Can alternative heavy-duty trucking really change our world?

-A scenario analysis

By

Wenxuan Chen

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

Department of Supply Chain Management

University of Manitoba

Winnipeg

Copyright © 2023 by Wenxuan Chen

Content

1. ABSTRACT 5

2. INTRODUCTION 5

3. CURRENT RESEARCHES AND TECHNOLOGIES 9

3.1 LITERATURE REVIEW 9

3.2 CURRENT TECHNOLOGY OF BETS AND FCETS 13

3.3 CURRENT INFRASTRUCTURE TECHNOLOGY IN ZERO-EMISSION TRUCKING 15

3.3.1 Infrastructure of FCETs 15

3.3.2 Infrastructure of BETs 19

4. OVERALL RESEARCH DESCRIPTION 21

4.1 RESEARCH BOUNDARY 21

4.2 SCENARIOS 22

4.3 RESEARCH AREA 23

4.4 RESEARCH FRAMEWORK AND PROCESS 25

5. DATA AND METHODOLOGY 26

5.1 ESTIMATION OF INFRASTRUCTURE AND INVESTMENT FOR FCETS AND BETS 26

5.1.1 Estimation of heavy-duty trucking volume till 2050 27

5.1.2 Estimation of fuel consumption in predefined scenarios 28

5.1.3 Estimation of infrastructure and equipment for FCETs 30

5.1.4 Estimation of infrastructure and equipment for BETs 34

5.2 ESTIMATION OF EMISSION AND POLLUTION REDUCTION 35

5.3 ESTIMATION OF CONCENTRATION CHANGE 39

5.4 ESTIMATION OF HEALTH IMPACTS 42

5.4 MONETARY HEALTH IMPACT 44

5.4.1 Mortality-related economic impacts 45

5.4.2 Morbidity-related economic impacts 46

6. RESULTS AND DISCUSSION 47

6.1 CHANGES IN AIR POLLUTANT AND GHG EMISSIONS OF EACH SCENARIO 47

6.2 CHANGE OF POLLUTANTS CONCENTRATION 52

6.3 INFRASTRUCTURE INVESTMENT 54

6.4 QUANTIFIED HEALTH IMPACT 56

6.4.1 Mortality associated with air pollutants 56

6.4.2 Morbidity associated with air pollutants 57

6.5 MONETIZED HEALTH IMPACT 58

6.5.1 Monetized Mortality impact 59

6.5.2 Monetized Morbidity impact 60

6.6 COMPARISON OF EACH SCENARIOS 62

7. CONCLUSION 65

7.1 SUMMARY OF MAIN FINDINGS 65
7.2 LIMITATION AND IMPLICATIONS 66

REFERENCE LIST 67

Table 1: Comparison of three types of HDT Drivetrains 14
Table 2: Characteristics of Alkaline, PEM, and SOEC electrolyzes 18
Table 3: Scenario Settings 23
Table 4: Characteristics and market share of HDTs in China 29
Table 5: Fuel consumption rates of ICET, BET, and FECT in different years 30
Table 6: Fuel demand in various scenarios and years 30
Table 7: An overview of technical and economic information on HRS 32
Table 8: The projected amount of HRS in FCET50 and MIX50 scenarios 33
Table 9: Technical and economic aspects of charging stations and virtual power plants 34
Table 10: The projected amount of HRS in FCET50 and MIX50 scenarios 35
Table 11: Emission factors 38
Table 12: Air pollution Concentration in PRD region 40
Table 13: Emission Calculation for Previous years in PRD region 41
Table 14: Proportion of HDTs contributes to Air pollution 41
Table 15: Exposure-response coefficients (refer to Eq. (1)) and the baseline prevalence 43
Table 16: VSL and Per Capita GDP in PRD 46
Table 17: COI of morbidity 47
Table 18: Investment details of each scenario 55
Table 19: Quantified mortality cases associated with Air pollution 57
Table 20: Quantified morbidity cases associated with Air pollution 58
Table 21: Comparison of Investment and Benefit without cost of carbon 64
Table 22:Comparison of Investment and Benefit considering cost of carbon 64

Figure 1: The process of Well to Wheels 12
Figure 2: Powertrains of HDTs in this study 14
Figure 3: Grey, Blue, and Green Hydrogen 16
Figure 4: Current main process of hydrogen production and utilization 19
Figure 5: Boundary of research 22
Figure 6: The economic information of PRD region within Guangdong Province 25
Figure 7: The research framework 26
Figure 8: Estimation of equipment and infrastructure demand in PRD till 2050 28
Figure 9: Power generation structure in PRD region at current stage 37
Figure 10: Net change in mass and percentage of GHG and air pollutant emissions 49
Figure 11: Proportions of each air pollutant and GHG in fuel or operational cycle 51

Figure 12: Change of air pollutants concentration 53
Figure 13: Total Investment 56
Figure 14: Monetized health impact-Mortality 59
Figure 15: Air pollutant associated with particular monetized mortality 60
Figure 16: Monetized health impact-Morbidity 61
Figure 17: Total monetary health impact 62

Subscripts

d	*Discount rate*
f	Fuel cycle
i	Type of Health Endpoints
k	Type of Vehicle technology
t	Time or year
op	Operation cycle
p	Type of air pollutants or GHG

Abbreviation

BET	Battery Electric Truck
COI	Cost of Illness
COPD	Chronic obstructive pulmonary disease
EPA	U.S. Environment Protection Agency
FCET	Fuel Cell Electric Truck
FECV	Fuel Cell Electric Vehicle
PHET	Plug-in hydrogen electric trucks
GH_2	Gaseous Hydrogen
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HDT	Heavy-Duty Truck
HRS	Hydrogen Refueling Station
ICET	Internal Combustion Engine Truck
IEA	International Energy Association
LH_2	Liquid Hydrogen
MMBtu	Million British Thermal Units
NPV	Net present value
PEM	Polymer Electrolyte Membrane
PGDP	Per capita gross domestic products
PRD	Pearl River Delta
QALY	Quality-adjusted life year
SMR	Steam Methane Reforming
SOEC	Solid oxide water electrolysis Cell
TCO	Total Cost of Ownership
VKT	Vehicle kilometers Travelled
VOC	Volatile Organic Compound
VSL	Value of Statistical Life
WTP	Willingness to Pay

1. Abstract

China's rapid economic growth has led to substantial air pollution and Greenhouse Gas (GHG) emissions from logistics and heavy-duty trucks. Battery and hydrogen fuel cell trucks are being considered as two promising approaches for achieving zero emissions in heavy-duty trucking.

This study focuses on the Pearl River Delta (PRD) region and presents four alternative trucking scenarios till 2050, considering the gradual integration of renewable resources. The research aims to compare the techno-economic benefits of these scenarios and assess the monetary health impacts in the PRD region.

Using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model and realistic projections from literature, the study calculates fuel consumption, emission reductions, and air pollution concentration changes within these scenarios. The monetary health benefit stemming from the adoption of alternative trucking are also carefully computed and compared with the investment. The results reveal that due to the relative new nature of these technologies, zero-emission scenarios, especially those involving hydrogen fuel cell trucks, incur higher net costs, even with the introduction of a carbon tax.

This study employs a distinct quantitative measure through monetizing the health impact resulting from improvement in air quality. It provides a comprehensive analysis of alternative trucking strategies, with a particular focus on their applicability within a specified geographical context.

2. Introduction

In the past decades, China has experienced exponential economic growth, fueled by substantial capital investment and rapid productivity growth resulting from reform and opening-up policies. However, this economic development has led to increased energy consumption and emissions of greenhouse gases (GHGs) and air pollutants, due to the

promotion of infrastructure construction, rising income levels, and increased residents' consumption(W. Liang & Yang, 2019; Qiang Zhang et al., 2012). The logistics industry, which has flourished alongside economic growth, has seen a significant expansion of trucking, particularly heavy-duty trucks (HDTs), on the roads. HDTs disproportionately contribute to GHG and air pollutant emissions. In China, HDTs accounted for nearly 25% of fleet energy consumption and GHG emissions, despite representing only 5% of new vehicle sales between 2009 and 2019 (China Automotive Industry Yearbook, 2020).

Notably, diesel takes as much as 96% of the energy source of HDTs in China(CATRC, 2017; Lao et al., 2021). According to projections by Peng (2018) , GHG emissions from road transportation could be 4.6 times higher in 2030 compared to 2007 under a business-as-usual scenario. Furthermore, HDTs are anticipated to contribute around 40% of total GHG emissions by 2050 (F. Zhao et al., 2019). Those internal combustion engine trucks (ICETs), such as diesel trucks, emit air pollutants including particulate matter (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and Ozone(O_3), all of which have direct health impacts on the public(J. Huang et al., 2018; Manisalidis et al., 2020). In many developing countries, air pollution is a more urgent problem than climate change(Thurber, 2011). Road transport alone contributes to over 18% of global PM emissions (Xia et al., 2015), meanwhile in China, exposure to $PM_{2.5}$ led to 248 billion USD loss of welfare in 2015(Xu Zhang et al., 2017). The decreased welfare mainly came from the direct loss of premature death and expenditure in medical treatment, as well as the indirect loss from labor, productivity and leisure all associated with the exposure(Matus et al., 2011). It is crucial to address the impact of HDTs on climate change mitigation and air quality improvement in order to facilitate the shift towards decarbonization initiatives in China. Additionally, the logistics industry itself accounted for 996.99 million tons of CO_2 emissions in 2015(Quan et al., 2020), constituting 10.7% of the total sectoral carbon emissions of 9265.1 million tons (Shan et al., 2018). Therefore, HDTs in logistics industry is the key starting point to achieve the goal of a low- and zero-emission transportation.

The global energy mix is undergoing a transition towards renewable energy technologies in order to combat climate change and global warming, and China is no exception. As China emitted around 27% of carbon dioxide and 33% of the GHG in the world in 2021(World Bank, 2022), significant emissions reductions in the country can yield significant benefits. In 2020, China announced its commitment to strive for carbon neutrality by 2060(Lao et al., 2021).

In the transportation domain, hydrogen fuel cell vehicles (HFCVs) and battery electric vehicles (BEVs) are the two primary advanced technologies for decarbonizing strategies, offering promising solutions for reducing GHGs emissions and air pollutants. For road freight, some studies argue that hydrogen fuel cell trucks (HFCTs) have certain advantages over battery electric trucks (BETs), such as shorter refueling time, greater load capacity (as BETs sacrifice load capacity for heavy batteries), and longer driving range, particularly in extreme weather conditions(Brotherton et al., 2016; Goodall & Robartes, 2023). However, the alternative energy vehicle industry in China exhibits some differences. China has witnessed a boom in battery electric passenger vehicles over the past decade (Irle, 2023; Ou et al., 2019), providing a relatively solid foundation and infrastructure preparation for BETs. With regard to extreme weather conditions, the Pearl River Delta (PRD), which is my targeted area in this study, locates in southern China enjoying a warm climate at an average temperature of 22.89°C (C. He & Yang, 2011). Additionally, China is proactively pursuing hydrogen industry development, being the world's largest hydrogen producer with over 20 million tons produced in 2018(China Hydrogen Alliance, 2019). Moreover, PRD is one of the leading regions in China's hydrogen industry, with the presence of the Xianhu Hydrogen Valley focused on technological innovation, promotion, application, and the development of hydrogen FCEVs (Taghizadeh-Hesary et al., 2022； http://en.xianhulab.com). However, the lack of key technologies and high infrastructure costs still impede the widespread development and usage of hydrogen vehicles in China. Therefore, considering the specific context of PRD and China, both hydrogen and battery electric trucking have their merits and disadvantages.

Investing in new energy technologies and infrastructures, such as hydrogen fuel cells and battery electric systems, represents a significant and long-term endeavor. Especially considering 73.3% of the freight was transported on roads (China Ministry of Transport, 2022), which means it would be a huge challenge to push forward the transition. Currently, the initial stage of the hydrogen economy relies heavily on financial support from the public sector, as private investors await a profitable market and consumers seek reliable resources. This raises the question of whether investing in the hydrogen industry is worthwhile, shall the public sector choose a relatively mature approach for example, via the battery industry? Furthermore, we need to evaluate if battery-electric trucking is sufficient for our target region and whether there are other benchmarks available to assess and compare the benefits and costs of different pathways toward low- and zero-emission transportation.

To answer these questions, this study introduces quantified and monetized health benefits as an assessment metric. By reducing air pollutants and GHG emissions, we can potentially mitigate mortality and morbidity associated with exposure to the pollutants such as PM_{10}, $PM_{2.5}$, Ozone, NO_x and SO_2. Within the framework of current technological development and geographical conditions, this study aims to compare different pathways for achieving low-and zero-emission trucking in the targeted area. Specifically, it seeks to address the following questions:

Which pathway, FCETs or BETs, is more suitable for achieving zero-emission trucking in PRD region?

If we consider the quantification of health benefits resulting from emission reductions from applying HECTs or BETs in the freight sector, what are the economic implications?

By addressing these questions, this study aims to provide valuable insights into the most appropriate pathway for achieving low- and zero-emission trucking in PRD region, while also considering the economic outcomes associated with the quantified health benefits resulting from emission reductions.

This study aims to offer valuable insights into the most suitable approach for achieving

low- and zero-emission trucking in the PRD region. It takes into account economic implications linked to quantified health benefits resulting from reductions in air pollutant emissions. The research highlights the need for assessing the economic feasibility of investing in FCETs and BETs for freight transportation. Additionally, it highlights the importance of comparing these technologies to determine their suitability for the region. Furthermore, the study introduces quantified and monetized health benefits as an assessment metric for emission reduction strategies. Lastly, it emphasizes the significance of considering both technological and geographical factors when evaluating emission reduction pathways so that the recommendations to the public sectors are valid and feasible.

3. Current researches and technologies

This section provides an overview of recent studies focusing on alternative energy trucking, encompassing various aspects such as technical and economic factors, emission assessment, as well as studies analyzing air pollutant caused health impact. In the second part, a concise introduction and comparison of FCETs and BETs was provided, highlighting their distinctive features and associated concerns. Furthermore, the section reviews the infrastructure requirements for FCETs and BETs, addressing the necessary support systems needed for successful implementation.

3.1 Literature review

A growing body of literature has emerged around the transition from conventional energy sources to zero-emission and alternative energy fleets (Cunanan et al., 2021; F. Liu et al., 2021; Xizhao Zhang et al., 2022). Financial analyses of electric economy infrastructure and technology development have also been extensively studied(Das et al., 2020; Deng et al., 2020; König et al., 2021; Sanguesa et al., 2021; Zeng et al., 2019), as well as the hydrogen economy(Greene et al., 2020; X. He et al., 2021; S. Li et al., 2019, 2022; Y. Li & Taghizadeh-

Hesary, 2022). Specifically focusing on heavy-duty vehicles, various studies have explored plug-in, battery electric, catenary, and hydrogen fuel cell vehicles as the main emerging electric-drive technologies (Cunanan et al., 2021; C. Ma et al., 2021; R. Wang & Liu, 2021; H. Zhao et al., 2018).

Comparisons of different pathways to achieve zero-emission trucking have gained momentum in recent years. Zhao et al.,(2018) have stated the challenges related to vehicle technologies, infrastructure, emissions, and operation and maintenance costs for various FCETs, catenary systems for electric vehicles, and dynamic inductive charging vehicles (a wireless charging method using inductive power transfer (Panchal et al., 2018)). Gunawan & Monaghan(2022) compared five powertrains (BET, plug-in hydrogen-electric trucks PHET, ICET, Direct electric freight trucks DEFT, and FCET) and the combination of wind and/or grid electricity through an assessment of the total cost ownership (TCO) of trucks. Recent studies have found that even without considering the subsidies, the TCO of BETs will be lower than ICETs as early as in 2025, and the gap between FCETs and ICETs will also narrow by 2030(Mao et al., 2021), from which the low maintenance fee contributes a lot. China Automotive Technology and Research Center (CATARC) estimated that essential elements of fuel cell vehicles will decline very quickly, as the fuel cell stacks will be 50% and 62% cheaper than battery counterparts no later in 2030 and 2050(CATARC, 2021; Mao et al., 2021). Those studies have provided us with more evidence that low-and zero-emission trucking is economically viable in the near future.

Additionally, there were also some researchers providing region-specific analyses. Zhang et al., (2022) emphasized that green electricity and green hydrogen are crucial factors in reducing life-cycle emissions of GHG and air pollutants across different heavy-duty truck electrification pathways in China. (Mojtaba Lajevardi et al., 2019) assessed the well-to-wheel emissions(explained in Figure 1), total cost of ownership, and abatement costs of 16 different drivetrains for heavy-duty trucking technologies, focusing on the reality of British Columbia with abundance of hydro and renewable natural gas. Mojtaba's study revealed that

hydroelectricity-powered batteries emit 95% less GHG than diesel, and emphasized the importance of the rapid deployment of hydrogen refueling stations for achieving significant GHG emissions reductions.

Organizations in the United States have also played a pioneering role in exploring electrification in the transportation sector. The National Renewable Energy Laboratory (NREL) and Argonne National Laboratory have published numerous studies covering various aspects of alternative energy and zero-emission trucking, including technology predictions, total cost of ownership, fuel consumption, emission factors, and infrastructure development (Brooker et al., 2021; Meintz & Starke -Oak, 2021; Murphy et al., 2021; Vijayagopal et al., 2019). Models developed by these organizations, such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, and the System Advisor Model(enable modeling and analyzing various renewable energy systems, including photovoltaic, battery storage, wind power, concentrating solar power), have been widely applied in research worldwide (Al-Thani et al., 2020; Da Silva, 2017; G. He & Kammen, 2016; Lao et al., 2021; X. Liu et al., 2021; Mitchell, 2009; Sen et al., 2017). Over the years, there has been significant progress in the comprehensive assessment of emissions, including GHGs and air pollutants. Life-cycle assessment is broadly acknowledged as one of the most thorough methods for measuring emissions under various temporal and spatial conditions. It incorporates both the fuel cycle and the vehicle cycle. The fuel cycle assessment considers energy consumption and emissions associated with fuel extraction, delivery, and utilization. Meanwhile, the vehicle cycle focuses on emissions during vehicle material and component production, assembly, and recycling(Lao et al., 2021; Xizhao Zhang et al., 2022). The GREET model, which was mentioned earlier, is based on the life-cycle assessment concept. It employs a bottom-up approach to evaluate regional emissions generated by vehicles (Urgun-Demirtas, 2019). The MOtor Vehicle Emission Simulator (MOVES) model, developed by the U.S. Environmental Protection Agency (EPA), is also frequently utilized as a benchmark for comparison in studies(Jiang et al., 2018). Another important model is the Greenhouse Gas and Air Pollutant

Interaction and Synergies (GAINS) model, designed by the International Institute for Applied Systems Analysis (IIASA), which focuses on analyzing cost-effective response strategies for combating air pollution while considering emission and pollution reduction strategies, as well as economic benefits (Amann et al. 2011). These models contribute to a comprehensive understanding of emissions and their interactions, providing valuable insights for assessing different pathways to low- and zero-emission transportation.

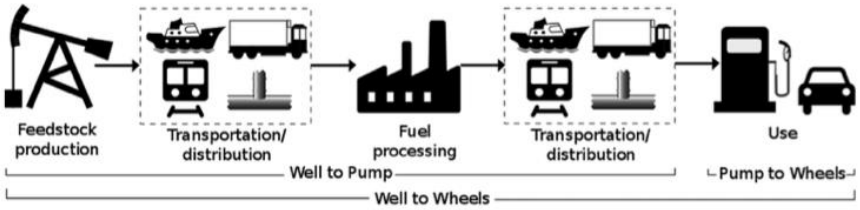


Figure 1: The process of Well to Wheels

The recognition and quantification of health benefits resulting from the reduction of air pollution have gained increasing attention in the literature across various countries (Y. L. Chen et al., 2013; Chiu et al., 2020; Contreras et al., 2014; T. Wang et al., 2020). Although GHG emissions do not have an immediate direct impact on human health, it has been verified that air pollutants are emitted alongside GHG during fuel combustion. Consequently, there are explorations focusing on air quality co-benefits associated with reducing GHG emissions, in addition to climate change mitigation(Bollen & Brink, 2014; Quam et al., 2017; Williams et al., 2012). Zero-emission vehicles have emerged as a prominent area of studies examining the benefits of air quality control policies (Chiu et al., 2020; Contreras et al., 2014; Lao et al., 2021).

In China, Liang et al., (2019) revealed that alternative energy vehicles can deliver significant air quality improvements, particularly in densely populated urban areas with heavy traffic and intense health risks. Since monetary welfare deriving from these benefits is combined with local income levels and per capita GDP, the welfare can outweigh the net climate benefits alone. However, the comparative assessment of different pathways to achieve low- or zero-emission trucking, based on the concept of health benefits, has received limited

attention in the literature, especially in terms of realistic technological backgrounds and financial feasibility within specific regions.

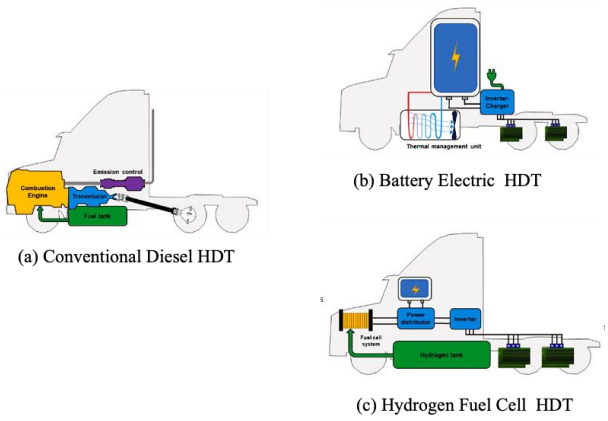
3.2 Current technology of BETs and FCETs

Heavy duty trucks, typically weighing more than 14 tons, encompass various types of cargo vehicles such as tractor trucks, dump trucks, or truck trailers etc. The definition of HDTs in China is comparable with Class 8 Long Haul trucks in North America. Conventional HDTs generally refers to the use of diesel or clean fuel (natural gas, methanol) as the power fuel utilizing internal combustion engines (ICE) as their power units. ICETs emit GHG and air pollutants, for which they are criticized under the trend of decarbonization and clean air initiatives. To address this, strategies such as improving fuel efficiency, reducing tire rolling resistance, and implementing hybrid powertrains have been developed for ICETs(Hountalas & Mavropoulos, 2010; Joshi et al., 2020; Taylor & Coy, 2000; H. Zhao et al., 2013). Typically, a diesel HDT can carry 500-1000 liters of fuel, allowing it to cover a range of 1400-2800 km without refueling, and a single refueling takes approximately 10-15 minutes to fill a 1000-liter capacity tank(Cunanan et al., 2021; Marcinkoski et al., 2019). BETs utilize electric motors powered by batteries. Compared to ICETs, BETs have simpler powertrain systems, resulting in lower maintenance costs(Kleiner & Friedrich, 2017; Mao et al., 2021). This factor is also considered when comparing the total cost of ownership. However, BETs face challenges of range limitations and temperature adaptability. The range of BETs depends on battery technology, vehicle weight, and load. Usually, a battery-empowered class 8 long-haul truck can cover a travel distance of around 200-500 km before requiring a recharge (Bernard et al., 2022; Cunanan et al., 2021). Tesla claims that its new battery semi-truck can travel up to 800 km without recharging (https://www.tesla.com/en_ca/semi). Nikola also produced a Class 8 semi truck (E-truck-Tres) stating the coverage up to 550km with a 733kWh battery (https://www.nikolamotor.com/tre-bev/). However, the prevalent battery-powered trucks run on the roads in China typically offer a range of approximately 300 kilometers with a battery

capacity of around 282kWh or 350kWh(Basma & Rodríguez, 2021; J. L. Liu & Danilovic, 2021). Meanwhile, recharging time for BETs is another concern and it varies by battery capacity and charger output power. For example, using a level 3 charger (25 kW), it would take about 14 hours to fully charge a 350 kWh battery. However, with an output from the Megawatt Charging System in 1 MW, the recharging time can be significantly reduced to around 1 hour. FCETs is another zero-emission powertrain option driven by electric motors. FCETs use hydrogen fuel cells to convert chemical energy into electricity. Similar to BETs, FCET powertrains are relatively simpler than those of diesel HDTs. The key distinction of FCETs from BETs lies in the fuel source, as FCETs are powered by hydrogen (in gaseous or liquid form). FCETs offer a typical range of 800-1600 km within a single fueling session, achieved by carrying 80-120 kg of hydrogen fuel in two tanks at a pressure of 35 Mbar(Cunanan et al., 2021; Marcinkoski et al., 2019). The average refueling time for FCETs is approximately 16 minutes, making it comparable in efficiency to conventional diesel trucks(Cunanan et al., 2021).

The following figure and table illustrate the comparison of three powertrains discussed in this study.

Figure 2: Powertrains of HDTs in this study



(a) Conventional Diesel HDT

(b) Battery Electric HDT

(c) Hydrogen Fuel Cell HDT

Table 1: Comparison of three types of HDT Drivetrains

Criteria	Diesel	Battery	Hydrogen Fuel Cell
GHG emissions	Yes	No	No

Pollutant emissions	Yes	No	No
Well-to-Wheel efficiency	19.78%	37.60%	34.20%
Fuel consumption	37.37L/100 km	125 kWh/100km	6.8-11.2 kg H_2/100 km
Range	1400-2800 km	100-800 km	1000-1750 km
Refueling/Recharging Time	6-12 min	2.85-20 h	16 min
Specific efficiency	42.9 MJ/kg	0.432-0.792 MJ/kg	118 MJ/kg
Temperature adaptability	Wide adaptability	60% capacity below -10°C 22% capacity below - 40°C	Wide adaptability
Existing Infrastructure	Over 6000 Gas stations	3450 centralized charging stations	39 H_2 refueling stations

Source:(Cunanan et al., 2021; DWards et al., 2014; Kalghatgi, 2018; Schoettle et al., 2016), Author's calculation.

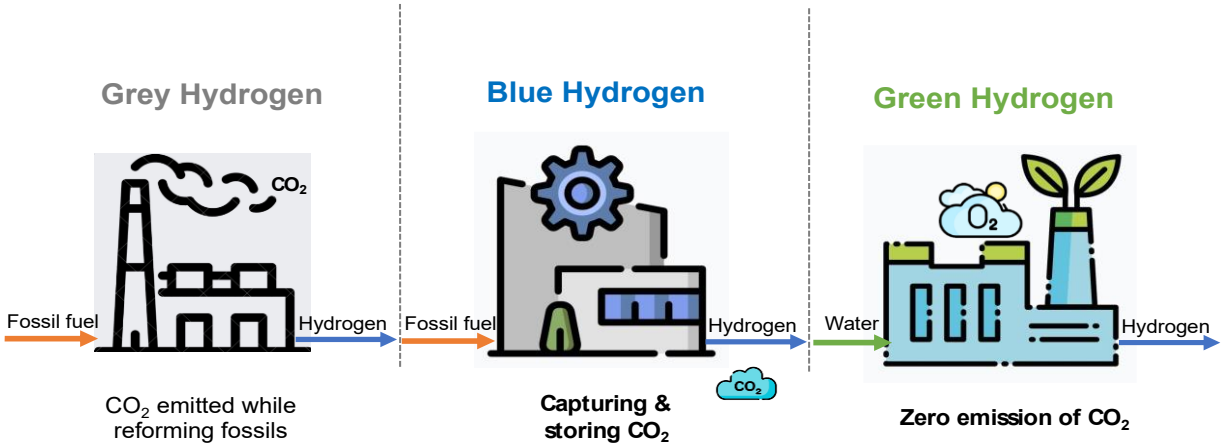
3.3 Current infrastructure technology in zero-emission trucking

3.3.1 Infrastructure of FCETs

Hydrogen can be produced using various methods such as steam methane reforming (SMR), thermal cracking of methane, coal gasification, and water electrolysis (with grid electricity or renewable energy). According to the source and the emission of production, hydrogen is often classified by colour as grey hydrogen, blue hydrogen and green hydrogen(Yu et al., 2021). It is not difficult to speculate from the names that grey hydrogen is produced via fossil fuels (such as natural gas or by-products from chemical processes) using methods such as SMR with emission of CO_2. Grey hydrogen production has gained large-scale application in China and globally for its low cost and the ease of obtaining feedstock. Blue hydrogen production utilizes the same fossil fuel feedstocks but applies carbon-neutral status for example, the CCUS (Carbon Capture Use and Storage) technology. Meanwhile, green hydrogen is the ultimate goal of hydrogen production, which utilizes renewable energy sources such as wind/solar/biomass with the method of hydrolyse to produce hydrogen. In the process of green

hydrogen production, it is assumed there is zero emission of CO_2. Figure 3 shows the characteristics of these three pathways to produce hydrogen.

Figure 3: Grey, Blue, and Green Hydrogen



Source: Author

According to the most recent provincial plan of key constructions, Guangdong has initiated several large-scale hydrogen production projects via PEM (Proton-exchange membrane) water electrolysis method in PRD region(Guangdong Provincial Development and Reform Commission, 2022b). Furthermore, multiple electricity power plants, leveraging wind and solar power, are strategically located near the PRD region to optimize renewable resource utilization for hydrogen production(Guangdong Provincial Development and Reform Commission, 2022b). Therefore, this section will focus on the analysis of refueling stations and delivery infrastructure, with no further consideration of the central plant of hydrogen production.

There are two primary pathways for hydrogen delivery and distribution: off-site production then delivery to fueling stations and on-site production stations. In the first pathway, hydrogen is generated at a central plant and delivered to refueling stations through tube-trailers, railways, or pipelines, etc,. Currently, tube-trailers are the most widely used and economic method for transporting gaseous hydrogen. However, due to the low density of hydrogen and the weight of the tubes themselves, tube-trailers are only

suitable for short distances (less than 200 km) and low volume demands(Perna et al., 2022; Reddi et al., 2018). In the domestic market, a 20 MPa tube-trailer has the capacity to transport 347 kg of gaseous compressed hydrogen and the tube-trailer itself costs approximately 1,600,000 RMB (400,000 RMB for the truck and 1,200,000 RMB for the tubes)(Bai et al., 2023; B. Liu et al., 2020; Xing, 2021)

Pipelines, which is another option for gaseous hydrogen transportation, are superior at high efficiency and low unit costs but disputed for their huge initial investment (Dagdougui, 2012; Demir & Dincer, 2018; Miao et al., 2021; Semeraro, 2021). Generally, high pressurized pipeline is suitable for large-scale transmission of hydrogen because the capacity of a 30-cm pipeline is not designed for low-volume demand (X. J. Li et al., 2020). The high installment investment and low fixed operation costs allow for more efficient use of the capital.

For the station itself, both types of stations require common elements such as storage, heat exchangers, compressors, and dispensers(McKinney et al., 2015). On-site production refueling stations have additional units to produce hydrogen using either electrolysis or SMR (Apostolou & Xydis, 2019; Cheng, 2010). In addition, hydrogen can exist in two forms: gaseous and liquid hydrogen. Liquid hydrogen has a higher energy density, approximately 1.8 times that of gaseous hydrogen (at 70 MPa and 20°C), meaning more energy can be stored in the same volume. However, the liquefaction process requires a significant amount of energy and emits more GHGs than gaseous hydrogen, and the storage requirements such as higher pressusre and lower temperature for liquid hydrogen are more stringent compared to gaseous hydrogen(Aziz, 2021; Ratnakar et al., 2021). Therefore, this paper excludes liquid hydrogen as an option for refueling stations. In regards to electrolysis, the three leading approaches are Alkaline, Proton-exchange membrane (PEM), and Solid oxide water electrolysis cell (SOEC) methods. Alkaline electrolysis is the more mature and cost-efficient option among these three methods, and China is leading in this technology in the world(Y. Li et al., 2021).

The PEM method uses a solid membrane to separate the hydrogen from water molecules(Holland Innovation Network, 2019). PEM is higher in production cost but better in system flexibility and efficiency than Alkaline electrolyzer. What is more, PEM electrolyzers work in a lower temperature and easy to adjust the number of PEM stacks, which is more suitable for decentralized stations(Chai et al., 2021; Hydrogen Council, 2020; Mayyas et al., 2019). The SOEC method uses solid oxides as electrolytes. SOEC is advantaged in power conversion efficiency but with the shortage that has to be operated at as high temperature as 1000°C (L. Ren et al., 2020). Since SOEC is usually designed to work via nuclear and solar energy systems, it is still not in large-scale commercialization(Chai et al., 2021). The comparison and details of these three approaches are demonstrated in Table 2.

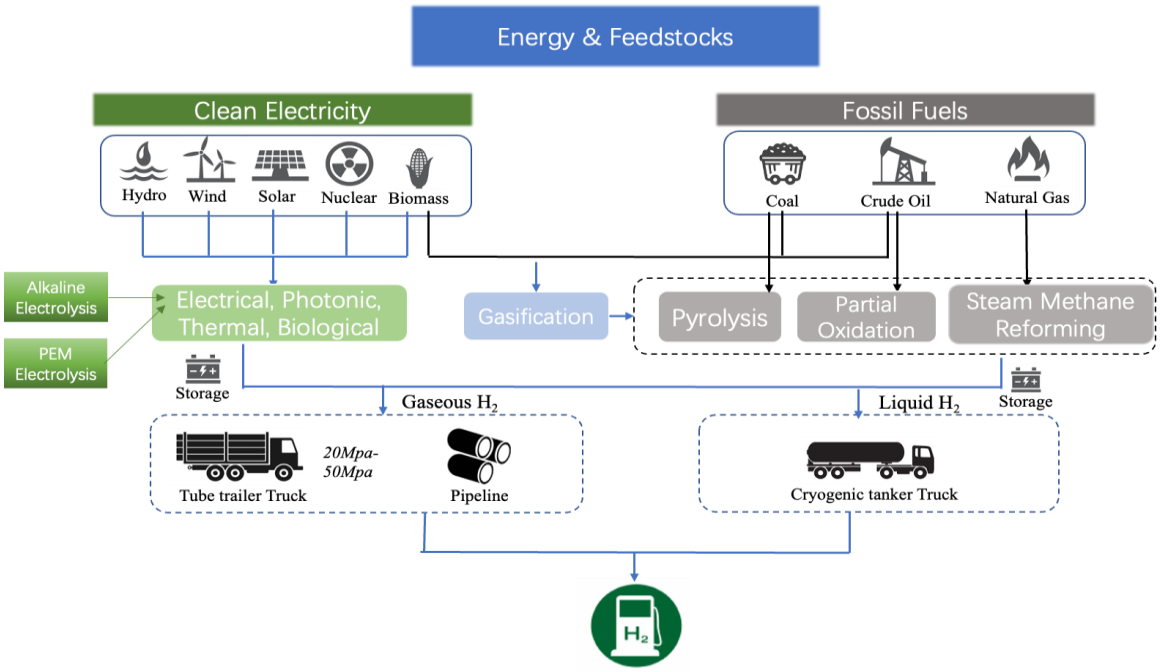
Table 2: Characteristics of Alkaline, PEM, and SOEC electrolyzes

Specification	Alkaline	PEM	SOEC
Operation Temperature	20-80°C	20-200°C	500-1000°C
Single Production volume	0.5-1000Nm3/H	0.01-500Nm3/H	/
Efficiency	59-70%	65-82%	up to 100%
Applicability	Commercial	Commercial	laboratory scale
Lifetime	10-20 years	10-20 years	N/A
Maintenance	Corrosive Electrolyte，High cost	Fast response/start-up, Low cost	N/A
Adaptability & renewable resource	Relatively stable power input	Adaptable to high variation in power generation system	Adaptable to high temperature and pressure
Cost in China	$300-400/KW (Domestic) $900-1100/KW (Imported)	1000-1800 USD/KW	N/A

Source: (Chai et al., 2021; Holland Innovation Network, 2019; Hydrogen Council, 2020; Y. Li et. al., 2021; Mayyas et al., 2019; L. Ren et al., 2020)

Figure 4 summarizes the main process of hydrogen production and utilization.

Figure 4: Current main process of hydrogen production and utilization



Source: Author

3.3.2 Infrastructure of BETs

With the rapid emergence and development of battery technology and plug-in electric vehicles (PEVs) in China(Irle, 2023; Ou et al., 2019), it is important to note that charging stations for battery passenger vehicles and light-duty vehicles are already very mature and well-established(Zeng et al., 2019). However, the existing charging infrastructure may not offer sufficient coverage for battery electric HDTs. Several technical aspects need to be considered when planning for infrastructure for BETs, including battery capacity and lifetime, battery price and performance, charging solutions, and the power system regulating technologies.

The various options for stationary charging infrastructure include slow alternating current (AC) charging, fast direct current (DC) charging, ultra-fast DC charging, and battery swapping(swapping a pre-charged battery with a worn-out battery)(Adu-Gyamfi et al., 2022), etc. Typically, slow AC chargers operate below 43 KW, fast DC chargers work within the range

of 60-150KW, while ultra-fast chargers can reach the power from 350KW-3MW(Bernard et al., 2022)

Currently, the mainstream BETs used in China have a battery capacity of 282 kWh, as produced by BYD (Basma & Rodríguez, 2021; J. L. Liu & Danilovic, 2021). Considering the fuel efficiency of long-haul trucks, which is around 0.5 kWh/0.5 miles, equivalent to 122 kWh/100 km, and assuming an average daily coverage of 200-300 km without charging(Bernard et al., 2022). This 282 kWh battery size meets the requirements of most HDTs used in port or short-distance logistics within a daily range of 300 km. In addition to the typical 282 kWh battery, the common battery size for HDTs ranges from 250 to 350 kWh. The charging time for these batteries varies depending on the charger capacity. When using a 30 kW AC charger, it takes approximately 12 hours to fully charge a 350kWh battery. With a 60 kW DC charger, the charging time is reduced to around 6 hours. Moreover, utilizing a 350 kW ultra-fast charger enables a charging time of about one hour.

The emerging Battery swapping option, with a typical time of 3-7 minutes swapping for a long-haul truck, is a time-efficient option compared to fast charging, which may take 30 minutes for Tesla vehicles and up to 90 minutes for MAN trucks using 300 kW chargers(https://www.man.eu/de/en/truck/emobility-truck/emobility-truck.html). Meanwhile, in terms of cost-efficiency, overnight charging stations are still preferred, especially for HDTs that follow predefined routes without extended stops and return to a home base in the evenings. Mainstream 30-60 kW chargers can provide a 282 kW HDT with a range of 300 km within 5-9 hours of charging, taking advantage of valley electricity rates during off-peak hours from 8 pm-6 am.

PV electricity generator integrated stations with solar energy storage are also emerging in China(Shi et al., 2020; M. Yang et al., 2021). These stations utilize solar energy during less busy hours, store the power in the batteries, and then provide it to the trucks during daytime hours. It helps overcoming the voltage fluctuations caused by high-demand fast charging(D. Li et al., 2020; Sun et al., 2020; W. Wang et al., 2022). Additionally, virtual power plants are

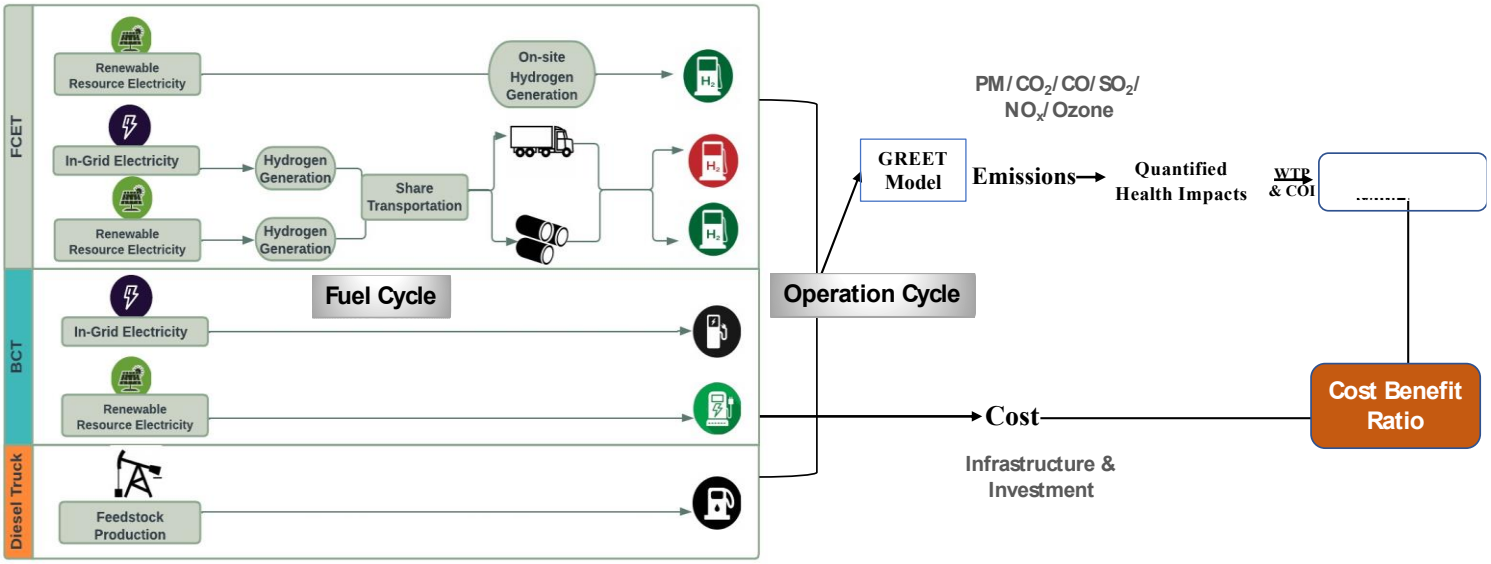
gaining attention and investment as a means to reduce the impact on the grid through peak-shaving and valley-filling (shifting the power load in a grid from the peak hours to the hours when the load is low) effect(Galus et al., 2012; Rouzbahani et al., 2021). Virtual power plants integrate distributed power sources, energy storage systems, controllable loads, (battery) electric vehicles, and other energy sources into a regulated group, reducing GHG and air pollutant emissions by optimizing energy usage(Bhuiyan et al., 2021; Piltan et al., 2022). They are also cost-efficient compared to thermal power plants, requiring only about 12-15% of the investment for regulating 5% of the existing power load, according to estimations by the State Grid Corporation of China(Liao, 2022).

4. Overall research description

4.1 Research Boundary

This study aims to provide reference points for public sectors in the formulation of policies and investment decisions in infrastructure development. The study focuses on investigating the economic and technological aspects of FCETs and BETs, while also exploring potential quantified health benefits. This includes examining green hydrogen supplies and on-site production options in hydrogen refueling stations (HRSs) within the PRD region, as well as the recharging stations for BETS and necessary power regulation systems to cope with the increasing demand for electricity. It is important to note that this study primarily emphasizes the perspective of the public sector. Therefore, the economic analysis will not cover daily hydrogen manufacturing costs, renewable/non-renewable resource costs, or vehicle expenditures and maintenance fees. Regarding emission analysis, the research primarily focuses on emissions related to the fuel cycle, as emissions from the fuel cycle typically contribute 70-90% of the total life cycle emissions(El Hannach et al., 2019; Lao et al., 2021; Zhou et al., 2017). The following figure demonstrates the boundary and elements of this study.

Figure 5: Boundary of research



Source: Author

4.2 Scenarios

This study creates four distinct scenarios to capture the uncertainties surrounding future technological developments and estimate the economic benefits of alternative trucking in the targeted area. The assessment focuses on three dimensions of alternative trucking: the choice between two approaches of alternative trucks (FCETs and BETs), the penetration of alternative trucks, and the penetration of renewable energy.

BaU (Business-as-Usual) Scenario: This scenario assumes that diesel trucks will continue to dominate heavy-duty trucking in the PRD region for the next few decades.

FCET50 Scenario: In this scenario, half of the HDTs in the PRD region will powered by hydrogen fuel cells by 2050 step by step along with the gradual replacement of renewable energy.

BET50 Scenario: Same pace as FCET50 scenario, except half of the HDTs in the PRD region will be powered by battery electricity.

MIX50 Scenario: This scenario increases the proportion of alternative trucks and divides it equally between BETs and FCETs, with the same penetration rate and pace of renewable energy as the other two alternative trucking scenarios.

By calculating and comparing the costs of infrastructure investment and the monetized health impacts of these various scenarios, this study aims to identify the cost-efficient approaches to achieve a more sustainable future for trucking in PRD region.

Table 3: Scenario Settings

ID	Scenario Cases	FCET or BET Penetrations	Renewable Energy Penetrations
BaU	Business as Usual	No FCET or BET trucks	No renewable energy involved
FCET50	50H_2-25~60R-2050	20% FCET-2030 40% FCET-2040 50% FCET-2050	25% renewable energy-2030 40% renewable energy-2040 60% renewable energy-2050
BET50	50Ele-25~60R-2050	20% BET-2030 40% BET-2040 50% BET-2050	Same as FCET50
MIX50	Half FCET-Half BET	15% FCET,15% BET-2030 25% FCET,25% BET-2040 35% FCET,35% BET-2050	Same as FCET50 & BET50

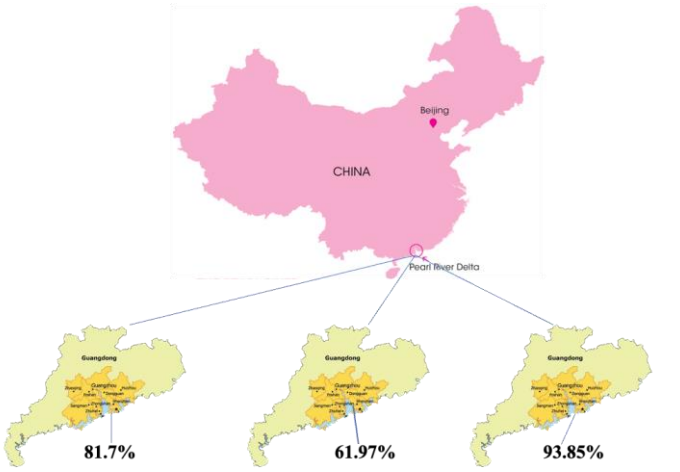
4.3 Research Area

The Pearl River Delta (PRD) region is one of the largest super-megacity areas in China, characterized by high population density and urbanization. In 2020, the PRD region contributed 1,421 billion US dollars to China's GDP, accounting for 8.8% in total(Guangdong Provincial Bureau of Statistics, 2021; National Bureau of Statistics of China, 2021). Moreover, it serves as a major manufacturing base for a wide range of products, earning its reputation as one of the world's workshops. Consequently, freight traffic in the PRD region is also a vital part for the economy, which accounted for 9.14% of

China's total in 2019(Guangdong Provincial Bureau of Statistics, 2020; National Bureau of Statistics of China, 2020). The geographical and economic information is shown in Figure 6. Within Guangdong Province, the PRD region is definitely the driving factor of the whole province's economy, as the contribution rate of regional economic product in PRD accounts for more than 80% in Guangdong. In addition to that, the freight industry of PRD accounts for almost 94% of Guangdong (Guangdong Provincial Bureau of Statistics, 2023). As a result, there is a significant and continuously growing demand for heavy-duty trucking in the region. The simultaneous existence of opportunities and challenges arises as the public sector has to deal with the task of effectively balancing the imperative for freight development with the concurrent requirements of energy demand, decarbonization, and air pollutant reduction.

To meet the requirement of green energy, as mentioned earlier, large-scale wind power plant and photovoltaic power plant projects are currently underway in Guangdong province since 2020. Meanwhile, to address the challenge of reconciling mismatched energy demands and inconstant renewable energy resources, the utilization of hydrogen fuel and batteries presents a promising solution for storage and distribution, with the added advantage of zero emissions. Green hydrogen, generated from power derived from renewable sources, can play a vital role in achieving steady-state power production, enhancing economic efficiency, prolonging the lifespan of power generation equipment, and maximizing the utilization of renewable resources(Chai et al., 2021; Y. Li & Taghizadeh-Hesary, 2022; Yu et al., 2021)

Figure 6: The economic information of PRD region within Guangdong Province



(a) Contribution rate of regional economic product in Guangdong

(b) Proportion of Population in Guangdong

(c) Contribution rate of Freight (*Ton-kilometers*) in Guangdong

Source: Author

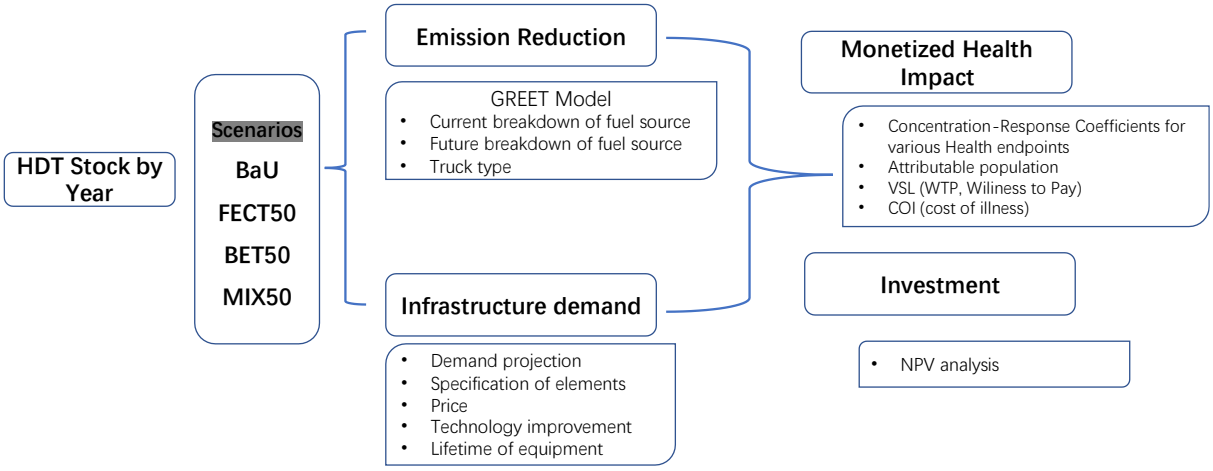
4.4 Research framework and process

The reasoning process of this study follows a systematic flow, which begins with projecting the future stocks of HDTs until 2050. Subsequently, the emissions resulting from both the fuel cycles and the vehicle operation cycle are calculated via the GREET model. The study then proceeds to assess the infrastructure requirements under different predefined scenarios.

In terms of economic analysis, it was divided into two parts, the investment and benefits/costs. The investment aspect involves evaluating the financial aspects associated with the required infrastructure. The health impacts resulting from emission reductions of air pollutants are quantified through the estimation of mortality and morbidity of attributable population in PRD region. This economic assessment is conducted using methods such as the Value of Statistical Life (VSL) and the Cost of Illness (COI) approaches, allowing for the monetization of health impacts.

The final step is to compare and evaluate the investment and benefit for preset scenarios. The basic idea of this study is illustrated in Figure 7.

Figure 7: The research framework



Source: Author

This research involves highly detailed but relatively generalized approaches that have already been employed elsewhere for evaluation of health-related impact, and also employs standard evaluation models in terms of GHG and pollutant emissions. The monetization of health impacts, in particular of transportation activities, including HDTs, has already been done in many locations. Given a practical focus on an analysis of the potential net health benefits of changing HDT from conventional diesel to zero-emission within the PRD, no comprehensive review of worldwide methodologies is undertaken, but example outlines are provided by (OECD, 2012)and (Chestnut & Civita, 2009), the latter specifically for Canada. A recent example of a related analysis undertaken within Canada regarding the impacts of diesel fuel consumption is (Brewer et al., 2016). The research in my work focuses on the PRD as discussed earlier, and as such primarily employs Chinese data sources.

5. Data and Methodology

5.1 Estimation of infrastructure and investment for FCETs and BETs

In this session, a three-stage analysis was applied to calculate the amount of infrastructure and equipment to meet the requirement of each scenario, and then determine the investment of

each scenario. I assume that the incremental cost of gasoline stations for diesel trucks is zero, given the situation of huge gasoline station stock and their lower investments compared to charging and refueling stations(Bekel & Pauliuk, 2019; L. Yang et al., 2022).

5.1.1 Estimation of heavy-duty trucking volume till 2050

Prediction of vehicle ownership involves various alternatives including economic factors such as per capita disposable income or gross domestic product(GDP)(Huo et al., 2007), technological factors like domestic manufacturing level. Upon consulting previous literature, I decided to adopt the prediction from the research on vehicle ownership analysis conducted by (Wu et al., 2014). This study clarifies the difference of influencing factors of China's vehicle ownership from other developing or developed countries in its extremely fast-growing speed in a short term and the government's invention. From (Wu)'s analysis, China's vehicle stock will increase quickly as the economic development in the prior period till 2030 and then keep in a relatively constant stock after that. Hence, in my study, projections of GDP annual growth in PRD will be the main driving force of the growth of trucks until 2030, followed with well-balanced replacement of scraped trucks. The projection of growth in GDP in this study mainly is sourced from the "Medium" scenario in International Energy Outlook by EIA (Energy Information Administration) (IEA, 2022)and World Economy Outlook by International Monetary Fund (https://www.imf.org/en/Publications/WEO/weo-database/2022/October/select-subjects?c=924) with minor revision based on the economic condition of PRD region. For the first period till 2030, the elasticity of truck stock to GDP growth is set to be 1.033 according to the analysis from (Huo et al., 2007), which indicates that the truck stock will increase by 1.033% as GDP's 1% increment.

The trend of GDP growth rate and estimation of HDTs stocks before and after 2030 is shown in Figure 8.

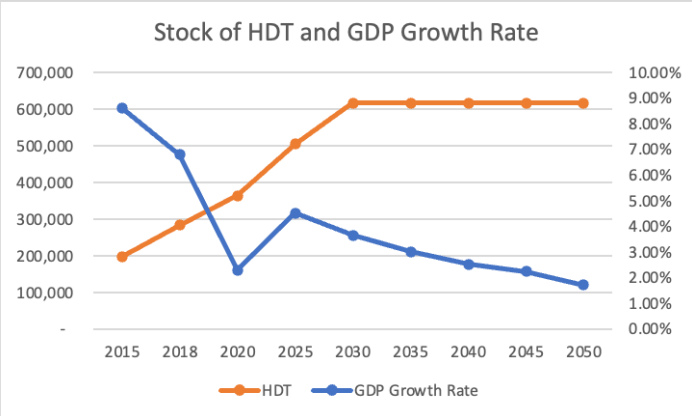


Figure 8: Estimation of equipment and infrastructure demand in PRD till 2050

5.1.2 Estimation of fuel consumption in predefined scenarios

In order to estimate the demand of equipment and infrastructure to implement the alternative energy trucking initiatives, besides the stock of trucks, truck fleet energy consumption, vehicle kilometers traveled (VKT), and the potential development of vehicle/recharging/refuelling technology is essential to warrant thoughtful evaluation. The following Equation (1) can calculate the energy consumption of the fleet,

$$Fuel = Stock_{t,k}, \times VKT \times FC_{t,k} \quad (1)$$

Where Stock represents the projection of HDTs stock in a certain year, VKT means the vehicle kilometers traveled, and FC is the fuel consumption rate per 100km in a certain year. It is noted that the FC is also based on the projection of fuel efficiency rate in related researches. Subscripts *t,k* represent the year and technology of HDTs, respectively.

In China, the characteristics of HDTs and their fuel consumption rate are illustrated in Table 4. HDTs here is comparable to Class 8 Long-Haul trucks (15,000 kg or 33,000 lb and above) in North America. Diesel is still the dominant fuel used in HDTs of gross weight above 24t, which is still up to 99% (CATRC, 2017). The average VKT and fuel consumption rate of diesel HDTs used in this study are calculated according to the proportion of various types of trucks and their mileage every year, which is 100,000 km per year and 37.37 L/100km (IEA, 2017; Lao et al., 2021).

Table 4: Characteristics and market share of HDTs in China

	Tractor Truck			Dump Truck			Freight Truck			Special Truck		
Image of HDTs												
Main applications	Glass, steel, cement			Brick trash			Logistics			Concrete		
Annual VKT (km)	150,000-200,000			80,000-100,000			200,000-250,000			30,000-60,000		
Fuel efficiency by weight (ton)	14-24	24-31	31-60	14-24	24-31	31-60	14-24	24-31	31-60	14-24	24-31	31-60
Diesel (L/100km)	39.5	45.2	47.7	30.7	37.8	39.5	30.9	37.1	39.8	31.1	37.9	40.2
-Proportion	24.71%	74.88%	0.41%	9.42%	54.76%	35.82%	77.62%	17.38%	5%	37.59%	42.68%	19.73%

Source: (Lao et al., 2021, Author's calculation)

In the latest researches of fuel consumption for diesel and zero-emission HDTs, comprehensive assessments and predictions have been conducted on the fuel consumption rates of diesel, electricity, and hydrogen. The U.S. Department of Energy (DOE) has projected that by 2030, during the interim stage, class 8 long-haul trucks equipped with fuel cell powertrains can achieve a lifespan of 25,000 to 30,000 hours (equals to 8-10 years). By the ultimate stage of 2050, the projected fuel consumption for these trucks will range from 7.1 to 9.0 kg H_2 per 100 km (11.1 to 14 mpkg) by 2030 and 5.9 to 8.1 kg H_2 per 100 km (12.4 to 17.0 mpkg) (Marcinkoski et al., 2019).

Regarding BETs, current energy consumption stands at about 125 kWh per 100 km (0.5 mile/kWh). However, due to limited research providing accurate projections of fuel consumption rates for BETs over longer ranges, reliable data for future fuel consumption rates is currently lacking. Nonetheless, based on the findings of (Mao et al., 2021), it is projected that by 2030, Class 8 BETs should be able to exhibit energy consumption of about 88.7 kWh per 100 km.

Similarly, the DOE also provided fuel consumption estimates for conventional diesel trucks of the same size. These estimates indicate fuel consumption values of 18.1 to 21.6 liter per 100 km (10.9 to 13.0 mpg) by 2030 and 15.1 to 19.8 liter per 100 km (11.9 to 15.6 mpg) by 2050(Marcinkoski et al., 2019).

Considering the conditions specific to China, the fuel consumption for current and future HDTs with three different powertrains is revised and presented in the following table 5.

Table 5: Fuel consumption rates of ICET, BET, and FECT in different years

lm	ICET Diesel L/100 km	BET kWh/100 km	FCET kg H_2/100km
2017-current stage	37.37	124.28	6.61
2030-interim stage	28.74	88.7	5.18
2050-ultimate stage	23.96	88.7	4.14

Source: *(Cunanan et al., 2021; Marcinkoski et al., 2019, Author's calculation)*

Applying those projections results in Equation (1), this study calculated the energy consumption of four scenarios till 2050, as reported in Table 6.

Table 6: Fuel demand in various scenarios and years

	BaU	FCET50		BET50		MIX50		
	Diesel (L)	H2 (kg)	Diesel (L)	Electricity(kWh)	Diesel (L)	H2 (kg)	Electricity(kWh)	Diesel (L)
2025	18,676,199,677	333,143,021	16,808,579,710	6,273,184,043	16,808,579,710	249,857,266	4,704,888,032	15,874,769,726
2030	17,729,525,768	637,891,559	14,183,620,614	10,944,096,966	14,183,620,614	478,418,669	8,208,072,724	12,410,668,037
2035	17,729,525,768	944,079,508	12,481,586,140	16,197,263,509	12,481,586,140	645,865,204	11,080,898,178	10,549,067,832
2040	17,729,525,768	1,275,783,119	10,637,715,461	21,888,193,931	10,637,715,461	797,364,449	13,680,121,207	8,864,762,884
2045	17,729,525,768	1,448,013,840	9,680,321,069	24,843,100,112	9,680,321,069	972,784,628	16,689,747,873	6,914,515,049
2050	14,779,505,173	1,277,788,097	7,389,752,586	27,360,242,414	7,389,752,586	894,451,668	19,152,169,689	4,433,851,551

5.1.3 Estimation of infrastructure and equipment for FCETs

As discussed in an earlier section, there are two main types of hydrogen refueling stations (HRS) at the present time, on-site production stations and off-site delivery stations. In this study,

considering the objective is to maximize emission reduction, the on-site production unit will choose electrolysis and Proton Exchange Membrane (PEM) method in FCET50 and MIX50 scenarios. PEM electrolysis systems are preferred due to their ease of deployment and flexibility, making them a better option for small to medium-sized on-site production stations(Hydrogen Council, 2020; Mayyas et al., 2019).

Table 7 provides an overview of technical and economic information on these two types of HRS. The prices of the elements are mainly derived from the (McKinney et al., 2015)report, while construction costs and some domestic equipment costs are sourced from Chinese research and bidding documents of implemented hydrogen refueling station projects(China National HDT Group Jinan Haworth Co., 2020; Foshan Pan Yue Hydrogen Energy Technology Co., n.d.; Hangzhou Bus Station Co., 2023). It is important to consider economies of scale, cost reductions, standardized elements, and higher production volume as price affecting factors. A manufacturing competitiveness analysis for HRS also suggests that station-related costs would decline by 76% with the establishment of 100 stations in an area and up to a 40% decrease in investment for 50 stations(McKinney et al., 2015). Meanwhile, China also benefits from cost advantages compared to the U.S., such as lower labor and building costs(Mayyas & Mann, 2019).

In terms of delivery for off-site hydrogen stations, tube-trailers are chosen as the tools to meet the relatively low demand of hydrogen delivery.

Regarding pipeline construction, as hydrogen demand increases, transportation through pipelines becomes the most cost-effective and low-maintenance option. Therefore, in the FCET50 scenario and later years of the MIX50 scenario, to meet the high demand for hydrogen, the construction of a pipeline from the seashore hydrogen plants to the middle of the PRD region would plan to begin in 2025 and 2030, respectively. Due to the lack of detailed and sufficient evidence on the cost of domestic pipeline construction and the variations between China and other countries, this study adopts an estimated cost of 4,000,000 RMB per kilometer(China Hydrogen Alliance, 2019; Zhu et al., 2023)for pipeline construction, and the

distance of the pipeline is around 150km. This distance is determined by the measurement from the offshore wind power plant to the hydrogen valley in Foshan City.

Table 7 summarizes the cost and specification of the elements and construction of the two types of HRSs.

Table 7: An overview of technical and economic information on HRS

	Site Type	Specification	Price(2020)	Lifetime	Reference
Storage Unit	Off-site & Onsite	250kg	2,497,500	15 years	(McKinney et al., 2015)
Compressor	Off-site & Onsite	35 mPa	1,822,500	15 years	
Cooler system	Off-site & Onsite		1,012,500	15 years	(McKinney et al., 2015)
Dispenser	Off-site & Onsite	Dual-hose, 350 and 700 Bar	1,822,500		
Production unit-Electrolyser	On-site	PEM Electrolyser	8,835,750		(McKinney et al., 2015)
Energy Generator	On-site				
Trailer-tractor	Off-site		1,600,000	15 years	(Bai et al., 2023; B. Liu et al., 2020)
Pipeline & Construction	Off-site		4,000,000/km	n/a	(China Hydrogen Alliance, 2019; Zhu et al., 2023)

Material & Equipment	Off-site	Including Fiba Type 2 storage tube, valve and POS etc.	3,692,250	10-15 years	(McKinney et al., 2015)
Site	On-site		5,589,000	n/a	
Construction	Off-site		2,752,650	n/a	

In this study, the capacity of HRS is set to be three categories, which were also widely discussed in industry: 500 kg off-site delivery refueling stations, 1000 kg off-site delivery refueling stations, and 500 kg on-site production refueling stations. Based on the calculation of energy consumption for heavy-duty trucks with daily range of about 300km, a hydrogen refueling station with a capacity of 500 kg can meet the demand of refueling 25 FCETs per day in the current stage, 31 FCETs in 2030, and 40 FCETs in 2050, respectively. Similarly, a station with a capacity of 1000 kg can refuel 50 FCETs, 62 FCETs in 2030, and 80 FCETs every day in 2050, due to the improvement of fuel efficiency(Marcinkoski et al., 2019). These estimates provide an indication of the number of trucks that can be serviced by the respective station capacities on a daily basis. Consequently, the infrastructure and equipment for HRS are listed below in Table 8.

Table 8: The projected amount of HRS in FCET50 and MIX50 scenarios

	FCET50			MIX50		
	Off-Site-500kg	Off-Site-1000kg	On-site	Off-Site-500kg	Off-Site-1000kg	On-site
2025	913	457	0	685	343	0
2030	923	937	700	692	703	525
2035	1366	1387	1035	934	949	708
2040	1846	1874	1399	1153	1171	874
2045	1905	2222	1587	1280	1493	1067
2050	1681	1961	1401	1177	1373	981

5.1.4 Estimation of infrastructure and equipment for BETs

In accordance with the varying requirements of battery trucking, overnight slow charging stations, PV generators with solar energy storage stations, and battery swapping stations are analyzed and set to be the three types of infrastructure in this study. As previously discussed, addressing the disparity between peak generation of wind or photovoltaic power and real-life peak electricity consumption is crucial, even though we have utilized solar energy storage stations. One step further is to implement virtual power plants. Given the anticipated increase in the burden on the electric grid in the coming years due to BETs, virtual power plants will be integrated at different stages within BET50 and MIX50 scenarios. This method proves to be less costly and emits fewer emissions, as it does not require heavy physical construction. The assumptions regarding the implementation process and the proportion of different types of infrastructure align with the local government's development plans and projections from professionals(Energy Bureau of Guangdong Province, 2021; Guangdong Provincial Development and Reform Commission, 2022b)

Table 9 presents the technical and economic aspects of charging stations and virtual power plants.

Table 9: Technical and economic aspects of charging stations and virtual power plants

Type of Stations	Station Elements					Maximum supply			Cost （CNY）				Capacity of service Trucks	Total Cost (CNY)
	Individual Charging Pole	Solar energy storage	PV Power Generating	Battery for replacement	Life-span	Total supply of Power	Power of individual pole or battery	Units of Charging pole or Batteries	Price of Charging pole or Batteries	Price of PV generator	Cost of Solar energy storage	Construction		
Overnight Charging	60kW	/	/		10 years	600kW	60kw	10	57,900			450/kW	20	849,000
Solar energy storage and PV fast-charging Station	60kW	350kWh	800kW/day		10 years	1160kW	60kw	6	57,900	1,200,000	2136/kW	450/kW	36	2,457,000
Battery Swraping	/	/	/	282kw/bar	8 years	11280 kWh	282kwh	40	350,000	/	/	4,210,000	40	18,210,000

Note: 1. The cost of elements and construction is expected to decrease by 3% per year (G. He et al., 2020; Richard et al., 2018)

2. Source: (CATL Energy, 2023; CATRC, 2020; GCL Energy Technology, 2022; Tesla, 2023) and author’s calculation.

Similar to HRS, the predicted amount of charging stations is also listed in Table 10.

Table 10: The projected amount of HRS in FCET50 and MIX50 scenarios

	BET50			MIX50		
	Overnight	Solar storage	Battery wrapping	Overnight	Solar storage	Battery wrapping
2025	2019	140	252	1514	237	189
2030	4935	343	617	3701	578	463
2035	6391	761	1370	4372	1171	937
2040	8637	1028	1851	5398	1446	1157
2045	8402	1371	2801	5645	2352	1882
2050	9254	1556	3085	6478	2699	2159

5.2 Estimation of emission and pollution reduction

To obtain accurate emissions estimates, this study utilizes the GREET model to analyze both the upstream fuel cycle and vehicle operation stage. The choice of fuel production pathways can significantly influence GHG and air pollutant emissions, thus necessitating the inclusion of specific characteristics such as feedstocks, hydrogen production pathways, electricity production pathways, and more as the criteria and features, in the GREET model.

For FCET trucking, estimation of fuel cycle emissions integrates the projection of the energy source system for hydrogen production over the next three decades derived from the hydrogen development plan in China and Guangdong Province(Guangdong Provincial Bureau of Energy, 2023; Guangdong Provincial Development and reform commission, 2022a; Guangzhou Development and Reform Commission, 2020). The ultimate goal by then is that production of hydrogen will predominantly rely on renewable energy sources, accounting for approximately 70% of the total production(Shuo & Yu, 2021). Combining with the scenario settings of a proportion of renewable energy, the result is included as the feedstock and hydrogen production pathways in the GREET model for the use of fuel cycle emission computing.

In the operation cycle for FCETs, the GREET model incorporates the existing features specific to fuel cell heavy-duty long-haul trucks utilizing gaseous hydrogen as fuel. It should be noted that in the operation cycle for FCETs, there are only tire and brake wear emissions, with no other emissions released at the tailpipe.

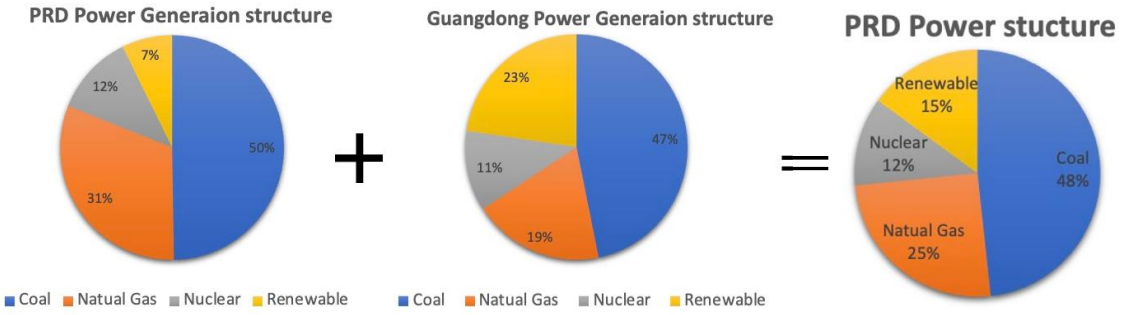
Similarly, for BET trucking, the estimation of fuel cycle emissions combines the projection of the energy source system for electricity power generation in the next three decades. The change in electricity power mix in PRD was derived from the existing structure (Energy Foundation China, 2022) and the projection from public sectors. This projection provides insights into the anticipated changes in the electricity generation mix and its associated environmental impacts. The operation cycle for BETs adopts the existing features specific to battery heavy-duty long-haul trucks available in the GREET model. As with FCETs, the operation cycle for BETs in GREET model only includes tire and brake wear emissions, with no additional emissions at the tailpipes.

In the BaU scenario, where ICETs continue to dominate, emissions calculations are based on the study by (Energy Foundation China). Additionally, low-sulfur diesel data from the GREET model is utilized to estimate the emissions associated with diesel trucks. The operation cycle for ICETs incorporates the features available for diesel heavy-duty long-haul trucks in the GREET model.

Regarding the power generation structure in the PRD region, with a within PRD-region power sufficiency rate of only 49.9%, coal power, gas power, nuclear power, and renewable energy constituted 49.8%, 31.3%, 11.7%, and 7.3% of installed capacity, respectively. Meanwhile, the external dependence of electricity accounted for 50.1%, and the share of coal power, gas power, nuclear power, and renewable energy was 46.8%, 19%, 11.5%, and 22.7% of the Guangdong power generation capacity, respectively. Hence, the actual power structure in the PRD region is listed in Figure 9. In the next few decades, according to projections from the IEA and China Energy Research Institute(Energy Research Institute of the National Development and Reform Commission, 2015; International Energy Agency, 2021)and the trend

of PRD, I computed the power system in PRD for the next few decades and applied them in the GREET model to derive the emission factor for the fuels and energy.

Figure 9: Power generation structure in PRD region at current stage



The total emission can be computed from the following Equation （2）

$$EM_k = EM_{k,f} + EM_{k,op} = \sum_{k=1}^{k} ST_{k,t} \times VKT \times EF_{k,f} + \sum_{k=1} Fuel_k \times EF_{op} \quad (2)$$

Where, $EM_{k,e}$ is the total emission of vehicle technology type k, including ICET, BET, or FCET.

$EM_{k,f}$, $EM_{k,op}$, $EF_{k,f}$, $EF_{k,Op}$ *are the emissions from the Fuel and Operation cycle,* and emission factors of Fuel and Operation cycle are calculated by the GREET model, *respectively.*

$ST_{k,t}$ is the stock of vehicle type k at the year of t, and VKT is the average distance travelled every year.

$Fuel_k$ is the fuel consumption from Equation (1) for each type of truck.

The Subscripts k, f, op, t present the vehicle type, fuel cycle, operation cycle, and time respectively.

The details of emission factors of various fuel types in different stages and power mixes are listed in Table 11.

Table 11: Emission factors

	GHG or Air Pollutant	Fuel Type	Emission Factor						
			2025		2030	2035	2040	2045	2050
Fuel Cycle	VOC-kg/1000L	Diesel	0.5742		n/a	n/a	n/a	n/a	n/a
	VOC-kg/1000kg	Hydrogen	1.4897		1.2535	1.1803	1.079	0.9486	0.8295
	VOC-kg/10000kWh	Electricity	0.6228		0.5217	0.4978	0.4504	0.3964	0.3452
	CO-kg/1000L	Diesel	0.7885		n/a	n/a	n/a	n/a	n/a
	CO-kg/1000kg	Hydrogen	2.7849		2.5049	2.4085	2.3251	2.1723	2.041
	CO-kg/10000kWh	Electricity	2.2319		2.0153	1.9562	1.8946	1.935	1.8686
	NOX-kg/1000L	Diesel	17.5043		n/a	n/a	n/a	n/a	n/a
	NOX-kg/1000kg	Hydrogen	3.2745		2.935	2.8312	2.7542	2.5978	2.4534
	NOX-kg/10000kWh	Electricity	4.7332		3.9868	3.7495	3.4076	3.087	2.7254
	PM10-kg/1000L	Diesel	0.2171		n/a	n/a	n/a	n/a	n/a
	PM10-kg/1000kg	Hydrogen	1.1024		0.9404	0.8872	0.8048	0.7172	0.629
	PM10-kg/10000kWh	Electricity	0.8888		0.7519	0.7091	0.634	0.5655	0.4912
	PM2.5 -kg/1000L	Diesel	0.5685		n/a	n/a	n/a	n/a	n/a
	PM2.5 -kg/1000kg	Hydrogen	0.2748		0.2408	0.2306	0.2182	0.2019	0.1855
	PM2.5 -kg/10000kWl	Electricity	0.4233		0.3611	0.3418	0.311	0.2848	0.2536
	SOx-kg/1000L	Diesel	0.6479		n/a	n/a	n/a	n/a	n/a
	SOx-kg/1000kg	Hydrogen	2.8096		2.465	2.3606	2.2288	2.0751	1.9079
	SOx-kg/10000kWh	Electricity	5.4399		4.6408	4.3812	3.9335	3.5569	3.1227
	CH4-kg/1000L	Diesel	4.3385		n/a	n/a	n/a	n/a	n/a
	CH4-kg/1000kg	Hydrogen	24.8330		20.6108	19.4385	17.7481	15.4665	13.4293
	CH4-kg/10000kWh	Electricity	11.4593		11.4593	8.7757	7.8435	6.6795	5.6387
	N2O-kg/1000L	Diesel	0.0314		n/a	n/a	n/a	n/a	n/a
	N2O-kg/1000kg	Hydrogen	0.0796		0.074382	0.07199	0.077146	0.08545	0.08804
	N2O-kg/10000kWh	Electricity	0.1373		0.1199	0.113	0.1067	0.1053	0.09863
	CO2-kg/1000L	Diesel	1529.5416		n/a	n/a	n/a	n/a	n/a
	CO2-kg/1000kg	Hydrogen	4587.2000		3926.473	3788.472	3620.708	3282.289	3009.987
	CO2-kg/10000kWh	Electricity	6283.7649		5165.399	4840.923	4393.468	3665.394	3082.635
	GHG or Air Pollutant	Fuel Type	Emission Factor						
Operational Cycle	VOC-kg/100km	Diesel	0.0034	0.0031	evap				
		Hydrogen							
		Electricity							
	CO (kg/100km)	Diesel	0.1801						
		Hydrogen							
		Electricity							
	NOx (kg/100km)	Diesel	0.1131						
		Hydrogen							
		Electricity							
	PM10 (kg/100km)	Diesel	0.00029	0.0058	Tire Brake				
		Hydrogen		0.0058	Tire Brake				
		Electricity		0.0058	Tire Brake				
	PM2.5 (kg/100km)	Diesel	0.00027	0.000763	Tire Brake				
		Hydrogen		0.000763	Tire Brake				
		Electricity		0.000763	Tire Brake				
	SOx (kg/100km)	Diesel	0.0006						
		Hydrogen							
		Electricity							
	CH4 (kg/100km)	Diesel	0.0009						
		Hydrogen							
		Electricity							
	N2O (kg/100km)	Diesel	0.0001						
		Hydrogen							
		Electricity							
	CO2 (kg/100km)	Diesel	88.4612						
		Hydrogen							
		Electricity							

Source:(ANL, 2021)

5.3 Estimation of concentration change

In this study, due to the lack of up-to-date observation data from authorities, the estimation of change in air pollutant concentration is based on the comparison of previous concentrations. The concept is comparing the previous and predicted emission volume, and combining the proportion of HDTs contributes to each kind of pollutant into the air and then deriving the relative change of concentration of air pollution.

The observation data from (http://www.aqistudy.cn，http://www.pm25.in) is collected and presented in Table 12. Due to the intermittent lockdown during the pandemic, the reduced transportation, industrial activity and residential mobility led to an improvement in air quality. This trend is not limited to the PRD region but has been validated by recent studies worldwide(Adam et al., 2021; Rodríguez-urrego & Rodríguez-urrego, 2020). To ensure objectivity and consistency, data spanning more than five years has been collected for this dataset.

Table 12: Air pollution Concentration in PRD region

City	Average Concentration	PM2.5	PM10	NO2	CO	SO2	03 8h
Shenzhen	2017	28.08	44.50	29.58	0.81	7.82	86.67
	2018	24.17	40.58	26.67	0.58	6.75	82.42
	2019	24.08	41.67	25.42	0.63	5.00	93.83
	2020	19.33	35.25	22.75	0.60	5.75	79.92
	2021	18.08	36.83	24.17	0.59	6.00	85.25
	2022	16.25	31.00	19.75	0.61	5.33	88.42
	2023	**20.2**	**39.2**	**19.6**	**0.6354**	**5.8**	**89.2**
	Accumulative A	21.46	38.43	23.99	0.64	6.06	86.53
Guangzhou	2017	35.42	55.83	12.00	52.42	0.94	93.25
	2018	32.67	49.75	9.08	45.33	0.76	90.58
	2019	29.92	53.17	6.75	44.75	0.83	101.17
	2020	23.08	43.08	6.92	36.50	0.76	98.33
	2021	23.92	46.58	7.58	34.33	0.72	102.67
	2022	21.42	38.67	6.33	28.83	0.72	98.92
	2023	**26.40**	**47.40**	**6.00**	**30.60**	**0.71**	**88.60**
	Accumulative A	27.55	47.78	7.81	38.97	0.78	96.22
Zhuhai	2017	29.42	42.33	32.33	0.72	7.33	84.33
	2018	25.42	40.17	27.67	0.60	6.17	89.50
	2019	24.50	41.08	27.25	0.67	5.17	94.00
	2020	18.67	33.75	24.17	0.57	4.67	84.08
	2021	19.58	36.83	22.25	0.58	6.25	90.17
	2022	17.33	30.25	19.25	0.50	7.83	92.33
	2023	**21.00**	**38.40**	**20.00**	**0.46**	**5.60**	**96.00**
	Accumulative A	22.27	37.55	24.70	0.59	6.15	90.06
Jiangmen	2017	36.92	60.00	0.88	38.25	11.67	99.92
	2018	28.75	51.33	0.73	31.83	8.42	91.25
	2019	26.92	49.50	0.79	32.33	6.92	104.17
	2020	20.92	40.75	0.71	26.25	6.92	93.67
	2021	22.58	45.50	0.64	30.17	7.25	100.67
	2022	20.33	39.58	0.62	26.50	6.42	99.67
	2023	24.40	45.80	0.64	25.60	6.40	94.00
	Accumulative A	25.83	47.50	0.72	30.13	7.71	97.62
Zhaoqin	2017	40.42	56.83	37.00	13.83	1.04	91.00
	2018	35.67	50.25	32.92	11.58	0.79	85.42
	2019	31.75	49.67	33.42	9.42	0.83	92.67
	2020	23.17	37.08	25.92	9.33	0.58	79.00
	2021	22.17	37.58	25.67	9.75	0.60	93.67
	2022	21.75	34.83	23.00	9.25	0.64	97.67
	2023	27.00	44.20	25.20	9.00	0.56	88.00
	Accumulative A	28.85	44.35	29.02	10.31	0.72	89.63
Huizhou	2017	29.50	51.08	25.33	0.84	8.50	89.42
	2018	25.83	43.33	22.33	0.64	7.67	90.25
	2019	24.75	46.58	24.17	0.68	7.58	94.58
	2020	20.08	38.50	18.08	0.60	8.00	89.33
	2021	19.25	40.08	19.58	0.54	7.75	99.00
	2022	17.00	32.83	15.92	0.57	4.58	92.33
	2023	22.40	40.80	16.00	0.59	5.60	91.00
	Accumulative A	22.69	41.89	20.20	0.64	7.10	92.27
Dongguan	2017	37.08	51.00	12.08	0.97	40.50	100.50
	2018	33.67	45.58	9.08	0.74	35.67	96.08
	2019	31.92	49.08	9.67	0.79	36.58	110.67
	2020	24.33	37.58	8.17	0.64	26.92	99.00
	2021	21.92	41.42	8.58	0.63	29.08	107.58
	2022	20.25	35.75	8.00	0.71	25.92	108.42
	2023	23.40	43.40	8.40	0.61	25.20	99.60
	Accumulative A	27.51	43.40	9.14	0.73	31.41	103.12
Foshan	2017	39.58	62.58	0.88	12.83	44.50	99.33
	2018	31.92	55.33	0.72	9.75	37.83	92.33
	2019	29.75	56.50	0.85	9.00	40.83	99.83
	2020	22.33	42.92	0.68	7.42	31.17	92.33
	2021	23.42	45.75	0.63	7.50	32.42	101.75
	2022	21.42	37.92	0.66	6.17	28.58	98.25
	2023	25.6	45.4	0.6686	6.4	29.6	87
	Accumulative A	27.72	49.49	0.73	8.44	34.99	95.83
Zhongshan	2017	33.42	48.42	10.25	36.08	0.89	96.17
	2018	27.67	41.25	8.17	29.00	0.69	86.75
	2019	27.50	44.08	6.08	31.50	0.72	100.25
	2020	20.08	36.33	4.92	24.67	0.64	87.50
	2021	20.33	39.42	4.67	25.25	0.60	94.17
	2022	18.75	34.00	5.00	22.50	0.58	96.08
	2023	22.40	38.80	5.20	21.80	0.52	90.60
	Accumulative A	24.31	40.33	6.33	27.26	0.66	93.07
Final Average concentration in PRD		**25.353**	**43.412**	**28.963**	**7.6715**	**0.6881**	**93.817**

In regards to the previous emission from HDTs, this study computes emissions through utilizing the conventional diesel fuel cycle emissions factors, and the long haul trucks features

in GREET model, as well as the HDTs stocks and VKT in PRD region from 2017-2022, via Equation (2) and then get the results Table 13.

Table 13: Emission Calculation for Previous years in PRD region

Emission factors for Long Haul trucks and Low-sulfur Diesel			Average emission during past 5 years	
	Fuel cycle	Operation only		
VOC (kg/hkm)	0.01180000	0.003400	VOC-kg	31953958.89
CO (kg/hkm)	0.19410000	0.180100	CO-kg	72627944.35
NOx (kg/hkm)	0.13450000	0.113100	NOX-kg	269079165.9
PM10 (kg/hkm)	0.00180000	0.000294	PM10-kg	2954170.967
PM2.5 (kg/hkm)	0.00160000	0.000270	PM2.5-kg	7562824.277
SOx (kg/hkm)	0.00650000	0.000611	SOx-kg	8723660.199
CH4 (kg/hkm)	0.12630000	0.000887	CH4-kg	57307040.51
CO2 (kg/hkm)	103.28300000	88.461200	CO2-kg	50680339991
N2O (kg/hkm)	0.00039309	0.000119	N2O-kg	454057.1636
PM10_TBW (kg/hkm)		0.005800		
PM2.5_TBW (kg/hkm)		0.000763		
VOC_evap (kg/hkm)		0.003100		
Stock of HDTs in PRD region				
2017	254,651			
2018	283,709			
2019	314,473			
2020	363,622			
2021	419,469			

As for the proportion of emissions emitted by HDTs accounting for the total air pollutants, it is found that NO_x emitted by HDTs accounts for 76.1% in the on-road mobile source, while the share of mobile source in total anthropogenic air pollutant emission is around 39% (Ministry of Ecology and Environment of China, 2021; Zhong et al., 2018). This means the reduction from alternative trucking in NO_x could generate considerable improvement in air quality in terms of NO_x concentration. Utilizing the same idea, CO, PM_{10}, $PM_{2.5}$, and Ozone from HDTs contribute around 4.03%, 2.32%, 4.12%, and 4.78% to the total air pollution, respectively, as listed in Table 14.

Table 14: Proportion of HDTs contributes to Air pollution

HDTs to On-road Mobile Source	On-road Mobile to anthropogenic air pollutant emission	HDTs to Total Air pollution

NO_x	76.1%		39%	(Zhong et al., 2018)	29.68%
CO	10.60%	(Ministry of Ecology	38%	(Bian et al., 2019)	4.03%
PM_{10}	51.5%	and Environment of	3.5%	(Bian et al., 2019)	2.32%
$PM_{2.5}$	51.5%	China, 2021)	8%	(Bian et al., 2019)	4.12%
Ozone	12%		39.81%	(EPD Hong Kong, 2011)	4.78%

Therefore, by comparing the increase or reduction in emissions with existing emission levels and considering the proportion of HDT emissions within total anthropogenic air pollution, we can get an idea of the relative change in concentration.

5.4 Estimation of health impacts

According to the epidemiological literature, exposure to fine particulate (PM_{10} and $PM_{2.5}$), NO_x, SO_2, Ozone and CO are related to various adverse health outcomes， including lung cancer, Chronic obstructive pulmonary disease (COPD), Respiratory disease, Cardiovascular disease, Asthma attack, Diabetes(type 2), brain damage, and hypertension, etc(Aunan & Pan, 2004; Cui et al., 2015; Y. Huang et al., 2021; M. Liu et al., 2021; Yin et al., 2017; Z. Zhang et al., 2018). The increasing risk in human health associated with air pollutants brings harm to well-being and enormous economic loss(S. Chen, 2018; Y. L. Chen et al., 2013; Kim et al., 2020; S. Ren et al., 2021; Yin et al., 2017). It should be emphasized that the criteria for selected health endpoints are those that can be quantitively calculated and monetized, occurring under the long-term exposure to the air pollutants. Although the latest study demonstrated that air pollutants especially fine particulates also show a correlation to dementia, Alzheimer, and Parkinson's disease, the exposure and response function is still not fully clear yet(Yin et al., 2017). To avoid overlap in assessing the health impacts, health endpoints used in this study are classified into two categories: mortality and morbidity, and based on the ICD-11 report (11th version of the international classification of diseases (ICD-11, 2022). Hence, the analyzed health endpoints in this study are premature death caused by Cardiovascular disease, Respiratory disease, COPD, Lung cancer, and Diabetes; Hospital admission due to

Cardiovascular and Respirator diseases, COPD, and Cerebrovascular diseases. The last two health endpoints are quantifiable are Diabetes T2 and Asthma attack.

Table 15 shows the relationship between air pollutants and health endpoints found in previous epidemiological studies. Given the situation that air pollution levels in PRD region and the context of fast-growing with dense population area, data were chosen under the similar conditions (keywords: long-term, China, Asia, high pollution, etc.) researches, especially the incidence baseline of every health endpoint.

Table 15: Exposure-response coefficients (refer to Eq. (1)) and the baseline prevalence

Health Endpoint	Baseline	Exposure-response coefficients				
		CO	NO2	Ozone	PM10	PM2.5
Respiratory Mortality	0.00065 (NHFPC, 2020)		0.0227(Faustini et al., 2014)	0.0042(Lim et al., 20)	0.0109 (Aunan & Pan, 2004)	0.0005 (Yin et al., 2017)
Cardiovascular Mortality	0.00497 (NHFPC, 2020)	0.0477(Yao et al., 2020)	0.0056 (Caudle et al., 2021)	0.0045 (Cai et al., 2019)	0.0006 (Omidi Khaniabadi et al., 2019)	0.0014 (Yin et al., 2017)
Lung cancer Mortality	0.000487 (NHFPC, 2020)		0.0953 (Y. Huang et al.)		0.0049 (Cui et al., 2015)	0.0034 (Yin et al., 2017)
COPD Mortality	0.00053 (M. Liu et al., 2021)	13.01% excess risk(Cai et al., 2019	0.0026 (Z. Zhang et al., 2018)	0.01095 (Mingyao Yao et al., 202	0.0322 (Ju et al., 2012)	0.01220 (Cai et al., 2019)
Diabetes Mortality	0.00019 (NHFPC, 2020)		0.0086 (Lim et al., 2018)			0.0174 (Cai et al., 2019)
Cardiovascular HD	0.00546 (Omidi Khaniabadi et al., 201	0.0439(Yao et al., 2020)	0.0012(D. Zhang et al., 2019)	0.00175 (D. Zhang et al., 20)	0.0012 (Aunan & Pan, 2004)	0.0008 (Chen, 2018)
Respiratory HD	0.0126 (Huang and Zhang, 2013)	0.044(Yao et al., 2020)	0.0198 (Khaniabadi et al., 2018	0.00218 (D. Zhang et al., 20)	0.0007(Aunan & Pan, 2004)	0.0002 (Chen, 2018)
Cerebrovascular HD	0.00354 (Y. Peng et al, 2019)				0.000005 (Matus et al., 2011)	0.000008 (Ren et al., 2021)
COPD HD	0.02478 (Ramanathan et al.)		0.0004 (Khaniabadi et al., 2018	0.00086 (Khaniabadi et al., 2018)	0.0008 (Khaniabadi et al., 2018)	1.025 (Zhu et al., 2023)
Asthma attack	0.042 (Huang et al., 2019)		0.0028 (Yang et al., 2020)	0.00429 (Matus et al., 2011)	0.0003(Lu et al., 2020)	0.0068 (Chen, 2018)
Diabetes t2 Prevalence	0.066 (J. Liu et al.)		0.0043 (Lu et al., 2020)	0.00554 (Wang et al., 2022)	0.0005 (Yang et al., 2020)	0.0021(Yang et al., 2020)

Note:1. Data is based on all-age groups;

2. Given the transformable feature between exposure-response coefficients and relative risk. (excess risk, odds ratio), some coefficients are calculated from other forms of risk data.

In this study, log-linear exposure-response functions (Eqs (3)-(5)) were applied to calculate the health endpoints. This model was recommended to estimate the health impacts in highly polluted areas (WHO,2006). The Exposure-response coefficients indicate the incidence change of particular health endpoints *i* per μg/m3 air pollutant increment. This model helps to quantify the proportional change in health impacts coming from a certain change in air pollutant concentration, from which we can conduct the monetization of health outcomes in the next stage.

$$E_{i,p} = E_{0i,p} \times exp\left[{\beta_{i,p}}^{*}\left(C_p - C_{0,p}\right)\right] \quad (3)$$

$$HE_{i,p,t} = \sum_{i=1}^{l}\sum_{p=1}^{m}\sum_{t=1}^{n}\left(E_{i,p,t} - E_{0i,p}\right) \times Pop \quad (4)$$

Where, $E_{i,p}$, $E_{0i,p}$, represent incidence, and baseline incidence of particular health endpoint *i* in the targeted population, respectively.

β is the exposure-response coefficients collected from previous epidemiological literature referring to the air pollutants and health endpoints, including both mortality and morbidity risk.

$C_{p,t}$, $C_{0,p}$ represent calculated and baseline concentrations of certain air pollutants *p* in year *t*, respectively. ($C_{p,t}$ -$C_{0,p,t-5}$) refers to the change of concentration (μg/m3) of air pollution *p* under predefined scenarios in the period of five years' gap.

The Subscripts *i, t, p* represent health endpoint, year, and air pollutant, respectively, while *l,m,n* mean the certain type of health endpoints, particular year and a certain type of air pollutants, respectively.

Pop is the targeted population in the PRD region.

$HE_{i,p,t}$ is the total health endpoints among the targeted population attributable to air pollutants in the whole studied period till 2050.

5.4 Monetary health impact

Based on the estimated attributable mortality and morbidity outcomes associated with air pollutants in predefined scenarios, we can further assess the economic impacts. There are various economic evaluations designed to assess the health impacts and overall well-beings, including Value of statistical life (VSL), Cost of illness (COI), Human Capital Estimates (HCA), Years of potential life lost (YPLL), etc. Each model has its own advantages and limitations. This study seeks data from literature and adopts VSL and Cost of illness (COI) methods to calculate the monetized quantity of adverse health impacts. Willing to Pay (WTP) is the mainstream method to estimate VSL. The WTP approach assumes that human beings can make rational choices considering the trade-off between financial and health concerns. Given this condition, VSL is obtained in surveys estimating individuals' WTP for reducing the risk of mortality. The WTP method is suitable for the targeted population with awareness of health concerns and relatively high economic levels.

For the purpose of monetizing morbidity, the cost of illness (COI) method was adopted to estimate the minimum value of health loss through computing direct cost for curing the diseases, including diagnostic, treatment, expenditure on medicine, hospitalization cost, as well as the macroeconomic loss due to the illness. COI method is considered is not comprehensive due to the lack of health preference of individuals, it only covers the illness itself. However, another widely used method, the human capital approach (HCA), neglects the value of jobless and vulnerable group (children, seniors, and disabled people). COI method avoids the ethical flaw, while COI can measure the disease-related costs as well as levels of economic and social development in the targeted area (D. Huang et al., 2012). Since the reduction of air pollutants can help to avoid premature deaths and the potential prevalence of diseases, the benefit is available to be quantified in a positive result.

5.4.1 Mortality-related economic impacts

Through consulting literature about VSL in China, it is found that a survey in Beijing could fit in the condition of PRD in both economic development and individual's perception towards air pollution(Jin et al., 2020). I adopt the VSL suggested in Jin's study, and take into account the slight differences in per capita GDP between cities and years. Consequently, for mortality-related health endpoints, equation (5) is applied to assess economic benefit of avoided premature deaths in pre-set scenarios.

$$VSL_{PRD,t} = VSL_{BJ,2016}\left(\frac{PGDP_{PRD,t}}{PDGP_{BJ,2016}}\right)^{Elasticity} \quad (5)$$

Where $VSL_{PRD,t}$, $VSL_{BJ,2016}$ represent the VSL of residents in PRD regions in a given year t, VSL of residents in Beijing in 2016, respectively.

$PGDP_{prd,t}$, $PGD_{PBJ,2016}$ represent the per capita GDP in PRD region of a given year t, and the per capita GDP in Beijing in 2016, respectively.

Elasticity is the income elasticity coefficient, according to the literature, it is set to be 0.8. The VSL and predicted VSL are computed in alignment with the estimation of IEA of GDP for

China which was used in the fleet stock session, which was also applied in the estimation of stock of HDTs. The details of data are illustrated in Table 16.

Table 16: VSL and Per Capita GDP in PRD

		Beijing	PRD-computed
VSL (RMB)	2016	2,300,000	2,261,569
	2020	/	2,395,936
	2025	/	-
	2030	/	-
	2035	/	-
	2040	/	-
	2045	/	-
	2050	/	-
Per Capita GDP (RMB)	2016	114,690	114,281
	2020	/	148,500
	2025	/	153,455
	2030	/	186,376
	2035	/	219,075
	2040	/	250,120
	2045	/	281,499
	2050	/	309,762

5.4.2 Morbidity-related economic impacts

The following equation (6) assesses the Morbidity related economic impacts in pre-defined scenarios.

$$C_{morbidity,t} = \sum_{i}^{1} \left(C_i + DPGDP_{prd,t} \times D_i \right) \times HE_{prd,t} \quad (6)$$

Where $C_{morbidity}$, C_i represent the total cost of morbidity associated with air pollutants, direct cost per case of medical treatment for certain health endpoint i, $DPGDP_{prd,t}$ is the daily per capita GDP, while D_i is the days of hospitalization or working day loss due to the health endpoints *i*.

The average cost of treatment, days of hospitalization or work loss were obtained from the China Health Statistical Yearbook 2022, and DPGDP was calculated and predicted from the Guangdong Statistical Yearbook 2022 and EIA. The details of each data set are listed in Table 17.

Table 17: COI of morbidity

Health Endpoints	Days of Hospital Admission/	2021	2021	2025	2030	2035	2040	2045	2050
		Treatment cost	COI （US$）						
Cardiovascular HA	8.96	1986.305714	2112.142521	2914.55482	3539.823387	4160.878226	4750.500448	5346.489486	5784.1651
Respiratory HA	7.53	1049.144286	1279.383413	1707.450208	2073.754845	2437.59093	2783.012666	3132.16431	3363.3397
COPD HA	11.96	1656.857143	2257.263186	2700.584976	3279.949922	3855.410489	4401.74604	4953.980992	5319.0638
Cerebrovascular HA	10.5	1892.307143	2082.308043	2894.588418	3515.57353	4132.373782	4717.956747	5309.862913	5726.8263
Health Endpoints	Days of restricted activity	Treatment cost	COI （US$）						
Diabetes t2	9.39	1128.104286	1604.657597	1913.630467	2324.1676	2731.938095	3119.070648	3510.383508	3758.9574
Asthma attack	7.63	951.3928571	1353.10353	1596.506661	1939.010231	2279.205646	2602.183206	2928.64832	3138.2845
Per Capita GDP in PRD region （US$）			18323.42857	21922.11179	26625.13104	31296.45632	35731.35807	40214.14845	44251.653
Per Capita GDP in PRD region by day （US$）			7.17159631	8.580082892	10.42079493	12.24910228	13.98487596	15.73939274	17.319629

Note: HA represents Hospital Admission

6. Results and discussion

In this section, the presented results follow a logical sequence that consists of changes in emissions, concentration levels, infrastructure investment, monetary health impacts, and a final financial comparison of each scenario. Given the relatively large numbers of scenarios and range of individual pollutants, including GHG, considered, a significant array of results is presented, which can be difficult to follow in detail. The point of this section is to highlight the extent of reductions for each pollutant that may be possible to characterize which scenario provides the most reductions, albeit this without considering the costs or the monetized benefit values of associated reductions.

6.1 Changes in air pollutant and GHG emissions of each scenario

In general, the penetration rate of alternative energy trucks and renewable energy resources leads to a reduction of most air pollutants and GHG emissions. However, certain pollutants such as SO_2 and PM_{10} may not follow this trend in specific situations. Figure 10 illustrates the net change in mass and percentage of GHG and air pollutant emissions for various scenarios compared to the BaU base, in five-year intervals till 2050.

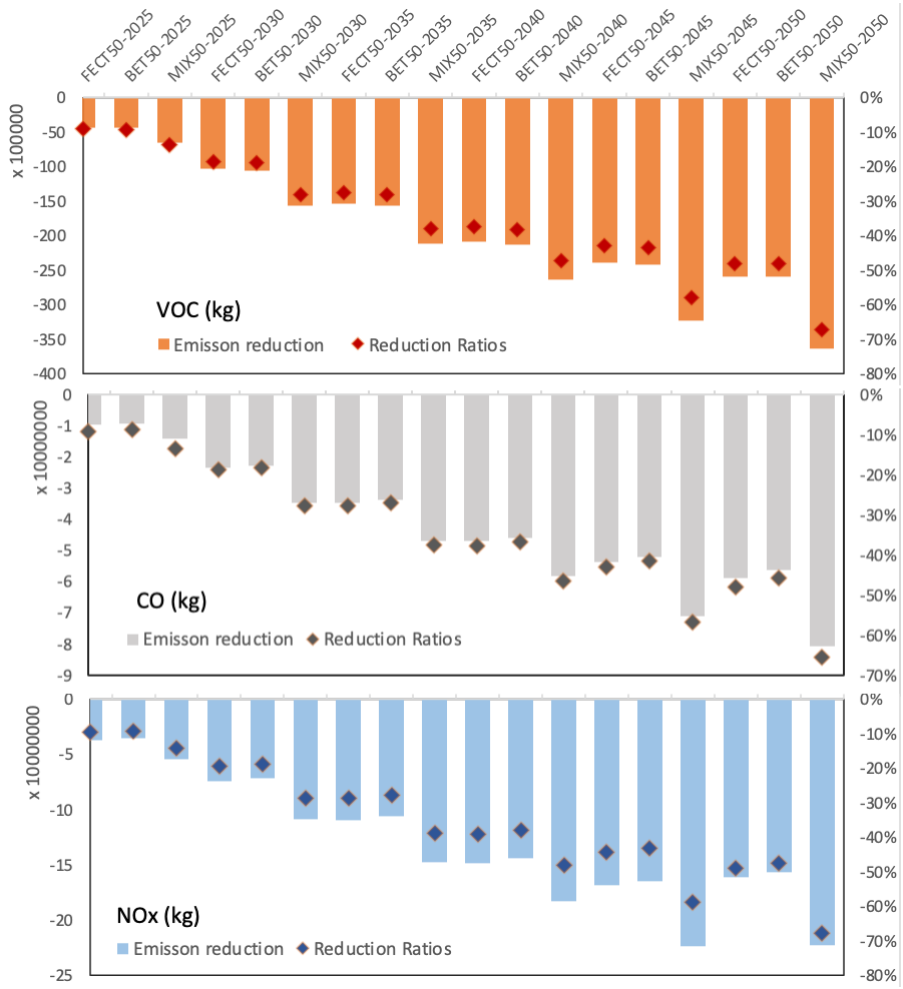
Among the pollutants, Ozone (VOCs, emitted by trucks, are key precursors of Ozone(Z. He et al., 2019)) shows the largest reduction in the MIX50 scenario, in which the BETs and FCETs split equally among the penetration of alternative trucking. Similarly, CO, NO_x, $PM_{2.5}$, and CO_2 exhibit the same trend as Ozone, with the MIX50 scenario showing the greatest reduction potential. It's important to note that the net change in emissions from zero-emission trucking has been narrowing down over the last decade due to improved fuel efficiency of conventional diesel trucks, but the rate of emission reduction is still increasing.

Unlike other air pollutants, PM_{10} and SO_x emissions behave differently. Due to the relatively higher PM_{10} emissions from BETs compared to FCETs, the BET50 scenario does not show a reduction until 2035, so does MIX50 scenario, which also involves half of BETs implementation.

In terms of operational cycle emissions, the GREET model assumes that FCETs and BETs only emit PM_{10} and $PM_{2.5}$ from tire and brake wear emissions and VOCs from evaporation, without any other tailpipe emissions. *Which means PM emissions are higher than normal perception in the whole process of alternative trucking*.

SO_x emissions display a similar trend in the BET50 and MIX50 scenarios, in spite of different underlying reasons. From Figure 11 we can find that the fuel cycle emissions of SO_x contribute much higher than the operational stage. Due to higher emission factors during the electricity power generation process, SO_x emissions from adopting BETs are higher than those from FCETs and ICETs, even with the introduction of renewable energy resources through power generation. However, the good news is that the intensifying SO_x emissions due to the penetration of BETs account for a negligible portion of the overall SO_x concentration in the air. Based on the calculation of source-to-pollutant proportions in the air, HDTs contribute 29.68% of total anthropogenic NO_x emissions, 2.32% of PM_{10} emissions, 4.12% of $PM_{2.5}$ emissions, 3.03% of Ozone emissions, and 0.4% of SO_x emissions, respectively. Therefore, in the subsequent analysis, the changes in SO_x concentration will not be considered due to the very minor proportion caused by HDTs.

Figure 10: Net change in mass and percentage of GHG and air pollutant emissions



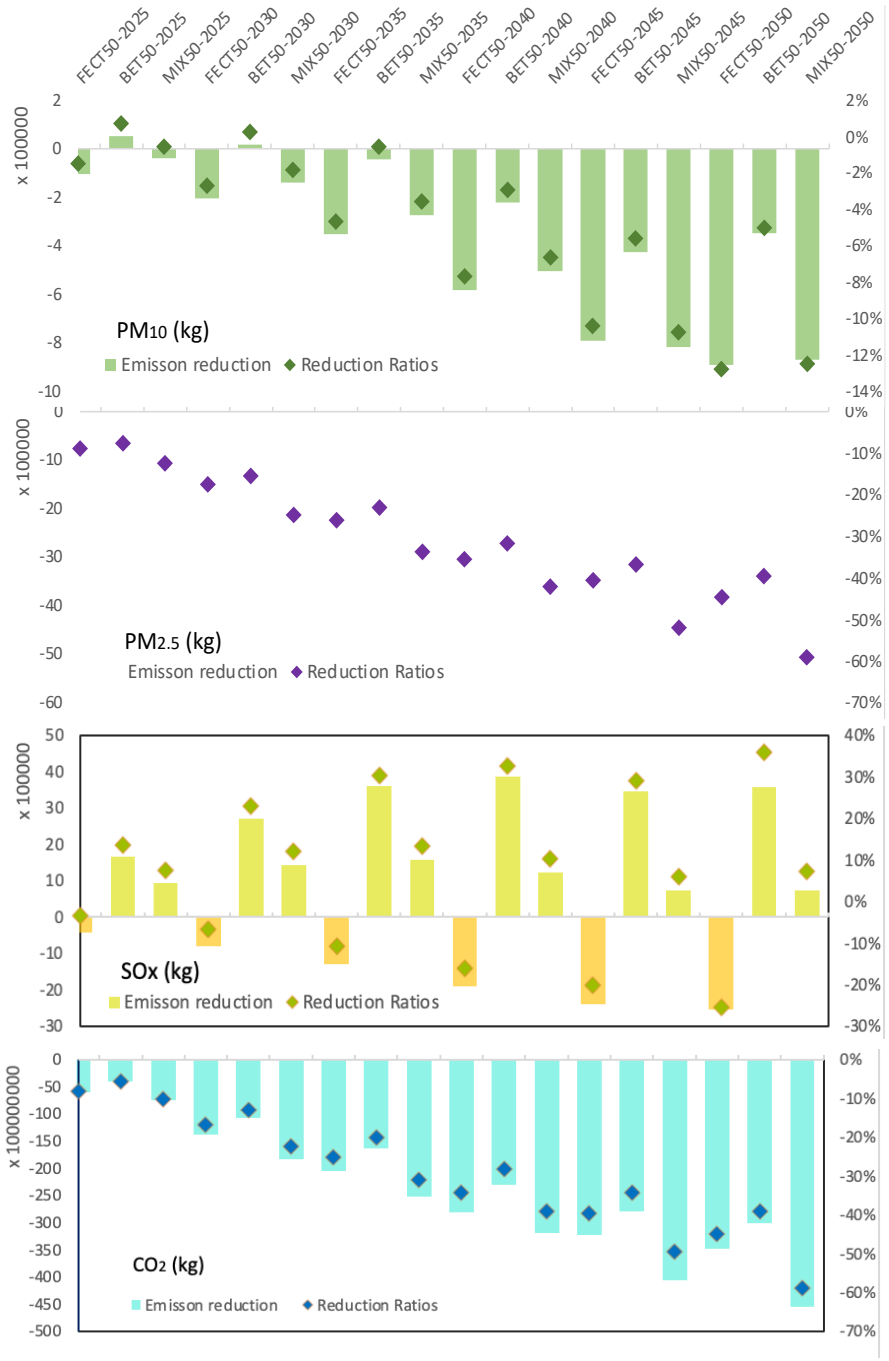
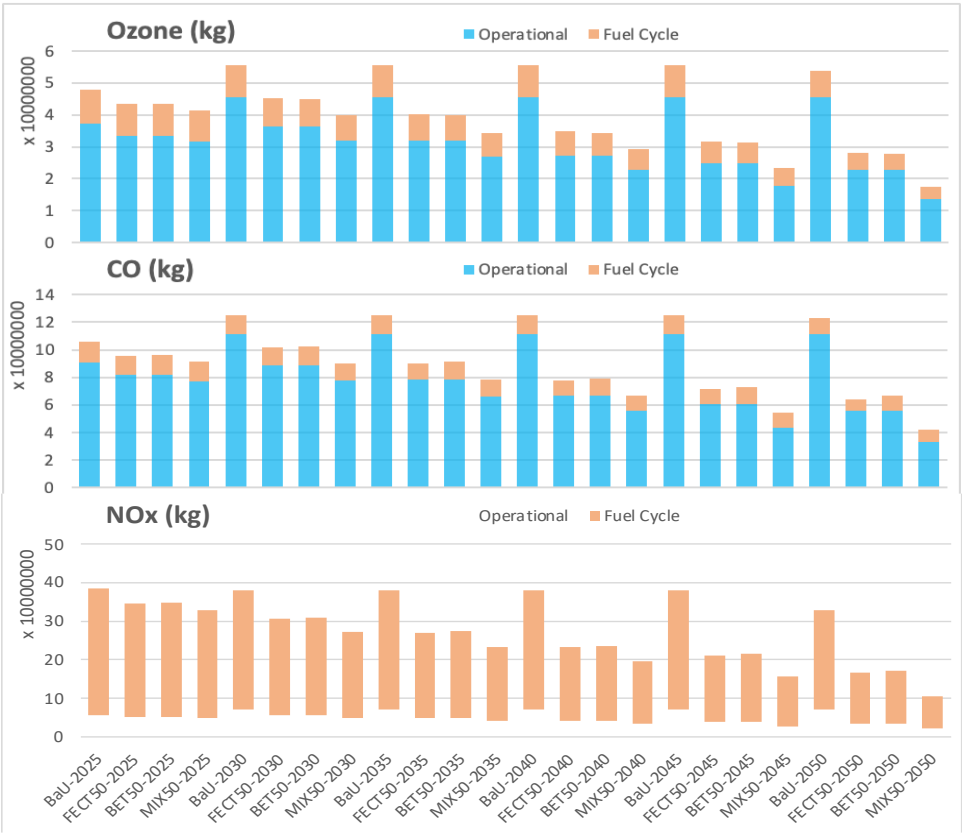


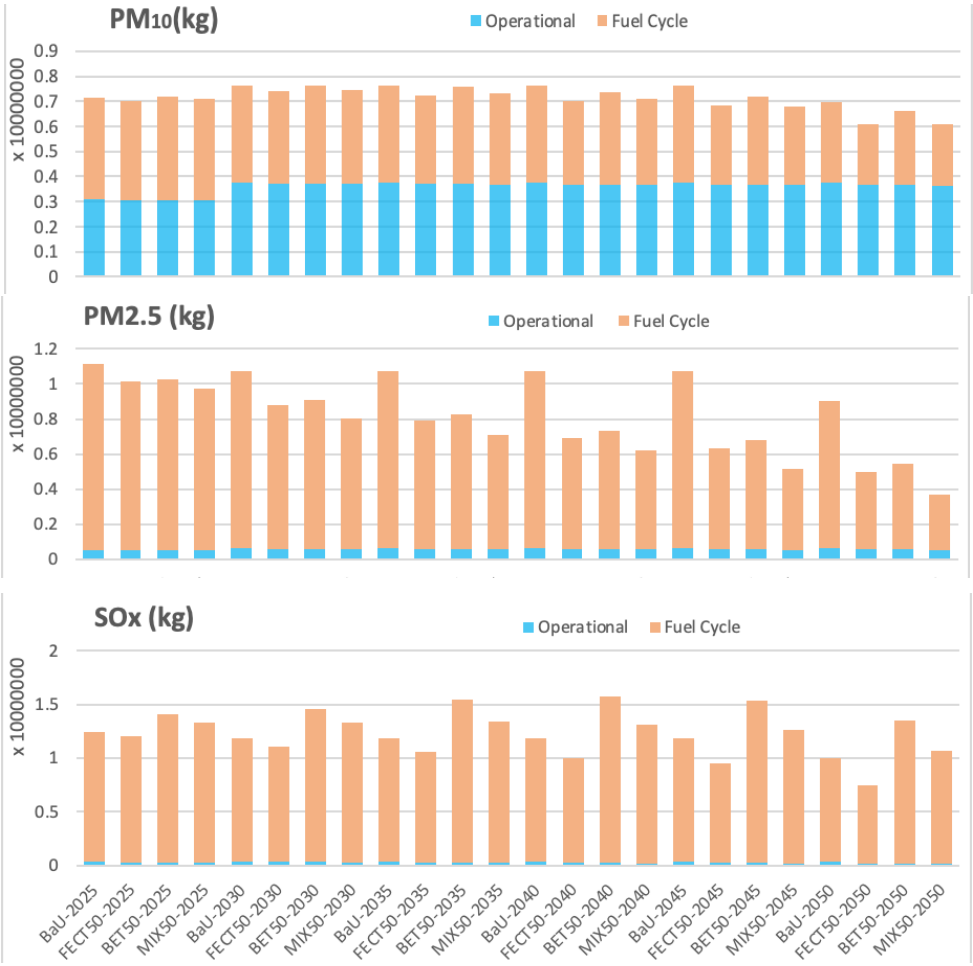
Figure 11 presents the detailed proportions of each air pollutant and GHG in fuel or operational cycle of different scenarios, considering the total emissions

computed in this study. Ozone and CO are primarily emitted during the operational stage, and their proportions do not significantly differ between the BaU scenario and other alternative trucking scenarios. This is because the fuel cycle emissions have minimal impact on the total emissions, indicating that the penetration of renewable energy would not have a significant

influence. On the other hand, NO_x, SO_x, and $PM_{2.5}$ emissions show the opposite pattern. Fuel cycle emissions have a much greater impact than in the operational stage, particularly for SO_x as discussed earlier. While PM_{10} emissions during the operational stage are relatively close to the share of fuel cycle emissions, the proportion of fuel cycle emissions decreases with the increasing penetration of renewable energy resources, resulting in a slight decrease in PM_{10} emissions in the last decade of the study.

Figure 11: Proportions of each air pollutant and GHG in fuel or operational cycle





6.2 Change of Pollutants concentration

The concentration trends of air pollutants are similar to the emissions trends, with a particular focus on Ozone, CO, PM_{10}, $PM_{2.5}$, and NO_x, which are associated with negative and quantifiable health impacts. The concentrations of NOx, Ozone, and CO initially increase until 2030 in the solely implementation of FCETs or BETs. However, the MIX50 scenario exhibits an early reduction in both VOC and CO concentrations by 2030. In subsequent years, the MIX50 scenario consistently demonstrates as the most effective approach in decreasing VOC, CO, $PM_{2.5}$, and NO_x concentrations. Notably, PM_{10} follows a different pattern, aligning with the emission trends discussed earlier. Due to the substantial contribution from the operational stage, specifically tire and brake wear emissions, the reduction in PM_{10} concentration is not solely related to the implementation of ZETs but mostly from the distance travelled.

Consequently, in the FCET50 and MIX50 scenarios, the concentration of PM10 does not decrease until 2035.

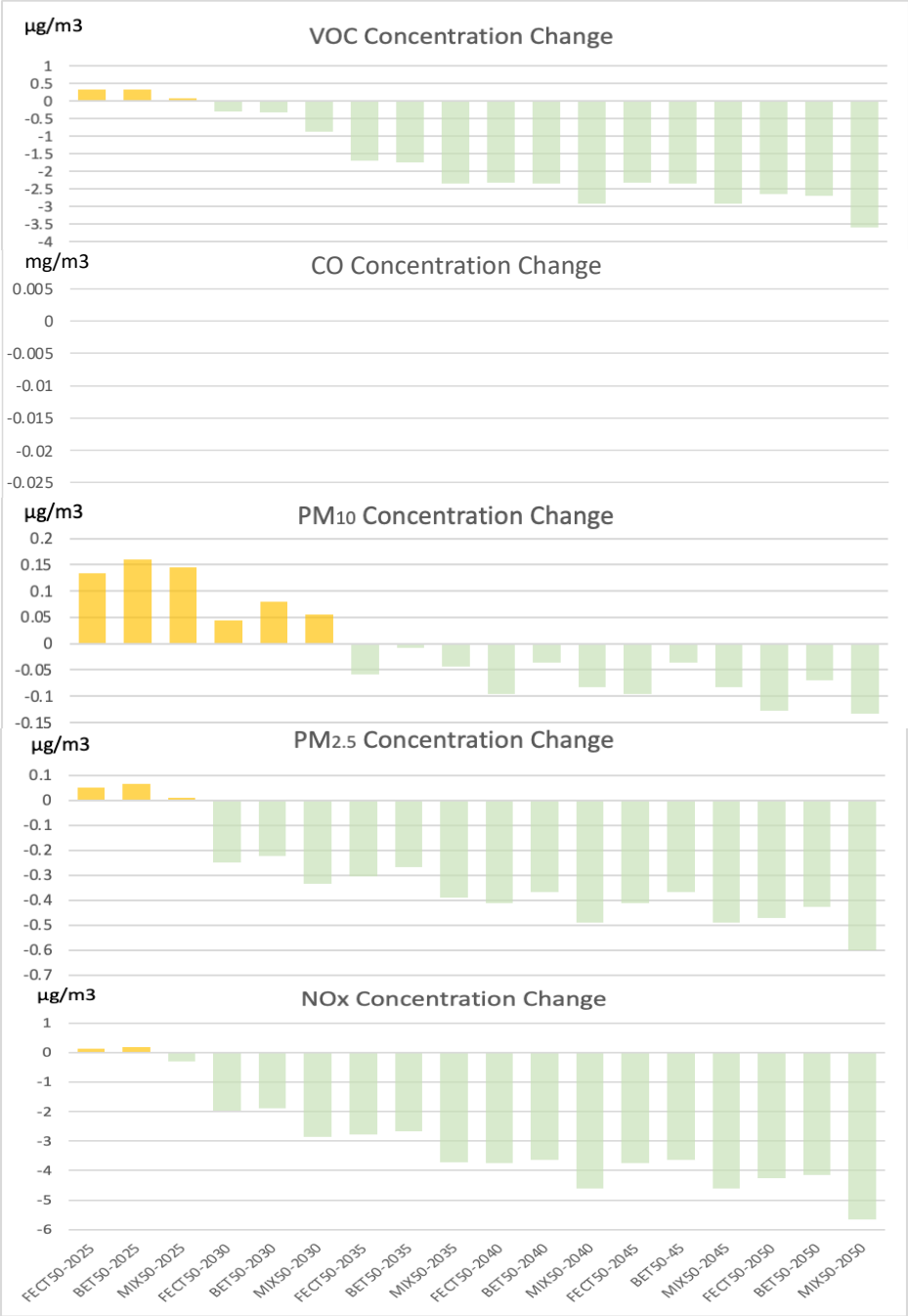


Figure 12: Change of air pollutants concentration

6.3 Infrastructure Investment

Investment of BET scenarios includes the cost of building charging stations and virtual power plant. Investment of FCET scenarios considers the building cost of HRS and pipeline, as well as purchasing cost of tube-trailers for hydrogen delivery. In the MIX50 scenario, all the infrastructure and trucks required for both alternatives are included, but slightly differ in the year of investment due to the implementation process of trucks and demand of fuel. All the lifespan of infrastructure and elements are also taken into account so that the renewal cost is computed in the results.

As outlined in section 5.1, the different scenarios provide varying ranges of reductions for the pollutants considered. At the same time, all of the scenarios involve different physical requirements and levels of costs associated with infrastructure investment, which need to be considered too.

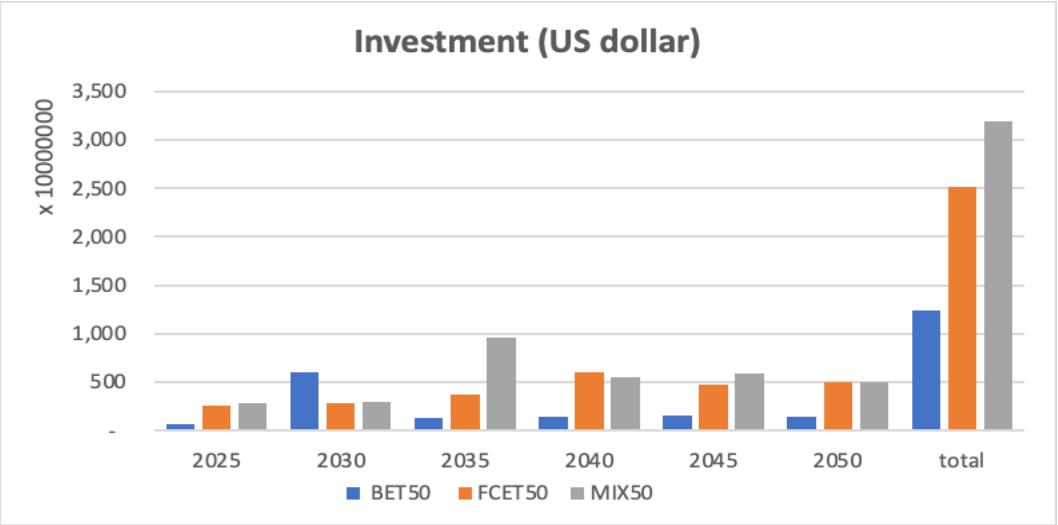
The details of investment in each scenario and particular year are listed in Table 18 and Figure 13.

Table 18: Investment details of each scenario

(US dollar)	Cost of Charging stations					
	BET50			Mix50		
	Over-night Charging	Solar Generation and Storage station	Battery swapping	Over-night Charging	Solar Generation and Storage station	Battery swapping
2025	244,881,753	364,750,747	88,585,758	183,661,315	615,516,885	66,439,318
2030	247,592,393	368,788,237	89,566,329	185,694,295	622,330,150	67,174,747
2035	253,721,556	874,400,106	212,362,543	159,548,955	1,298,929,886	140,207,391
2040	450,903,794	821,638,275	199,548,459	296,825,629	1,148,937,651	124,017,125
2045	177,027,871	1,055,813,406	309,089,107	132,855,157	2,033,555,625	219,503,401
2050	381,751,190	810,563,699	190,070,580	264,249,815	1,223,379,074	132,052,384
Subtotal	1,755,878,557	4,295,954,470	1,089,222,776	1,222,835,166	6,942,649,271	749,394,366
(US dollar)	Cost of Hydrogen Refueling Stations					
	FECT50			MIX50		
	Delivery-500kg	Delivery-100kg	On-site production stations	Delivery-500kg	Delivery-100kg	On-site production stations
2025	1,380,511,897	978,306,617	-	1,035,383,923	733,729,963	-
2030	15,182,104	1,029,796,045	1,645,105,814	11,386,578	772,347,034	1,233,829,360
2035	1,618,772,382	1,533,312,549	623,408,519	1,106,647,577	995,413,351	340,926,534
2040	1,674,832,800	2,409,723,194	1,974,126,976	1,088,090,388	1,565,527,404	1,282,533,151
2045	1,688,890,980	2,122,492,709	974,075,811	1,256,901,716	1,539,635,989	698,087,664
2050	1,407,523,809	1,967,720,222	1,627,541,885	965,082,527	1,362,130,429	1,123,044,723
Subtotal	7,785,713,972	10,041,351,336	6,844,259,004	5,463,492,709	6,968,784,171	4,678,421,432
(US dollar)	Cost of pipeline		Cost of tube-trailers for Hydrogen		Cost of virtural power plant	
	FCET50	MIX50	FCET50	MIX50	BET50	MIX50
2025	-	-	260,777,316	195,582,987	-	-
2030	85,714,286	-	110,948,087	83,211,065	5,285,714,286	-
2035	-	85,714,286	-	192,282,799	-	5,285,714,286
2040	-	-	-	-	-	-
2045	-	-	-	-	-	-
2050	-	-	-	-	-	-
Subtotal	85,714,286	85,714,286	371,725,403	471,076,851	5,285,714,286	5,285,714,286
Scenario	FECT50		BET50		MIX50	
2025	2,619,595,830		698,218,258		2,830,314,391	
2030	2,886,746,335		5,991,661,245		2,975,973,228	
2035	3,775,493,449		1,340,484,205		9,605,385,064	
2040	6,058,682,971		1,472,090,528		5,505,931,349	
2045	4,785,459,500		1,541,930,384		5,880,539,552	
2050	5,002,785,917		1,382,385,468		5,069,938,952	

In total, the MIX50 costs the most among these three alternative trucking scenarios, because in this scenario, every BET cost less than half of the MIX50 scenario, due to the less expensive infrastructure expenditure of charging stations.

Figure 13: Total Investment



6.4 Quantified health impact

6.4.1 Mortality associated with air pollutants

The different scenarios produce varying ranges of reductions for pollutants considered. In each case the it is important to understand the anticipated human health benefits for each. Results are broken down into two major categories: mortality-related, involving reductions in premature deaths; and morbidity-related, involving illness reductions.

In the table presented, it is evident that cardiovascular-related mortality is influenced by all six air pollutants, with the highest number of cases. Among the six pollutants, Ozone and NOx emissions exhibit a significant negative impact on human health. On the bright side, the reduction of these two pollutants also provides promising potential for positive health outcomes, especially when HDTs are a great contributor in NOx and VOC.

The alternative trucking scenarios show favorable results in mitigating pollutant-related fatalities, particularly in the case of cardiovascular disease and lung cancer. Among the scenarios considered, MIX50 stands out as the most effective in reducing mortality rates, regardless of the investment considerations.

It is worth noting that the air quality concern in PRD region has changed from PM caused pollution to ozone-dominated photochemical harm, and vehicular emission was the leading source (Z. He et al., 2019; Yim et al., 2019). Thus, improvement of Ozone could be particularly beneficial for human health in the PRD region.

Table 19: Quantified mortality cases associated with Air pollution

Mortality-Cases		2025				2030				2035				2040				2045				2050			
Pollutant	Health Endpoints	BaU	FECT5	BET50	MIX50	BaU	FECT5	BET50	MIX50	BaU	FECT50	BET50	MIX50	BaU	FECT50	BET50	MIX50	BaU	FECT50	BET50	MIX50	BaU	FECT50	BET50	MIX50
CO	Cardiovascular mortality	76	22	25	-5	110	-22	-18	-86	0	-197	-191	-267	0	-268	-261	-331	0	-306	-296	-406	-14	-349	-334	-474
Ozone		1443	589	571	150	1510	-509	-554	-1547	0	-2990	-3050	-4126	0	-4065	-4141	-5122	0	-4650	-4725	-6285	-332	-5364	-5386	-7375
PM_{10}		36	32	38	35	19	11	19	13	0	-14	-2	-11	0	-23	-9	-20	0	-31	-17	-32	-25	-59	-38	-58
$PM_{2.5}$		33	11	14	2	-10	-52	-47	-70	0	-64	-64	-82	0	-86	-77	-102	0	-99	-89	-126	-38	-129	-119	-158
NO_x		2343	290	373	-672	-213	-4255	-4120	-6159	0	-5985	-5801	-8041	0	-8082	-7869	-9944	0	-9177	-8968	-12141	-2828	-11520	-11289	-14782
CO	COPD Mortality	22	1	1	-1	1	-1	-1	-1	0	-2	-2	-3	0	-3	-3	-4	0	-3	-3	-4	-1	-4	-4	-5
Ozone		372	152	147	39	390	-131	-143	-397	0	-765	-780	-1053	0	-1038	-1057	-1305	0	-1186	-1205	-1598	-86	-1366	-1372	-1871
PM_{10}		203	180	214	194	104	59	108	73	0	-78	-10	-60	0	-128	-49	-110	0	-172	-93	-178	-139	-332	-215	-327
$PM_{2.5}$		80	26	34	5	-24	-127	-114	-169	0	-154	-154	-198	0	-209	-187	-248	0	-239	-216	-305	-92	-313	-288	-384
NO_x		115	15	19	-33	-11	-209	-202	-303	0	-294	-285	-395	0	-397	-387	-490	0	-452	-441	-599	-139	-568	-556	-730
$PM_{2.5}$	Diabetes mortality	41	13	18	3	-12	-65	-58	-86	0	-79	-79	-101	0	-107	-96	-126	0	-122	-110	-156	-47	-160	-147	-195
NO_x		138	17	22	-40	-13	-250	-242	-361	0	-351	-340	-470	0	-473	-460	-581	0	-536	-524	-708	-166	-672	-658	-860
PM_{10}	Lung cancer mortality	38	34	41	37	20	12	21	14	0	-15	-2	-12	0	-24	-10	-21	0	-33	-18	-34	-27	-63	-41	-62
$PM_{2.5}$		28	9	12	2	-8	-44	-40	-59	0	-54	-54	-69	0	-73	-65	-86	0	-83	-75	-106	-32	-108	-100	-133
NO_x		528	65	84	-151	-48	-952	-922	-1376	0	-1337	-1297	-1793	0	-1802	-1755	-2214	0	-2045	-1998	-2697	-634	-2561	-2510	-3276
Ozone	Respiratory mortality	177	72	70	19	185	-63	-68	-189	0	-366	-373	-504	0	-497	-506	-626	0	-568	-578	-768	-41	-656	-658	-901
PM_{10}		9	8	9	9	5	3	5	4	0	-4	-1	-3	0	-6	-3	-5	0	-8	-4	-8	-6	-14	-10	-14
$PM_{2.5}$		12	4	5	1	-4	-19	-17	-25	0	-23	-23	-29	0	-31	-28	-36	0	-35	-32	-45	-14	-46	-42	-56
NO_x		126	16	20	-36	-12	-229	-222	-332	0	-323	-313	-434	0	-436	-425	-537	0	-496	-484	-657	-152	-623	-611	-802

6.4.2 Morbidity associated with air pollutants

With regard to the morbidity related to air pollution, Ozone, PM10, PM2.5, and NOx also has wide-ranging negative impacts on human health, specifically in relation to hospital admission for Cardiovascular disease, Respiratory disease, Cerebrovascular disease, COPD disease, Diabetes type 2 Prevalence, and Asthma attacks.

In China, the prevalence of type 2 diabetes is already high (J. Liu et al., 2023; R. C. W. Ma, 2018), and PM demonstrates significant association with the increased prevalence of this condition. Furthermore, COPD and Cerebrovascular diseases are major causes of hospital admissions, and their occurrence is also influenced by these air pollutants. Consistent with the mortality cases, the MIX50 scenario still presents the most favorable outcomes in reducing the incidence of these diseases.

In addition, along with the associated mortality, Ozone and NOx are also found to have more considerable impact on prevalence of the mentioned diseases. The details of quantified morbidity are listed in Table 20.

Table 20: Quantified morbidity cases associated with Air pollution

Morbidity-Cases		2025				2030				2035				2040				2045				2050			
Pollutant	Health Endpoints	BaU	FECT5	BET50	MIX50	BaU	FECT5	BET50	MIX50	BaU	FECT5	BET50	MIX50	BaU	FECT5	BET50	MIX50	BaU	FECT5	BET50	MIX50	BaU	FECT50	BET50	MIX50
CO	Cardiovascular HD	77	22	25	-5	111	-22	-18	-87	0	-199	-194	-270	0	-271	-264	-335	0	-309	-300	-410	-14	-353	-338	-479
	Respiratory HD	178	51	57	-11	257	-50	-42	-201	0	-459	-447	-623	0	-626	-610	-774	0	-715	-692	-949	-31	-815	-781	-1108
Ozone	Cardiovascular HD	616	252	244	64	644	-218	-237	-662	0	-1280	-1306	-1768	0	-1742	-1774	-2196	0	-1993	-2025	-2697	-142	-2300	-2310	-3167
	Respiratory HD	1767	722	700	183	1849	-624	-679	-1899	0	-3673	-3746	-5072	0	-4997	-5090	-6301	0	-5718	-5811	-7737	-407	-6599	-6627	-9085
	COPD HD	1367	558	542	142	1430	-483	-525	-1470	0	-2846	-2903	-3931	0	-3873	-3946	-4886	0	-4433	-4505	-6002	-315	-5118	-5139	-7050
	Diabetes t2 Prevalence	23606	9629	9341	2439	24706	-8317	-9046	-25294	0	-48866	-49841	-67409	0	-66418	-67653	-83659	0	-75958	-77185	-102623	-5418	-87606	-87969	-120370
	Asthma attack	11620	4741	4599	1201	12161	-4097	-4456	-12464	0	-24091	-24572	-33246	0	-32757	-33366	-41275	0	-37469	-38076	-50652	-2669	-43226	-43406	-59435
PM_{10}	Cardiovascular HD	79	70	83	75	41	23	42	29	0	-30	-4	-24	0	-50	-19	-43	0	-67	-36	-69	-54	-129	-84	-128
	Respiratory HD	106	94	112	101	54	31	56	38	0	-41	-6	-31	0	-67	-26	-58	0	-90	-49	-93	-73	-174	-113	-172
	Cerebrovascular HD	1	1	1	1	1	1	1	1	0	-1	-1	-1	0	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	-1
	COPD HD	237	210	250	226	121	69	126	85	0	-91	-12	-70	0	-149	-57	-129	0	-201	-108	-208	-163	-389	-252	-383
	Diabetes t2 Prevalence	6672	5908	7039	6374	3415	1941	3534	2399	0	-2543	-319	-1958	0	-4193	-1609	-3626	0	-5669	-3046	-5854	-4585	-10958	-7096	-10803
	Asthma attack	240	213	254	230	123	70	128	87	0	-92	-12	-71	0	-151	-58	-131	0	-205	-110	-211	-166	-395	-256	-390
$PM_{2.5}$	Cardiovascular HD	55	18	23	3	-16	-87	-78	-115	0	-105	-105	-135	0	-143	-128	-169	0	-163	-148	-209	-63	-214	-197	-262
	Respiratory HD	35	11	15	2	-10	-55	-50	-73	0	-67	-67	-86	0	-91	-81	-108	0	-104	-94	-133	-40	-136	-125	-167
	Cerebrovascular HD	1	1	1	1	-1	-1	-1	-1	0	-1	-1	-1	0	-1	-1	-2	0	-2	-2	-2	-1	-2	-2	-2
	COPD HD	2148	685	900	116	-622	-3409	-3054	-4535	0	-4146	-4146	-5332	0	-5631	-5039	-6666	0	-6428	-5817	-8222	-2473	-8429	-7757	-10336
	DiabetesT2 Prevalence	5599	1786	2347	301	-1620	-8887	-7961	-11822	0	-10808	-10808	-13902	0	-14680	-13136	-17379	0	-16758	-15165	-21435	-6448	-21975	-20225	-26949
	Asthma attack	1096	350	460	59	-318	-1741	-1559	-2316	0	-2117	-2117	-2724	0	-2876	-2574	-3406	0	-3284	-2971	-4202	-1263	-4308	-3964	-5284
NO_x	Cardiovascular HD	532	66	85	-153	-49	-973	-942	-1411	0	-1371	-1329	-1846	0	-1855	-1806	-2287	0	-2109	-2060	-2798	-646	-2653	-2599	-3416
	Respiratory HD	2115	262	337	-608	-193	-3862	-3739	-5599	0	-5440	-5272	-7321	0	-7358	-7164	-9068	0	-8363	-8170	-11091	-2564	-10518	-10306	-13534
	COPD HD	796	99	127	-229	-73	-1457	-1411	-2114	0	-2054	-1990	-2766	0	-2780	-2706	-3428	0	-3161	-3088	-4197	-967	-3979	-3898	-5126
	DiabetesT2 Prevalence	15838	1958	2522	-4547	-1443	-28880	-27961	-41857	0	-40670	-39416	-54711	0	-54991	-53538	-67742	0	-62488	-61051	-82825	-19177	-78554	-76970	-101011
	Asthma attack	10079	1246	1605	-2894	-918	-18379	-17794	-26637	0	-25881	-25083	-34816	0	-34994	-34070	-43109	0	-39766	-38851	-52707	-12204	-49989	-48981	-64280

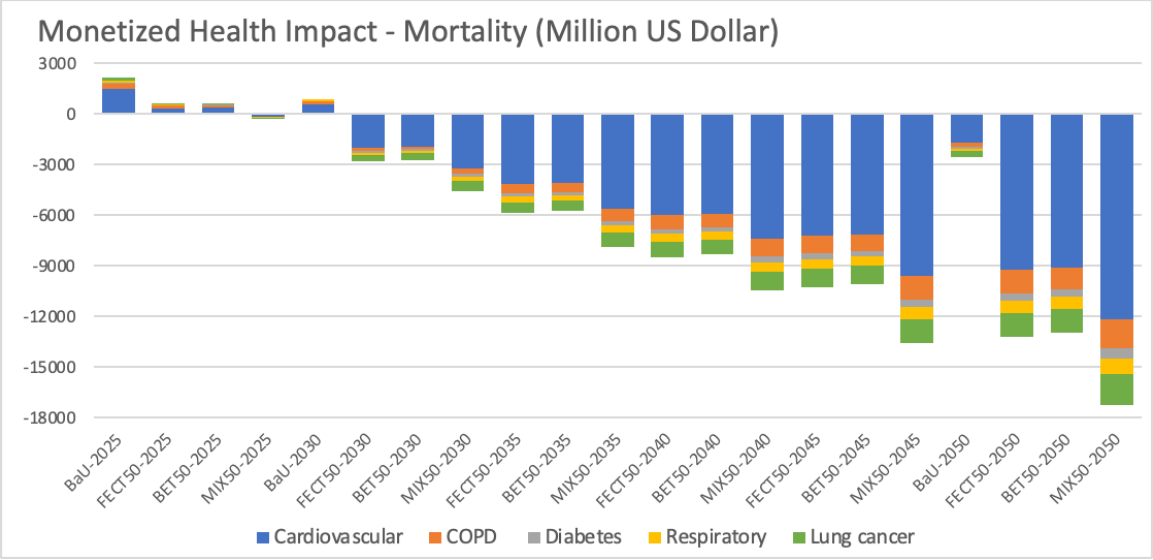
6.5 Monetized health impact

With health improvements as characterized in the last section, it important to further monetize health benefits in order to more comprehensively understand the extent of overall benefits for all of the scenarios, this given that reductions in certain pollutant produce higher cost savings than others. Results are again broken down into two major categories: mortality-related benefits, associated with reductions in premature deaths; and morbidity-related benefits, associated with reductions in illnesses.

6.5.1 Monetized Mortality impact

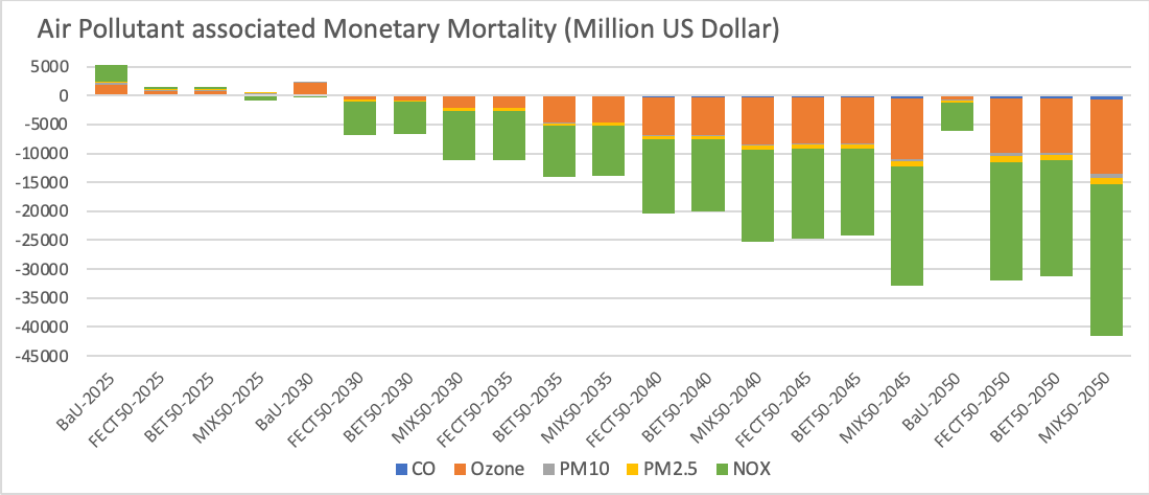
In accordance with the previous discussion, the Value of Statistical Life (VSL) is utilized in this study to assess the economic impacts resulting from premature mortality related to air pollution. Figure 14 illustrates the monetized health impact, specifically focusing on mortality rates. Since cardiovascular disease exhibits significantly higher prevalence compared to other diseases associated with air pollutants, the economic results mirror this trend, with estimates reaching up to 12 billion US dollars in the MIX50 scenario by the year of 2050. Considering the rapidly aging population in China(Gu et al., 2021; Han et al., 2020), it is anticipated that cardiovascular disease will continue to contribute to even greater economic losses in the coming years beyond 2050.

Figure 14: Monetized health impact-Mortality



From the perspective of each air pollutant related monetary loss/benefit, NO_x and Ozone accounts for more than 90% of the total economic loss in every scenarios of this study. Figure 15 shows the results of monetary implications related to all five air pollutants.

Figure 15: Air pollutant associated with particular monetized mortality



6.5.2 Monetized Morbidity impact

Regarding to the morbidity associated with air pollution, as discussed in previous section, the COI method is utilized to assess the economic impacts resulting from the cost of treatment, days of hospitalization or work loss. Unlike premature associated with air pollution, chronic diseases seem to show a different pattern in economic impact. Diabetes prevalence is high in baseline incidence rate and exposure-response coefficients, which make it to be the major contributor to the monetary morbidity impact. MIX50 scenario keeps its leading role of reduction in economic impact. FECT50 scenario performs slightly better than BET50. However, narrowing the gap between investment and benefits between two scenarios appears to be still challenging.

Figure 16: Monetized health impact-Morbidity

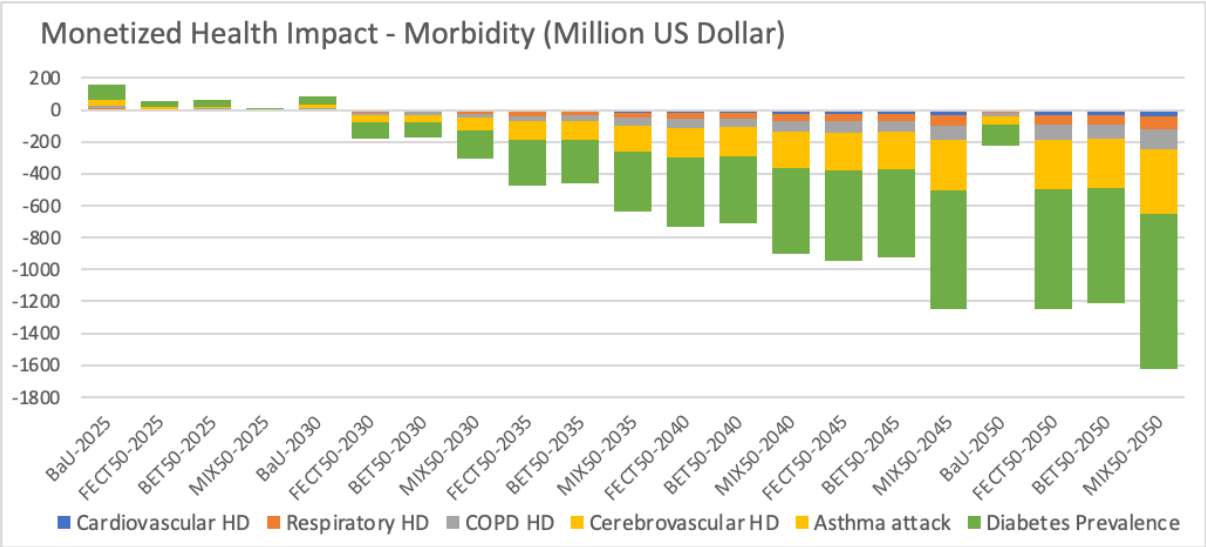


Figure 17 illustrates the breakdown of the combined monetary health impacts resulting from mortality and morbidity in various scenarios until 2050. Among these scenarios, NOx emissions reduction contributes significantly to the alleviated economic loss, or in other words, increased social welfare, in the form of VSL, medical expenditures, and per capita GDP. Ozone emissions rank second in terms of their contribution.

However, it is important to note that PM_{10} and $PM_{2.5}$ emissions do not exhibit the presumed potential for reducing economic losses, at least in the heavy-duty trucking scenarios. This is primarily due to the composition of air pollutant emissions, where operational emissions from tire and brake wear contribute significantly to PM_{10} levels, overshadowing the positive impact of reduced emissions from the fuel cycle. Introduction of renewable energy sources in alternative trucking scenarios does not change the operational emission-dominant pattern. Additionally, $PM_{2.5}$ emissions account for a minor portion of the overall economic impact. This is mainly because the reduction of $PM_{2.5}$ achieved through the adoption of alternative trucks only represents a small proportion of total air pollution. In other words, achieving more efficient alleviation of $PM_{2.5}$ would require reductions in other industries such as construction and industrial sectors.

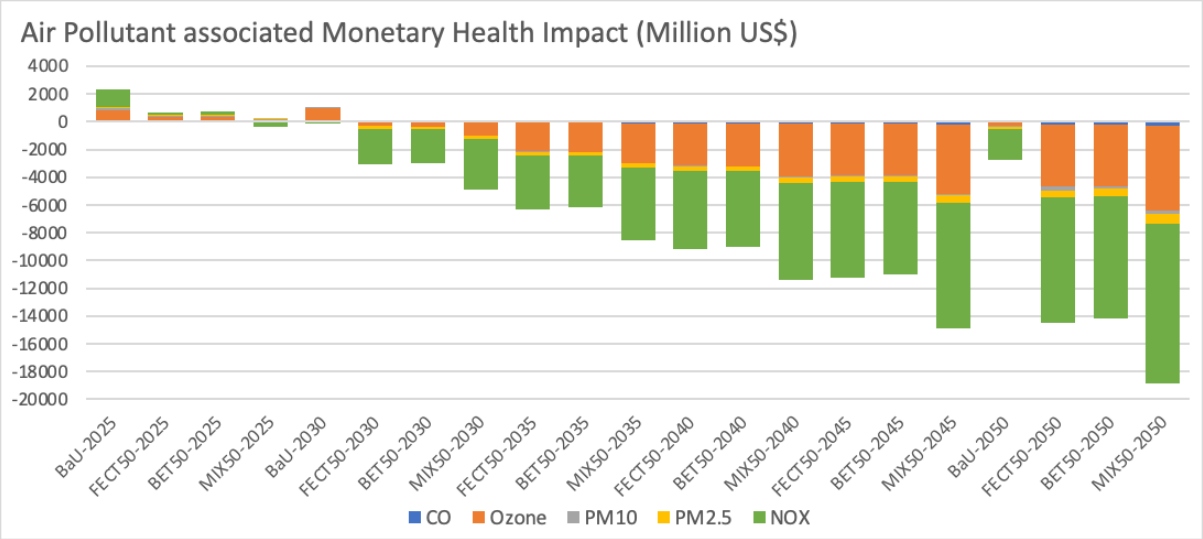


Figure 17: Total monetary health impact

6.6 Comparison of each scenarios

Analyses in the earlier sections regarding monetized health benefits, and infrastructure and other costs, finally allow a comparison of overall benefits and costs for each separate scenario. Briefly, all of the scenarios involve higher costs than the "business as usual" to start, whether or not carbon-taxes are applied, but begin within ten years (by 2035 or so) showing some positive benefits. The BET50 scenario clearly shows the best economic performance. Without carbon-taxes, all of the scenarios end up overall to have negative values, but with BET50 only a very small negative value. With carbon-taxes, BET50 show overall positive results, while the other scenarios are all still negative. Details of results are presented below.

When evaluating the cost and benefit of implementing alternative trucking scenarios over every five-year interval, the cumulative number of attributable cases of premature death or disease were computed in five-year time frame. Therefore, when comparing with the investment made over a specific five-year period, the monetary benefits should be attributed to the beginning of the subsequent five-year interval, while the investment was computed within the present period. Net present value (NPV) is a widely utilized indicator to assess whether an investment is worthwhile. It represents the difference between the present value of future capital

inflows (monetary benefits in this study) and the present value of future capital outflows (continuous investment).

The following Equation (7) depicts the calculation process for NPV:

$$NPV = \sum_{t=1}^{n} (C_b - C_o)_t \, (1 + d)^{-t} \tag{7}$$

Where, C_b represents the monetary benefit in the year t, C_o denotes the value of the investment amount, also in the year t, d stands for the discount rate, which is set at 8% in this study.

Table 21 presents the results from analyzing the investment and economic outcomes derived in this study. The findings indicate that only the BET50 scenario gets close to breaking even by the end of 2050. While the MIX50 scenario achieves the most favorable outcomes in terms of emission reduction, prevention of premature death and attributable cases, the considerable investment required for both BET and FCET infrastructures results in a loss of 4,322 million US dollars. However, as discussed above, due to the mismatch in the timing of investments and benefits, the NPV method emphasized the near-term benefit/loss, even though the long-term economic benefit is huge, it is still not as cost-efficiency as we expected.

If we consider the benefits for the next five years, which have also been factored into the investment at the beginning of 2050, the BET50 scenario yields a positive benefit of 1,275 million US dollars. Additionally, the other two alternative trucking scenarios help narrowing down the gap between costs and benefits. If exploring the future trends, benefit is expected to increase while cost is going down. Benefits will rise with the growth of GDP and the projected value of life, while the cost of infrastructure will decrease as the economy scales up and standardized production becomes more prevalent.

Taking a long-term perspective, the short-term losses can be attributed to the high initial investment, with monetary benefits realized in the middle or later stages of alternative trucking implementation.

Table 21: Comparison of Investment and Benefit without cost of carbon

NPV (Million US$)	BaU	FCET50	BET50	MIX50
2025	-	(2,426)	(646)	(3,017)
2030	(1,473)	(2,221)	(4,219)	(2,102)
2035	(390)	(331)	669	(2,154)
2040	-	79	1,379	680
2045	-	880	1,486	1,030
2050	-	839	1,300	1,241
Total	(1,864)	(3,179)	(30)	(4,322)
Considering the benefit from 2050 interval	(1608)	(1846)	1275	(2584)

However, if taking carbon price into account, the results of the cost and benefit analysis may increase the benefit. In China, there are eight carbon trading markets, and Guangdong is one of them. The average carbon trading price in Guangdong carbon market was CNY 76.53 (USD 11.35)/ton CO_2 in 2022(ICAP, 2023). There are various approaches to predict the carbon price, if applying the predicted carbon price in (Qi et al., 2022)'s study, which was based on a multi-scale integrated model, the comparison of investment and benefit could be changed as in Table 22.

Table 22:Comparison of Investment and Benefit considering cost of carbon

NPV (Million US$)	BaU	FCET50	BET50	MIX50
2025	-	(2,620)	(698)	(3,259)
2030	(1,473)	(2,174)	(4,187)	(2,043)
2035	(390)	(219)	756	(2,005)
2040	-	242	1,509	881
2045	-	1,105	1,672	1,286
2050	-	1,114	1,539	1,586

Total	(1,864)	2,550	590	(3,554)
0Considering the benefit from 2050 interval	(1,565)	(899)	1,258	(1,387)

7. Conclusion

7.1 Summary of Main Findings

To analyze the economic feasibility in a particular area, in this study, a range of scenarios were considered involving application of zero-emission technologies for transport trucks involved in supply-chains in the PRD area of China. In accordance with the current technology and market, two major options available are battery electric trucks and fuel cell electric trucks, with various combinations of vehicle types considered in different scenarios. In order to gain a comprehensive idea of cost and benefit comparison of alternative trucking, health and environmental benefits are considered compared to infrastructure and other costs for each separate scenario, in the form of net-present value analyses.

The results show that to start, all of the zero-emission scenarios have net higher net costs. This is not necessarily surprising, given the still relative new nature of the technologies involved. Over time, different scenarios begin to show some positive benefits, i.e., starting by about 2035, with results calculated out to 2050. Overall when carbon-taxes are not considered, all of the scenarios out to 2050 show overall negative results, although with the BET50 scenario only showing a small negative result. If carbon-taxes are applied, the economics shift and BET50 shows a reasonable positive value considering out to 2050, while other scenarios still show net negative values.

The BET50 scenario involves 50% of all trucks assumed to be BET. The results suggest that within the PRD area of China, battery-electric technology appears to show the best opportunity of achieving overall positive benefits compared to fuel-cell electric technology.

7.2 Limitation and implications

This study has several limitations. First, the benefit of mitigation in climate change is underestimated in this study. In China, healthcare is generally regarded a more important and straightforward issue to deal with(Economist, 2008). From the study of(Thurber, 2011), air pollution is a more urgent situation than climate change in some developing countries, especially for China, which has experience dramatically development and severe air pollution in the past three decades. Although climate change and air pollution are closely interlinked, quantifying the economic impact of climate change is beyond the capability and scope of this paper. The impact of climate change could start from agriculture, forestry, sea levels, fishery, biodiversity, to mental health and physical health (Cianconi et al., 2020; Haines et al., 2006; Kirilenko & Sedjo, 2007; McNutt, 2013; Tol, 2018). Therefore, for the future analysis regarding the benefit of alternative trucking, the aspect of climate change and associated economic impact could be dig deeper. Secondly, it is important to acknowledge that the limitations of this study also stem from the inherent unpredictability of technological advancements and economic projections. There exists the possibility of significant breakthroughs in hydrogen storage or battery capacity occurring in the future, which are the two barriers in application of zero-emission trucking. Similarly, unanticipated economic fluctuations such as unforeseen events like the pandemic, could also potentially influence the outcomes of our research. While we have endeavored to account for and mitigate these uncertainties through horizontal scenario comparisons, it is important to recognize that unforeseen changes may still arise.

It is widely expected zero emission trucking can solve the air pollution problems and achieve decarbonization in a short time. However, as discussed in the text, investment and implementation of alternative trucking is a long-term project, even in BET50 scenario with the relatively mature infrastructure and public awareness and acceptance to battery vehicle, it is still not as profitable as we expected. However, based on the research findings, it is still recommended that public sectors prioritize the adoption of battery electric heavy-duty trucks as a preferable alternative for freight transportation in the PRD region. This recommendation is

based on several key factors: China's mature infrastructure and foundation of charging stations, widespread public acceptance of battery vehicles, stable and favorable weather conditions conducive to battery truck operation, and the relatively low investment required. Moreover, a robust power generation infrastructure and existing plans for renewable resource utilization in PRD region makes battery electric heavy-duty trucks a relatively easy choice. By adopting battery trucks, policy makers can simultaneously address economic, environmental, and infrastructural considerations, aligning with China's broader carbon-neutral objectives in 2060.

Reference list

Adam, M. G., Tran, P. T. M., & Balasubramanian, R. (2021). Air quality changes in cities during the COVID-19 lockdown: A critical review. *Atmospheric Research Journal*, *January*.

Adu-Gyamfi, G., Song, H., Obuobi, B., Nketiah, E., Wang, H., & Cudjoe, D. (2022). Who will adopt? Investigating the adoption intention for battery swap technology for electric vehicles. *Renewable and Sustainable Energy Reviews*, *156*(December 2021), 111979. https://doi.org/10.1016/j.rser.2021.111979

Al-Thani, H., Al-Ghamdi, S., Koc, M., & Isaifan, R. J. (2020). Emissions and fuel life cycle assessment of non-passenger diesel vehicles in qatar. *Pollution*, *6*(4), 705–723. https://doi.org/10.22059/poll.2020.300625.778

ANL. (2021). Summary of Expansions and Updates in GREET 2021. *Energy Systems Division*, *October 2021*, 5–7. https://greet.es.anl.gov/index.php?content=download2x

Apostolou, D., & Xydis, G. (2019). A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. *Renewable and Sustainable Energy Reviews*, *113*(July), 109292. https://doi.org/10.1016/j.rser.2019.109292

Aunan, K., & Pan, X. C. (2004). Exposure-response functions for health effects of ambient air pollution applicable for China - A meta-analysis. *Science of the Total Environment*, *329*(1–3), 3–16. https://doi.org/10.1016/j.scitotenv.2004.03.008

Aziz, M. (2021). *Liquid Hydrogen: A Review on Liquefaction, Storage, Transportation, and Safety*.

Bai, F., Zhao, F., Liu, X., Mu, Z., Hao, H., & Liu, Z. (2023). A techno-economic analysis of cross-regional renewable hydrogen supply routes in China. *International Journal of Hydrogen Energy*, *xxxx*. https://doi.org/10.1016/j.ijhydene.2023.06.048

Basma, H., & Rodríguez, F. (2021). *Race to zero: How manufacturers are positioned for zero-emission commercial trucks and buses in Europe*. *December*. https://theicct.org/publication/race-to-zero-ze-hdv-eu-dec21/

Bekel, K., & Pauliuk, S. (2019). Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany. *International Journal of Life Cycle Assessment*, *24*(12), 2220–2237. https://doi.org/10.1007/s11367-019-01640-8

Bernard, M. R., Tankou, A., Cui, H., & Ragon, P. (2022). Charging Solutions for Battery-Electric Trucks. *International Council on Clean Transportation*, *December*.

Bhuiyan, E. A., Hossain, M. Z., Muyeen, S. M., Fahim, S. R., Sarker, S. K., & Das, S. K. (2021). Towards next generation virtual power plant: Technology review and frameworks. *Renewable and Sustainable Energy Reviews*, *150*(January), 111358. https://doi.org/10.1016/j.rser.2021.111358

Bian, Y., Huang, Z., Ou, J., Zhong, Z., Xu, Y., Zhang, Z., Xiao, X., Ye, X., Wu, Y., Yin, X., Li, C., Chen, L., Shao, M., & Zheng, J. (2019). Evolution of anthropogenic air pollutant emissions in Guangdong Province, China, from 2006 to 2015. *Atmospheric Chemistry and Physics*, *19*(18), 11701–11719. https://doi.org/10.5194/acp-19-11701-2019

Bollen, J., & Brink, C. (2014). Air pollution policy in Europe: Quantifying the interaction with greenhouse gases and climate change policies. *Energy Economics*, *46*(2014), 202–215. https://doi.org/10.1016/j.eneco.2014.08.028

Brewer, K., Egyed, M., Huang, L., Ling, B., Matz, C., & Rouleau, M. (2016). *Human Health Risk Assessment for Diesel Exhaust*.

Brooker, A., Birky, A., Reznicek, E., Gonder, J., Hunter, C., Lustbader, J., Zhang, C., Sittler, L., Yip, A., Yang, F., Lee, D., Brooker, A., Birky, A., Reznicek, E., Gonder, J., Hunter, C., Lustbader, J., Zhang, C., Sittler, L., … Lee, D. (2021). *Vehicle Technologies and Hydrogen and Fuel Cell Technologies Research and Development Programs Benefits Assessment Report for 2020 Vehicle Technologies and Hydrogen and Fuel Cell Technologies Research and Development Programs Benefits Assessment Report fo*. *August*. https://www.nrel.gov/docs/fy21osti/79617.pdf

Brotherton, T., Gilde, A., & Tomic, J. (2016). 2015 e-truck task force: Key barriers affecting e-truck adoption, industry and policy implications, and recommendations to move the market forward. *World Electric Vehicle Journal*, *8*(3), 651–659. https://doi.org/10.3390/wevj8030657

CATARC. (2021). *Seminar on Measuring the Total Cost of Ownership of Commercial Vehicles*. China Automotive Technology and Research Center. http://www.catarc.info/news/11350.cshtml

CATL Energy. (2023). *QIJI Energy Heavy-duty Truck Battery Swapping Solution Launch*. https://www.catl.com/en/news/6041.html

CATRC. (2017). *China Freight System Assessment and Report*.

CATRC, E. F. (2020). *Research and Policy Suggestions on Roadmap of Infrastructure Construction to Support Hainan's 2030 New Energy Vehicle Development Goal*. https://www.efchina.org/Reports-en/report-ctp-20201103-2-en

Chai, S., Zhang, G., Li, G., & Zhang, Y. (2021). Industrial hydrogen production technology and development status in China: a review. *Clean Technologies and Environmental Policy*, *23*(7), 1931–1946. https://doi.org/10.1007/s10098-021-02089-w

Chen, S. (2018). Evaluation of Health Loss Caused by Haze Pollution in Beijing: Historical Changes and Current Situation. *Chinese Journal of Urban and Environmental Studies*, *6*(4), 1–15. https://doi.org/10.1142/S2345748118500276

Chen, Y. L., Shih, Y. H., Tseng, C. H., Kang, S. Y., & Wang, H. C. (2013). Economic and health benefits of the co-reduction of air pollutants and greenhouse gases. *Mitigation and Adaptation Strategies for Global Change*, *18*(8), 1125–1139. https://doi.org/10.1007/s11027-012-9413-3

Cheng, T.-P. (2010). *The Power of Experience Hydrogen Delivery Infrastructure Options Analysis: Final Report*. https://www.energy.gov/sites/prod/files/2014/03/f11/delivery_infrastructure_analysis.pdf

Chestnut, L. G., & Civita, P. De. (2009). Economic Valuation of Mortality Risk Reduction : Review and Recommendations for Policy and Regulatory Analysis. In *Policy* (Issue March).

China Hydrogen Alliance. (2019). *China Hydrogen and Fuel Cell Industry White Paper*. http://www.zg-kg.com/files/《中国氢能源及燃料电池产业白皮书》.pdf

China Ministry of Transport. (2022). *Statistical Bulletin on Transportation Sector Development*. https://xxgk.mot.gov.cn/2020/jigou/zhghs/202306/t20230615_3847023.html

China National HDT Group Jinan Haworth Co. (2020). *Jinan Bus Company Hydrogen Station Construction Project Bidding Documents*. https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjonv_4iJuAAxWdjokEHWtJDjE4ChAWegQIDRAB&url=http%3A%2F%2Fcnhtc.net%2Fueditor1%2Fnet%2Fupload%2F2020-09-04%2F5ff48424-20e5-4d5e-aadd-5f9c592d36e5.docx&usg=AOvVaw2lvL

Chiu, B. K., Lei, Y., Zhang, Y., & Chen, D. (2020). *Breathing Better: Linking Energy and GHG Reduction to Health Benefits in China*. 117–134.

Cianconi, P., Betrò, S., & Janiri, L. (2020). The Impact of Climate Change on Mental Health: A Systematic Descriptive Review. *Frontiers in Psychiatry*, *11*(March), 1–15. https://doi.org/10.3389/fpsyt.2020.00074

Contreras, J., Colligs, V., Hansen, S. P., Imbri, D., Seo, E. J., Kadioglu, O., Efferth, T., Opatz, T., Olowu, T. O., Sundararajan, A., Moghaddami, M., Sarwat, A. I., Unigwe, O., Okekunle, D., Kiprakis, A., Latif, A., Gawlik, W., & Palensky, P. P. (2014). HEALTH AND CLIMATE INCENTIVES FOR THE DEPLOYMENT OF CLEANER ON-ROAD VEHICLE TECHNOLOGIES. *CIRED - Open Access Proceedings Journal*, *2017*(July), 1–67. http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/RSA Distribution Tariff Code Vers 6.pdf%0Ahttp://www.nersa.org.za/

Cui, P., Huang, Y., Han, J., Song, F., & Chen, K. (2015). Ambient particulate matter and lung cancer incidence and mortality: A meta-analysis of prospective studies. *European Journal of Public Health*, *25*(2), 324–329. https://doi.org/10.1093/eurpub/cku145

Cunanan, C., Tran, M. K., Lee, Y., Kwok, S., Leung, V., & Fowler, M. (2021). A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. *Clean Technologies*, *3*(2), 474–489. https://doi.org/10.3390/cleantechnol3020028

Da Silva, G. D. P. (2017). Utilisation of the System Advisor Model to Estimate Electricity Generation by Grid-Connected Photovoltaic Projects in all Regions of Brazil. *International Journal of Software Engineering and Its Applications*, *11*(7), 1–12. https://doi.org/10.14257/ijseia.2017.11.7.01

Dagdougui, H. (2012). Models, methods and approaches for the planning and design of the future hydrogen supply chain. *International Journal of Hydrogen Energy*, *37*(6), 5318–5327. https://doi.org/10.1016/j.ijhydene.2011.08.041

Das, H. S., Rahman, M. M., Li, S., & Tan, C. W. (2020). Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. *Renewable and Sustainable Energy Reviews*, *120*(November 2019). https://doi.org/10.1016/j.rser.2019.109618

Demir, M. E., & Dincer, I. (2018). Cost assessment and evaluation of various hydrogen delivery scenarios. *International Journal of Hydrogen Energy*, *43*(22), 10420–10430. https://doi.org/10.1016/j.ijhydene.2017.08.002

Deng, J., Bae, C., Denlinger, A., & Miller, T. (2020). Electric Vehicles Batteries: Requirements and Challenges. *Joule*, *4*(3), 511–515. https://doi.org/10.1016/j.joule.2020.01.013

DWards, R., Mahieu, V., Griesemann, J.-C., Larive, J.-F., & Rickeard, D. J. (2014). Well-to-wheels analysis of future automotive fuels and powertrains in the European context. *Journal of Fuels*, *113 (4)*(and lubricants), 1072–1084.

Economist. (2008). Just Good Business. *Economist*, *386*(8563), 3–6. http://search.ebscohost.com/login.aspx?direct=true%7B&%7Ddb=aph%7B&%7DAN=28548161%7B&%7Dsite=ehost-live

El Hannach, M., Ahmadi, P., Guzman, L., Pickup, S., & Kjeang, E. (2019). Life cycle assessment of hydrogen and diesel dual-fuel class 8 heavy duty trucks. *International Journal of Hydrogen Energy*, *44*(16), 8575–8584. https://doi.org/10.1016/j.ijhydene.2019.02.027

Energy Bureau of Guangdong Province. (2021). *14th Five-year plan for renewable energy development*.

Energy Foundation China. (2022). *Implementation Plan and Comprehensive Benefit Evaluation of Electric Promotion and Application of Heavy Truck Sector in Shenzhen City*. https://www.efchina.org/Attachments/Report/report-ctp-20220801-2/深圳市重型货车电动化推广应用实施方案及综合效益评估.pdf

Energy Research Institute of the National Development and Reform Commission. (2015). *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study*. https://www.efchina.org/Attachments/Report/report-20150420/中国2050高比例可再生能源发展情景暨途径研究-摘要报告.pdf

EPD Hong Kong. (2011). *Study on Volatile Organic Compounds and Photochemical Ozone Pollution in the Pearl River Delta Region*. https://www.nutechinst.com/study-of-voc-and-photochemical-ozone-pollution-in-the-pearl-river-delta-region/

Foshan Pan Yue Hydrogen Energy Technology Co. (n.d.). *Hydrogen Transportation Demonstration and Operation Service Project for Xianhu Hydrogen Valley Special Town-Bidding document*. http://www.nanhai.gov.cn/attachment/0/241/241896/5177018.pdf

Galus, M. D., Wietor, F., & Andersson, G. (2012). Incorporating valley filling and peak shaving in a utility function based management of an electric vehicle aggregator. *IEEE PES Innovative Smart Grid Technologies Conference Europe*, 1–8. https://doi.org/10.1109/ISGTEurope.2012.6465894

GCL Energy Technology. (2022). *Feasibility Analysis Report of New Energy Vehicle Exchange Station Construction Project*. https://pdf.dfcfw.com/pdf/H2_AN202208151577239050_1.pdf

Goodall, N. J., & Robartes, E. (2023). Feasibility of Battery Electric Pickup Trucks in a State Department of Transportation Fleet. *Transportation Research Record*, 03611981231172501. https://doi.org/10.1177/03611981231172501

Greene, D. L., Ogden, J. M., & Lin, Z. (2020). Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. *ETransportation*, *6*. https://doi.org/10.1016/j.etran.2020.100086

Gu, D., Andreev, K., & Dupre, M. E. (2021). Major Trends in Population Growth Around the World. *China CDC Weekly*, *3*(28), 604–613. https://doi.org/10.46234/ccdcw2021.160

Guangdong Provincial Bureau of Energy. (2023). *Implementation Program for Promoting High-Quality Development of Energy in Guangdong Province*.

Guangdong Provincial Bureau of Statistics. (2020). *Guangdong Statistical Yearbook 2020*. https://doi.org/http://stats.gd.gov.cn/gdtjnj/content/post_3098041.html

Guangdong Provincial Bureau of Statistics. (2021). *Guangdong Statistical Yearbook 2021*. http://stats.gd.gov.cn/gdtjnj/

Guangdong Provincial Bureau of Statistics. (2023). *Guangdong Statistical Yearbook 2022*. http://tjnj.gdstats.gov.cn:8080/tjnj/2022/

Guangdong Provincial development and reform commision. (n.d.). *Action Plan for Accelerating the Construction of Fuel Cell Vehicle Demonstration City Clusters in Guangdong Province (2022-2025)*.

Guangdong Provincial development and reform commision. (2022a). *Action Plan for Accelerating the Construction of Fuel Cell Vehicle Demonstration Cities in Guangdong Province (2022-2025)*. http://drc.gd.gov.cn/ywtz/content/post_3993253.html

Guangdong Provincial development and reform commision. (2022b). *Key construction projects in Guangdong Province 2023*. http://drc.gd.gov.cn/attachment/0/516/516342/4137130.pdf

Guangzhou Development and Reform Commission. (2020). *Guangzhou Hydrogen Energy Industry Development Plan(2019—2030)*.

Gunawan, T. A., & Monaghan, R. F. D. (2022). Techno-econo-environmental comparisons of zero- and low-emission heavy-duty trucks. *Applied Energy*, *308*(November 2021), 118327. https://doi.org/10.1016/j.apenergy.2021.118327

Haines, A., Kovats, R. S., Campbell-Lendrum, D., & Corvalan, C. (2006). Climate change and human health: Impacts, vulnerability and public health. *Public Health*, *120*(7), 585–596. https://doi.org/10.1016/j.puhe.2006.01.002

Han, Y., He, Y., Lyu, J., Yu, C., Bian, M., & Lee, L. (2020). Aging in China: perspectives on public health. *Global Health Journal*, *4*(1), 11–17. https://doi.org/10.1016/j.glohj.2020.01.002

Hangzhou Bus Station Co. (2023). *Tender Notice for Hydrogen refueling Station Project*. https://www.yuhang.gov.cn/art/2023/3/4/art_1229374049_59037910.html

He, C., & Yang, L. (2011). Urban Development and Climate Change in China's Pearl River Delta. *Land Lines*, *July 2011*, 2–7. https://www.lincolninst.edu/publications/articles/urban-development-climate-change-chinas-pearl-river-delta

He, G., & Kammen, D. M. (2016). Where, when and how much solar is available? A provincial-scale solar resource assessment for China. *Renewable Energy*, *85*, 74–82. https://doi.org/10.1016/j.renene.2015.06.027

He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., & Phadke, A. (2020). Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. *Nature Communications*, *11*(1), 1–9. https://doi.org/10.1038/s41467-020-16184-x

He, X., Wang, F., Wallington, T. J., Shen, W., Melaina, M. W., Kim, H. C., De Kleine, R., Lin, T., Zhang, S., Keoleian, G. A., Lu, X., & Wu, Y. (2021). Well-to-wheels emissions, costs, and feedstock potentials for light-duty hydrogen fuel cell vehicles in China in 2017 and 2030. *Renewable and Sustainable Energy Reviews*, *137*(January 2020). https://doi.org/10.1016/j.rser.2020.110477

He, Z., Wang, X., Ling, Z., Zhao, J., Guo, H., Shao, M., & Wang, Z. (2019). Contributions of different anthropogenic volatile organic compound sources to ozone formation at a receptor site in the Pearl River Delta region and its policy implications. *Atmospheric Chemistry and Physics*, *19*(13), 8801–8816. https://doi.org/10.5194/acp-19-8801-2019

Holland Innovation Network. (2019). Overview of hydrogen and fuel cell developments in China. *Kingdom of the Netherlands*, *January*.

Hountalas, D., & Mavropoulos, G. (2010). Potential for Improving HD Diesel Truck Engine Fuel Consumption Using Exhaust Heat Recovery Techniques. *New Trends in*

Technologies: Devices, Computer, Communication and Industrial Systems, *2*. https://doi.org/10.5772/10428

Huang, D., Xu, J., & Zhang, S. (2012). Valuing the health risks of particulate air pollution in the Pearl River Delta, China. *Environmental Science and Policy*, *15*(1), 38–47. https://doi.org/10.1016/j.envsci.2011.09.007

Huang, J., Pan, X., Guo, X., & Li, G. (2018). Health impact of China's Air Pollution Prevention and Control Action Plan: an analysis of national air quality monitoring and mortality data. *The Lancet Planetary Health*, *2*(7), e313–e323. https://doi.org/10.1016/S2542-5196(18)30141-4

Huang, Y., Zhu, M., Ji, M., Fan, J., Xie, J., Wei, X., Jiang, X., Xu, J., Chen, L., Yin, R., Wang, Y., Dai, J., Jin, G., Xu, L., Hu, Z., Ma, H., & Shen, H. (2021). Air pollution, genetic factors, and the risk of lung cancer. A prospective study in the UK biobank. *American Journal of Respiratory and Critical Care Medicine*, *204*(7), 817–825. https://doi.org/10.1164/rccm.202011-4063OC

Huo, H., Wang, M., Johnson, L., & He, D. (2007). Projection of Chinese motor vehicle growth, oil demand, and CO2 emissions through 2050. *Transportation Research Record*, *2038*, 69–77. https://doi.org/10.3141/2038-09

Hydrogen Council. (2020). *Path to hydrogen competitiveness: a cost perspective*. *January*, 88. www.hydrogencouncil.com.

ICAP. (2023). Emissions Trading Worldwide Status Report 2023. In *International Carbon Action Partnership*.

ICD-11. (2022). *International Statistical Classification of Diseases and Related Health Problems 11th Revision*. https://icd.who.int/en

IEA. (2017). The Future of Trucks – Implications for Energy and the Environment. In *International Energy Agency*.

IEA. (2022). International Energy Agency (IEA) World Energy Outlook 2022. In *Https://Www.Iea.Org/Reports/World-Energy-Outlook-2022/Executive-Summary*. https://www.iea.org/reports/world-energy-outlook-2022

International Energy Agency. (2021). *China Power System Transformation*.

Irle, R. (2023). *Global EV Sales for 2022*. EV-Volumes. https://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/

Jiang, Z., McDonald, B. C., Worden, H., Worden, J. R., Miyazaki, K., Qu, Z., Henze, D. K., Jones, D. B. A., Arellano, A. F., Fischer, E. V., Zhu, L., & Folkert Boersma, K. (2018). Unexpected slowdown of US pollutant emission reduction in the past decade. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(20), 5099–5104. https://doi.org/10.1073/pnas.1801191115

Jin, Y., Andersson, H., & Zhang, S. (2020). Do preferences to reduce health risks related to air pollution depend on illness type? Evidence from a choice experiment in Beijing, China. *Journal of Environmental Economics and Management*, *103*. https://doi.org/10.1016/j.jeem.2020.102355

Joshi, S., Dahodwala, M., Koehler, E. W., Franke, M., Tomazic, D., & Naber, J. (2020). Trade-Off Analysis and Systematic Optimization of a Heavy-Duty Diesel Hybrid Powertrain. *SAE Technical Papers*, *2020-April*(April), 1–12. https://doi.org/10.4271/2020-01-0847

Kalghatgi, G. (2018). Is it really the end of internal combustion engines and petroleum in transport? *Applied Energy*, *225*(February), 965–974. https://doi.org/10.1016/j.apenergy.2018.05.076

Kim, S. E., Xie, Y., Dai, H., Fujimori, S., Hijioka, Y., Honda, Y., Hashizume, M., Masui, T., Hasegawa, T., Xu, X., Yi, K., & Kim, H. (2020). Air quality co-benefits from climate mitigation for human health in South Korea. *Environment International*, *136*(January), 105507. https://doi.org/10.1016/j.envint.2020.105507

Kirilenko, A. P., & Sedjo, R. A. (2007). Climate change impacts on forestry. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(50), 19697–19702. https://doi.org/10.1073/pnas.0701424104

Kleiner, F., & Friedrich, H. E. (2017). Maintenance & repair cost calculation and assessment of resale value for different alternative commercial vehicle powertrain technologies. *EVS 2017 - 30th International Electric Vehicle Symposium and Exhibition*, 1–16.

König, A., Nicoletti, L., Schröder, D., Wolff, S., Waclaw, A., & Lienkamp, M. (2021). An overview of parameter and cost for battery electric vehicles. *World Electric Vehicle Journal*, *12*(1), 1–29. https://doi.org/10.3390/wevj12010021

Lao, J., Song, H., Wang, C., Zhou, Y., & Wang, J. (2021). Reducing atmospheric pollutant and greenhouse gas emissions of heavy duty trucks by substituting diesel with hydrogen in Beijing-Tianjin-Hebei-Shandong region, China. *International Journal of Hydrogen Energy*, *46*(34), 18137–18152. https://doi.org/10.1016/j.ijhydene.2020.09.132

Li, D., Zouma, A., Liao, J. T., & Yang, H. T. (2020). An energy management strategy with renewable energy and energy storage system for a large electric vehicle charging station. *ETransportation*, *6*, 100076. https://doi.org/10.1016/j.etran.2020.100076

Li, S., Djilali, N., Rosen, M. A., Crawford, C., & Sui, P. C. (2022). Transition of heavy-duty trucks from diesel to hydrogen fuel cells: Opportunities, challenges, and recommendations. *International Journal of Energy Research*, *46*(9), 11718–11729. https://doi.org/10.1002/er.8066

Li, S., Long, J., Sui, P. C., Hou, Z., Chahine, R., & Xiao, J. (2019). Addition of hydrogen refueling for fuel cell bus fleet to existing natural gas stations: A case study in Wuhan, China. *International Journal of Energy Research*, *43*(13), 7557–7572. https://doi.org/10.1002/er.4728

Li, X. J., Allen, J. D., Stager, J. A., & Ku, A. Y. (2020). Paths to low-cost hydrogen energy at a scale for transportation applications in the USA and China via liquid-hydrogen distribution networks. *Clean Energy*, *4*(1), 26–47. https://doi.org/10.1093/ce/zkz033

Li, Y., Phoumin, H., & Kimura, S. (2021). *Hydrogen Sourced from Renewables and Clean Energy-A Feasibility Study of Achieving Large scale Demonstration* (Issue Chapter 3).

Li, Y., & Taghizadeh-Hesary, F. (2022). The economic feasibility of green hydrogen and fuel cell electric vehicles for road transport in China. *Energy Policy*, *160*(October 2021), 112703. https://doi.org/10.1016/j.enpol.2021.112703

Liang, W., & Yang, M. (2019). Urbanization, economic growth and environmental pollution: Evidence from China. *Sustainable Computing: Informatics and Systems*, *21*, 1–9. https://doi.org/10.1016/j.suscom.2018.11.007

Liang, X., Zhang, S., Wu, Y., Xing, J., He, X., Zhang, K. M., Wang, S., & Hao, J. (2019). Air quality and health benefits from fleet electrification in China. *Nature Sustainability*, *2*(10), 962–971. https://doi.org/10.1038/s41893-019-0398-8

Liao, R. (2022, September 22). "Virtual" power plants bring "real" security. *People's Daily Overseas Edition*. http://paper.people.com.cn/rmrbhwb/html/2022-09/20/content_25940524.htm

Liu, B., Liu, S., Guo, S., & Zhang, S. (2020). Economic study of a large-scale renewable hydrogen application utilizing surplus renewable energy and natural gas pipeline transportation in China. *International Journal of Hydrogen Energy*, *45*(3), 1385–1398. https://doi.org/10.1016/j.ijhydene.2019.11.056

Liu, J. L., & Danilovic, M. (2021). *Electrification of the transportation system in China. Exploring battery swapping for heavy trucks in China 1.0* (Issue September). https://hh.se/download/18.7b11fe917c2ac07303bf9d3/1632994342544/Sweden-China Bridge - Exploring Battery Swapping for Heavy Trucks in China 1.0%5B68%5D.pdf

Liu, J., Liu, M., Chai, Z., Li, C., Wang, Y., Shen, M., Zhuang, G., & Zhang, L. (2023). Projected rapid growth in diabetes disease burden and economic burden in China: a spatio-temporal study from 2020 to 2030. *The Lancet Regional Health - Western Pacific*, *33*, 100700. https://doi.org/10.1016/j.lanwpc.2023.100700

Liu, M., Saari, R. K., Zhou, G., Li, J., Han, L., & Liu, X. (2021). Recent trends in premature mortality and health disparities attributable to ambient PM2.5 exposure in China: 2005–2017. *Environmental Pollution*, *279*, 116882. https://doi.org/10.1016/j.envpol.2021.116882

Liu, X., Elgowainy, A., Vijayagopal, R., & Wang, M. (2021). Well-to-Wheels Analysis of Zero-Emission Plug-In Battery Electric Vehicle Technology for Medium- And Heavy-Duty Trucks. *Environmental Science and Technology*, *55*(1), 538–546. https://doi.org/10.1021/acs.est.0c02931

Ma, C., Madaniyazi, L., & Xie, Y. (2021). Impact of the electric vehicle policies on environment and health in the Beijing–Tianjin–Hebei Region. *International Journal of Environmental Research and Public Health*, *18*(2), 1–14. https://doi.org/10.3390/ijerph18020623

Ma, R. C. W. (2018). Epidemiology of diabetes and diabetic complications in China. *Diabetologia*, *61*(6), 1249–1260. https://doi.org/10.1007/s00125-018-4557-7

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and Health Impacts of Air Pollution: A Review. *Frontiers in Public Health*, *8*(February), 1–13. https://doi.org/10.3389/fpubh.2020.00014

Mao, S., Hussein, B., Pierre-Louis, R., & Felipe, R. (2021). Total cost of ownership for heavy trucks in china: battery electric, fuel cell, and diesel trucks. *Icct*, *November*. https://theicct.org/publication/total-cost-of-ownership-for-heavy-trucks-in-china-battery-electric-fuel-cell-and-diesel-trucks/

Marcinkoski, J., Vijayagopal, R., Adams, J., James, B., Kopasz, J., & Ahluwalia, R. (2019). Technical Targets for Hydrogen-Fueled Long-Haul Tractor-Trailer Trucks. *Electrified Powertrain Roadmap*, 1–31.

Matus, K., Nam, K., Selin, N. E., Lamsal, L. N., & Reilly, J. M. (2011). Health Damages from Air Pollution in China. In *Joint Program on the Science and Policy of Global Change* (Issue 196).

Mayyas, A., & Mann, M. (2019). Manufacturing competitiveness analysis for hydrogen refueling stations. *International Journal of Hydrogen Energy*, *44*(18), 9121–9142. https://doi.org/10.1016/j.ijhydene.2019.02.135

Mayyas, A., Ruth, M., Pivovar, B., Bender, G., Wipke, K., Mayyas, A., Ruth, M., Pivovar, B., Bender, G., & Wipke, K. (2019). Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers. *National Renewable Energy Laboratory*, *August*, 65. https://www.nrel.gov/docs/fy10osti/72740.pdf.%0Ahttps://www.nrel.gov/docs/fy10osti/72740.pdf

McKinney, J., Bond, E., Crowell, M., & Odufuwa, E. (2015). *Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California*. *December*, 121. https://www.energy.ca.gov/publications/2015/joint-agency-staff-report-assembly-bill-8-assessment-time-and-cost-needed-attain

McNutt, M. (2013). Climate change impacts. *Science*, *341*(6145), 435. https://doi.org/10.1126/science.1243256

Meintz, A., & Starke -Oak, M. (2021). *Charging Infrastructure Technologies: Development of a Multiport, >1 MW Charging System for Medium-and Heavy-Duty Electric Vehicles National Renewable Energy Lab (Lead Lab) DOE Vehicle Technologies Program 2021 Annual Merit Review and Peer Evaluation Meet*.

Miao, B., Giordano, L., & Chan, S. H. (2021). Long-distance renewable hydrogen transmission via cables and pipelines. *International Journal of Hydrogen Energy*, *46*(36), 18699–18718. https://doi.org/10.1016/j.ijhydene.2021.03.067

Ministry of Ecology and Environment of China. (2021). China Mobile Source Management Annual Report 2021. 中华人民共和国生态环境部, 1–60. https://www.mee.gov.cn/hjzl/sthjzk/ydyhjgl/202109/W020210910400449015882.pdf

Mitchell, S. O. (2009). Clearing the air. *Concrete Producer*, *27*(2), 22.

Mojtaba Lajevardi, S., Axsen, J., & Crawford, C. (2019). Comparing alternative heavy-duty drivetrains based on GHG emissions, ownership and abatement costs: Simulations of freight routes in British Columbia. *Transportation Research Part D: Transport and Environment*, *76*(September), 19–55. https://doi.org/10.1016/j.trd.2019.08.031

Murphy, C., Mai, T., Sun, Y., Jadun, P., Muratori, M., Nelson, B., & Jones, R. (2021). *Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure*

Development for the United States. NREL/TP-6A20-72330. https://www.nrel.gov/docs/fy21osti/72330.pdf
National Bureau of Statistics of China. (2020). *China Statistical Yearbook 2020*.
National Bureau of Statistics of China. (2021). *China Statistical Yearbook 2021*. https://doi.org/http://www.stats.gov.cn/sj/ndsj/2022/indexeh.htm
OECD. (2012). Mortality Risk Valuation in Environment, Health and Transport Policies. *OECD*, 140. https://doi.org/https://doi-org.uml.idm.oclc.org/10.1787/9789264130807-en.
Ou, S., Hao, X., Lin, Z., Wang, H., Bouchard, J., He, X., Przesmitzki, S., Wu, Z., Zheng, J., Lv, R., Qi, L., & LaClair, T. J. (2019). Light-duty plug-in electric vehicles in China: An overview on the market and its comparisons to the United States. *Renewable and Sustainable Energy Reviews*, *112*(July 2018), 747–761. https://doi.org/10.1016/j.rser.2019.06.021
Panchal, C., Stegen, S., & Lu, J. (2018). Review of static and dynamic wireless electric vehicle charging system. *Engineering Science and Technology, an International Journal*, *21*(5), 922–937. https://doi.org/10.1016/j.jestch.2018.06.015
Peng, T., Ou, X., Yuan, Z., Yan, X., & Zhang, X. (2018). Development and application of China provincial road transport energy demand and GHG emissions analysis model. *Applied Energy*, *222*(April), 313–328. https://doi.org/10.1016/j.apenergy.2018.03.139
Perna, A., Minutillo, M., Di Micco, S., & Jannelli, E. (2022). Design and Costs Analysis of Hydrogen Refuelling Stations Based on Different Hydrogen Sources and Plant Configurations. *Energies*, *15*(2). https://doi.org/10.3390/en15020541
Piltan, G., Pirouzi, S., Azarhooshang, A., Rezaee Jordehi, A., Paeizi, A., & Ghadamyari, M. (2022). Storage-integrated virtual power plants for resiliency enhancement of smart distribution systems. *Journal of Energy Storage*, *55*(PB), 105563. https://doi.org/10.1016/j.est.2022.105563
Qi, S., Cheng, S., Tan, X., Feng, S., & Zhou, Q. (2022). Predicting China's carbon price based on a multi-scale integrated model. *Applied Energy*, *324*(May), 119784. https://doi.org/10.1016/j.apenergy.2022.119784
Qiang Zhang, Kebin He, & Hong Huo. (2012). Cleaning China's air. *Nature*, *2005*, 161–162.
Quam, V. G. M., Rocklöv, J., Quam, M. B. M., & Lucas, R. A. I. (2017). Assessing greenhouse gas emissions and health co-benefits: A structured review of lifestyle-related climate change mitigation strategies. *International Journal of Environmental Research and Public Health*, *14*(5), 1–19. https://doi.org/10.3390/ijerph14050468
Quan, C., Cheng, X., Yu, S., & Ye, X. (2020). Analysis on the influencing factors of carbon emission in China's logistics industry based on LMDI method. *Science of the Total Environment*, *734*, 138473. https://doi.org/10.1016/j.scitotenv.2020.138473
R, V., Prada, D. N., & Rousseau, A. (2019). fuel economy and cost estimates for medium- and heavy-duty trucks. In *Nucl. Phys.* (Vol. 13, Issue 1).
Ratnakar, R. R., Gupta, N., Zhang, K., van Doorne, C., Fesmire, J., Dindoruk, B., & Balakotaiah, V. (2021). Hydrogen supply chain and challenges in large-scale LH2

storage and transportation. *International Journal of Hydrogen Energy*, *46*(47), 24149–24168. https://doi.org/10.1016/j.ijhydene.2021.05.025

Reddi, K., Elgowainy, A., Rustagi, N., & Gupta, E. (2018). Techno-economic analysis of conventional and advanced high-pressure tube trailer configurations for compressed hydrogen gas transportation and refueling. *International Journal of Hydrogen Energy*, *43*(9), 4428–4438. https://doi.org/10.1016/j.ijhydene.2018.01.049

Ren, L., Zhou, S., & Ou, X. (2020). Life-cycle energy consumption and greenhouse-gas emissions of hydrogen supply chains for fuel-cell vehicles in China. *Energy*, *209*, 118482. https://doi.org/10.1016/j.energy.2020.118482

Ren, S., Wang, P., Dai, H., Zhao, D., & Masui, T. (2021). Health and Economic Impact Assessment of Transport and Industry PM 2 . 5 Control Policy in Guangdong Province. *Sustainablity*, *13*. https://doi.org/https://doi.org/10.3390/su132313049

Richard, S., Ralf, W., Gerhard, H., Tobias, P., & Martin, W. (2018). Performance and cost of materials for lithium-based rechargeable automotive batteries. *Nature Energy*, *3*(April), 267–278. http://dx.doi.org/10.1038/s41560-018-0107-2

Rodríguez-urrego, D., & Rodríguez-urrego, L. (2020). *Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID- 19 . The COVID-19 resource centre is hosted on Elsevier Connect , the company ' s public news and information . January*.

Rouzbahani, H. M., Karimipour, H., & Lei, L. (2021). A review on virtual power plant for energy management. *Sustainable Energy Technologies and Assessments*, *47*(November 2020), 101370. https://doi.org/10.1016/j.seta.2021.101370

Sanguesa, J. A., Torres-Sanz, V., Garrido, P., Martinez, F. J., & Marquez-Barja, J. M. (2021). A review on electric vehicles: Technologies and challenges. *Smart Cities*, *4*(1), 372–404. https://doi.org/10.3390/smartcities4010022

Schoettle, B., Sivak, M., & Tunnell, M. (2016). A Survey of Fuel Economy and Fuel Usage By Heavy-Duty Truck Fleets. *American Transportation Research Institute*, *October*, 58. http://atri-online.org/wp-content/uploads/2016/10/2016.ATRI-UMTRI.FuelEconomyReport.Final_.pdf

Semeraro, M. A. (2021). Renewable energy transport via hydrogen pipelines and HVDC transmission lines. *Energy Strategy Reviews*, *35*(May), 100658. https://doi.org/10.1016/j.esr.2021.100658

Sen, B., Ercan, T., & Tatari, O. (2017). Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. *Journal of Cleaner Production*, *141*(2017), 110–121. https://doi.org/10.1016/j.jclepro.2016.09.046

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., Mi, Z., Liu, Z., & Zhang, Q. (2018). China CO 2 emission accounts 1997-2015. *Scientific Data*, *5*, 1–14. https://doi.org/10.1038/sdata.2017.201

Shi, X., Shi, X., Dong, W., Zang, P., Jia, H., Wu, J., & Wang, Y. (2020). Research on Energy Storage Configuration Method Based on Wind and Solar Volatility. *2020 10th*

International Conference on Power and Energy Systems, ICPES 2020, 464–468. https://doi.org/10.1109/ICPES51309.2020.9349645

Shuo, X., & Yu, B. (2021). Current Development and Prospect of Hydrogen Energy Technology in China. *Journal of Beijing Institute of Technology*, *2018*(2).

Sun, Y., Zhao, Z., Yang, M., Jia, D., Pei, W., & Xu, B. (2020). Overview of energy storage in renewable energy power fluctuation mitigation. *CSEE Journal of Power and Energy Systems*, *6*(1), 160–173. https://doi.org/10.17775/CSEEJPES.2019.01950

Taghizadeh-Hesary, F., Li, Y., Rasoulinezhad, E., Mortha, A., Long, Y., Lan, Y., Zhang, Z., Li, N., Zhao, X., & Wang, Y. (2022). Green finance and the economic feasibility of hydrogen projects. *International Journal of Hydrogen Energy*, *47*(58), 24511–24522. https://doi.org/10.1016/j.ijhydene.2022.01.111

Taylor, R. I., & Coy, R. C. (2000). Improved fuel efficiency by lubricant design: A review. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, *214*(1), 1–15. https://doi.org/10.1177/135065010021400101

Tesla. (2023). *Tesla Megapack power storage system*. https://www.tesla.cn/megapack

Thurber, M. C. (2011). The Policy Tightrope in Gas-Producing Countries: Stimulating Domestic Demand Without Discouraging Supply. *2011 Pacific Energy Summit*.

Tol, R. S. J. (2018). The economic impacts of climate change. *Review of Environmental Economics and Policy*, *12*(1), 4–25. https://doi.org/10.1093/reep/rex027

Urgun-Demirtas, M. (2019). *GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*. https://www.energy.gov/eere/bioenergy/articles/greet-greenhouse-gases-regulated-emissions-and-energy-use-transportation

Wang, R., & Liu, J. (2021). Life Cycle Assessment of Energy Consumption and CO2 Emission from HEV, PHEV and BEV for China in the Past, Present and Future. *Journal of Medical Ethics*, *47*(6), 361. https://doi.org/10.1136/medethics-2021-107592

Wang, T., Jiang, Z., Zhao, B., Gu, Y., Liou, K. N., Kalandiyur, N., Zhang, D., & Zhu, Y. (2020). Health co-benefits of achieving sustainable net-zero greenhouse gas emissions in California. *Nature Sustainability*, *3*(8), 597–605. https://doi.org/10.1038/s41893-020-0520-y

Wang, W., Yuan, B., Sun, Q., & Wennersten, R. (2022). Application of energy storage in integrated energy systems — A solution to fluctuation and uncertainty of renewable energy. *Journal of Energy Storage*, *52*(PA), 104812. https://doi.org/10.1016/j.est.2022.104812

Williams, C., Hasanbeigi, A., Wu, G., & Price, L. (2012). *International Experiences with Quantifying the Co-Benefits of Energy-Efficiency and Greenhouse-Gas Mitigation Programs and Policies*. 102. http://eta-publications.lbl.gov/sites/default/files/lbl-5924e-co-benefitssep-2012.pdf

World Bank. (2022). *Country climate and development report-China*. www.worldbank.org

Wu, T., Zhao, H., & Ou, X. (2014). Vehicle ownership analysis based on GDP per capita in China: 1963-2050. *Sustainability*, *6*(8), 4877–4899. https://doi.org/10.3390/su6084877

Xia, T., Nitschke, M., Zhang, Y., Shah, P., Crabb, S., & Hansen, A. (2015). Traffic-related air pollution and health co-benefits of alternative transport in Adelaide, South Australia. *Environment International*, *74*, 281–290. https://doi.org/10.1016/j.envint.2014.10.004

Xing, L. (2021). Economic analysis and business model exploration of hydrogen transport - Case study of heavy-duty FCV demonstration in China. *IOP Conference Series: Earth and Environmental Science*, *827*(1). https://doi.org/10.1088/1755-1315/827/1/012013

Yang, L., Yu, B., Malima, G., Yang, B., Chen, H., & Wei, Y. M. (2022). Are electric vehicles cost competitive? A case study for China based on a lifecycle assessment. *Environmental Science and Pollution Research*, *29*(5), 7793–7810. https://doi.org/10.1007/s11356-021-15139-z

Yang, M., Zhang, L., Zhao, Z., & Wang, L. (2021). Comprehensive benefits analysis of electric vehicle charging station integrated photovoltaic and energy storage. *Journal of Cleaner Production*, *302*, 126967. https://doi.org/10.1016/j.jclepro.2021.126967

Yim, S. H. L., Wang, M., Gu, Y., Yang, Y., Dong, G., & Li, Q. (2019). Effect of Urbanization on Ozone and Resultant Health Effects in the Pearl River Delta Region of China. *Journal of Geophysical Research: Atmospheres*, *124*(21), 11568–11579. https://doi.org/10.1029/2019JD030562

Yin, H., Pizzol, M., & Xu, L. (2017). External costs of PM2 . 5 pollution in Beijing , China : Uncertainty analysis of multiple health impacts and costs *. *Environmental Pollution*, *226*, 356–369. https://doi.org/10.1016/j.envpol.2017.02.029

Yu, M., Wang, K., & Vredenburg, H. (2021). Insights into low-carbon hydrogen production methods: Green, blue and aqua hydrogen. *International Journal of Hydrogen Energy*, *46*(41), 21261–21273. https://doi.org/10.1016/j.ijhydene.2021.04.016

Zeng, X., Li, M., Abd El-Hady, D., Alshitari, W., Al-Bogami, A. S., Lu, J., & Amine, K. (2019). Commercialization of Lithium Battery Technologies for Electric Vehicles. *Advanced Energy Materials*, *9*(27), 1–65. https://doi.org/10.1002/aenm.201900161

Zhang, Xizhao, Lin, Z., Crawford, C., & Li, S. (2022). Techno-economic comparison of electrification for heavy-duty trucks in China by 2040. *Transportation Research Part D: Transport and Environment*, *102*(December 2021), 103152. https://doi.org/10.1016/j.trd.2021.103152

Zhang, Xu, Ou, X., Yang, X., Qi, T., Nam, K. M., Zhang, D., & Zhang, X. (2017). Socioeconomic burden of air pollution in China: Province-level analysis based on energy economic model. *Energy Economics*, *68*, 478–489. https://doi.org/10.1016/j.eneco.2017.10.013

Zhang, Z., Wang, J., & Lu, W. (2018). Exposure to nitrogen dioxide and chronic obstructive pulmonary disease (COPD) in adults: a systematic review and meta-analysis. *Environmental Science and Pollution Research*, *25*(15), 15133–15145. https://doi.org/10.1007/s11356-018-1629-7

Zhao, F., Liu, F., Liu, Z., & Hao, H. (2019). The correlated impacts of fuel consumption improvements and vehicle electrification on vehicle greenhouse gas emissions in China.

Journal of Cleaner Production, *207*(2019), 702–716. https://doi.org/10.1016/j.jclepro.2018.10.046

Zhao, H., Burke, A., & Miller, M. (2013). Analysis of Class 8 truck technologies for their fuel savings and economics. *Transportation Research Part D: Transport and Environment*, *23*(2013), 55–63. https://doi.org/10.1016/j.trd.2013.04.004

Zhao, H., Wang, Q., & Fulton, L. (2018). *A comparison of Zero-Emission Highway Trucking Technologies*. https://doi.org/10.7922/G2FQ9TS7

Zhong, Z., Zheng, J., Zhu, M., Huang, Z., Zhang, Z., Jia, G., Wang, X., Bian, Y., Wang, Y., & Li, N. (2018). Recent developments of anthropogenic air pollutant emission inventories in Guangdong province, China. *Science of the Total Environment*, *627*, 1080–1092. https://doi.org/10.1016/j.scitotenv.2018.01.268

Zhou, T., Roorda, M. J., MacLean, H. L., & Luk, J. (2017). Life cycle GHG emissions and lifetime costs of medium-duty diesel and battery electric trucks in Toronto, Canada. *Transportation Research Part D: Transport and Environment*, *55*, 91–98. https://doi.org/10.1016/j.trd.2017.06.019

Zhu, Z., Liao, Q., Qiu, R., Liang, Y., Song, Y., & Xue, S. (2023). Technical and economic analysis on long-distance hydrogen pipeline transportation. *Petroleum Science Bulletin*, *8*(1), 112–124. https://doi.org/10.3969/j.issn.2096-1693.2023.01.008