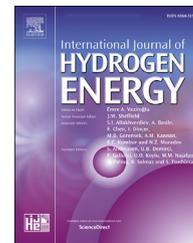




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Deployment of fuel cell vehicles in China: Greenhouse gas emission reductions from converting the heavy-duty truck fleet from diesel and natural gas to hydrogen

Feiqi Liu ^{a,b}, Denise L. Mauzerall ^{b,c,*}, Fuquan Zhao ^a, Han Hao ^a

^a State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing, 100084, China

^b Princeton School of Public and International Affairs, Princeton University, Princeton, NJ, 08544, USA

^c Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, 08544, USA

HIGHLIGHTS

- Heavy-duty truck (HDT) fleet GHG emissions in China are calculated for various fuel cell scenarios.
- Improvements in HDT fuel economy will be offset by increased total miles travelled.
- Increasing penetration of HDTs powered with hydrogen can effectively reduce fleet GHG emissions.
- Moving towards non-fossil electrolysis of water as a source of hydrogen is critical.

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ABSTRACT

Hydrogen fuel cells, as an energy source for heavy duty vehicles, are gaining attention as a potential carbon mitigation strategy. Here we calculate the greenhouse gas (GHG) emissions of the Chinese heavy-duty truck fleet under four hydrogen fuel cell heavy-duty truck penetration scenarios from 2020 through 2050. We introduce Aggressive, Moderate, Conservative and No Fuel Cell Vehicle (No FCV) scenarios. Under these four scenarios, the market share of heavy-duty trucks powered by fuel cells will reach 100%, 50%, 20% and 0%, respectively, in 2050. We go beyond previous studies which compared differences in GHG emissions from different hydrogen production pathways. We now combine an analysis of the carbon intensity of various hydrogen production pathways with predictions of the future hydrogen supply structure in China along with various penetration rates of heavy-duty fuel cell vehicles. We calculate the associated carbon intensity per vehicle kilometer travelled of the hydrogen used in heavy-duty trucks in each scenario, providing a practical application of our research. Our results indicate that if China relies only on fuel economy improvements, with the projected increase in vehicle miles travelled, the GHG emissions of the heavy-duty truck fleet will continue to increase and will remain almost unchanged after 2025. The Aggressive, Moderate and Conservative FCV Scenarios will achieve 63%, 30% and 12% reductions, respectively, in GHG emissions in 2050 from the heavy duty truck fleet compared to the No FCV Scenario. Additional reductions are possible if the current source of hydrogen from fossil fuels was displaced with increased use of hydrogen from water electrolysis using non-fossil generated electricity.

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* Corresponding author. Princeton School of Public and International Affairs, Princeton University, Princeton, NJ, 08544, USA.

E-mail address: mauzerall@princeton.edu (D.L. Mauzerall).

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Introduction

Growing commutes, travel and logistics demands have led to surging vehicle needs in China. Vehicle sales have increased from 1.6 million in 1998 to 25.8 million in 2019 with an annual growth rate of 15.4% [1]. The vehicle stock reached 260 million at the end of 2019 [2]. CO₂ emissions from the transportation sector in China accounted for 9.6% of national emissions in 2017 [3].

The boom in vehicle stocks in China have led to much research focused on calculating vehicle fleet energy consumption and greenhouse gas (GHG) emissions. Yan et al. (2009) designed a model to analyze historical trends in energy demand and GHG emissions in China's road transport sector and to project future trends until 2030. Reduction potentials were estimated by comparing different scenarios and they found private vehicle control, fuel economy regulation and fuel taxes to be the three most effective measures to control future energy consumption and GHG emissions [4]. Ou et al. (2010) calculated China's future road transport energy demand and resulting GHG emissions [5]. Under the business as usual scenario, they estimated that GHG emissions generated by road transportation in 2050 would be 5.6 times the 2007 level. Zhao et al. (2019) analyzed the impact of fuel economy improvements and vehicle electrification on vehicle fleet GHG emissions from 2015 through 2050 and found the proportion of the total fleet GHG emissions originating from commercial vehicles would increase [6].

Based on current policies in China, most energy-saving regulations and subsidy measures are applied to passenger vehicles. These include the Corporate Average Fuel Consumption (CAFC) rule, New Energy Vehicle (NEV) credits and NEV purchase subsidies, etc. Some related regulations are being considered for heavy-duty vehicles, but they are still under discussion. China is one of only four countries with fuel economy standards for heavy-duty vehicles [7]. However, compared with passenger vehicles, the fuel efficiency and GHG emission reduction measures for heavy-duty trucks (HDTs) are relatively weak. Though HDTs only accounted for about 5% of new vehicle sales in China between 2009 and 2019, they were responsible for nearly a quarter of energy consumed and GHGs emitted by the entire vehicle fleet [1]. According to a study by Zhao et al. (2019), HDTs will be responsible for an increasing proportion of GHG emissions from the entire vehicle fleet in China, from 23% in 2015 to around 40% in 2050, due to a lack of GHG emission controls [6]. Thus, controlling the energy demand and GHG emissions from HDTs will become a key aspect of limiting GHG emissions in the road transport sector [8,9].

Electrification provides an effective means of reducing vehicle life cycle carbon emissions, especially for passenger vehicles, and particularly when the source of electricity is decarbonized [10,11]. However, due to low volumetric and gravimetric energy density, battery electric vehicles may not be the best choice for heavy-duty vehicles. Substantial energy and volume are consumed by carrying heavy large batteries. Besides, Hao et al. (2019) indicates that future constraints in lithium availability may limit the use of battery electric propulsion for heavy-duty vehicles [12]. Such a resource

constraint does not exist for fuel cell vehicles in terms of their demand for platinum group metals [13]. Fuel cell powertrains with hydrogen are considered a promising new way to realize fossil fuel savings and tail-pipe emission reductions for heavy-duty vehicles [14]. Fuel cell trucks can be refueled much more quickly than battery electric trucks and usually have a longer range [15–17]. In addition, high-utilization of fuel cell commercial vehicles are an effective way to balance the high cost of hydrogen refilling stations [18]. Demonstration projects are underway to test the reliability of fuel cell trucks [19,20]. Estimates of the change in GHG emissions resulting from replacement of internal combustion engines with deployment of fuel cell HDTs in China is needed to determine whether they can provide an efficient mechanism to reduce GHG emissions in China. We analyze the potential change in GHG emissions from the deployment of fuel cell HDT using four scenarios to study the impact of different fuel cell HDT penetration rates and hydrogen sources on GHG emissions.

Previous studies have calculated the life-cycle energy consumption and GHG emissions of fuel cell vehicles in China. Some research has focused on the fuel cycle and compared fuel cell vehicles with other powertrain vehicles. Wang et al. (2013) analyzed the life cycle GHG emissions of internal combustion engines, battery electric and fuel cell vehicles in China. Various pathways to produce hydrogen were considered (e.g. hydrogen from: electrolysis of water powered by the Chinese electricity grids, from natural gas reforming in central power plants, from natural gas reforming in refueling stations and from electrolysis of water powered by nuclear energy) [21]. Huang et al. (2016) calculated well-to-wheel energy use and GHG emissions for fuel cell vehicles using ten different hydrogen production pathways based on cases in Shanghai, China [22]. Hao et al. (2018) analyzed GHG emissions for fuel cell buses using 19 different hydrogen production pathways for China [23]. Chen et al. (2019) evaluated the life cycle of fuel cell vehicles including both the fuel cycle (including feedstock-related stages, fuel-related stages and vehicle operation) and vehicle cycle (including the acquisition of raw materials, parts manufacturing, vehicle assembly, use maintenance, and scrap recycling) and compared energy consumption and GHG emissions under various hydrogen production schemes [24]. All of the above studies, however, only analyzed passenger vehicles. According to the aforementioned research, steam reforming of methane is the most common form of hydrogen production, hydrogen from water electrolysis based on the current power grid in China is the most carbon intensive pathway, while hydrogen from water electrolysis from renewably generated electricity is the least carbon intensive pathway. Research to date has compared different hydrogen production pathways, but none has considered the current status of hydrogen development or the likely hydrogen production development pathways.

Just like the transformation of the power grid from thermal power generation to renewable energy generation is a process, it is impossible to immediately realize all production of hydrogen from renewable energy. Therefore, it is also crucial to examine the current H₂ production situation and combine it with potential roadmaps to the future in order to identify a feasible and lowest carbon emission pathway for current to

future hydrogen production. Our research addresses this need. We first summarize the development of China's hydrogen industry and then calculate the average carbon intensity of the hydrogen industry based on the predictions of China's hydrogen supply structure by the China Hydrogen Alliance (CHA) and the carbon intensity of different production methods.

Given the previous review, this is an area that earlier work has neglected. Despite emphasizing the importance of the deployment of fuel cell HDTs, no research has quantitatively calculated the impact of fuel cell technology on GHG emissions from heavy duty trucks in China. There is also no research that evaluates the carbon intensity of hydrogen based on actual potential development pathways of the entire hydrogen industry from today through 2050. Better understanding of the implications of increased penetration of fuel cell HDT on future GHG emissions in China is also needed. Here we examine the potential for fuel cell HDT to reduce emissions of GHG in China. We examine both the carbon intensity of upstream sources of hydrogen based on the hydrogen development roadmap for 2050 from the CHA and the downstream GHG emission reductions possible by the deployment of fuel cells rather than internal combustion engines in HDTs. Section [Method and data](#) introduces our analysis method and data used in this research including the HDT market, technology deployment scenarios and hydrogen production pathways. Section [Results and discussion](#) provides the results of the penetration of fuel cell HDT under different scenarios, carbon intensity of hydrogen and their impact on fleet GHG emissions. The final section summarizes the study and makes recommendations for future work.

Method and data

We use a bottom-up method to calculate the GHG emissions generated by HDTs in China from 2020 through 2050. This method has been widely used in related studies [4,5,25,26]. Trucks with a gross vehicle weight more than 14 tons are defined as HDTs. The detailed classification of HDT types will be introduced in later section. Vehicle sales, survival rates, fuel types, annual travel distances, fuel economy and GHG emission intensities of different fuel types are key factors determining GHG emissions over the life cycle of the vehicle, as shown in equation (1).

$$GHG_i = \sum_f \sum_{j=i-l_t}^i Sales_{f,j} \times SR_{i-j} \times VKT \times FCR_{f,j} \times GI_f \quad (1)$$

Where,

GHG_i is the GHG emissions of the HDT fleet in target year i (kg $CO_{2,eq}$); $Sales_{f,j}$ is the sales of HDTs with fuel type f in year j (unit); SR_{i-j} is the vehicle survival rate in the $(i-j)$ th year (%); VKT is the vehicle kilometers travelled annually (100 km/year); $FCR_{f,j}$ is the fuel consumption rate of vehicles with fuel type f sold in year j (L/100 km for diesel/gasoline/natural gas vehicles, kg/100 km for hydrogen vehicles); GI_f is the GHG intensity of fuel type f (kg $CO_{2,eq}$ /L for diesel/gasoline/natural gas vehicles, kg $CO_{2,eq}$ /kg H_2)

HDT sales, survival rate and stock

Vehicle sales, survival rates and total stocks are closely related. The historical data for HDT sales (1995–2019) and vehicle stocks (2010–2019) is obtained from the China Automotive Industry Yearbook and the China Statistical Yearbook [1,27]. A logistic model simulating vehicle survival rates is used in this study, shown in Equation (2) [28,29]. We base survival rates on historical sales and stock data to update the survival rate curve of HDTs in China, shown in Fig. 1. The curve provides a well fitted result, as shown in Fig. 2.

$$SR_j = \frac{1}{1 + e^{\alpha(L-j)}} \quad (2)$$

Where,

SR_j is the survival rate of vehicles in year j ; α is the shape factor; L is the vehicle age at which 50% of the vehicles will have retired.

The prediction of HDT sales in 2050 China is based on Liu et al.'s (2018) study, shown in Fig. 3 [26]. Gan et al. (2019) described an elasticity of truck stock growth to gross domestic production growth, shown as Equation (3) [30]. Based on the sales data and survival rate, we calculate the HDT stock in 2050 and compare the stock growth with GDP growth [31]. The resulting β is in accord with previous research [30,32]. The value of β is around 1 and the standard deviation of β is 0.02. Therefore, we believe our assumption of HDT sales to be reliable.

$$\frac{y_m}{y_{m-1}} = \beta \times \frac{x_m}{x_{m-1}} \quad (3)$$

Where,

y_m and y_{m-1} are the HDT stock in year m and $m-1$; x_m and x_{m-1} are the GDP in year m and $m-1$; β is the empirical elasticity of truck stock growth to GDP growth.

Fuel type

Historical data

Fig. 4 shows the proportion of various fuel types in HDT sales in China since 1999 [1,33]. Diesel has dominated, representing over 95% of fuel used in all but one year. Gasoline HDTs accounted for less than 2% of sales for a few years and have since been withdrawn from the HDT market. Over the past decade, the proportion of natural gas HDT sales has increased to between 0.5% and 5% with year-to-year variability.

Future trends

Diesel, gasoline and natural gas are considered to be conventional fossil fuels. As mentioned in the introduction, due to the low gravimetric and volumetric energy density, battery electric vehicles are not considered to be a good solution for HDT trucks. Therefore, only hydrogen fuel cells are analyzed here as a new fuel type for HDTs.

Current predictions for fuel cell truck deployment in China are outlined in the Technology Roadmap for Energy Saving and New Energy Vehicles drawn up by the China Society of Automotive Engineers (SAE-China) [34]. Many studies have referenced the Roadmap for future new energy vehicle market

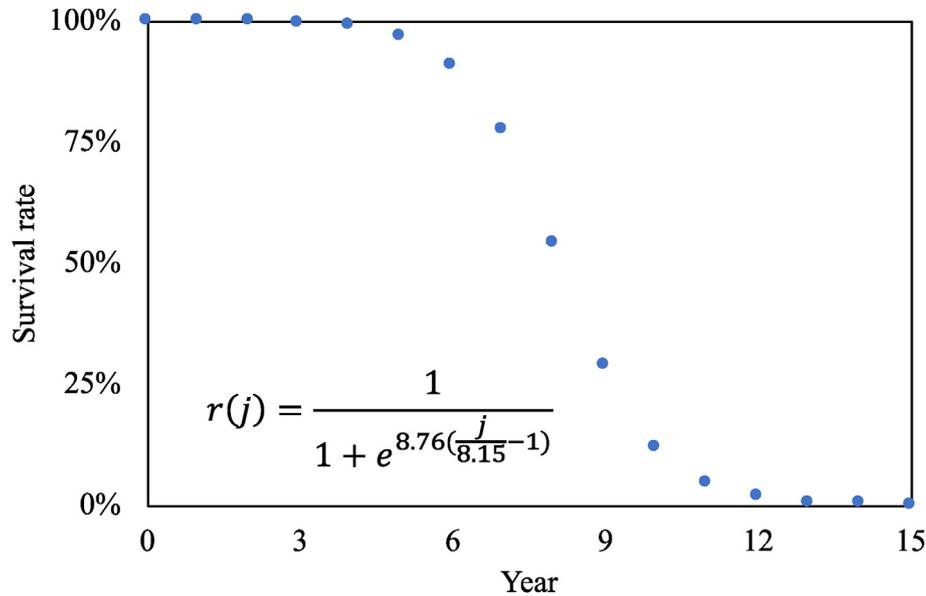


Fig. 1 – Survival rate of HDTs used in this study.

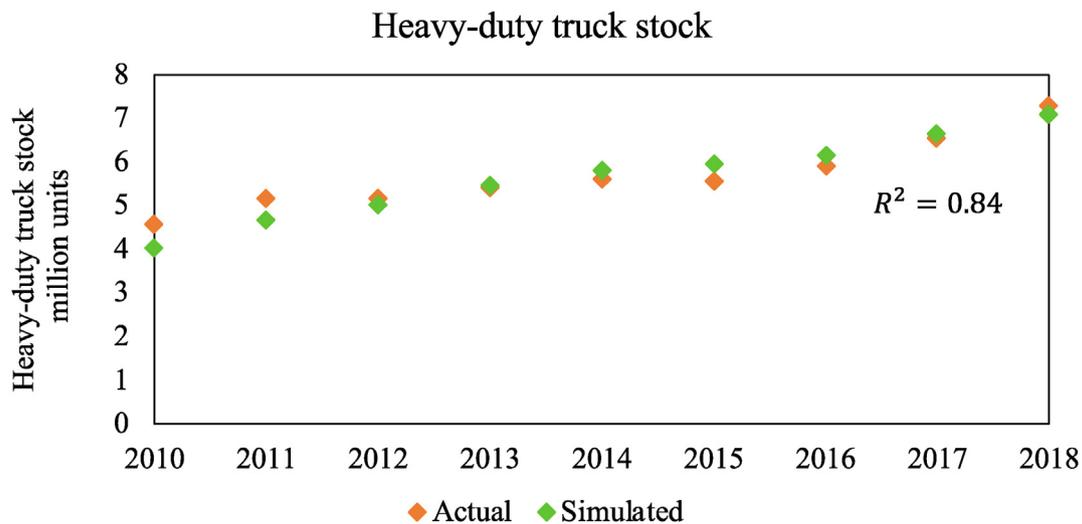


Fig. 2 – Actual data and simulated results of for heavy-duty vehicle stocks in China [1].

development in China [35–37]. This report predicts that the stock of all types of fuel cell vehicles will reach 5 thousand, 50 thousand and 1 million in 2020, 2025 and 2030, out of total vehicles estimated by Liu et al. of approximately 250, 267, and 300 million, respectively [26]. Commercial vehicles will be a key part of fuel cell vehicle development. However, the report does not include information on the sales or stock numbers for fuel cell commercial vehicles or fuel cell HDTs. We develop four scenarios to analyze the impacts of deployment of fuel cell HDTs in terms of GHG emissions, shown as Table 1. Fuel cell HDTs are projected to account for 100%, 50%, 20% and 0% in sales in 2050 under Aggressive, Moderate, Conservative and No Fuel Cell Vehicle (No FCV) scenarios. The Aggressive Scenario is an ambitious case in which we examine the maximum potential for emission reductions from technically

feasible fuel cell penetration in HDTs given aggressive policies encouraging their utilization. This scenario is most consistent with China's recent pledge to be carbon neutral by 2060. The assumption in the Moderate Scenario is consistent with the case provided by the California Energy Commission (CEC). In the recent 2020 CEC report, they assumed that half of the diesel demand for medium- and heavy-duty trucks would be met by hydrogen in 2050 [38]. The Conservative Scenario provides a relatively slow penetration of fuel cells in the HDT market that we provide for comparison.

As for HDTs powered by conventional fuels, which account for the rest of the market, diesel is expected to remain the dominant fuel. As shown in Fig. 4, the market share of natural gas HDT fluctuated greatly over the past eight years and there was no continuous growth. According to historical data, we

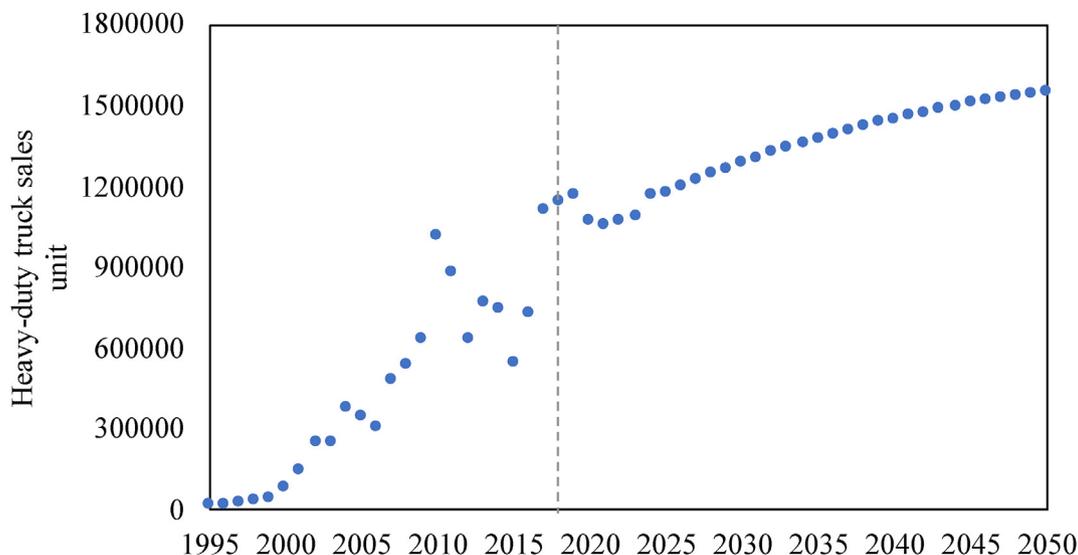


Fig. 3 – HDT sales in China, historical data and future projections adapted from Liu et al. (2018) [26].

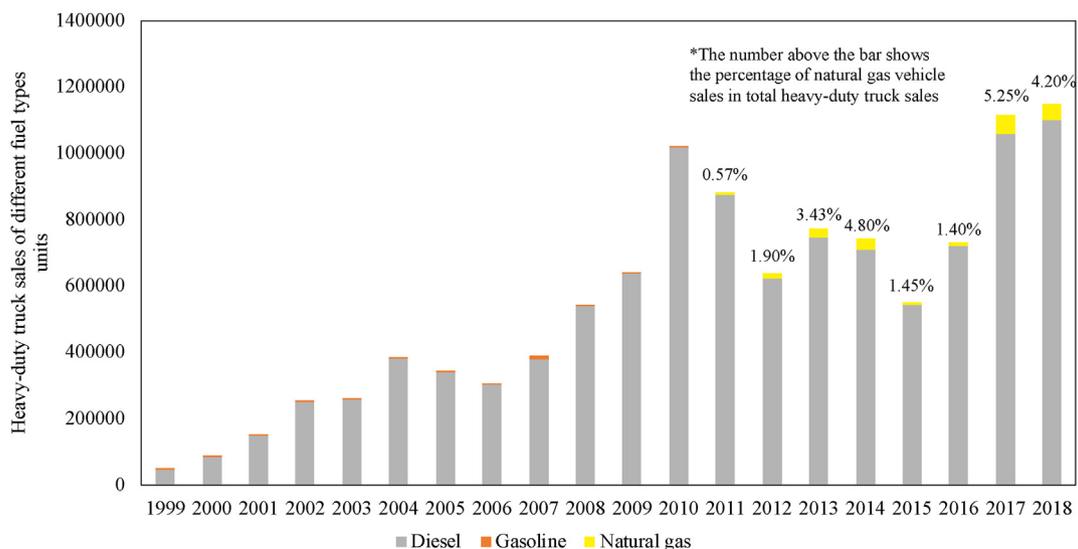


Fig. 4 – The market share of various fuel types in HDT sales in China [1,33]. Diesel dominates the market.

Table 1 – Projections of market share of fuel cell HDT sales under aggressive, moderate, conservative, and no penetration scenarios.

	Aggressive Scenario	Moderate Scenario	Conservative Scenario	No FCV Scenario
2020	0%	0%	0%	0%
2030	30%	12.5%	5%	0%
2040	70%	30%	12%	0%
2050	100%	50%	20%	0%

assume natural gas will account for 5% of conventional fuel HDT sales and diesel will fuel the remaining 95%. As historical data shows that the proportion of gasoline for heavy-duty vehicles is tiny, we do not consider gasoline as a possible fuel for HDTs in the future.

Fuel consumption rates

Conventional fuel

As mentioned above, China is one of four countries (including US, Japan and Canada) with fuel economy regulations for heavy-duty commercial vehicles. Therefore, existing fuel efficiency standards are used as a status quo reference in this study. To date, two related vehicle fuel efficiency standards have been published in China. The first standard was developed from QC/T 924–2011, GB 30510–2014 and GB 30510–2018 which provided three phases of Fuel Consumption Limits for Heavy-duty Commercial Vehicles [39,40]. The first phase was set as an automotive industry standard published by the Ministry of Industry and Information Technology of the People’s Republic of China and the following two phases were turned into a national

standard and published by the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and Standardization Administration of the People's Republic of China. The second regulation system (JT 719) is a transportation industry standard, called Limits and Measurement Methods of Fuel Consumption for Commercial Vehicles for Cargo Transportation, published by Ministry of Transport of the People's Republic of China [41]. Four phases have been published in the JT 719 series. HDTs are included in both the JT719 and the GB30510 regulation systems. Fig. 5 summarizes the fuel consumption limits of these regulations. Both of the fuel economy regulations are for diesel vehicles, and the limits for gasoline vehicles are set at 1.2 times those of diesel vehicles. The fuel economy difference between natural gas and diesel vehicles are quoted from Song et al. [42].

Because GB/T 30,510 series has a wider coverage and is set as the national standard, we use it as the fuel economy reference in this study. As shown in Fig. 5, fuel consumption limits are based on vehicle types and vehicle gross weights. We list the sales data for HDTs by type from 2015 to 2017, as shown in Table 2, and provide the base sales we use in our study [1]. The gross weight of HDTs vary greatly, and the weight distribution will also have significant impacts on the vehicle fleet average fuel economy. We use the fractions of different gross vehicle weights in the HDT market from the study by Huo et al. (2012) [43]. The detailed data used in this research is shown in Table 3.

According to regulations, the annual decrease in fuel consumption rates for HDTs were 6% and 3% for periods 2013 to 2014 and 2015 to 2019. Therefore, we assumed annual fuel economy improvement rates will be 2% from 2020 to 2030 and 1% from 2031 to 2050 for HDTs. The assumption is consistent with that from Argonne National Laboratory's Program Success Cases [44]. There are also differences between real-world and label fuel economies. We compared the fuel consumption rates based on standards and the results from the International Council of Clean Transportation (ICCT) which were based on real-world vehicle operating data [45]. The comparison indicates that the real-world fuel consumption rates will be 11.5% higher than those in the regulations.

Hydrogen

For fuel cell HDTs, fuel economies are collected from currently operating vehicle models, shown as Fig. 6 [46–53]. The gross vehicle weights of these fuel cell HDTs are concentrated between 36 and 38 tons, and their fuel consumption rates are around 8 kg-H₂/100 km. Due to limited data, the gross vehicle weight and vehicle type market shares of conventional fuel HDTs are applied to fuel cell HDTs. The fuel economy improvement rate is set at 1% from 2020 to 2050 for fuel cell HDTs in this study, based on data from Ou et al.(2013) and Chen et al.(2019) [54,55]. The differences between real-world and label fuel consumption rates are also considered for fuel cell vehicles.

Fuel carbon intensity

In this section, the carbon intensities of diesel, natural gas and hydrogen fuel for HDTs are described. We next introduce the

sources of hydrogen for currently operating hydrogen refueling stations in China. The source of hydrogen has a large influence on the carbon intensity of hydrogen vehicles. Then, the history and future outlook of hydrogen production capacity and demand are summarized. Finally, we predict the carbon intensity of hydrogen from 2020 to 2050 based on our analysis.

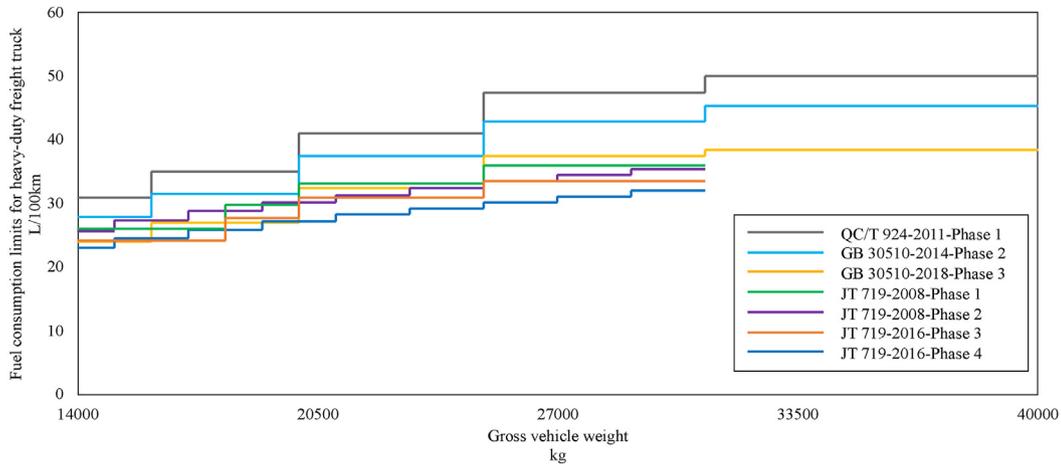
Conventional fuel

For diesel and natural gas, we obtain life cycle carbon intensities from a literature review, and assume carbon intensities will remain constant over time [42,56–58].

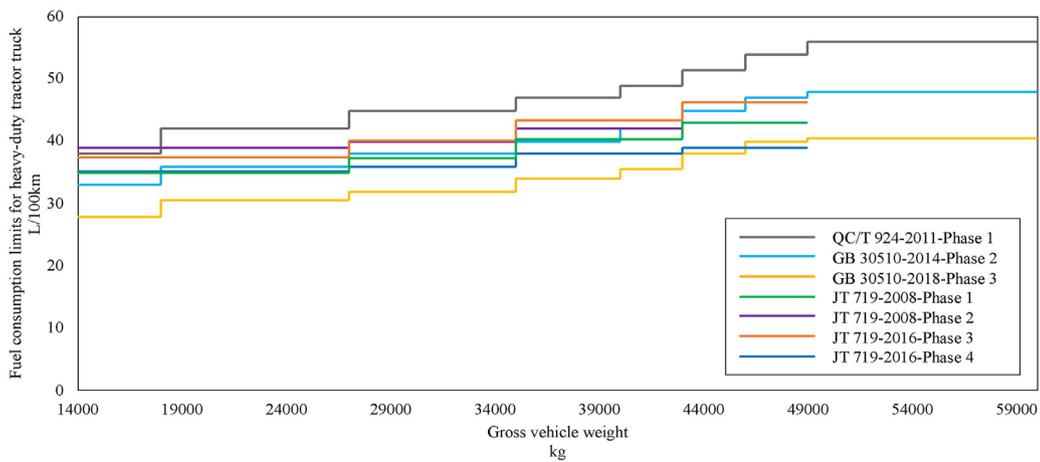
Hydrogen

Hydrogen has always been defined as a chemical product in China. The recently published Energy Law of the People's Republic of China (in draft form available for public comments in 2020) listed hydrogen as an energy source for the first time. This is a good sign for the future use of hydrogen as a fuel [59]. Hydrogen can be made in variety ways including coal gasification, steam methane reforming, thermochemical production, and water electrolysis, etc. [60]. Any hydrogen originating from fossil fuel contributes to CO₂ emissions. Hydrogen is only a carbon neutral fuel when derived by water electrolysis using carbon free electricity. Fig. 7 describes the hydrogen source of currently operating hydrogen refueling stations in China [61–68]. Hydrogen in some refueling stations is supplied by gas companies, like the refueling station in Foshan. Hydrogen is also provided by chemical companies and industry clusters (eg. from iron and steel companies), like refueling stations in Shanghai and Zhengzhou. Some projects also produce hydrogen on-site by water electrolysis using electricity from the local grid which is powered largely by coal. Refueling stations in Zhangjiakou and Dalian are attempting to use electricity from renewable energy to split water into hydrogen.

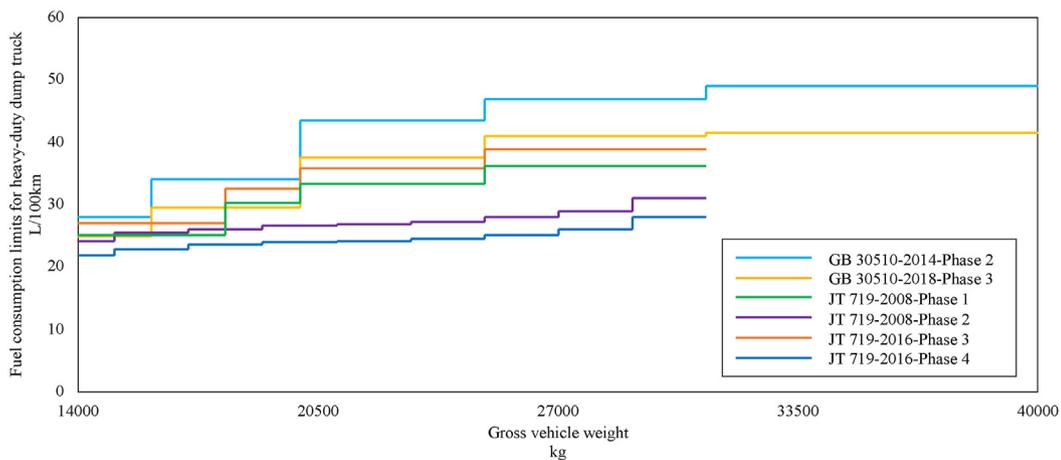
Understanding the development roadmap of the hydrogen industry is also crucial in order to predict the evolution of the future carbon intensity of hydrogen. Although hydrogen from renewable energy water electrolysis will be virtually free of GHG emissions, converting the existing hydrogen production and electricity generation structure that relies heavily on fossil fuels to clean energy will take time. Fig. 8 shows historical data and a possible future development roadmap for hydrogen production and consumption, from both the global and China perspectives [60,69–74]. We obtain the future projection shown in Fig. 8 and used in this study from the report, White Paper on China's Hydrogen Energy and Fuel Cell Industry (hereinafter referred to as White Paper), published by CHA [72]. CHA is an organization established under the guidance of the Ministry of Science and Technology of the People's Republic of China and Ministry of Industry and Information Technology of the People's Republic of China and composed of a number of large-scale energy related enterprises, universities and research institutions. According to the White Paper, hydrogen from renewable energy water electrolysis will grow from 3% in 2020 to 70% in 2050. The percentage of hydrogen made from fossil fuel is projected to gradually drop from 67% in 2020 to 20% in 2050. Industry by-product hydrogen will account for 30% in 2020 and is projected to decrease to 5% in 2040. In 2050 10% of hydrogen is projected to come from new sources.



(a) Fuel consumption limits for heavy-duty freight trucks.



(b) Fuel consumption limits for heavy-duty tractor-trailer trucks



(c) Fuel consumption limits for heavy-duty dump trucks

Fig. 5 – Fuel consumption limits for HDTs in China [39–41].

The carbon intensities of various hydrogen production pathways play an essential role in determining the carbon intensity of the resulting hydrogen. Much research has

compared the GHG emission intensities of various hydrogen production pathways. Based on the White Paper from CHA, six pathways are used in this study, listed in approximate

Table 2 – Sale share of various types of HDTs [1].

Sales	Tractor	Freight	Dump	Special use
2015	203,274 (57.9%)	66,246 (18.9%)	36,404 (10.4%)	44,957 (12.8%)
2016	337,436 (63.3%)	92,358 (17.3%)	68,312 (12.8%)	35,065 (6.6%)
2017	527,845 (60.7%)	101,354 (11.7%)	166,024 (19.1%)	74,507 (8.6%)
This study	60%	15%	15%	10%

Table 3 – Sales share of various gross vehicle weight HDTs (2009) [43].

Gross vehicle weight (tons)	Sales share
14–19	17.6%
19–26	54.7%
26–32	27.0%
>32	0.7%

decreasing order of carbon intensity: coal gasification (CG), chlor-alkali by-product (CB), steam methane reforming (SMR), grid-power water electrolysis (GPWE), solar-power water electrolysis (SPWE), and wind-power water electrolysis (WPWE). To calculate the life-cycle GHG emissions of hydrogen, hydrogen production, compression/liquefaction, transportation and storage processes are all considered. Data in Fig. 9 comes from our literature review [23,75–87]. The carbon intensity of the power grid is based on projections for China for 2020–2050 [88–90]. All hydrogen is assumed to be produced in central plants and not in refueling stations or on-board vehicles.

More details than are provided by the CHA roadmap are needed. Because steam methane reforming is the most cost-efficient way to produce hydrogen today, we assume that 90% of hydrogen made from fossil fuel will be produced this way through 2050 [70]. The remaining 10% of hydrogen produced from fossil fuels will come from coal gasification. Wind and solar power are each projected to account for 50% of renewable energy water electrolysis production through 2050. We assume all by-product hydrogen, will be produced from

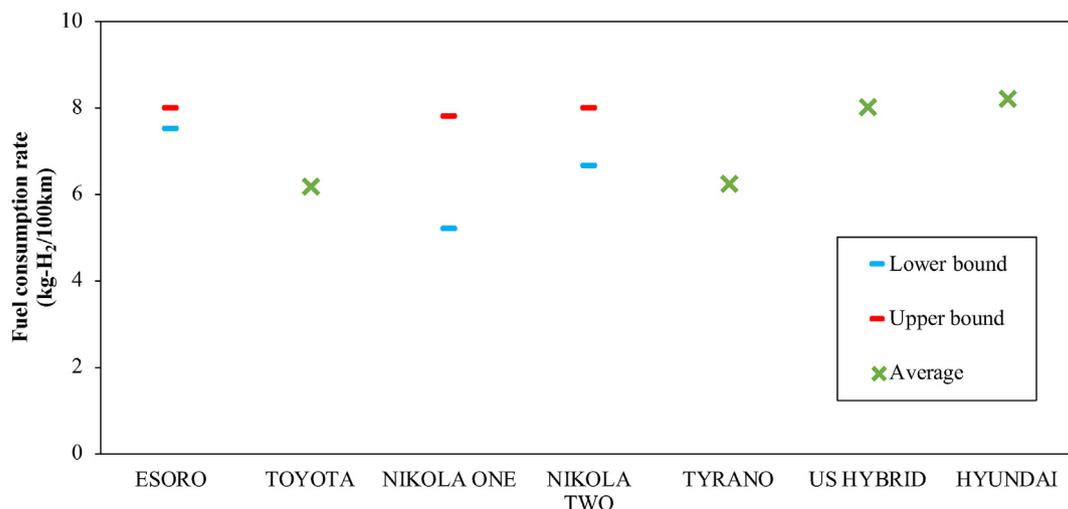
the chlor-alkali industry. Based on current practices, most hydrogen (90%) is assumed to be transported in a gaseous state.

Results and discussion

Here we provide the evolution of vehicle stocks in China under different fuel cell HDT deployment scenarios, carbon intensities of hydrogen (based on future projections in the CHA hydrogen development White Paper), and GHG emissions of the entire HDT fleet with various penetrations of the fuel cell powertrain.

Fig. 10 indicates the share of various fuel types in the HDT fleet under the scenarios mentioned in sector 2.2. It reflects how the proportion of different fuels in vehicle sales affect the structure of vehicle stocks. Under the Aggressive Scenario, fuel cells will account for 18.5% of HDT stock in 2030 and 88.2% in 2050. Under the Moderate Scenario, this proportion will grow from 7.4% in 2030 to 22.3% in 2040 to 41.4% in 2050. Under the Conservative Scenario, only 16.6% of HDTs will be powered by hydrogen in 2050. Only diesel and natural gas vehicles share the market under the No FCV Scenario.

Based on hydrogen production portfolios and carbon intensities of different hydrogen production pathways, the evolution over time of GHG emission intensities of hydrogen production is shown in Fig. 11. As more hydrogen comes from water electrolysis powered by renewable energy, the carbon intensity will decrease dramatically. It will drop from ~15 kg-CO_{2,eq}/kg-H₂ in 2020, to ~12 kg-CO_{2,eq}/kg-H₂ in 2030 and to ~5 kg-CO_{2,eq}/kg-H₂ in 2050.

**Fig. 6 – Fuel consumption rates of currently operating fuel cell HDTs with gross vehicle weight of 36–38 tons.**

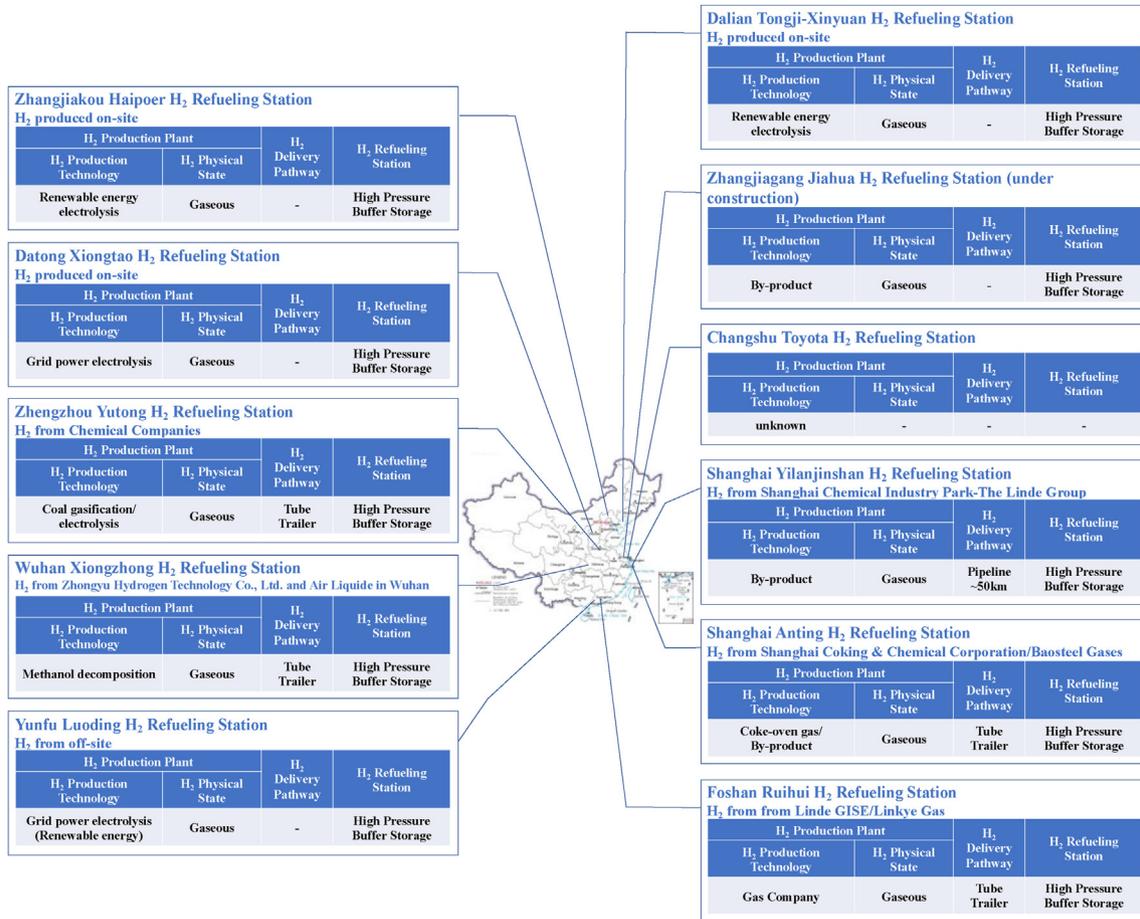


Fig. 7 – Currently operating hydrogen refueling stations in China.

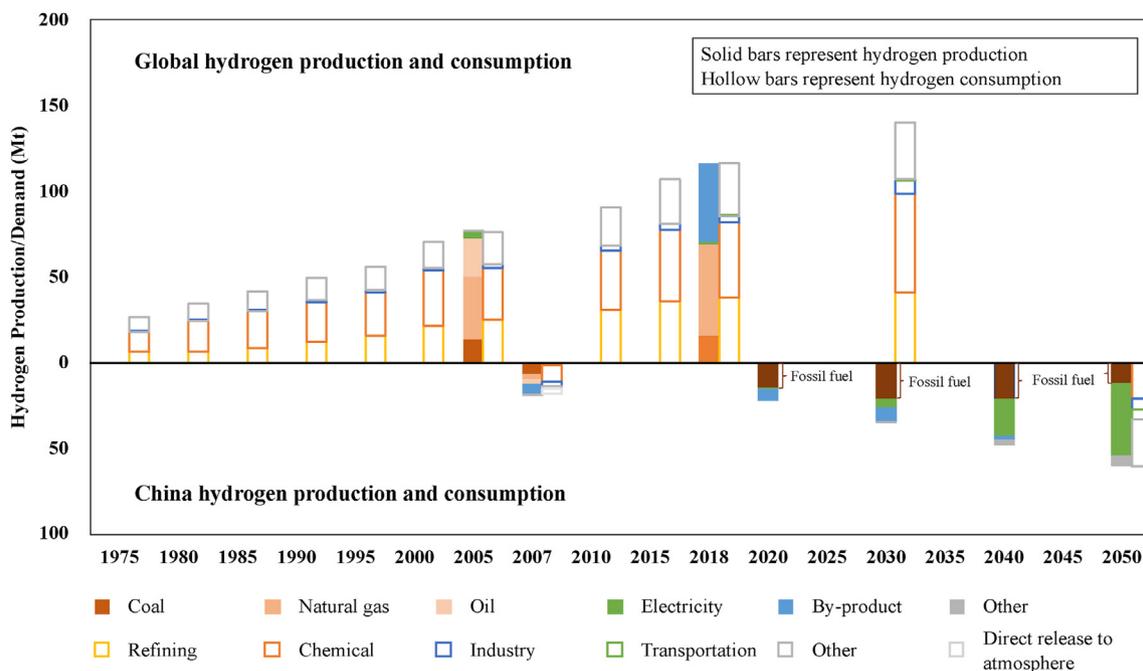


Fig. 8 – Hydrogen production/consumption globally (top half of figure) and for China (bottom half of figure) using all available data. Historical data is shown for 1975–2018 and a future roadmap is shown from 2020 to 2050 [60,69–74].

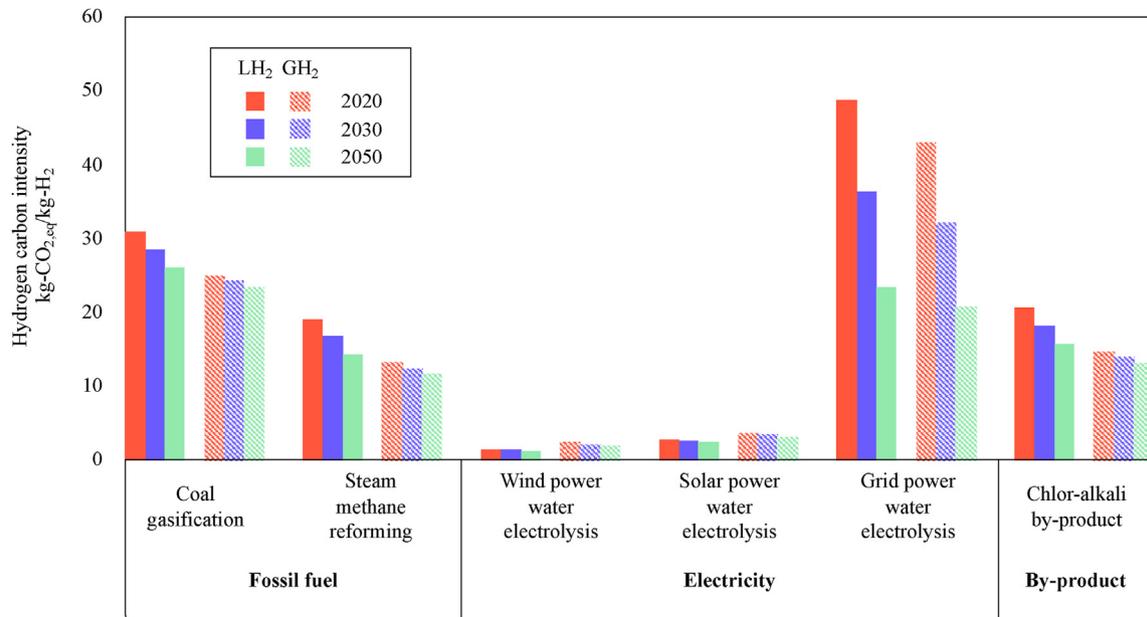


Fig. 9 – Carbon intensity of various hydrogen production pathways. Supplementary notes: 1. LH₂: liquid hydrogen, GH₂: gaseous hydrogen. 2. Electricity used in compression/liquefaction process comes from power grid, except wind-power and solar power water electrolysis pathways. 3. Electricity consumed in hydrogen storage processes come from the power grid for all pathways.

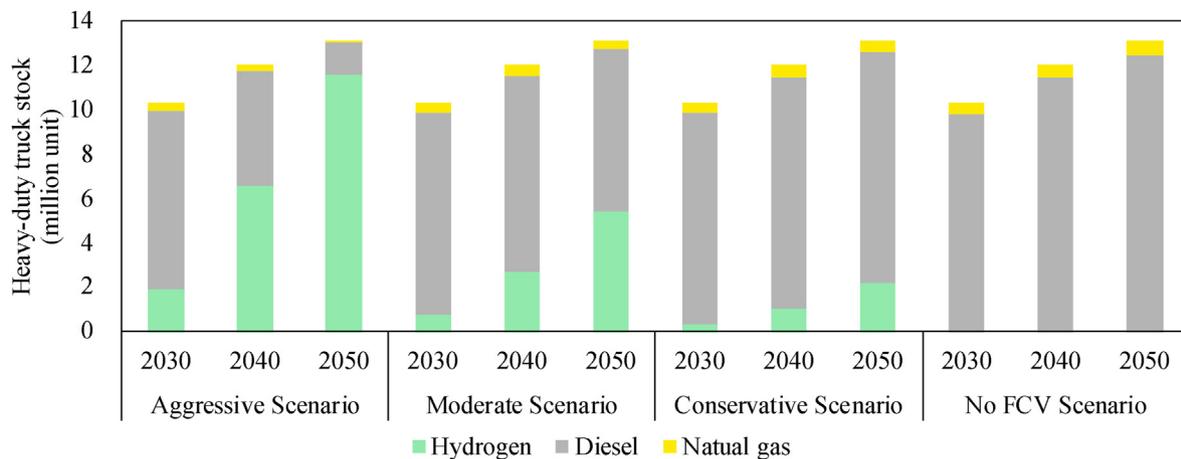


Fig. 10 – HDT stocks of various fuel types based on sales of fuel cell HDTs under the Aggressive (30%, 70%, 100%), Moderate (12.5%, 30%, 50%) and Conservative (5%, 12%, 20%) scenarios in 2030, 2040 and 2050, respectively.

Based on the data and assumptions of fuel consumption rates and the GHG emission intensities of various fuels, the resulting GHG emissions from HDTs per 100 km travelled, using a variety of fuels, are shown in Fig. 12. GHG emission reductions from diesel and natural gas trucks result from fuel economy improvement. For fuel cell HDTs, both fuel efficiency improvements and a cleaner power grid contribute to the drop in GHG emissions from fuel cell HDTs. The less fossil fuel used to produce electricity for the power grid makes the electricity consumed by hydrogen in production, compression, liquefaction and other processes emit less GHG. Therefore, the decarbonization of the power grid will also have an important impact

on the GHG emissions of hydrogen fuel cell vehicles. In 2020, fuel cell HDTs using hydrogen from grid power water electrolysis will have the highest GHG emissions per unit driving distance, followed by hydrogen produced by coal gasification. In 2050, HDTs using hydrogen from grid power water electrolysis and coal gasification still will lead to more GHG emissions than using other fuels. The emissions differences between hydrogen from grid power water electrolysis and coal gasification will likely decrease. As the electricity from the power grid relies less on fossil fuels, the GHG intensities of hydrogen from other production pathways will also decrease. Although the production of hydrogen by steam methane reforming is the most

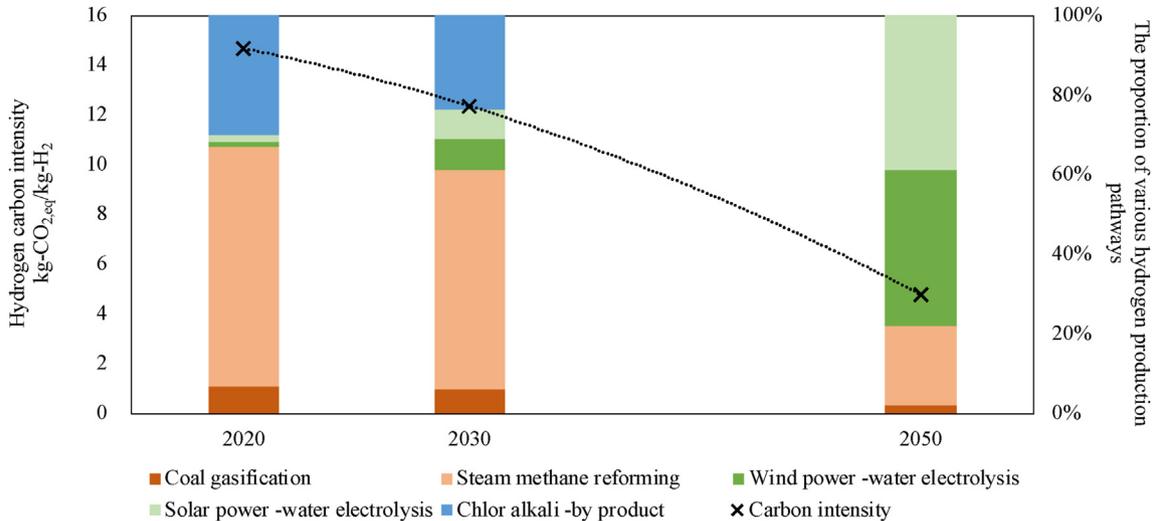


Fig. 11 – Hydrogen GHG emission intensities. These carbon intensities are applied to all scenarios. Colors indicate hydrogen production pathways, X indicates resulting hydrogen carbon intensity [23,75–87]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

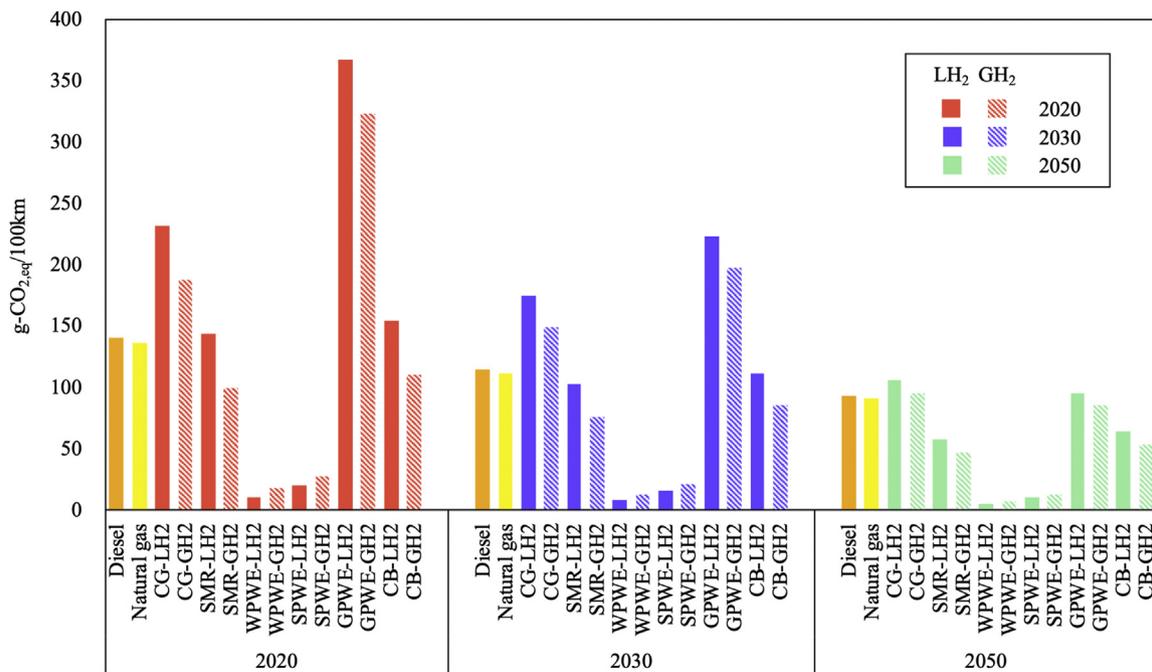


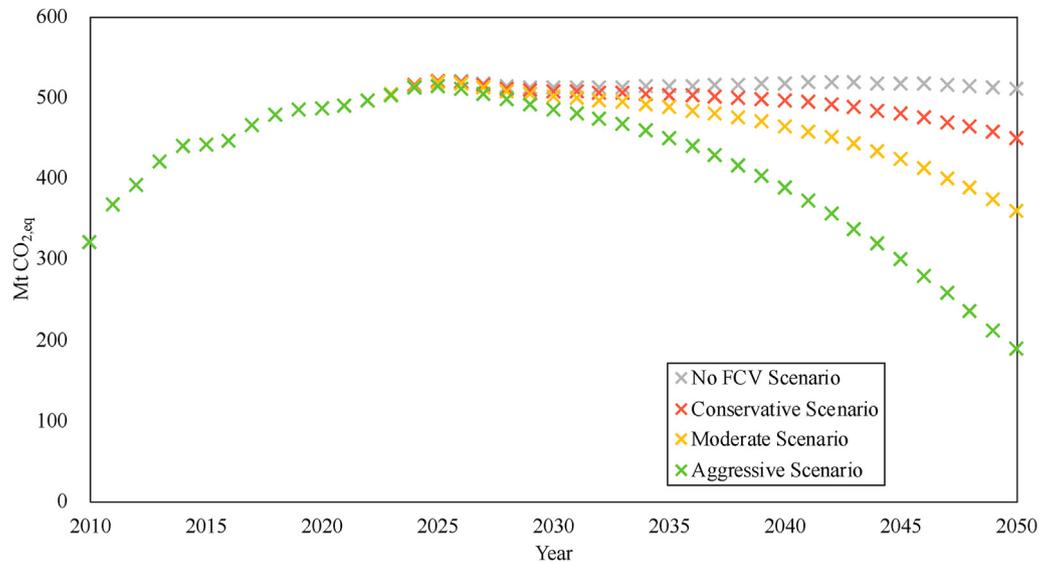
Fig. 12 – GHG emissions of HDTs using various fuels per 100 km travelled. Supplementary notes: coal gasification (CG), steam methane reforming (SMR) solar-power water electrolysis (SPWE), wind-power water electrolysis (WPWE), grid-power water electrolysis (GPWE), chlor-alkali by-product (CB), liquid hydrogen (LH2), and gas hydrogen (GH2).

economical method at present, the GHG emissions per unit mileage of HDTs using hydrogen produced by this method may still be higher than that of diesel and natural gas. With the improvement of fuel economy and a cleaner power grid, the GHG emissions per unit driving distance of hydrogen-powered HDT will gradually decrease.

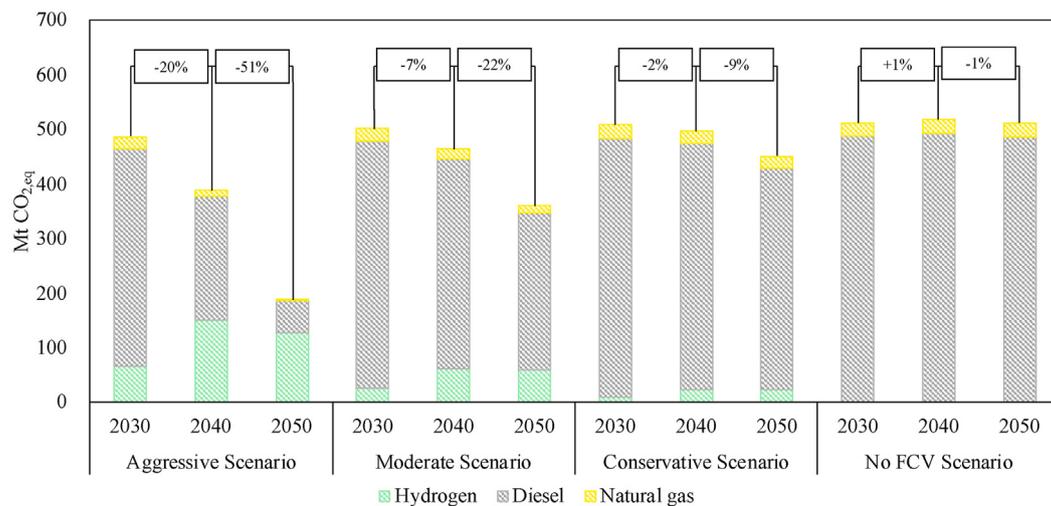
Based on the results of the vehicle stock structure and GHG emissions of different fuel types, the GHG emissions of the HDT vehicle fleet are calculated for each scenario and shown

in Fig. 13. Under the No FCV Scenario, the GHG emissions of the HDT fleet will be relatively constant after 2025. The promotion of fuel cell HDTs will effectively lower the GHG emissions of fleet. In 2050, under the Conservative Scenario, the reduction will be 12% and under the Aggressive Scenario, there will be about a 63% reduction in GHG emissions compared with the No FCV Scenario.

Fig. 13(a) compares GHG emissions under each of our four scenarios over time, and Fig. 13(b) compares the differences



(a) Annual HDT fleet GHG emissions.



(b) HDT fleet GHG emissions for each scenario for 2030, 2040 and 2050. Sources of the GHG emissions are indicated by the color of the bars. Numbers in boxes indicate the decrease in GHG emissions from one decade to the next for each scenario.

Fig. 13 – HDT fleet GHG emissions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

every decade for a single scenario. In all scenarios the upstream GHG emissions from H₂ production are the same, but decrease each decade as shown in Fig. 11.

Conclusions and policy implications

Most analyses and policies examining ways to reduce GHG emissions from road transport focus on passenger vehicles. Few address commercial vehicles, especially heavy-duty trucks

(HDTs). However, HDTs account for an increasing proportion of energy consumption and GHG emissions from vehicle fleets. Fuel cells are increasingly considered to be an effective technology by which heavy-duty vehicles can maintain long range and rapid refueling while reducing emissions. However, the source of hydrogen is important in determining the level of GHG emission reductions that result from the use of fuel cells. Hydrogen is currently mostly obtained from methane, but is an important future energy source allowing the storage of renewably generated electricity. Previous research on fuel cell

vehicles has been limited to comparing the energy consumption and GHG emissions of vehicles under different hydrogen production pathways, but has neglected the importance of the hydrogen production portfolio. Therefore, in this study, based on the hydrogen development White Paper from the CHA, which describes the evolution of H₂ production from 2020 to 2050, we calculate the influence of deployment of fuel cell HDTs on GHG emissions under four scenarios of fuel cell penetration in the HDT sector. We find:

- Reductions in GHG emissions from increases in diesel and natural gas fuel efficiency will be offset by increased HDT stock. As a result, without introducing new powertrains to the HDT fleet, the fleet's GHG emissions will increase slightly to 2040 and then remain relatively constant. Therefore, it is crucial to identify methods to reduce GHG emissions from HDTs in China. Hydrogen fuel cells are an attractive option.
- The GHG emission intensities of different hydrogen production pathways will greatly influence how large the reduction in GHG emissions will be when hydrogen fuel cells are adopted. Some hydrogen production pathways will lead to fuel cell HDTs generating higher GHG emissions than trucks powered by diesel and natural gas. In particular, coal gasification and water electrolysis relying on electricity from a fossil fuel intense power grid will increase GHG emissions relative to diesel and natural gas. In contrast, hydrogen produced from water hydrolysis using renewably generated electricity will have the lowest carbon intensity.
- Decarbonization of the power grid will play an essential role in GHG emission reductions derived from the use of hydrogen, because many processes in the upstream hydrogen life cycle will be powered by electricity from the grid, including compression and liquefaction. With a cleaner power grid, the GHG emission intensities of hydrogen will also decrease, increasing the advantages of using hydrogen as a fuel.
- Based on the hydrogen development roadmap from the CHA, fuel cell HDTs provide an efficient way to reduce GHG emissions generated by the HDT fleet. If by 2050, all new HDTs sold are powered by hydrogen (Aggressive Scenario), the GHG emissions of the HDT fleet will decrease by ~63% compared with the No FCV HDT penetration scenario. If by 2050, fuel cell HDTs account for half of sales (Moderate Scenario), the HDT fleet GHG emissions will fall by ~30% compared to the No FCV Scenario. We thus conclude that fuel cell HDTs appear to be an effective and promising way to decarbonize the HDT fleet, and will become even more attractive as dependence on fossil fuel in H₂ production and electricity generation decreases.

Compared with passenger vehicles, there are relatively few policies and measures focused on energy saving and GHG emission reduction of HDTs in China. According to our study, policy makers in China should consider fuel cell use in HDTs as a possible solution to reduce HDT fleet GHG emissions. More detailed supporting policies and subsidies are needed to promote the deployment of fuel cell HDTs. The development of related facilities and industries is also a concern for policy

makers. The number of hydrogen refilling stations in China is low and their geographical location is uneven. They cannot currently meet the demand generated by a large-scale promotion of fuel cell vehicles. Although the hydrogen development outlook provided by CHA already describes the reduction of GHG emissions possible from fuel cell HDTs, additional policies are needed to facilitate a low GHG emission development pathway for the hydrogen production industry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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