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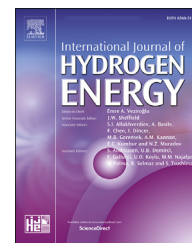
Research on atmospheric pollutant and greenhouse gas emission reductions of trucks by substituting fuel oil with green hydrogen: A case study

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HIGHLIGHTS

- A solution of developing without eco-sacrifice for strategic yet high-emission China GBA.
- The H_2 availability in the China GBA is 1.36×10^{10} GJ/a able to fuel all trucks in the region.
- A 45% reduction in regional greenhouse gas emissions in the China GBA.
- Up to 60% emission reductions of atmospheric pollutants by vehicles in the China GBA.

ARTICLE INFO

ABSTRACT

Trucks has caused serious atmospheric pollutant and greenhouse gas emissions in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), China, while substituting the truck fuel (gasoline/diesel) by green hydrogen is a critical way to solve the problems. Accordingly, we established a Hydrogen availability-Greenhouse gas and Atmospheric Pollutant emission reduction (HGAP) evaluation model. We revealed that the annual available green hydrogen energy in the GBA reached 1.36×10^{10} GJ, which could fuel all the trucks in the region. Via truck fuel substitution by hydrogen, a 45% reduction in regional greenhouse gas emissions in the GBA could achieve. The emission reductions of CO and HC by vehicles in the GBA achieved approximately 1/4, NOx was about 1/2 and PM was about 60%. We served a solution of developing without eco-sacrifice for developed, strategic yet high-emission coastal regions and countries.

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Introduction

On-road transportation has been considered as one of the main culprits causing serious greenhouse gas (GHG), CO, hydrocarbon (HC), NOx and particle matters (PM) emissions in China even over the world [1–3]. From the China Mobile Source Environmental Management Annual Report in last decade, it is reported that vehicles have been the dominant contributors to total GHG and atmospheric pollutants emissions [4–11]. In particular, over 80% of the CO and over 70% of the HC emissions are from passenger cars while over 80% of

the NOx and over 90% of the PM emissions are from trucks [12–16].

Extensive emissions of GHG causes the global warming and climate change, while the large number of NOx and PM emissions result in the server haze weather. Hence to limit the truck emissions is the key step to mitigate the climate change and haze weather [17–20]. Furthermore, it is the fuel oil of trucks consisting of diesel and gasoline, where especially the diesel that produces massive GHG, NOx and PM emissions from combustion and high-temperature exhausts during truck operation [21–24]. The foundation to limit truck emissions is to figure out a feasible and practical truck fuel substitution scheme [25,26].

Hydrogen, especially the carbon-free and renewable green hydrogen, which could power vehicles via fuel cell at low operation temperature, is the ideal substituting fuel for trucks [16,20,27,28]. On the one hand, the reaction products of hydrogen fuel are only water and a little heat without any GHG and carbon-contained atmospheric pollutants emissions [29–32]. Particulate matters dominated by carbon black particles fail to form either [33]. On the other hand, at the low operation temperature, hydrogen is conversed to electricity with higher efficiency and less heat loss [34–38]. Meanwhile, NOx emissions are well limited since lacking the high temperature condition for reactions between nitrogen and oxygen from air [39–42].

Nevertheless, the truck fuel substitution scheme is preferable for regions that with fine hydrogen availability and serious GHG and atmospheric pollutant emissions [43–46]. The Guangdong-Hong Kong-Macao Greater Bay Area (GBA), China, is a desirable research region. In terms of hydrogen availability, plenty of hydrogen could be produced from the South Sea China via offshore wind power and water electrolysis. From the perspective of emission status, due to the boosting economy development and infrastructure construction in this region, population of trucks keeps increasing causing constant growing emissions.

Life cycle assessment (LCA), fuel cycle assessment (FCA) and other general from bottom to top methods have been adopted to evaluate the environmental performances of trucks [18,20,27,47–50]. These methods impressively achieve comprehensive evaluations on GHG and pollutant emissions by trucks starting from truck raw material [27,49,50] productions and fuel extractions, comprising truck component and fuel transport, fuel combustion and other potential emission processes and ending at scrapped truck recycles. Nevertheless, a model considering more details and sections would introduce more assumptions and approximations, bringing higher computational complexities and narrowing the application scenarios of the model. Here in this work, we concentrate on gross hydrogen availability and eventual emissions by fuel consumption, which is named as the state method.

In this research, we conceived a state model of Hydrogen availability-Greenhouse gas and Atmospheric Pollutant emission reduction (HGAP) evaluation standing out from bottom-up models, focusing on the fuel availability and emissions by fuel consumption. We pioneered revealing the offshore wind power based green hydrogen availability of the China GBA and clarifying the potential of greenhouse gas and atmospheric

pollutant emission reduction by truck fuel substitution by hydrogen (TFSH). This work is significant for serving a solution of developing without eco-sacrifice for developed, strategic yet high-emission coastal regions and countries.

Methodology

Since the Greater Bay Area, China is developed, strategic yet high-emission, we conceive a study of environmental benefits from truck fuel substitution by hydrogen on this region to propose a scheme that developing without sacrificed the environment. We design a scheme of truck fuel substitution by hydrogen. We establish a general model with specific assumptions. We acquire data from authoritative departments and organizations [4–11,51].

Study region

The Guangdong-Hong kong-Macao Greater Bay Area is located in the southeast coast of China, which consists of Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, Zhaoqing 9 cities and Hong Kong, Macao 2 special administrative regions, specifically. The particular geographical location of the China GBA has been marked in blue distinguished from other areas in Fig. 1. In 2020, the gross regional product of the China GBA was 11,596 billion RMB, accounting for approximately 10% of the GDP of China while covering only 0.58% of China land area.

Nevertheless, the China GBA performed unsatisfactorily in greenhouse gas and atmospheric pollutant emission reductions. From 2013 to 2020, the greenhouse gas emissions in the China GBA has been over 32,000 ton GHG close to 40,000 ton GHG accounting for around 4% of the domestic GHG emissions, remember that the region covers only 0.58% of China land area, however. Besides, in terms of atmospheric pollutant emissions, the China GBA performed worse from 2013 to 2020. In particular, the CO, hydrocarbon (HC), NOx and particulate matter (PM) emissions by vehicles in the China GBA accounted for nearly 7% of the domestic CO, HC, NOx and PM emissions by vehicles. The data comparison has been shown in Table 1 in details.

Truck fuel substitution scheme

Trucks are generally classified as 4 types consisting of Heavy-duty truck, Medium-duty truck, Light-duty truck and Mini truck from tonnage perspective. In specific, Heavy-duty trucks are defined as trucks ranged from over 14 ton. Medium-duty trucks are defined as trucks ranged from 6 ton to 14 ton. Light-duty trucks are defined as trucks ranged from 1.8 ton to 6 ton. While mini trucks are defined as trucks ranged under 1.8 ton. Trucks in diverse styles are presented in Fig. 2.

Notably, the serious greenhouse gas and atmospheric pollutant emissions are mostly due to the transportation industry especially the on-road truck transportation. Although it is the truck fuel combustion cause the sever emissions, there are several mechanisms for diverse type of emissions [52–55]. Firstly, the adequate combustion of truck fuel produces the GHG emissions while the inadequate combustion

Fig. 1 — The studied Guangdong-Hong Kong-Macao Greater Bay Area, China.

Table 1 — Data comparison of GHG emissions and CO, HC, NOx and PM emissions by vehicles between the GBA and the country (Unit: 10^4 ton).

Year	Country emissions	The GBA emissions	Country emissions by vehicles				The GBA emissions by vehicles			
	GHG	GHG	CO	HC	NOx	PM	CO	HC	NOx	PM
2013	989,400	34241.7	3439.7	431.2	640.6	59.4	274.0	33.0	51.5	4.5
2014	980,600	35450.5	3433.7	428.4	627.8	57.4	250.1	32.5	48.4	4.5
2015	964,900	35619.6	3430	426.1	606.5	55.5	260.8	33.0	46.6	4.2
2016	946,300	32772.8	3419.3	422	577.8	53.4	244.8	28.8	39.7	3.9
2017	927,400	35600.1	3327.3	407.1	574.3	50.9	232.2	29.6	42.3	3.5
2018	927,500	34704.7	3089.4	368.8	562.9	44.2	205.4	24.9	37.5	3.2
2019	928,800	36884.1	771.6	189.2	635.6	7.4	52.0	13.4	41.7	0.5
2020	924,300	38130.0	769.7	190.2	626.3	6.8	53.5	13.2	44.6	0.5

causes the CO, HC and PM which mainly consists of carbon black particles emissions. Moreover, due to the high temperature up to 900 °C and generous amount of heat produced by combustion, at the exhaust outlet formed and emitted abundant NOx through the reaction between nitrogen and oxygen in air [56—61].

Accordingly, a carbon-free energy and a low-temperature operating and highly efficient method of energy combustion for trucks are requested [27,62—64]. Fortunately, hydrogen is considered as the ideal substitution fuel for trucks while fuel cell works in low temperature and remarkable energy conversion efficiency [18,20,47,49,65,66]. Hence the truck fuel substitution scheme of substitution fuel oil (diesel and gasoline) by hydrogen was proposed [50,67—69]. The comparisons between hydrogen and fuel oil and between fuel cell and combustion engine are shown in Table 2.

Fig. 2 − Truck type and truck fuel substitution scheme.

Table 2 − Comparisons between hydrogen and fuel oil and between fuel cell and combustion engine.

Comparison between hydrogen and fuel oil			
	Hydrogen	Diesel	Gasoline
Calorific value (MJ/kg)	143	33	44
Density (atm) (kg/m³)	0.089	850	760
Comparison between fuel cell and combustion engine			
	Fuel cell	Diesel engine	Gasoline engine
Operation efficiency	≥60%	40%−45%	30%−40%
Mileage range (km)	500−700	600−800	600−800
Lowest start-up temperature	−30 °C	−15 °C	−15 °C
Filling time (min)	10−15	10−15	10−15

Model and assumptions

To evaluate the potential of hydrogen availability and GHG, CO, HC, NOx and PM emission reductions in the China GBA, a Hydrogen availability-Greenhouse gas and Atmospheric Pollutant emission reduction (HGAP) evaluation model was established. A scheme map of the HGAP model is shown in Fig. 3.

Generally, the HGAP model is divided into three sections. First is to obtain the hydrogen availability. In this research, water electrolysis by offshore wind power is adopted for hydrogen production, due to the vast South China Sea and adequate offshore wind resources. Truck data consists of energy consumption, population and emissions are collected from China National Bureau of Statistics, Ministry of Ecology and Environment of China and Beilong Zedata Co. Ltd.

Particularly, the annual hydrogen availability (GJ/A) of the China GBA is obtained by product of offshore area (m²), offshore wind power (GW/m²), wind farm operation time (s/a) and total hydrogen productivity (%). Second step is to obtain the GHG and atmospheric pollutant emission reductions. Via dividing hydrogen availability into energy consumed by trucks (GJ each), the quantity of substituted trucks is got. Then multiplying the quantity of substituted trucks by emission per truck (t each), the GHG and atmospheric pollutant emission reductions (t) are obtained. Eventually, through dividing the GHG and atmospheric pollutant emission reductions into annual travel distance (100 km), the GHG and atmospheric pollutant emission factors of trucks are obtained.

In particular, the offshore area is a rectangular area with a linear length of the GBA coastline, 303.89 km and width of the distance of sovereignty, 37.04 km. The average offshore wind power of the South China Sea is 350 W/m² as record. We use the common wind farm operation time, 200 whole days annually. We assume the total hydrogen productivity is 20% by considering the energy loss and mechanical efficiency. After getting the hydrogen availability, we evaluate the GHG and atmospheric pollutant emission reductions. Energy consumed by per truck is evenly assessed according to the gross truck energy consumption and truck population in specific tonnage [51]. Besides, emission per truck is evaluated according to the gross truck population and emissions in specific tonnage [4−11,51]. Eventually yet notably, based on the evaluated GHG and atmospheric pollutant emission reductions and annual travel distance of trucks from official departments, we further furnish the GHG and atmospheric pollutant emission factors for the future demands on efficient emission assessments.
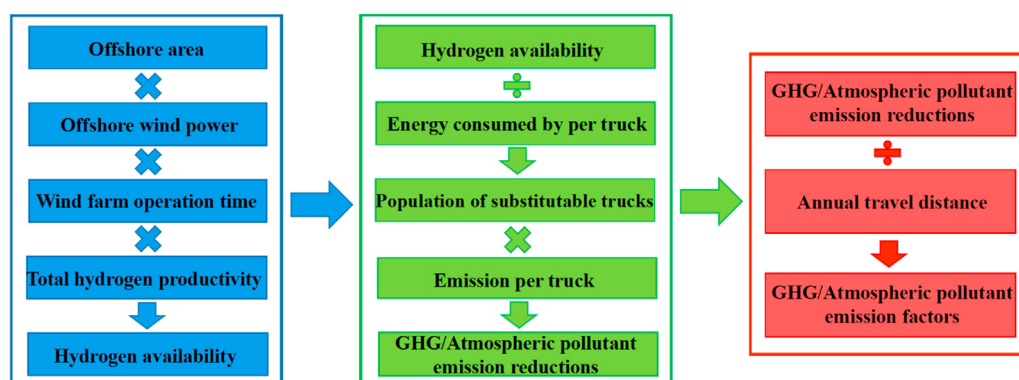

Fig. 3 − The scheme map of established and adopted HGAP model in this research.

Data sources

Original data presented in this work is obtained from the public reports and data base of China National Bureau of Statistics and Ministry of Ecology and Environment of China [4–11,51]. Moreover, the Beilong ZeData (Beijing) Co. Ltd, China offers the market analyse and views to this work. Generally, the dynamic population data from 2013 to 2020 of Mini trucks, Light-duty trucks, Medium-duty trucks and Heavy-duty trucks in the China GBA has been respectively presented in Fig. 4 from Fig 4 (a) to Fig 4 (d). Moreover, the annual growth rate of truck population has also been plotted.

It is demonstrated that from 2013 to 2020, the population of diverse types of trucks have changed to a great extent. Light-duty trucks and Heavy-duty trucks especially Light-duty trucks were originally the dominant truck types in the China GBA, while whose population kept growing in this period. Specifically, the population of Light-duty trucks have increased by over 30% from 1.19 million to 1.62 million while that of Heavy-duty trucks have increased by over 100% from 0.20 million to 0.40 million. On the contrast, the population of Mini trucks and Medium-duty trucks have decreased by approximately 50% from 0.16 million to 0.88 million and from 29.83 thousand to 14.10 thousand, respectively.

In particular, merchandises carried by Mini trucks and Light-duty trucks are commonly consumer and trading goods such as furniture, home decoration, food and daily necessities, which are closely related to regional consumption level. Besides, services by Medium-duty trucks and Heavy-duty trucks are mainly for logistics and engineering especially infrastructure construction, reflecting the consumption and modernization lever in the China GBA. The raising demands transferred from Mini trucks and Medium-duty trucks to Light-duty trucks and Heavy-duty trucks reveal that consumption, construction and modernization of the China GBA have rapidly developed in the past decade.
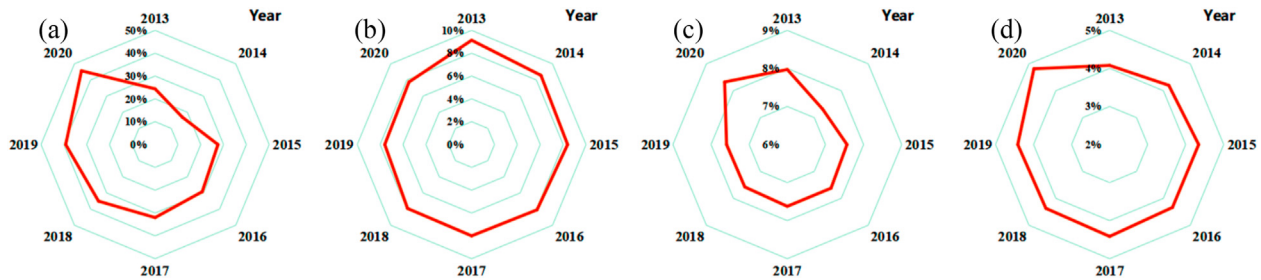
The truck population of China GBA as a percentage in the country is respectively shown in Fig. 5 from Fig 5 (a) to Fig 5 (d). According to Fig. 5, a new perspective is found that Light-duty, Medium-duty and Heavy-duty trucks in the China GBA account for less than 10% of that in the country while Mini trucks account for 25% initially near 50% lately. It could be known that consumption and trading industries in the China GBA have been thriving and become the pillar industries.

Results

Based on the HGAP model, we estimate the environmental benefits from truck fuel substitution by hydrogen of the China GBA. We first reveal the hydrogen availability and truck fuel consumption in GBA. Afterwards, we clarify the GHG and atmospheric pollutant emission reductions achieved by fuel substitution in GBA. Eventually we furnish the dynamic emission factors of trucks in GBA.
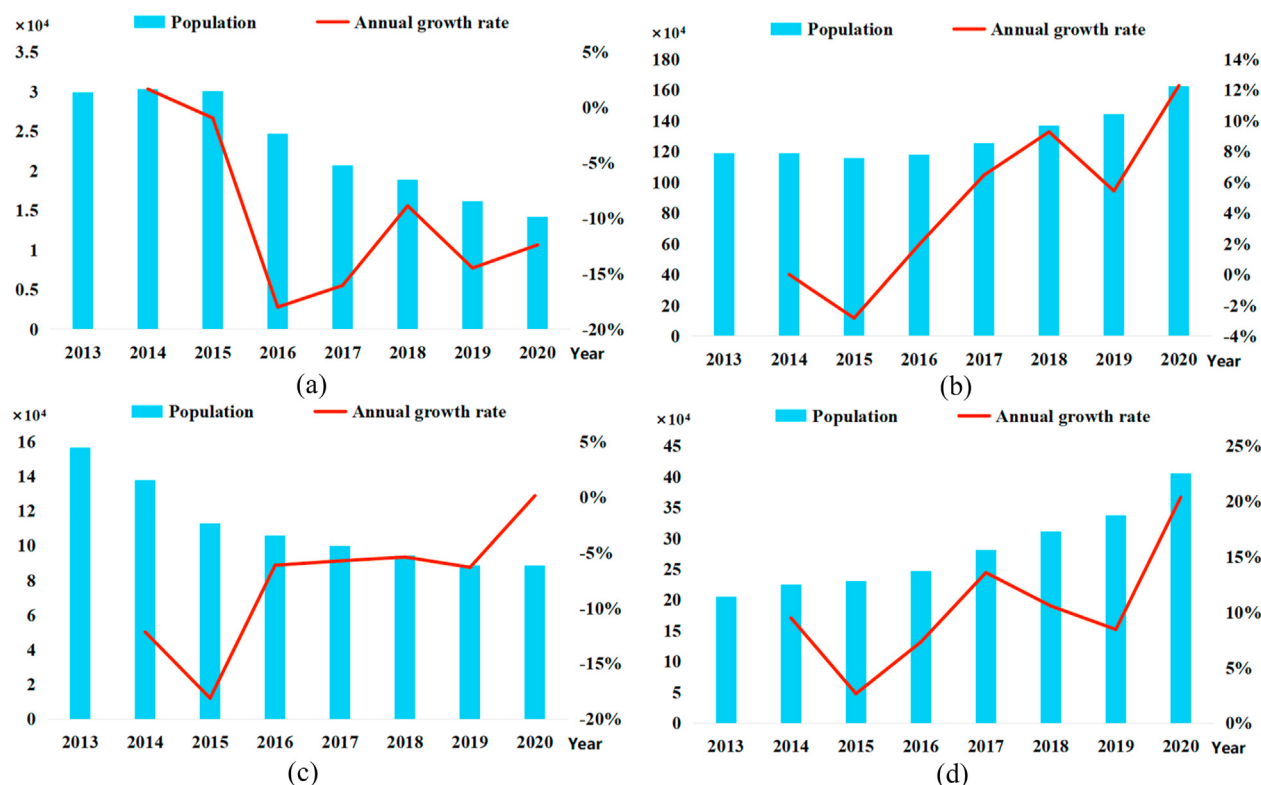
Fig. 4 — The dynamic population and corresponding annual growth rate of trucks in the China GBA. (a) The dynamic population and corresponding annual growth rate of Mini trucks. (b) The dynamic population and corresponding annual growth rate of Light-duty trucks. (c) The dynamic population and corresponding annual growth rate of Medium-duty trucks. (d) The dynamic population and corresponding annual growth rate of Heavy-duty trucks.

Fig. 5 – The truck population of China GBA as a percentage in the country from 2013 to 2020. (a) The Mini truck population of China GBA as a percentage in the country. (b) The Light-duty truck population of China GBA as a percentage in the country. (c) The Medium-duty truck population of China GBA as a percentage in the country. (d) The Heavy-duty truck population of China GBA as a percentage in the country.

Hydrogen availability and truck fuel consumption in GBA

In general, the available hydrogen in the China GBA is considerable. The energy consumption by trucks in the China GBA from 2013 to 2020 and the hydrogen availability in the China GBA is presented in Fig. 6. It could be seen that the hydrogen availability of the China GBA is 1.36×10^{10} GJ, way more than the total energy consumption by trucks. Although total energy consumption by trucks boosted in the past several years, that in 2020 was 0.34×10^{10} GJ, approximately 25% of the hydrogen availability. From energy supply and consumption perspective, 100% of trucks in the China GBA could be substituted from 2013 to 2020 even in the future several decades according to present energy consumption growth rate. The truck fuel substitution scheme in the China GBA could be considered as long-term feasible.

It is also found that the Light-duty trucks and Heavy-duty trucks consumed the most energy. According to the population and energy consumption per unit of diverse tonnage of

trucks, it is known that the high energy consumption of Light-duty trucks due to the large population while that of Heavy-duty trucks due to the high energy consumption per unit.

Specifically, The energy consumption by trucks and annual growth rate of total energy consumption in the China GBA from 2013 to 2020 is shown in Fig. 7. From 2013 to 2016, the growth rate of energy consumption of trucks remain a value near even lower than 0. However, from 2017 to 2020 the energy consumption of trucks increased in a constantly raising growth rate that in 2020 the energy consumption growth rate reached 13.42%. Moreover, energy consumption of Light-duty trucks and Heavy-duty trucks increased while that of Mini trucks and Medium-duty trucks decreased since the population change basically.

GHG emission reductions by TFSH in GBA

The GHG emissions before and after the truck fuel substitution by hydrogen (TFSH) and rate of emission reductions by
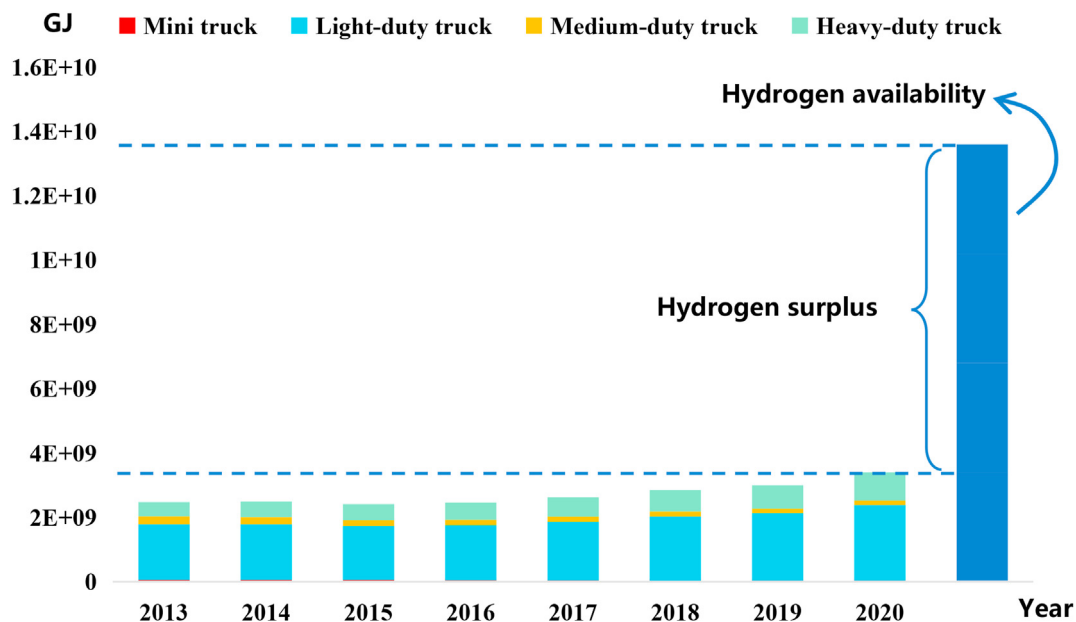
Fig. 6 – The energy consumption by trucks in the China GBA from 2013 to 2020 and the hydrogen availability in the China GBA.
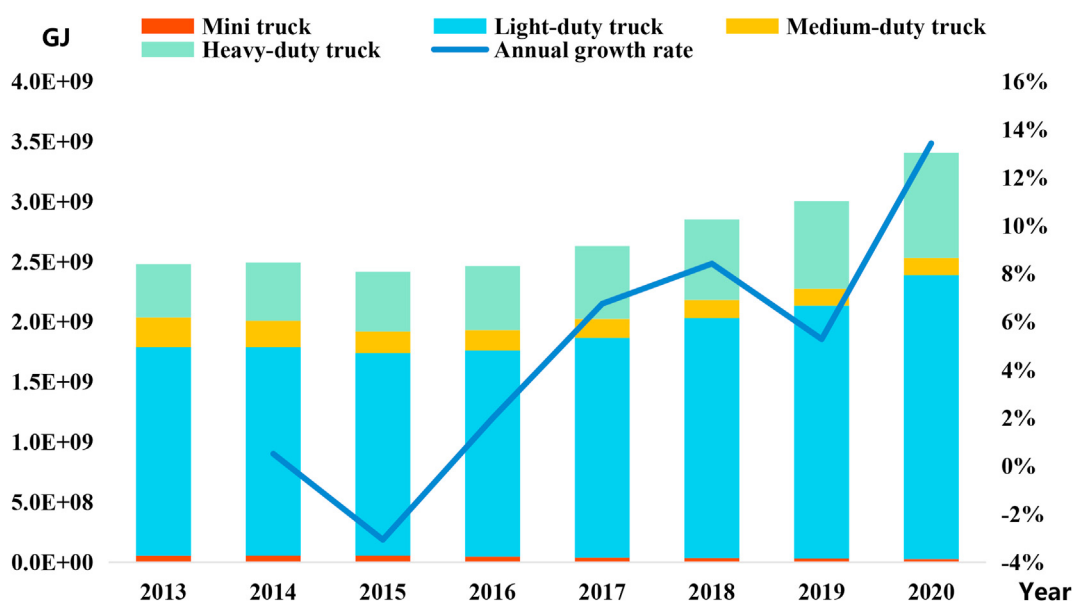
Fig. 7 – The energy consumption by trucks and annual growth rate of total energy consumption in the China GBA from 2013 to 2020.
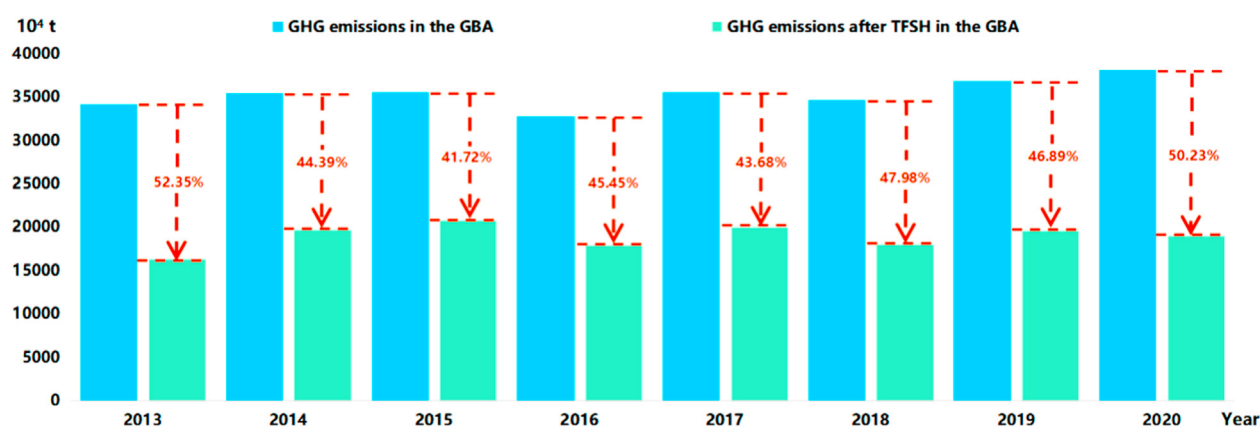

Fig. 8 – The GHG emissions before and after the truck fuel substitution by hydrogen (TFSH) and rate of emission reductions by TFSH in the China GBA.

TFSH in the China GBA is demonstrated in Fig. 8. According to the evaluation results from the HGAP model, the truck fuel substitution with hydrogen could achieve a 45% reduction at average in regional greenhouse gas emissions in the Greater Bay Area, China. In particular, The most significant reduction of greenhouse gas emissions by substituting fuel oil with hydrogen of trucks occurred in 2013 at 52.35%, while the least occurred in 2015 at 41.72% as shown below.

Besides, the contribution of diverse type of trucks to the greenhouse gas emission reductions is shown in Fig. 9. The contribution of the Light-duty trucks to the greenhouse gas emission reduction reached more than 80%, while that of Mini trucks, Heavy-duty trucks and Medium-duty trucks reached 16.62% in common. Specifically, the mini truck contributed the least with 8.65% in that 16.62%. Heavy-duty trucks and Medium-duty trucks contributed 44.24% and 47.10% in that 16.62%, respectively.

Atmospheric pollutant emission reductions by TFSH in GBA

The atmospheric pollutant emissions by vehicles before and after TFSH and rate of emission reductions by TFSH in the China GBA are presented in Fig. 10. From the atmospheric pollutant emission reduction perspective, the CO emission reduction of vehicles in the Greater Bay Area achieved about 1/4, while that of HC was approximately 1/4, NOx was about 1/2 and PM was about 60%. It should be noted that the NOx and PM are mainly responsible for the haze wether in the Greater Bay Area, China. The fuel oiil substitution by hydrogen of trucks is of great significance for the air quality improvement and residual health enhancement. More details have been shown in curves on the right hand side.

Furthermore, the contributions to atmospheric pollutant emission reductions by diverse type of trucks are shown in Fig. 11. In Fig. 11, the row that per lattice locates indicates the
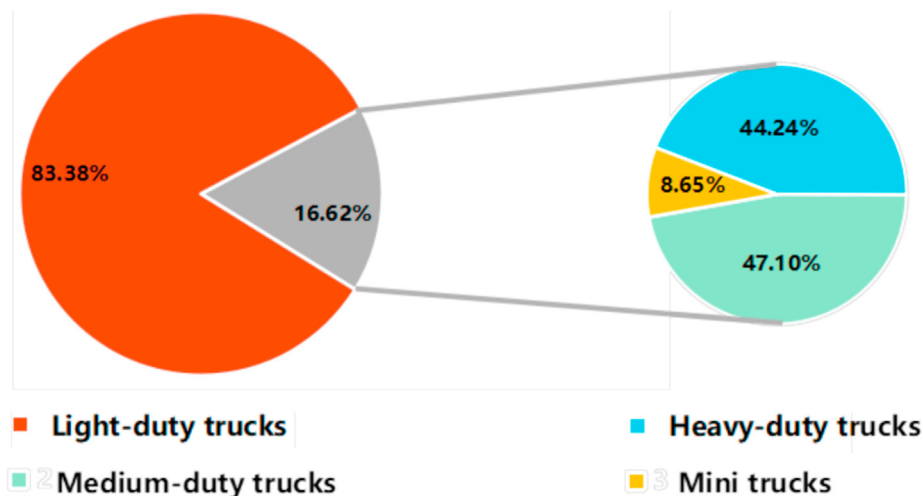
Fig. 9 – The contribution of diverse type of trucks to the greenhouse gas emission reductions.
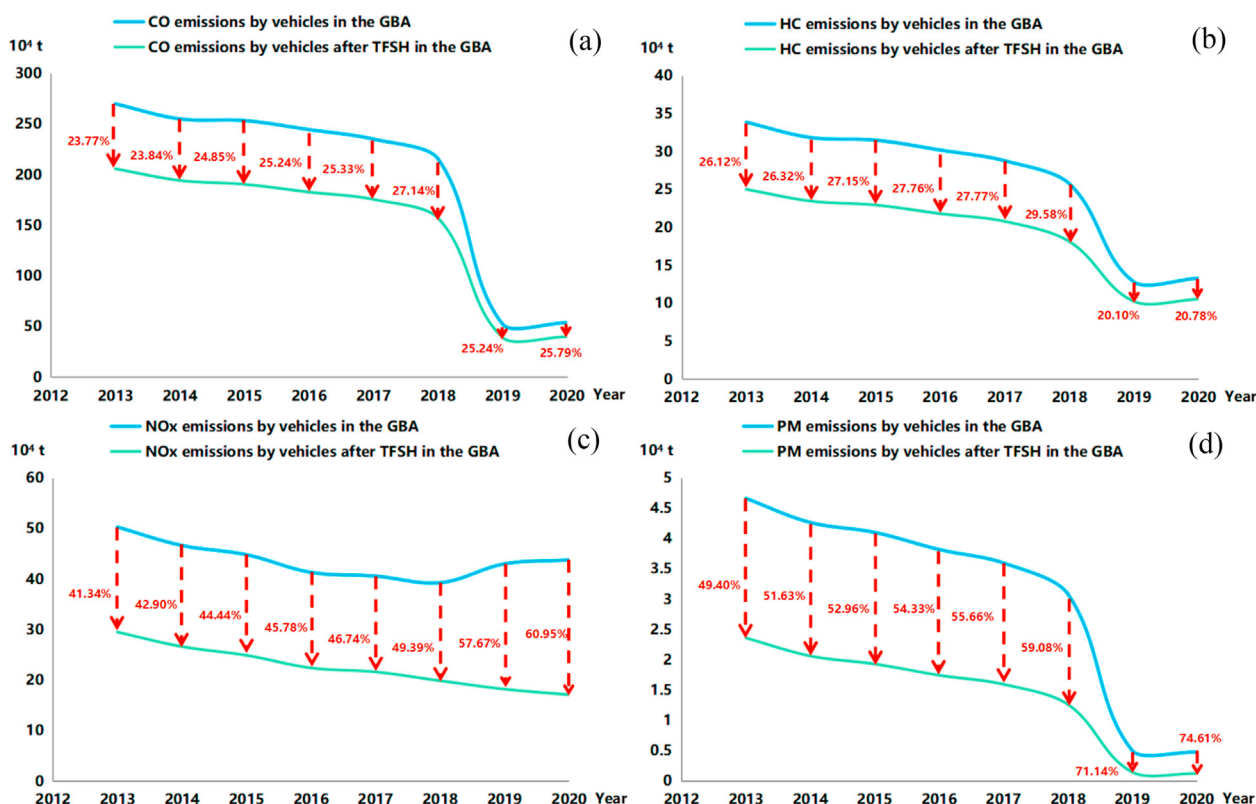

Fig. 10 – The atmospheric pollutant emission reductions by vehicles before and after TFSH and rate of emission reductions by TFSH in the China GBA. (a) The CO emission reductions by vehicles. (b) The HC emission reductions by vehicles. (c) The NOx emission reductions by vehicles. (d) The PM emission reductions by vehicles.

year, while the column per lattice locates indicates the emission reduction item of a specific truck type. The color of per unit corresponds to a specific value ranging from 0 to 100%. Specific to the truck type, the heavy-duty trucks contributed more than 1/2 of the NOx emission reduction, while the light-duty trucks contributed more than 1/3 to PM emission reduction. For the heavy-duty trucks, it is because most of which are fueled by diesel that emitted the NOx seriously. For the light-duty trucks, it is due to that the population of which

account for more than 3/4 of total vehicle population in the Greater Bay Area. More details have been shown in heat map on the right hand side.

The dynamic emission factors of trucks in GBA

The dynamic emission factors of diverse type of trucks in China GBA are provided in Fig. 12 from Fig. 12(a)–12(d). Generally, truck population in the China GBA grew at about
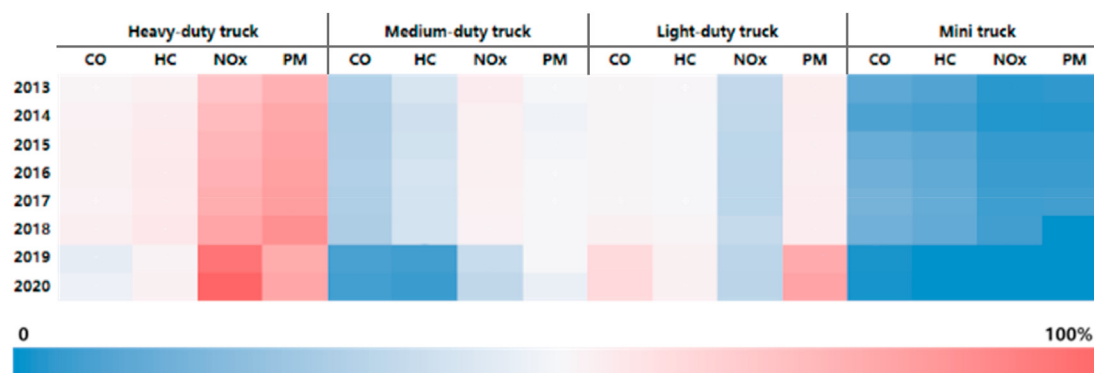
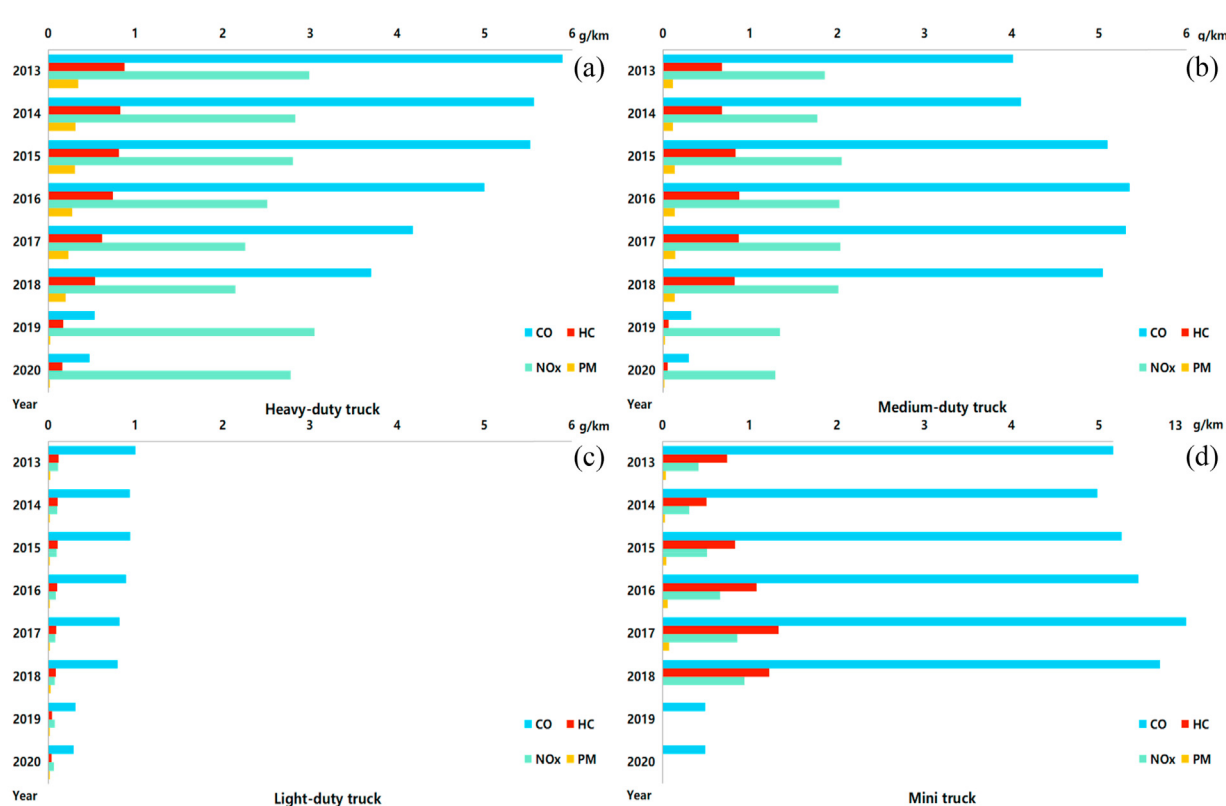**Fig. 11 – The contributions to atmospheric pollutant emission reductions by diverse type of trucks.**

Fig. 12 – The dynamic emission factors of diverse type of trucks in China GBA. (a) The dynamic emission factors of Heavy-duty trucks. (b) The dynamic emission factors of Medium-duty trucks. (c) The dynamic emission factors of Light-duty trucks. (d) The dynamic emission factors of Mini trucks.

4.4% annually. As the trucks were optimized, emission factor growth rate of CO, HC, NOx and PM were at average −23.0%, −18.8%, −0.7% and −26.6%, respectively. However, the NOx emissions remain grim.

According to Fig. 12 from Fig. 12(a)–12(d), it is revealed that the heavy-duty truck and medium-duty truck are the core target to conduct the fuel substitution for NOx and PM emission reduction, while CO emission reduced most by applying fuel substitution mini trucks.

Discussions

In this research, the potentials of hydrogen availability, GHG emission reductions and atmospheric pollutant emission reductions in the China GBA were analyzed and clarified based on the history data from 2013 to 2020 via adopting the HGAP model. It is worth noting that researches on predictions of hydrogen availability, GHG emission reductions and

atmospheric pollutant emission reductions in the China GBA in future are desirable as well. Feasible methods such as the data fitting, statistics regression, machine learning and others are recommended for mining the history data and establish models. Based on the formed models, the trends or predictions of the hydrogen availability, GHG emission reductions and atmospheric pollutant emission reductions in the China GBA could be obtained.

In addition to water electrolysis by offshore wind power mentioned in this work, other hydrogen production methods are preferable to popularize the hydrogen availability estimation in the Greater Bay Area world wide. The key rule is to adopt the most appropriate method basing on the ecological environment. For instance, water electrolysis by offshore solar power is preferred in the Greater Bay Area in low latitude. Hydrogen refined from the by-product of coal gas, ammonia synthesis and caustic soda industries is desirable for the Greater Bay Area in heavy-industry regions.

Actually, up to date truck fuel consists of natural gas and electricity besides diesel and gasoline yet diesel and gasoline still hold the major part. Researches on discussing the environmental and economic benefits from hydrogen comparing to those from natural gas and electricity are desirable to reveal a more comprehensive cognition to truck fuel application. Furthermore, from another research perspective, environmental and economical benefits from substituting passenger vehicle fuel by hydrogen could be analyzed and discussed in the Greater Bay Area.

In general, we conduct this work to propose a solution of renewable hydrogen availability and emission reductions for regions and countries which are developed, strategic yet high-emission. The China Greater Bay Area is selected as an illustration in this work. Notably, for other Greater Bay Areas and island countries as well, the findings of this work are referential and transferable. Moreover, more enhancements and conditions could be incorporated in the HGAP model for a more general and reliable application.

Conclusion

The extensive use of trucks has caused serious atmospheric pollutant and greenhouse gas emissions in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), China, bringing a harsh climate to the region while seriously affecting the respiratory health of residuals. Hydrogen fuel cell trucks substituting the fuel (gasoline/diesel) trucks is an effective way to solve the above problems. In this research, a HGAP evaluation model was established based on the truck data and emission data of the China GBA. The hydrogen availability of the China GBA was revealed. The potential of greenhouse gas and atmospheric pollutant emission reduction by substituting truck fuel by hydrogen was clarified eventually.

We revealed that the annual available hydrogen energy in the GBA, China reached 1.36×10^{10} GJ, which could fuel all the trucks in the region. Via truck fuel substitution by hydrogen, a 45% reduction in regional greenhouse gas emissions in the GBA could achieve. The emission reductions of CO and HC by vehicles in the GBA achieved approximately 1/4, NOx was about 1/2 and PM was about 60%. We generally proposed a

solution of developing without sacrificing environments for developed, strategic yet high-emission coastal regions and countries.

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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