using vehicles. However, cars, as consumer durable goods, can be used for a certain period of time, during which fuel purchase is required. According to the statistics given by the Ministry of Land, Infrastructure and Transport, a passenger car's average life span in 2017 was 12.9 years. Thus, we assume that the car purchased will be used for a slightly longer period of 15 years. We obtained the effect of CO_2 emissions for 15 years of vehicle and fuel substitution, as summarized in Table 12.

Table 12 shows the calculation for hydrogen production using the method of direct decomposition of methane. According to this table, CO_2 emissions increased by 176,288 t-CO_2 only in the first year due to vehicle substitution; however, CO_2 reduction for fuel substitution, which occurs when using the car for 15 years, is 9372 t-CO_2 per year in the industrial sector, 99,072 t-CO_2 in the household sector, and the cumulative effects of 15 years show 140,580 t-CO_2 and 1,486,080 t-CO_2, respectively, amounting to 1,450,372 t-CO_2.

This effect varies with the choice of hydrogen production technology. Table 13 shows the kind of change that occurs depending on the ratio of the two hydrogen production technologies. This table shows values for on-site production. Thus, when the ratio of hydrogen production for direct decomposition of methane is 0% (hydrogen produced by methane steam reforming method), 20% case, 40% case, 60% case, 80% case, and 100% (hydrogen produced by direct decomposition of methane only), the cumulative effect of CO_2 emissions in the 15th year, as shown in Table 12, is compared.

Table 11 Hydrogen production by direct decomposition of methane method. *Source*: Authors' calculation

	(1) Gasoline vehicle purchase	(2) FCV purchase	(3) Gasoline purchase	(4) Hydrogen purchase	(5) Vehicle substitution (2)–(1)	(6) Fuel substitution (4)–(3)	Unit
Final demand	197,140	197,140	5878	3545	0	− 2334	mil. Yen
Production	509,121	497,773	7384	5653	− 11,347	− 1731	mil. Yen
Gross added value	165,861	156,998	2788	2977	− 8863	189	mil. Yen
Employment	25,374	25,743	339	136	369	− 202	Persons
CO_2 emissions	509,445	685,733	114,074	5630	176,288	− 108,444	t-CO_2
Industrial sector	509,445	685,733	15,002	5630	176,288	− 9372	t-CO_2
Household sector	0	0	99,072	0	0	− 99,072	t-CO_2

Table 12 Hydrogen production by direct decomposition of methane: Indicative of accumulated effect only (Unit: t-CO_2). *Source*: Authors' calculation

Year	(5) Vehicle substitution	(6) Fuel substitution (industrial)	(6) Fuel substitution (household)	Total
1	176,288	− 9372	− 99,072	67,844
2	176,288	− 18,744	− 198,144	− 40,600
3	176,288	− 28,116	− 297,216	− 149,044
4	176,288	− 37,488	− 396,288	− 257,488
5	176,288	− 46,860	− 495,360	− 365,932
6	176,288	− 56,232	− 594,432	− 474,134
7	176,288	− 65,604	− 693,504	− 582,820
8	176,288	− 74,976	− 792,576	− 691,264
9	176,288	− 84,348	− 891,648	− 799,708
10	176,288	− 93,720	− 990,720	− 908,152
11	176,288	− 103,092	− 1,089,792	− 1,016,596
12	176,288	− 112,464	− 1,188,864	− 1,125,040
13	176,288	− 121,836	− 1,287,936	− 1,233,484
14	176,288	− 131,208	− 1,387,008	− 1,341,928
15	176,288	− 140,580	− 1,486,080	− 1,450,372

In Table 13, the total CO_2 reduction effect of hydrogen production by methane steam reforming method only (0%) was 1,191,461 t-CO_2, whereas in the case of hydrogen production by direct decomposition of methane method only (100%), it was 1,450,372 t-CO_2. The latter reduces about 21.7% more CO_2 emissions than the former.

This effect can be divided into the impact of vehicle substitution and effects of fuel substitution. The effect of fuel substitution can be further divided into industrial sector and household sector. Among them, the most effective CO_2 reduction method is the effect of fuel substitution in the household sector, and this effect will be constant at 1,486,080 t-CO_2, regardless of the hydrogen production technology.

Furthermore, the effect of vehicle substitution is constant but increasing at 176,288 t-CO_2 for the choice of hydrogen production technology. The effect varies

Table 13 Hydrogen production rate and changes in CO_2 emissions by direct decomposition of methane (on-site) (Unit: t-CO_2). ***Source*****: Authors' calculation**

	0%	20%	40%	60%	80%	100%
Vehicle substitution	176,288	176,288	176,288	176,288	176,288	176,288
Fuel substitution (industry)	118,331	66,549	14,767	− 37,015	− 88,798	− 140,580
Industry, total	294,619	242,837	191,054	139,272	87,490	35,708
Fuel substitution (household)	− 1,486,080	− 1,486,080	− 1,486,080	− 1,486,080	− 1,486,080	− 1,486,080
Total	− 1,191,461	− 1,243,243	− 1,295,026	− 1,346,808	− 1,398,590	− 1,450,372
Vehicle substitution	1.000	1.000	1.000	1.000	1.000	1.000
Fuel substitution (industry)	1.000	0.562	0.125	− 0.313	− 0.750	− 1.188
Industry, total	1.000	0.824	0.648	0.473	0.297	0.121
Fuel substitution (household)	1.000	1.000	1.000	1.000	1.000	1.000
Total	1.000	1.043	1.087	1.130	1.174	1.217

strongly for fuel substitution in the industrial sector, from 118,331 t-CO_2, increasing in the case of hydrogen production only with methane steam reforming (0%), to 140,580 t-CO_2, decreasing in the case of hydrogen production by the decomposition method (100%).

Table 14 shows the accumulated effect of the selection of on-site or off-site hydrogen production, as well as the selection of two production technologies. Changes in CO_2 emissions from vehicle substitution and fuel substitution occurring in the industrial and household sectors are shown by the selection of hydrogen production technology (0% or 100%). The values for the three rows at the bottom of the column for 100%, which shows the case of direct decomposition of methane (on-site production), correspond to CO_2 emissions in the 15th-year effect in Table 12.

It is evident here that CO_2 emissions in the hydrogen production sector for both fuel on-site and off-site are about seven times more in the methane steam reforming method (320,822 t-CO_2) than in the methane direct decomposition method (45,436 t-CO_2). Although fuel substitution in the industrial sector augments 118,331 t-CO_2 in the methane steam reforming method, it saves 140,580 t-CO_2 in direct decomposition method.

In off-site hydrogen production, hydrogen has to be transported to the hydrogen refueling station, so that induced production increases and CO_2 emissions also rise. As a result, the saving effect of CO_2 emissions will lower, according to the results in Table 14.

5 Conclusions

Japan is moving toward its target of reducing GHG emissions by 26% by 2030 from the 2013 levels. To attain this target, it becomes inevitable to introduce energy-saving technologies in industries, transportation, business, and household sectors to transit from a society dependent on fossil fuels to one based on renewable energy, and obtain fuels that do not emit CO_2. Fuel cells with hydrogen fuel are emerging as a viable solution and attracting wider attention.

We analyze the economic and environmental impact of defusing FCVs using hydrogen fuel with the selection of several production technologies. The overall effect of production on the economy, value-added, employment, and CO_2 emissions is obtained by the scenario input–output analysis model. As for the hydrogen production technology, we compared the steam reforming method, which is currently considered mainstream, and

Table 14 Differences in CO_2 emissions between on-site and off-site hydrogen production (Unit: t-CO_2). *Source*: Authors' calculation

	On-site production				Off-site production			
	Steam reforming of methane (0%)		Direct decomposition of methane (100%)		Steam reforming of methane (0%)		Direct decomposition of methane (100%)	
	Vehicle substitution	Fuel substitution	Vehicle substitution	Fuel substitution	Vehicle substitution	Fuel substitution	Vehicle substitution	Fuel substitution
Agriculture, forestry, and fishery	− 1	− 2	− 1	− 0	− 1	− 2	− 1	− 0
Mining	3357	− 628	3357	− 528	3357	− 628	3357	− 527
Hydrogen	0	320,822	0	45,436	0	320,822	0	45,436
Petroleum products	1575	− 161,062	1575	− 160,244	1575	− 160,968	1575	− 160,150
Gasoline vehicles	− 7903	0	− 7903	0	− 7903	0	− 7903	0
FCVs	7903	0	7903	0	7903	0	7903	0
Other manufacturing industries	151,759	− 1805	151,759	− 368	151,759	− 1767	151,759	− 330
Electricity	15,803	− 26,949	15,803	− 22,374	15,803	− 26,801	15,803	− 22,226
City gas	− 99	4863	− 99	11,709	− 99	4863	− 99	11,710
Other tertiary industries	3894	− 16,907	3894	− 14,211	3894	− 14,819	3894	− 12,123
Industrial sector total	176,288	118,331	176,288	− 140,580	176,288	120,700	176,288	− 138,211
Household sector	0	− 1,486,080	0	− 1,486,080	0	− 1,486,080	0	− 1,486,080
Total	176,288	− 1,367,749	176,288	− 1,626,660	176,288	− 1,365,380	176,288	− 1,624,291

our newly developed methane direct decomposition method. The findings obtained are as follows.

1. Substituting conventional vehicles with FCVs has a negative effect on production value, added value, and employment, because the ripple effect of producing FCVs is relatively small compared to conventional vehicles. However, CO_2 emissions increase by 176,285 t-CO_2 because carbon products are used in FCV production.
2. Fuel substitution from gasoline to hydrogen has the dominant effect of reducing CO_2 emissions, 1,486,080 t-CO_2, in the household sector.
3. In the industrial sector, the effect depends on the selection of the hydrogen production technology. Both technologies have CO_2 emissions directly in their production. However, the methane direct decomposition method lowers CO_2 emissions to 14.1% by the methane steam reforming method.
4. In addition, substitution of fuels in the industrial sector augments 118,331 t-CO_2 in the methane steam reforming method, although it saves 140,580 t-CO_2 in the methane direct decomposition method.
5. The effect on the broader economy is the reduction of CO_2 emissions for any hydrogen production technology because the saving effect in the household sector is dominant for any method. However, hydrogen production by the methane direct decomposition method saves CO_2 emissions by 21.7% more than that by the methane steam reforming method.

In our analysis, we compared gasoline vehicles and FCVs of the same price and same volume. However, there is another possibility in comparison of cheaper but fuel-inefficient conventional vehicles with expensive but fuel-efficient FCVs. This might be important criteria of comparison. Also, we do not consider the impact of the construction of hydrogen refueling station and the capital investment effect due to expansion of automobile production. These effects increase production, added value, employment, and CO_2 emissions and, therefore, reduce the effect evaluated in this research. Effective utilization of the solid carbon, obtained as by-product in the hydrogen production by the direct decomposition of methane, is another remaining issue. Furthermore, we focused on diffusion of FCVs and selecting hydrogen production technology, but hydrogen use is not limited only to vehicles. The potential of using hydrogen for fuel combustion and generating electric power exists. Issues concerning the economic and environmental impact of the technology choice will form the focus of our future research.

Authors' contributions

All authors have contributed equally to designing the research, the process of data collection and calculation, and drafting and revision of the manuscript. All authors have read and approved the final manuscript.

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