INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 48 (2023) 11555–11566

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

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

Junming Lao [a], *Hongqing Song* [a,*], *Cheng Wang* [b], *Yang Zhou* [b]

[a] *School of Civil and Resource Engineering, University of Science and Technology Beijing, China*
[b] *Beilong ZeData (Beijing) Co. Ltd, China*

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

Article history:
Received 2 December 2021
Received in revised form
22 February 2022
Accepted 26 February 2022
Available online 20 March 2022

Keywords:
Truck fuel substitution by hydrogen
Emission reductions
Greenhouse gas
Atmospheric pollutants
The guangdong-Hong Kong-Macao
Great bay area

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.

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

* *Corresponding author.*
E-mail address: songhongqing@ustb.edu.cn (H. Song).
https://doi.org/10.1016/j.ijhydene.2022.02.230

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

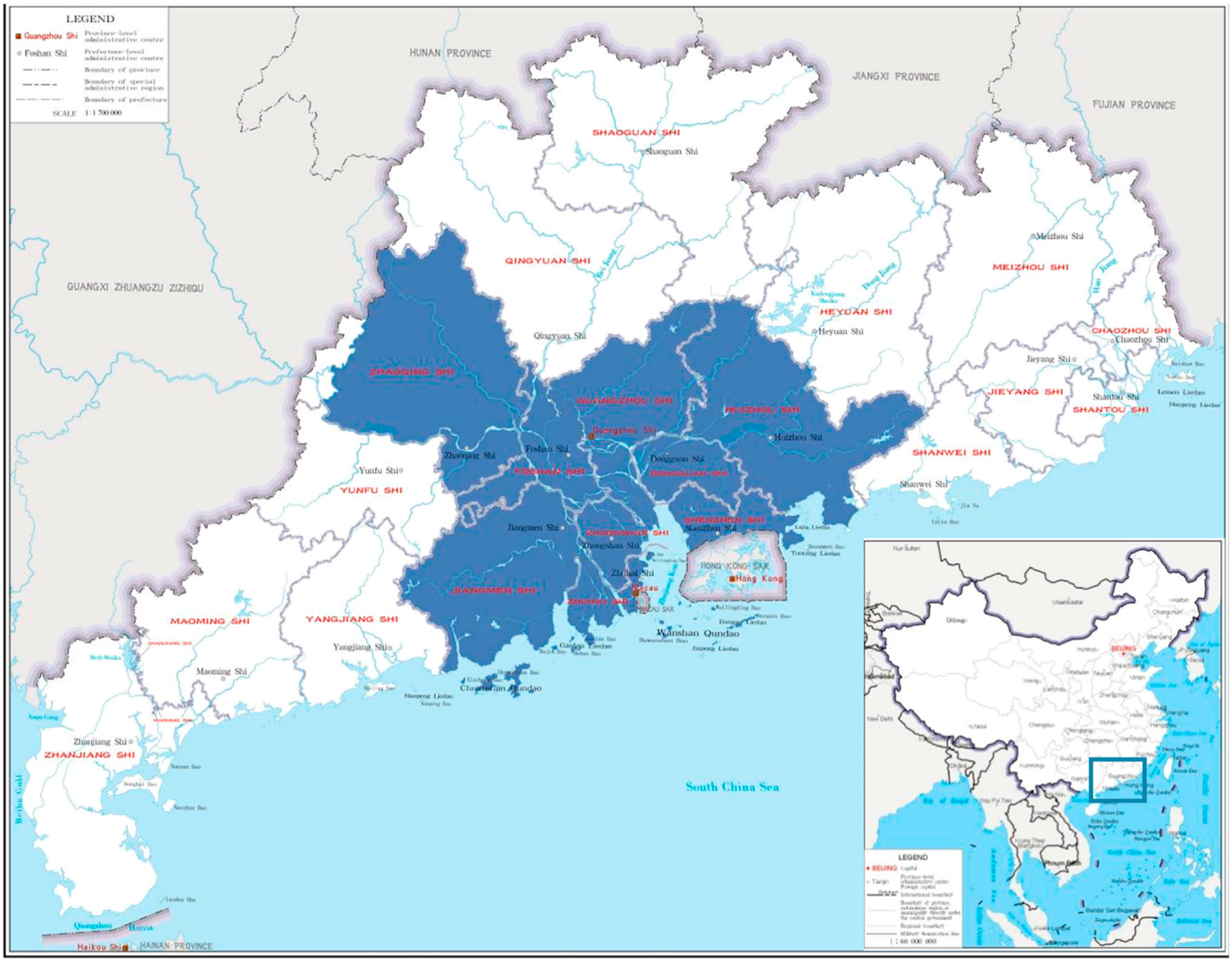

Fig. 1 – The studied Guangdong-Hong Kong-Macao Greater Bay Area, China.

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/m^3)	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 (m^2), offshore wind power (GW/m^2), 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/m^2 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.

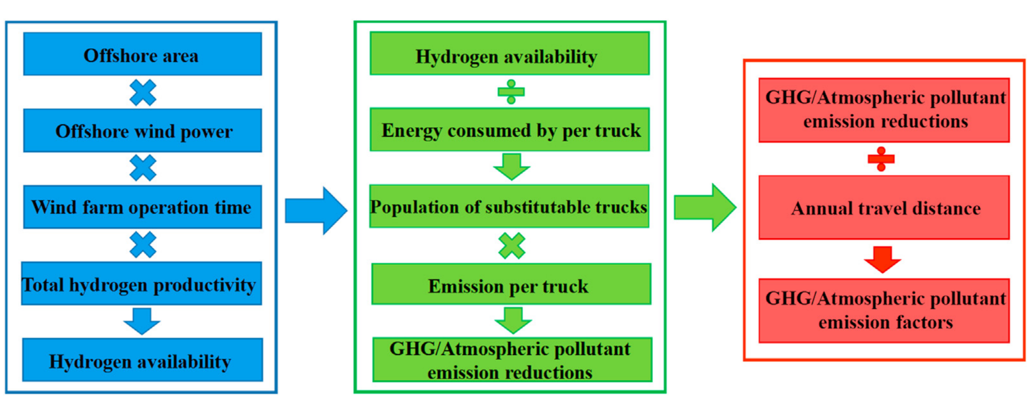

Fig. 3 – The scheme map of established and adopted HGAP model in this research.

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.

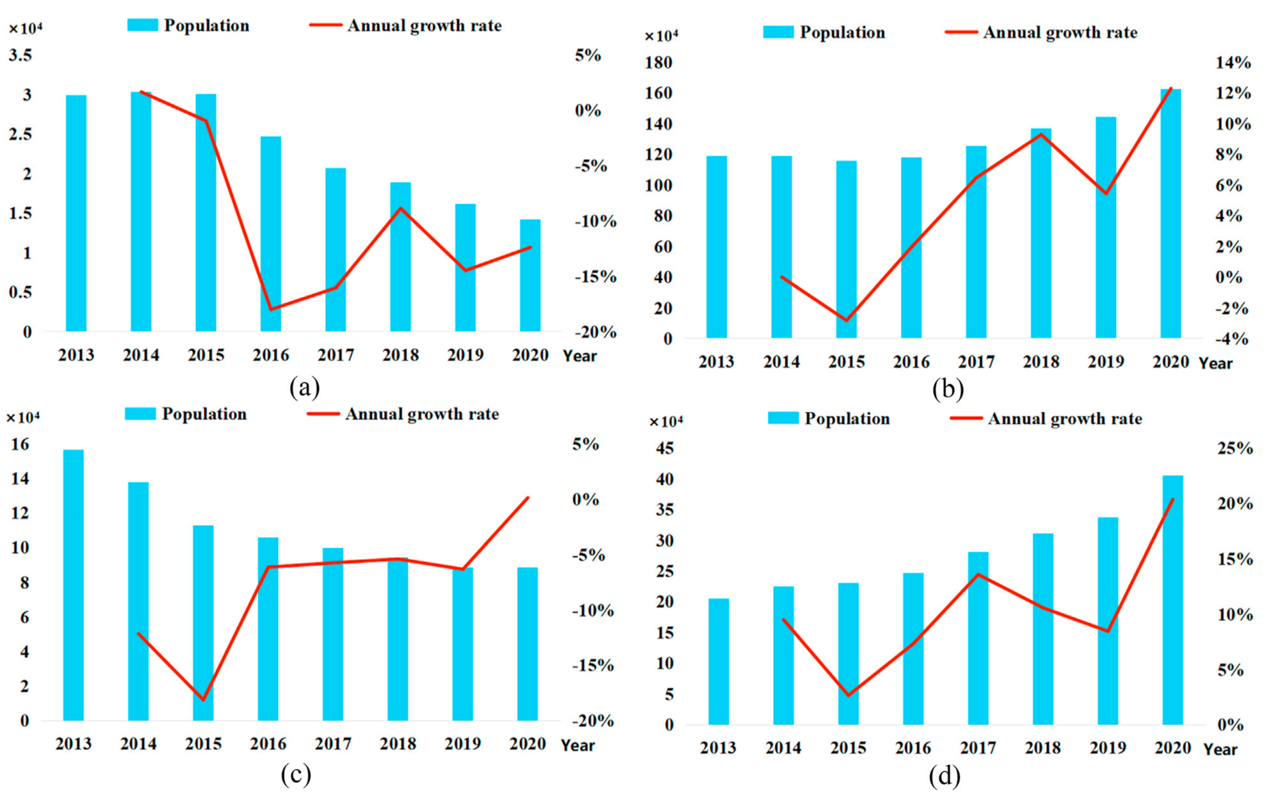

Fig. 4 – The dynamic population and corresponding annual growth rate of trucks in the China GBA. (a) The dynamic population and corresponding annual growth rate of Mini trucks. (b) The dynamic population and corresponding annual growth rate of Light-duty trucks. (c) The dynamic population and corresponding annual growth rate of Medium-duty trucks. (d) The dynamic population and corresponding annual growth rate of Heavy-duty trucks.

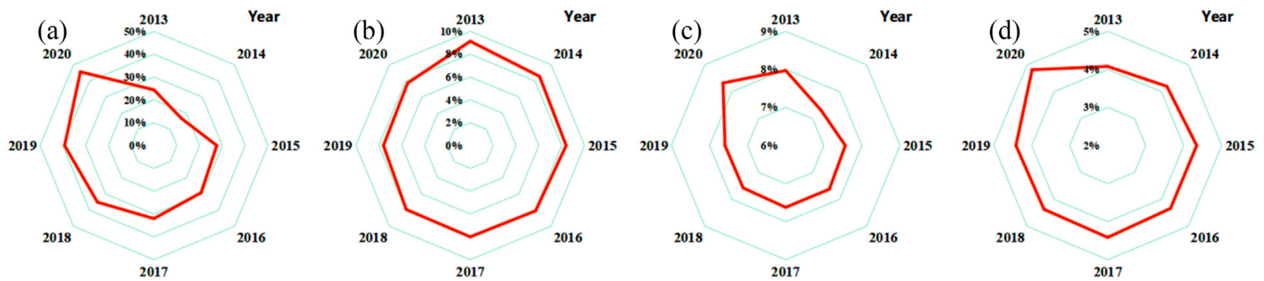

Fig. 5 – The truck population of China GBA as a percentage in the country from 2013 to 2020. (a) The Mini truck population of China GBA as a percentage in the country. (b) The Light-duty truck population of China GBA as a percentage in the country. (c) The Medium-duty truck population of China GBA as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

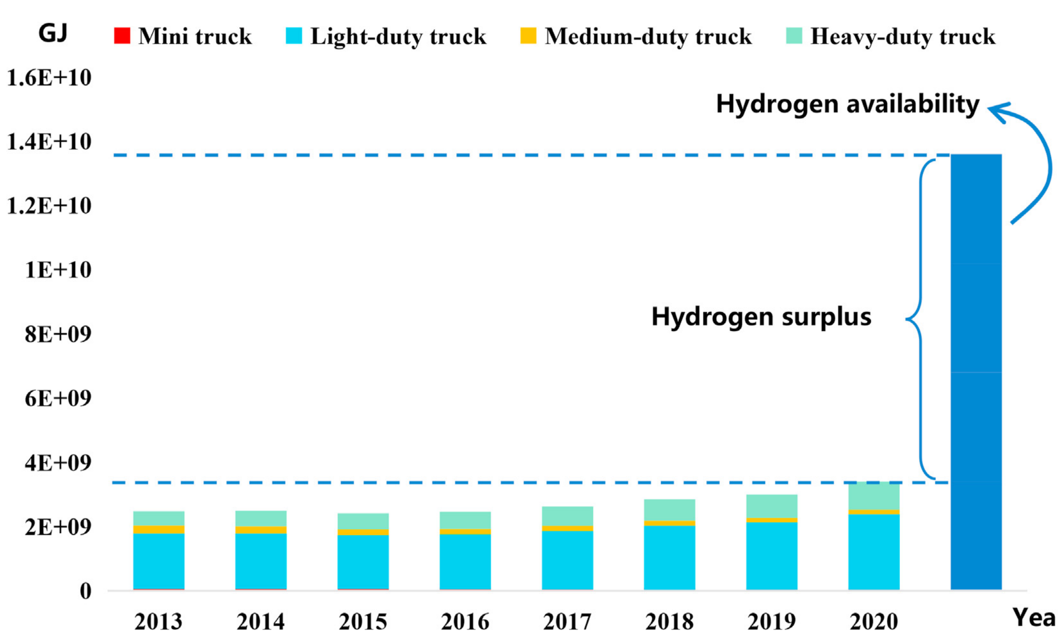

Fig. 6 – The energy consumption by trucks in the China GBA from 2013 to 2020 and the hydrogen availability in the China GBA.

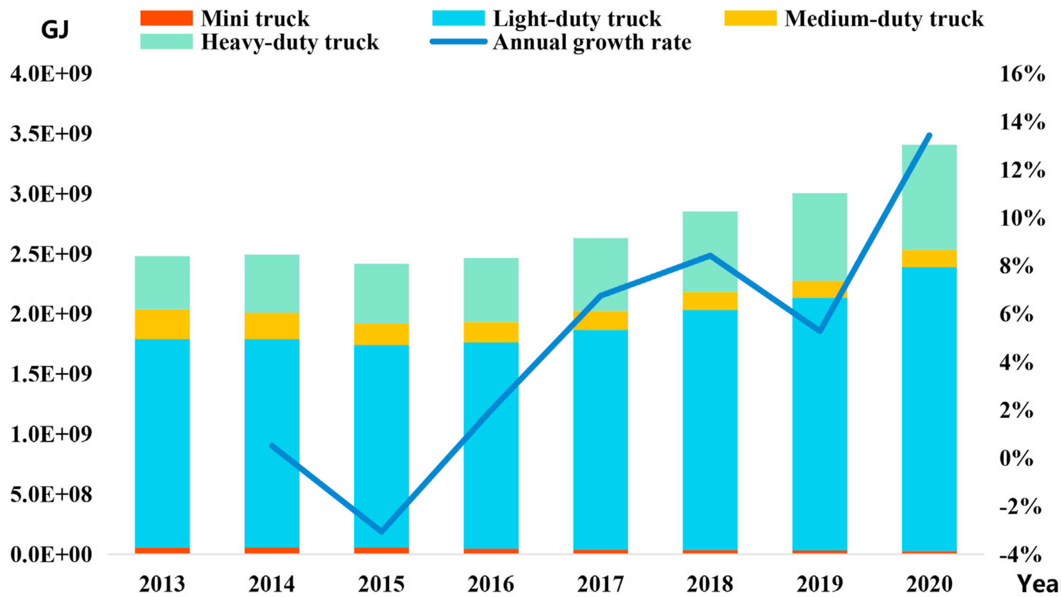

Fig. 7 — The energy consumption by trucks and annual growth rate of total energy consumption in the China GBA from 2013 to 2020.

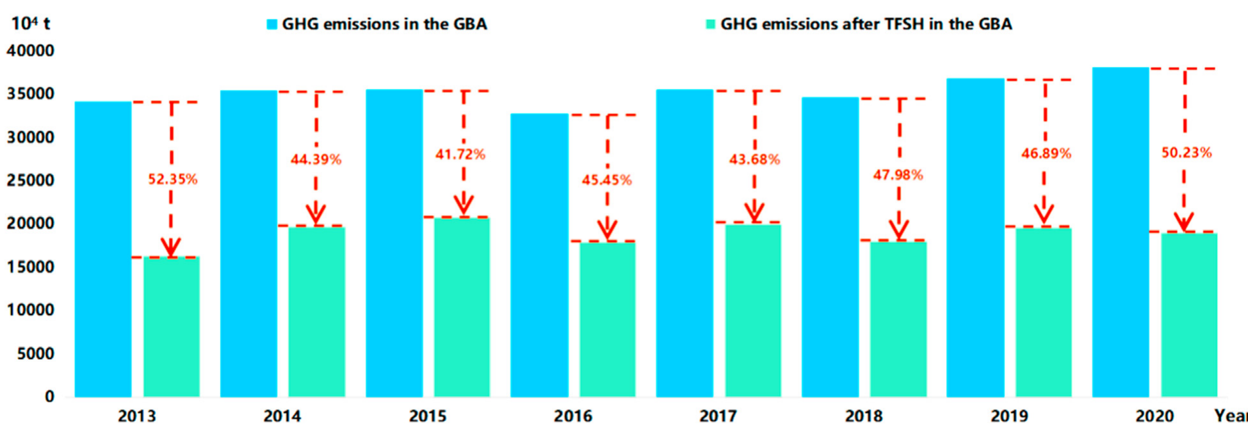

Fig. 8 — The GHG emissions before and after the truck fuel substitution by hydrogen (TFSH) and rate of emission reductions by TFSH in the China GBA.

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

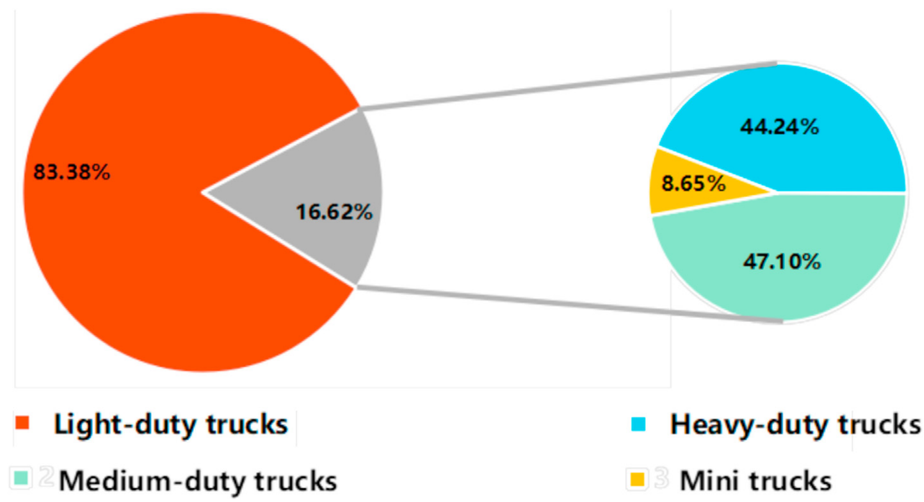

Fig. 9 – The contribution of diverse type of trucks to the greenhouse gas emission reductions.

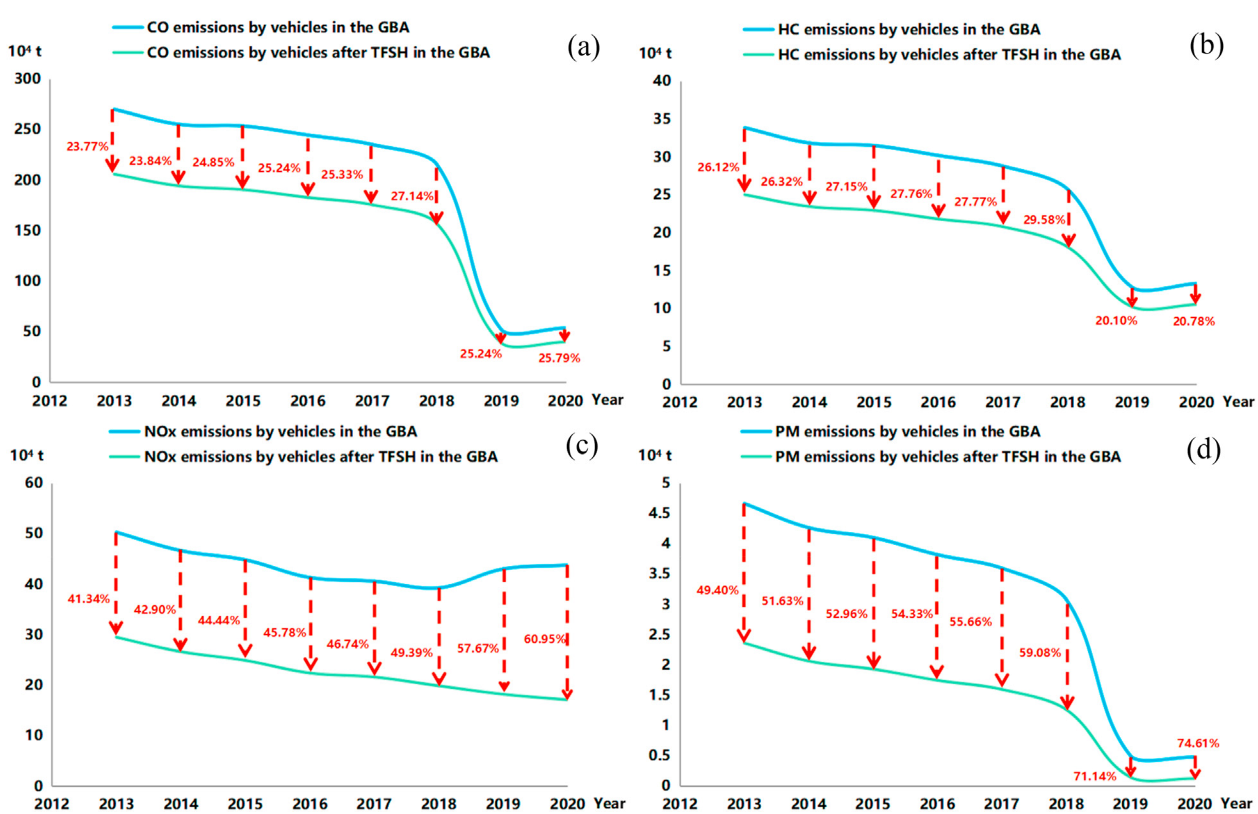

Fig. 10 – The atmospheric pollutant emission reductions by vehicles before and after TFSH and rate of emission reductions by TFSH in the China GBA. (a) The CO emission reductions by vehicles. (b) The HC emission reductions by vehicles. (c) The NOx emission reductions by vehicles. (d) The PM emission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

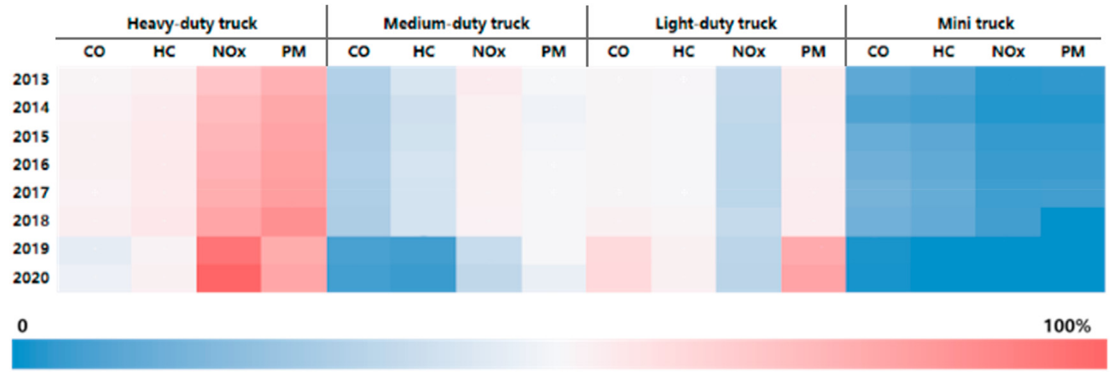

Fig. 11 – The contributions to atmospheric pollutant emission reductions by diverse type of trucks.

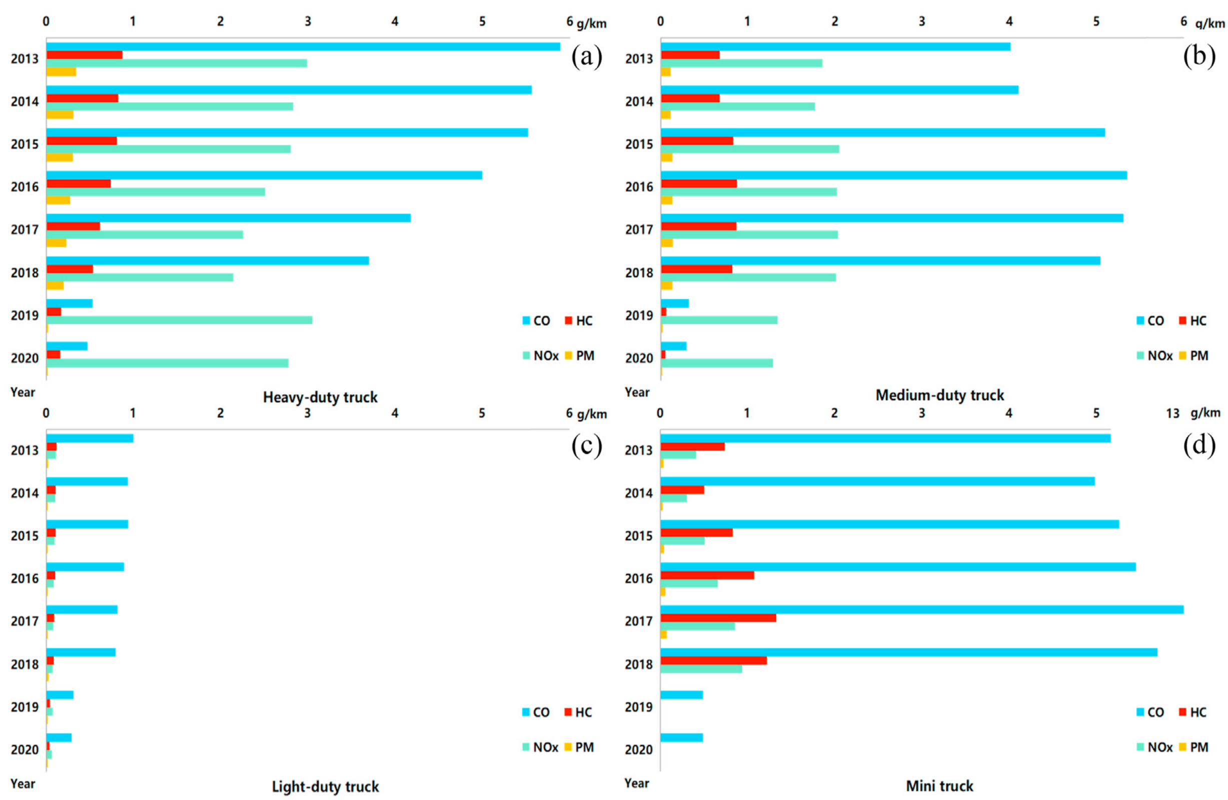

Fig. 12 – The dynamic emission factors of diverse type of trucks in China GBA. (a) The dynamic emission factors of Heavy-duty trucks. (b) The dynamic emission factors of Medium-duty trucks. (c) The dynamic emission factors of Light-duty trucks. (d) The dynamic emission factors of Mini trucks.

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.

Funding

The National Natural Science Foundation of China (Grant No.11972073).

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.

Acknowledgements

The authors acknowledge the funding support from the National Natural Science Foundation of China (Grant No. 11972073).

REFERENCES

[1] Frey HC, Zhai HB, Rouphail NM. Regional on-road vehicle running emissions modeling and evaluation for conventional and alternative vehicle technologies. Environ Sci Technol 2009;43:8449–55.

[2] Sacchi R, Bauer C, Cox BL. Does size matter? The influence of size, load factor, range autonomy, and application type on the life cycle assessment of current and future medium- and heavy-duty vehicles. Environ Sci Technol 2021;55:5224–35.

[3] Song LY, Song HQ, Lin JY, Wang C, Yu MX, Huang XX, et al. PM2.5 emissions from different types of heavy-duty truck: a case study and meta-analysis of the Beijing-Tianjin-Hebei region. Environ Sci Pollut Res 2017;24:11206–14.

[4] China mobile Source environmental management annual report. Ministry of Environmental Protection of the People's Republic of China; 2019.

[5] China mobile Source environmental management annual report. Ministry of Environmental Protection of the People's Republic of China; 2020.

[6] China mobile Source environmental management annual report. Ministry of Environmental Protection of the People's Republic of China; 2021.

[7] China vehicle emission control annual report. Ministry of Environmental Protection of the People's Republic of China; 2013.

[8] China vehicle emission control annual report. Ministry of Environmental Protection of the People's Republic of China; 2014.

[9] China vehicle emission control annual report. Ministry of Environmental Protection of the People's Republic of China; 2015.

[10] China vehicle emission control annual report. Ministry of Environmental Protection of the People's Republic of China; 2017.

[11] China vehicle emission control annual report. Ministry of Environmental Protection of the People's Republic of China; 2018.

[12] Forrest K, Mac Kinnon M, Tarroja B, Samuelsen S. Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Appl Energy 2020:276.

[13] Di Ilio G, Di Giorgio P, Tribioli L, Bella G, Jannelli E. Preliminary design of a fuel cell/battery hybrid powertrain for a heavy-duty yard truck for port logistics. Energy Convers Manag 2021:243.

[14] Jiao JD, Huang Y, Liao CP. Co-benefits of reducing CO2 and air pollutant emissions in the urban transport sector: a case of Guangzhou. Energy Sustain Dev 2020;59:131–43.

[15] Talebian H, Herrera OE, Tran M, Merida W. Electrification of road freight transport: policy implications in British Columbia. Energy Pol 2018;115:109–18.

[16] Zhang J, Song HQ, Zhu WY, Wang JL. Liquid transport through nanoscale porous media with strong wettability. Transport Porous Media 2021;140:697–711.

[17] Casolari BL, Ellington MA, Oros JM, Schuttinger P, Radley CJ, Kiley KA, et al. Model study of a fuel cell range extender for a neighborhood electric vehicle (NEV). Int J Hydrogen Energy 2014;39:10757–87.

[18] El Hannach M, Ahmadi P, Guzman L, Pickup S, Kjeang E. Life cycle assessment of hydrogen and diesel dual-fuel class 8 heavy duty trucks. Int J Hydrogen Energy 2019;44:8575–84.

[19] Kast J, Vijayagopal R, Gangloff JJ, Marcinkoski J. Clean commercial transportation: medium and heavy duty fuel cell electric trucks. Int J Hydrogen Energy 2017;42:4508–17.

[20] Lao JM, Song HQ, Wang C, Zhou Y, Wang JL. Reducing atmospheric pollutant and greenhouse gas emissions of heavy duty trucks by substituting diesel with hydrogen in Beijing-Tianjin-Hebei-Shandong region, China. Int J Hydrogen Energy 2021;46:18137–52.

[21] Yin JJ, Wang JH, You J, Chen H, Shi W. Integrated energy system optimal operation in coal district with hydrogen heavy trucks. Front Energy Res 2021;9.

[22] Garcia A, Monsalve-Serrano J, Sari RL, Martinez-Boggio S. Energy sustainability in the transport sector using synthetic fuels in series hybrid trucks with RCCI dual-fuel engine. Fuel 2022;308.

[23] Wang JL, Song HQ, Wang YH. Investigation on the micro-flow mechanism of enhanced oil recovery by low-salinity water flooding in carbonate reservoir. Fuel 2020:266.

[24] Kang P, Lao JM, Yu MX, Song HQ, Wang C. Reliable prediction on emerging energy supply for national sustainability and stability: a case study on coal bed gas supply in China based on the dual-LSTM model. IEEE Access 2021;9:100694–707.

[25] Peters R, Breuer JL, Decker M, Grube T, Robinius M, Samsun RC, et al. Future power train solutions for long-haul trucks. Sustainability 2021;13.

[26] Sanford JR, Aguirre-Villegas HA, Larson RA. Pork production survey to assess factors of facility design and operation. Sustainability 2020;12.

[27] Liu FQ, Mauzerall DL, Zhao FQ, Hao H. 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. Int J Hydrogen Energy 2021;46:17982–97.

[28] Liu FQ, Zhao FQ, Liu ZW, Hao H. The impact of fuel cell vehicle deployment on road transport greenhouse gas emissions: the China case. Int J Hydrogen Energy 2018;43:22604–21.

[29] Lombardi S, Tribioli L, Guandalini G, Iora P. Energy performance and well-to-wheel analysis of different powertrain solutions for freight transportation. Int J Hydrogen Energy 2020;45:12535–54.

[30] Matulic N, Radica G, Barbir F, Nizetic S. Commercial vehicle auxiliary loads powered by PEM fuel cell. Int J Hydrogen Energy 2019;44:10082–90.

[31] Radica G, Tolj I, Markota D, Lototskyy MV, Pasupathi S, Yartys V. Control strategy of a fuel-cell power module for electric forklift. Int J Hydrogen Energy 2021;46:35938–48.

[32] Thomas CES. How green are electric vehicles? Int J Hydrogen Energy 2012;37:6053–62.

[33] Masson PJ, Brown GV, Soban DS, Luongo CA. HTS machines as enabling technology for all-electric airborne vehicles. Supercond Sci Technol 2007;20:748–56.

[34] Hong BK, Kim SH, Kim CM. Powering the future through hydrogen and polymer electrolyte membrane fuel cells current commercialisation and key challenges with focus on work at hyundai. Johnson Matthey Technol Rev 2020;64:236–51.

[35] Gangloff JJ, Kast J, Morrison G, Marcinkoski J. Design space assessment of hydrogen storage onboard medium and heavy duty fuel cell electric trucks. J Electrochem Energy Convers Storage 2017;14.

[36] Venetsanos AG, Huld T, Adams P, Bartzis JG. Source, dispersion and combustion modelling of an accidental release of hydrogen in an urban environment. J Hazard Mater 2003;105:1–25.

[37] Lee DY, Elgowainy A, Kotz A, Vijayagopal R, Marcinkoski J. Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks. J Power Sources 2018;393:217–29.

[38] Mac Kinnon M, Zhu SP, Cervantes A, Dabdub D, Samuelsen GS. Benefits of near-zero freight: the air quality and health impacts of low-NOx compressed natural gas trucks. J Air Waste Manag Assoc 2021;71:1428–44.

[39] Song HQ, Guo HH, Wang YH, Lao JM, Zhu HY, Tang LG, et al. A novel hybrid energy system for hydrogen production and storage in a depleted oil reservoir. Int J Hydrogen Energy 2021;46:18020–31.

[40] Stephens-Romero S, Samuelsen GS. Demonstration of a novel assessment methodology for hydrogen infrastructure deployment. Int J Hydrogen Energy 2009;34:628–41.

[41] Wulf C, Kaltschmitt M. Life cycle assessment of hydrogen supply chain with special attention on hydrogen refuelling stations. Int J Hydrogen Energy 2012;37:16711–21.

[42] Baral NR, Asher ZD, Trinko D, Sproul E, Quiroz-Arita C, Quinn JC, et al. Biomass feedstock transport using fuel cell and battery electric trucks improves lifecycle metrics of biofuel sustainability and economy. J Clean Prod 2021:279.

[43] Cernat A, Pana C, Negurescu N, Fuiorescu D, Nutu C, Mirica I. Experimental aspects of hydrogen use at diesel engine by diesel gas method. Therm Sci 2018;22:1385–94.

[44] Booto GK, Espegren KA, Hancke R. Comparative life cycle assessment of heavy-duty drivetrains: a Norwegian study case. Transport Res Transport Environ 2021;95.

[45] Cabukoglu E, Georges G, Kung L, Pareschi G, Boulouchos K. Fuel cell electric vehicles: an option to decarbonize heavy-duty transport? Results from a Swiss case-study. Transport Res Transport Environ 2019;70:35–48.

[46] Lajevardi SM, Axsen J, Crawford C. Comparing alternative heavy-duty drivetrains based on GHG emissions, ownership and abatement costs: simulations of freight routes in British Columbia. Transport Res Transport Environ 2019;76:19–55.

[47] Song HQ, Ou XM, Yuan JH, Yu MX, Wang C. Energy consumption and greenhouse gas emissions of diesel/LNG heavy-duty vehicle fleets in China based on a bottom-up model analysis. Energy 2017;140:966–78.

[48] Talebian H, Herrera OE, Merida W. Policy effectiveness on emissions and cost reduction for hydrogen supply chains: the case for British Columbia. Int J Hydrogen Energy 2021;46:998–1011.

[49] Zhang JR, Meerman H, Benders R, Faaij A. Techno-economic and life cycle greenhouse gas emissions assessment of liquefied natural gas supply chain in China. Energy 2021;224.

[50] Lee DY, Elgowainy A. By-product hydrogen from steam cracking of natural gas liquids (NGLs): potential for large-scale hydrogen fuel production, life-cycle air emissions reduction, and economic benefit. Int J Hydrogen Energy 2018;43:20143–60.
[51] China statistical yearbook. National Bureau of Statistics; 2021.
[52] Ishaq H, Dincer I. Investigation of an integrated system with industrial thermal management options for carbon emission reduction and hydrogen and ammonia production. Int J Hydrogen Energy 2019;44:12971–82.
[53] Jhang SR, Chen KS, Lin SL, Lin YC, Amesho KTT, Chen CB. Evaluation of the reduction in carbonyl emissions and ozone formation potential from the exhaust of a heavy-duty diesel engine by hydrogen-diesel dual fuel combustion. Appl Therm Eng 2018;132:586–94.
[54] Resitoglu IA, Keskin A. Hydrogen applications in selective catalytic reduction of NOx emissions from diesel engines. Int J Hydrogen Energy 2017;42:23389–94.
[55] Takagi Y, Mori H, Mihara Y, Kawahara N, Tomita E. Improvement of thermal efficiency and reduction of NOx emissions by burning a controlled jet plume in high-pressure direct-injection hydrogen engines. Int J Hydrogen Energy 2017;42:26114–22.
[56] Harvey LDD. Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060. Appl Energy 2018;212:663–79.
[57] Song HQ, Zhang J, Ni DD, Sun YQ, Zheng YC, Kou J, et al. Investigation on in-situ water ice recovery considering energy efficiency at the lunar south pole. Appl Energy 2021:298.
[58] Takeshita T. Assessing the co-benefits of CO2 mitigation on air pollutants emissions from road vehicles. Appl Energy 2012;97:225–37.
[59] Zhao JH, Wang XZ, Song HQ, Du Y, Cui WJ, Zhou YC. Spatiotemporal trend analysis of PM2.5 concentration in China, 1999-2016. Atmosphere 2019:10.
[60] Machado PG, Teixeira ACR, Collaco FMD, Hawkes A, Mouette D. Assessment of greenhouse gases and pollutant emissions in the road freight transport sector: a case study for sao paulo state, Brazil. Energies 2020;13.
[61] Shamsi H, Munshed M, Tran MK, Lee Y, Walker S, The J, et al. Health cost estimation of traffic-related air pollution and assessing the pollution reduction potential of zero-emission vehicles in toronto, Canada. Energies 2021;14.
[62] Cen SH, Li K, Liu QW, Jiang YL. Solar energy-based hydrogen production and post-firing in a biomass fueled gas turbine for power generation enhancement and carbon dioxide emission reduction. Energy Convers Manag 2021:233.
[63] Chintala V, Subramanian KA. Hydrogen energy share improvement along with NOx (oxides of nitrogen) emission reduction in a hydrogen dual-fuel compression ignition engine using water injection. Energy Convers Manag 2014;83:249–59.
[64] Uusitalo V, Vaisanen S, Inkeri E, Soukka R. Potential for greenhouse gas emission reductions using surplus electricity in hydrogen, methane and methanol production via electrolysis. Energy Convers Manag 2017;134:125–34.
[65] Bellocchi S, De Iulio R, Guidi G, Manno M, Nastasi B, Noussan M, et al. Analysis of smart energy system approach in local alpine regions - a case study in Northern Italy. Energy 2020:202.
[66] Ohara S. Energy and exergy flows of a hydrogen supply chain with truck transportation of ammonia or methyl cyclohexane. Energy 2019;174:848–60.
[67] Chintala V, Benaerjee D, Ghodke PK, Porpatham E. Hydrogen rich exhaust gas recirculation (H2EGR) for performance improvement and emissions reduction of a compression ignition engine. Int J Hydrogen Energy 2019;44:18545–58.
[68] Dhyani V, Subramanian KA. Control of backfire and NOx emission reduction in a hydrogen fueled multi-cylinder spark ignition engine using cooled EGR and water injection strategies. Int J Hydrogen Energy 2019;44:6287–98.
[69] Hsu CK, Lee CL, Wang CH, Jou CJG. Reduction of energy consumption and pollution emissions for industrial furnace using hydrogen-rich tail gas. Int J Hydrogen Energy 2014;39:9675–80.