COMPARATIVE SUSTAINABILITY ASSESSMENT OF BATTERY ELECTRIC AND GASOLINE VEHICLES IN HEILONGJIANG PROVINCE, CHINA

By

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The transition to battery electric vehicles (BEVs) is a crucial step towards sustainable mobility, yet their comparative sustainability remains under explored, particularly in regions with unique climatic and energy conditions such as Heilongjiang Province, China. This study assesses the sustainability of BEVs versus gasoline vehicles (GVs) in Heilongjiang Province using a Life Cycle Sustainability Assessment (LCSA) approach that integrates economic, environmental, and social dimensions into a unified monetary framework. The study evaluates the economic feasibility, environmental emissions, and social impacts of BEV adoption under the constraints of the Northeast Regional Power Grid, which is heavily reliant on non-renewable energy sources and subject to extreme temperature variations.

The methodological approach involves Life Cycle Costing (LCC), Life Cycle Impact Assessment (LCIA), and Social Life Cycle Assessment (S-LCA), all of which are monetized for a comprehensive evaluation. Economic analysis indicates that BEVs achieve a cost advantage over GVs after five years of use, even in the absence of subsidies, primarily due to their lower operational costs. The environmental assessment reveals that, despite higher land transformation emissions, BEVs produce 22% lower total CO_2 emissions per kilometer than GVs. However, their environmental advantage fluctuates with seasonal temperature variations and grid composition, with winter months showing a 15% increase in emissions due to reduced battery efficiency. Socially, while consumer environmental awareness is rising, BEVs still face challenges in perceived social value, particularly concerning infrastructure availability and resale value.

The findings underscore the need for targeted policy interventions to enhance BEV adoption, including incentives for cleaner grid electricity and improved consumer perception of BEV social benefits. This research provides quantifiable insights for policymakers, industry stakeholders, and academia, facilitating data-driven strategies for sustainable transportation transitions. By integrating economic, environmental, and social sustainability into a single monetary framework, the study offers a replaceable methodological blueprint for assessing vehicle sustainability in regions with complex energy and climatic conditions.

Keywords: Battery Electric vehicle, Gasoline vehicle, Monetization, Sustainability, Life cycle sustainability assessment

SDG: GOAL 12: Responsible consumption and production, GOAL 13: Climate action

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENILAIAN KEMAMPANAN PERBANDINGAN BATERI KENDERAAN ELEKTRIK DAN PETROL DI WILAYAH HEILONGJIANG, CHINA

Oleh

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Peralihan kepada kenderaan elektrik bateri (BEV) merupakan langkah penting ke arah mobiliti lestari, namun kelestarian perbandingan BEV masih kurang diterokai, terutamanya di kawasan dengan keadaan iklim dan tenaga yang unik seperti Wilayah Heilongjiang, China. Kajian ini menilai kelestarian BEV berbanding kenderaan petrol (GV) di Wilayah Heilongjiang menggunakan pendekatan Penilaian Kelestarian Kitaran Hayat (LCSA) yang mengintegrasikan dimensi ekonomi, alam sekitar, dan sosial ke dalam satu rangka kerja kewangan yang bersatu. Kajian ini menilai daya maju ekonomi, pelepasan alam sekitar, dan kesan sosial penggunaan BEV di bawah batasan Grid Kuasa Wilayah Timur Laut, yang sangat bergantung pada sumber tenaga tidak boleh diperbaharui dan tertakluk kepada variasi suhu yang melampau.

Pendekatan metodologi melibatkan Kos Kitaran Hayat (LCC), Penilaian Impak Kitaran Hayat (LCIA), dan Penilaian Sosial Kitaran Hayat (S-LCA), yang

semuanya dimonetisasi untuk penilaian yang komprehensif. Analisis ekonomi menunjukkan bahawa BEV mencapai kelebihan kos berbanding GV selepas lima tahun penggunaan, walaupun tanpa subsidi, terutamanya disebabkan oleh kos operasi yang lebih rendah. Penilaian alam sekitar mendedahkan bahawa, walaupun BEV menghasilkan pelepasan transformasi tanah yang lebih tinggi, ia menghasilkan 22% lebih rendah pelepasan CO_2 setiap kilometer berbanding GV. Walau bagaimanapun, kelebihan alam sekitar BEV berfluktuasi dengan variasi suhu bermusim dan komposisi grid tenaga, di mana bulan-bulan musim sejuk menunjukkan peningkatan pelepasan sebanyak 15% akibat penurunan kecekapan bateri. Dari segi sosial, walaupun kesedaran alam sekitar pengguna semakin meningkat, BEV masih menghadapi cabaran dalam nilai sosial yang dirasakan, terutamanya berkaitan dengan ketersediaan infrastruktur dan nilai jual semula.

Penemuan ini menekankan keperluan intervensi dasar yang disasarkan untuk meningkatkan penggunaan BEV, termasuk insentif bagi grid elektrik yang lebih bersih dan usaha untuk memperbaiki persepsi sosial terhadap BEV. Kajian ini menyediakan pandangan yang dapat diukur kepada pembuat dasar, pihak industri, dan akademia untuk memudahkan strategi berasaskan data dalam peralihan pengangkutan lestari. Dengan mengintegrasikan kelestarian ekonomi, alam sekitar, dan sosial ke dalam satu rangka kerja kewangan yang bersatu, kajian ini menawarkan pelan metodologi yang boleh diguna pakai untuk menilai kelestarian kenderaan di kawasan dengan keadaan tenaga dan iklim yang kompleks.

Kata Kunci: Kenderaan Elektrik Bateri, Kenderaan Petrol, Monetisasi, Kelestarian, Penilaian Kelestarian Kitaran Hayat

SDG: MATLAMAT 12: Penggunaan dan pengeluaran yang bertanggungjawab, MATLAMAT 13: Tindakan iklim

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BEV	Battery electric vehicles
CBA	Cost-Benefit assessment
CH_4	Methane
CO_2	Carbon dioxide
CVM	Contingent Valuation Method
EPS	The Environmental Priorities Strategies
eq	equivalent
EV	Electric vehicles
FCEV	Fuel cell electric vehicles
FCVs	Fuel cell vehicles
GHG	Greenhouse gas
GV	Gasoline vehicles
GWP 100	100-year time horizon global warming potentials
HFC	Hydrofluorocarbon
HFCV	Hydrogen Fuel Cell Vehicles
ICEVs	Internal combustion engine vehicles
IPCC	Intergovernmental Panel on Climate Change
ISO	International organization for standardization
KWh	Kilowatt-hour
LCA	Life cycle assessment
LCC	Life cycle costing
LCIA	Life Cycle Impact Assessment

LCSA	Life cycle sustainability assessment
LCT	Life cycle thinking
LIME	Life-cycle Impact Assessment Method based on Endpoint Modelling
Mt	Metric ton
N_2O	Nitrous oxide
NEV	New energy vehicles
NPV	Net present value
PED	Primary energy demand
PHEV	Plug-in Hybrid Electric Vehicles
PV	Present value
SCC	Social cost of carbon
SDG	Sustainability development goes
S-LCA	Social life cycle assessment
TBL	Triple bottom line
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
VS	Versus
WTA	Willingness-to-accept
WTB	Willingness to buy
WTP	Willingness to pay
SWG	State Grid Southwest China Branch
NWG	State Grid Northwest China Branch
NECG	State Grid Northeast China Branch
NCGC	State Grid North China Branch

ECGC	State Grid East China Branch
CCG	State Grid Central China Branch
HSGV	Health and Safety of Gasoline vehicles
HSBEV	Health and Safety of Electric Vehicles
CPGV	Consumer privacy of Gasoline vehicles
CPBEV	Consumer privacy of Electric Vehicles
TGV	Transparency of Gasoline vehicles
TBEV	Transparency of Electric Vehicles
FMGV	Feedback mechanism of Gasoline vehicles
FMBEV	Feedback mechanism of Electric Vehicles
EFGV	End of life and future concern of Gasoline vehicles
EFBEV	End of life and future concern of Electric Vehicles

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter explores the sustainability of battery electric vehicles (BEVs) in China. It covers the research background, problem statement, research questions, research objectives, operational definitions, significance of the study, scope and limitations of the study, and organization of the thesis.

1.2 Background of the Study

Greenhouse gas (GHG) emissions are considered the leading cause of rising global temperatures, resulting in a global climate change (Ahmad et al., 2023; Z. Li et al., 2021). This global climate change may have detrimental emotional impacts on people (Semenza et al., 2008). Hence, it should be mitigated to avoid irreversible impacts on society. Transportation is one of the significant drivers of GHG emissions (Shafique et al., 2021). Governments of China and countries in Europe and North America have been actively promoting the use of electric vehicles (EVs) to improve air quality, address climate change, and promote industrial development (Kromydas, 2017). Developing the EV industry has become a global consensus promoted by national policies. In this global context, China's position as the largest market for EVs underscores its pivotal role in the transition (Gan et al., 2021). The market share of EVs in China's automotive industry increased from 2.5% of all passenger vehicle sales in 2019 to a substantial share in 2020 (National Bureau of Statistics of China, 2023). The core technology of China's new EVs has reached an internationally advanced level, resulting in strong international competitiveness (General Office of the State Council, 2020).

While EVs do not produce tailpipe emissions, the energy required to charge their batteries often originates from non-renewable sources. As of 2021, despite the country possessing the world's largest installed capacity for renewable energy, coal remained a primary energy source in China). This dependency on coal suggests that the widespread adoption of EVs might shift exhaust pollution and non-renewable energy consumption to power plants, raising concerns about whether this shift might paradoxically increase environmental pollution and non-renewable energy usage.

China has announced that it will stop selling combustion vehicles in 2035 and cease their use them entirely by 2050 in order to achieve carbon neutrality by 2060 (The State Council of the People's Republic China, 2021). Thus, the country needs to pay special attention to areas where implementation is difficult, solve existing problems, and increase adoption rates. BEV battery efficiency is significantly impacted by low temperatures, reducing vehicle range and increasing energy consumption for heating.The Northeast Regional Power Grid is dominated by coal-fired power, raising concerns about whether BEVs can genuinely reduce emissions in this region. Compared to coastal provinces, Heilongjiang province has one of the lowest BEV adoption rates, indicating structural and consumer barriers. Current policies do not adequately address the challenges of BEV adoption in colder, less urbanized regions. This study is necessary to understand these unique challenges and offer tailored sustainability assessments and policy recommendations.

Technological advancements are pivotal in shaping consumer perceptions and market growth (Research and Markets, 2024). Extensive consumer education to increase EV uptakes is crucial (International Energy Agency [IEA], 2023). BEV is a promising technology for reducing the environmental impacts of the transport sector (Koroma et al., 2022).

Government policies through fiscal incentives and regulatory frameworks significantly influence EV adoptions, underlining the synergy between policy initiatives and market dynamics. These policies are instrumental in fostering a sustainable transport ecosystem that aligns with the broader environmental goals (IEA, 2024).

Despite the extensive research conducted on EVs, there remain gaps in understanding the sustainability of their usage, often concerning the integration of economic, social, and environmental factors. In this regard, monetisation provides a unified approach, bridging these gaps for enhanced decision-making.

While the progress in EV adoption has been notable in developed regions, significant challenges persist in colder, less developed areas like Heilongjiang Province. Therefore, there is a need to understand and address the challenges faced by the people in this province, including the unique social, environmental, and economic challenges.

This research aims to contribute valuable insights into the practical challenges and opportunities of implementing EV policies in colder climates and less development cities, thereby enriching the discourse in sustainable transportation studies. The monetisation method is used to facilitate understanding among stakeholders, such as policymakers and decision makers, besides helping to educate the public.

1.3 Problem Statement

While significant research exists on BEVs, Based on the literature review, most studies focus on subsidies, infrastructure, and emissions without a holistic Life Cycle Sustainability Assessment (LCSA). Current research often isolates economic, environmental, or social factors, leading to fragmented sustainability assessments. Additionally, the unique challenges of Heilongjiang Province, such as extreme temperatures and a coal-dominated power grid, remain underexplored. This study bridges these gaps by providing a monetized, multi-dimensional sustainability evaluation of BEVs compared to GVs.

Life cycle cost analysis shows that although electric vehicles have a higher initial acquisition cost, they have lower energy and maintenance costs during the use phase. However, existing studies mainly focus on overall economic costs and lack in-depth analysis of consumers' personal holding costs. In addition, differences in electricity and fuel prices in different regions will also affect the economic feasibility of electric vehicles, and these factors have not been fully considered in existing studies. High initial costs dampen the market growth of BEVs (Anjos et al., 2020; Kim et al., 2017). Technological immaturity and high manufacturing costs pose challenges on BEVs (Z. Li et al., 2021). Therefore, comprehensive information on fuel, maintenance, repair, and insurance costs associated with BEV ownership and usage is crucial for consumer decision-making (Litman & Eric Doherty, 2011). Additionally, it is vital to investigate how changes in discount rates and the phasing out of government subsidies affect the total cost of BEV ownership. A higher discount rate results in a lower present value (PV) of future cash flows, making the investment less attractive (Hirshleifer, 1961). The primary benefit of BEVs lies in subsidy programme implementations and lower operating fees such as parking, tolls, road tax, and others (Stodola & Stodola, 2019). Substantial government subsidies have significantly influenced the adoption of BEVs (Wang et al., 2019). However, subsidies will end after 2027 with no further tax exemptions given for vehicle purchases (Ministry of Finance, State Administration of Taxation, Ministry of Industry and Information Technology, 2023). Hence, it is necessary to assess how the total cost of ownership affects the economic competitiveness of vehicles. Estimating costs from a life cycle perspective can provide a comprehensive understanding of the economic competitiveness of various vehicles (Z. Li et al., 2021).

Existing studies have shown that electric vehicles generally emit less carbon than traditional fuel vehicles over their entire life cycle. However, the carbon reduction effect varies in different regions, mainly depending on the cleanliness of the local power structure. For example, in areas dominated by coal-fired power, the carbon footprint of electric vehicles may be higher than that of fuel vehicles, while in areas where clean energy accounts for a higher proportion, the carbon emission advantage of electric vehicles is more significant (Y. Hu et al., 2021). The overall impact of BEVs on the environment heavily depends on the local energy mix. This study considers the power grid and combines it with regional characteristics to eliminate regional bias. The temperature effect is also incorporated in the study. Uneven electricity distribution in China may result in different environmental impacts across regions. While EVs are presented as a solution to air pollution emissions, their emission reduction effect is unclear (Yang et al., 2021). It is now more likely for China to transition to vehicles that are run entirely on electricity (Kromydas, 2017). However, energy consumption, emissions, and well-to-wheel efficiency are still up for debate and depend on the electricity mix (Wang et al., 2013). In fossil fuel-dependent areas, the usage phase is more critical (Marques et al., 2019). There is a potential to make BEVs better or worse than internal combustion engine vehicles (ICEVs) or hybrids, depending on the grid emissions (Holland et al., 2016; Michalek et al., 2011; Tessum et al., 2014; Weis et al., 2016). Further, it is necessary to eliminate regional deviations and reveal the specific case in China (Qiao et al., 2019). Regional characteristics, including temperature, need to be considered. The ambient temperature affects the charging and discharging efficiency of batteries (Zhang et al., 2010). This affects energy consumption and consumer convenience.

This research explores the social barriers to EV adoption such as range anxiety, limited charging infrastructure, and concerns about battery durability (Anjos et al., 2020; Kim et al., 2017). Various social impact categories influence consumers' purchase intentions towards BEVs and GVs. Social impact or social well-being is also influenced by consumer decision-making. According to Featherman et al. (2021), social influences play a crucial role in BEV adoption, particularly among younger consumers who are often swayed by key opinion leaders in their vehicle purchase decisions. For instance, in Northeast China, cold weather conditions and inadequate charging options have stifled BEV market growth, the impact of extreme cold temperatures on BEV performance, particularly battery efficiency, driving range, and energy consumption for heating systems. underscoring the importance of tailored market strategies for different regions (Lu, 2023). This variability in social impacts necessitates a deeper understanding of regional consumer behaviour to effectively boost BEV adoption.

The primary objective of this study is to provide a comprehensive evaluation of the sustainability of EVs in Heilongjiang Province, offering insights that can guide policy decisions and strategic planning. By integrating diverse sustainability indicators into a unified LCSA framework, this study enhances decision-making processes and fosters a deeper understanding of the specific conditions under which EVs can truly contribute to sustainable development goals (SDGs).

1.4 Research Questions

How can the replacement of GVs with BEVs in the Northeast Regional Power Grid of Heilongjiang Province be analysed to evaluate the economic, environmental, and social sustainability impacts, and how can these comprehensive impacts be quantified and monetised to support informed policy and consumer decision-making? Specially, this study's research questions are as follows:

i. How do the life cycle costs of GVs compare to BEVs in the Northeast Regional Power Grid of Heilongjiang Province, China?

ii. How does the sensitivity of real discount rate and subsidies affect the overall cost for consumers in the utilization of BEVs and GVs within the Northeast Regional Power Grid of Heilongjiang Province, China?”

iii. What are the comparative environmental impacts of GVs and BEVs in Heilongjiang Province, focusing on total emissions during their use stages (Refers to the phase when the vehicle is actively being driven and used by consumers)?

iv. How do the emissions associated with BEVs during their use stage vary across different power grids?

v. How does ambient temperature affect the emissions of BEVs compared to GVs in the Northeast Regional Power Grid of Heilongjiang Province, China?

vi. How do consumers' perceptions of social impacts (health and safety, privacy, transparency, feedback mechanism, and end-of-life) differ between BEVs and GVs in Heilongjiang Province?

vii. How do different social impact categories (health and safety, privacy, transparency, feedback mechanism, and end-of-life) influence consumers' decision-making towards BEVs and GVs in Heilongjiang Province, China?

viii. How does the willingness to pay (WTP) a carbon tax due to vehicle usage affect carbon emissions in Heilongjiang Province, China?

ix. How does the differences in social impact monetisation between BEVs and GVs, which vehicle type offers greater overall societal value in Heilongjiang Province?

x. How can the monetization of sustainability factors improve BEV assessments?

1.5 Research Objectives

The general objective of this study is to conduct a comprehensive decision analysis on the transition from GVs to BEVs in the Northeast Regional Power Grid of Heilongjiang Province, utilising the pillars of sustainable development to evaluate economic, environmental, and social impacts and to develop a monetisation framework that translates these diverse impacts into economic values for informed decision-making. Specifically, the objectives are:

i. To compare the life cycle costs of BEVs and GVs during their usage stage (refers to the phase when the vehicle is actively being driven and used by consumers) in the Northeast Regional Power Grid of Heilongjiang Province;

ii. To compare the GHG emissions and environmental impacts of BEVs and GVs during their use stage in the Northeast Regional Power Grid of Heilongjiang Province;

iii. To assess the social impacts (health and safety, privacy, transparency, feedback mechanism, and end-of-life) on consumers using BEVs versus GVs, particularly in the Northeast Regional Power Grid of Heilongjiang Province; and

iv. To integrates economic, environmental, and social dimensions by using quantitative monetization and enabling evidence-based policy formulation and consumer decision support for sustainable transportation.

The research questions in this study are directly aligned with the research objectives to ensure a structured and comprehensive analysis of BEV and GV sustainability in Heilongjiang Province. The study examines life cycle costs by comparing the total ownership expenses of BEVs and GVs, addressing the objective of evaluating economic feasibility. Sensitivity analysis on discount rates and subsidies further refines this economic assessment, providing insights into policy effectiveness. Environmental impacts are assessed through life cycle impact analysis (LCIA), specifically focusing on emissions differences under varying regional power grid compositions and seasonal conditions. The study also investigates consumer perceptions of social impacts such as health and safety, privacy, and infrastructure availability, aligning with the objective of evaluating the social dimensions of sustainability. Finally, to support decision-making, the study develops a monetized framework that integrates economic, environmental, and social factors, ensuring that sustainability assessments are actionable for policymakers. This alignment between research questions and objectives ensures that the study comprehensively evaluates BEV adoption in Heilongjiang while offering policy-relevant insights.

1.6 Operational Definitions

Life cycle costing (LCC) provides the input for a decision-making or an evaluation process, and it should typically also include inputs from other evaluations (ISO 15686-5). All the costs incurred by a product or service throughout the course of its life are included in the LCC. LCC considers the indirect costs associated with investment, usage, maintenance, and end of life in addition to the direct costs of planning, designing, building, operating, and disposing (International Organization for Standardization [ISO], 2017). The life cycle costs of BEVs and GVs include the overall costs associated with acquiring, operating, maintaining, and disposing of the vehicle. These costs are measured in monetary terms and are calculated over the estimated lifespan (15 years) with 20,000 km of vehicle mileage each year, considering the regional average temperature effects on charge and discharge efficiencies.

Sensitivity analysis is a test performed on an analysis's results by changing one or more parameters from their initial value(s). The sensitivity analysis can show how accurate the calculation is and how changing the input might affect the calculation (ISO, 2017). In this study, sensitivity analysis is performed to analyse the sensitivity of consumers' total cost to discount rate and subsidies by adjusting the discount rate within the 1%−10% range and subsidies from full to zero subsidies.

Environmental impacts are changes to the constructed or natural environment that are the direct outcome of an activity and may have adverse impacts on fish, animals, air, land, or ecosystem populations (Abdallah, 2017). Several environmental impacts are closely linked to the production and use of biomass energy. An example is the worsening environmental impact resulting from the use of fossil fuels, in which ceasing to use them can generate clear environmental advantage (Klass, 2004). The environmental impacts of BEVs and GVs can be quantified by computing the emissions generated throughout the operational phase of the cars. These emissions, typically expressed in terms of CO_2 equivalent per kilometre (CO_2-eq per km), also consider the regional temperature and Power composition.

Power plants produce electricity, which is then transported through a convoluted network known as the "grid". Power lines, transformers, and substations for electricity are all part of the grid, which links electricity producers and consumers. Most local grids are linked together for business and dependability reasons, creating a bigger, more stable network that allows providers to continuously produce the appropriate volume of power to fulfil demand (U.S. Energy Information Administration, 2024). There are six major regional power grids in China (General Office of the State Council of the People's Republic of China, 2006). The Northeast, Northwest, and Southwest power grids as the sending ends, and the North China, East China, and Central China power grids are the receiving ends (Wang, 2020). The power grid central to this study is the Northeast power grid due to this study's focus on

Heilongjiang Province, China. The remaining power grids are only used as comparisons with the Northeast power grid, as discussed in Subsection 4.2.1.

Unlike ICEVs, BEVs' operating range is greatly affected by cold weather (Yuksel & Michalek, 2015). The heating energy needs of pure electric cars (Iora & Tribioli, 2019) and the temperature sensitivity of lithium-ion batteries (S. Ma et al., 2018) are the two key variables that affect the cruising range at low temperatures. The main purpose of lithium-ion batteries in contemporary fully electric cars is for energy storage. The temperature effect in this study is based on Heilongjiang Province's average temperature in each season and average temperature in a year. The average charge and discharge efficiency or energy consumption in each season or in a year is also considered.

Social impact refers to the impact on people's quality of life and the services that the environment offers to them (Department of Environmental Protection and Conservation, 2024). The social life cycle assessment (S-LCA) guideline identifies five types of social stakeholders. However, in this study, only one stakeholder type is involved, which is consumers. As per the guideline, this study looks at the consumer social impact subcategories of health and safety, feedback mechanism, consumer privacy, transparency, and end of life responsibility (United Nations Environment Programme [UNEP], 2009). The social impacts on consumers are evaluated by analysing the survey responses about customer satisfaction compared BEVs with GVs. This assessment is conducted within the framework of the Northeast Regional Power Grid of

Heilongjiang Province. One way to measure satisfaction levels is by using a Likert scale.

Lee et al. (2008) and Olshavsky and Granbois (1979) define a purchase decision as an action taken by the customer to acquire the product. Therefore, a purchase decision is a process that customers undertake, starting with one of the available alternatives and culminating in an actual purchase activity. This study analyses the relationship between social impact and purchase intention, determining the social impact that affects consumers' purchase of BEVs or GVs in Heilongjiang Province, China.

Willingness to pay (WTP) is the amount of money a person is willing to pay for a product or service. Consumers are willing to pay when there is potential for them to gain (Rotteveel et al., 2020). In this study, questionnaires and open-ended questions are the tools used to obtain responses from Heilongjiang Province residents regarding their WTP for GV or BEV usage carbon emission tax to quantify the value of environmental impacts in monetary values.

Regarding social value, companies consider stakeholders' interests in order to fulfil their social responsibility mandate and ultimately create shared value, or corporate and social benefits (United Nations Environment Programme and SETAC, 2013). Social impact is calculated by computing the correlation coefficient between each social well-being impact category and purchase decision to obtain the impact category weight, the impact category value, and the real value of the impact category. The final result is negative social impact or positive social impact in monetary term.

The 1987 Brundtland Report is credited with initiating the idea of sustainability as a policy term (UN. Secretary-General & World Commission on Environment and Development, 1987). The contradiction between humankind's hope for a better existence and the constraints placed by nature was the subject of the written treatise. Over time, the idea has evolved to be understood in terms of three dimensions consisting of social, economic, and environmental dimensions (Kuhlman & Farrington, 2010). The Sustainability Assessment Framework's monetisation involves WTP or weight assignment to assign a monetary value to the economic, environmental, and social impacts of BEVs and GVs.

1.7 Significance of the Study

This study develops a monetized framework to assess BEV sustainability by integrating environmental, economic, and social factors. It provides policymakers, industry stakeholders, and researchers with data-driven insights for vehicle adoption, particularly in cold-climate, coal-dependent regions like Heilongjiang Province.

Findings support BEV policy optimization, aligning subsidies and incentives with regional energy structures and climate conditions. The study enhances consumer awareness by evaluating total ownership costs, social perceptions, and environmental trade-offs, aiding informed decision-making. Supporting SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), the study provides practical insights for achieving carbon reduction goals in the transportation sector.

LCC results underscore the significance of considering the total ownership costs of vehicles from a consumer's viewpoint, revealing the true costs incurred, especially in comparing BEVs and GVs (Onat et al., 2014). Consumers meticulously evaluate all costs, including fuel, maintenance, repair, and insurance, before making purchasing decisions (Litman & Eric Doherty, 2011).

This study employs the discount rate, a key financial principle that adjusts future cash flows to their PVs to accurately estimate the life cycle costs of vehicles (Fuller & Petersen, 1996). The discount rate is crucial in investment decision-making as it directly influences the valuation of investments, with higher rates reducing the attractiveness of investments (Hirshleifer, 1961).

EV subsidies are progressively decreasing despite multiple extensions(Ministry of Finance, State Administration of Taxation, Ministry of Industry and Information Technology, 2023). Subsidy policies may affect EVs' cost competitiveness (Bubeck et al., 2016; Parker et al., 2021). This study helps compare the competitiveness of GVs and BEVs and assists policymakers and consumers in decision-making regarding subsidy effectiveness.

Environmental impact and energy sources are critical, as the type of energy source significantly influences the environmental benefits of BEVs. As highlighted by Hsu (2013), the sustainability of BEVs hinges on the cleanliness of the energy grid. Therefore, it is crucial to assess whether BEVs truly result in lower environmental impacts compared to GVs in current conditions.

China is intensifying efforts to transition from GVs to BEVs to mitigate air pollution and climate change. This shift requires tailored sustainability evaluations to account for varying energy compositions across regional power grids, which impact pollution levels. Given the ongoing government incentives to promote BEVs (Wang et al., 2021), understanding the environmental impacts specific to each region’s power grid is essential.

In terms of environmental impacts, BEVs generally perform better than other types of vehicles (McCleese & LaPuma, 2002). However, accurate assessments of BEV environmental impacts require knowledge of local conditions like energy structure and ambient temperature, which influence battery efficiency (Zhang et al., 2010; Huo et al., 2015).This study tailors its sustainability evaluations to Heilongjiang Province, enhancing the relevance and applicability of its findings.

The social impact on consumers significantly affects their satisfaction with products. Perceptions of quality, value, and expectations contribute to customer satisfaction and underscore the importance of incorporating sustainability into marketing strategies and product quality to foster lasting customer loyalty (Gonçalves & Silva, 2021).

In today's dynamic and competitive market, understanding consumer decision-making is crucial for companies aiming to attract and retain customers. This complex process is shaped by various factors influencing purchasing decisions (Rybaczewska et al., 2020; Thaichon, 2017). An in-depth study of consumer behavior provides valuable insights into the underlying reasons behind consumer decisions (Singer & Özşahin, 2024). This study examines social impacts by analyzing consumer perceptions and decision-making processes regarding vehicle purchases.

Monetization bridges the gaps between environmental, social, and economic sustainability, enhancing assessment clarity and offering a replicable model for evaluating product sustainability comprehensively. This approach, which uses WTP and social value metrics, addresses the need for a holistic integration of sustainability factors often overlooked in research (Malandrino et al., 2020; Rosenfeld et al., 2019). Different product systems' sustainability should be evaluated considering environmental, economic, and social factors within the same system limits and units (Kloepffer, 2008; Klöpffer, 2003; Reap et al., 2008). Dewulf et al. (2015) emphasized the importance of considering all three sustainability pillars. By expressing impacts in monetary terms, this research closes the gap between sustainability dimensions and improves decision-making by making sustainability evaluations more transparent(Morel et al., 2018). Monetization fosters a cultural shift toward sustainability by providing policymaker and consumers with the necessary information to make sustainable decisions (Wang et al., 2021).

1.8 Scope and Limitations of the Study

This study only concerns BEV and GV, only focuses on passenger vehicles (private cars) only BEV and GV, selecting the BYD Dolphin Fashion Edition and Volkswagen Lavida as presentative brands, only considering use of vehicle and consumer as only stakeholders involved. justification as Chapter 2.2, focusing on the Northeast Regional Power Grid—specifically Heilongjiang Province. This study was limited to Heilongjiang Province within the Northeast regional grid. This regional focus may limit the generalizability of the findings to other regions with different energy infrastructure and economic conditions.

Based on the literature review find of research gaps, there are fewer studies on the use stage, and very limited studies consider consumers as stakeholders. But if China wants to use BEV to reply to GVs, consumers desires are very important. By focusing exclusively on the use stage and considering only consumers as stakeholders, the study might overlook important interactions and impacts pertaining to other stages of the BEV lifecycle, such as manufacturing, distribution, and end-of-life disposal.

The LCC approach depends heavily on the availability of detailed and accurate data across the EV's entire life cycle. As Bjørn et al. (2018) noted, the need for comprehensive data necessitates modelling that simplifies and generalises real-world complexities. This simplification can lead to discrepancies between modelled predictions and actual impacts, affecting the reliability and validity of the study's conclusions.

Open-ended questions are straightforward and simple to deal with in terms of statistical techniques. It is not vulnerable to anchoring or a starting point bias, in addition to being highly informative as the maximum WTP can be identified for each respondent. However, it is prone to strategic behaviour, leading to high non-response rates, protest answers, missing answers, outliers, and generally too unreliable responses (Abedini et al., 2016).

The S-LCA methodology is still new and developing, and its effectiveness is heavily dependent on the quality of the data collected via questionnaires. Factors such as the timing and location of data collection, as well as the demographic characteristics of the respondents (e.g., age), can significantly influence the results, introducing variability and potential biases into the analysis of social impacts.

The monetisation approach in LCSA is innovative but nascent. Hence, there is a need to conduct more case studies to refine and standardise this methodology across different regions, organisations, and products. The lack of established protocols and benchmarks for monetisation can lead to inconsistencies in how economic, social, and environmental impacts are valued and compared, potentially limiting the generalisability and applicability of the study’s findings beyond the immediate region of study.

1.9 Organisation of the Thesis

Chapter 1 outlines the general introduction to the study, including the background, problem statement, research questions, objectives, operational definitions, significance, scope and imitations, and the organisation of the thesis.

Chapter 2 provides a discussion of BEVs in China, including a political review and a systematic literature review on BEV sustainability studies in China. The life cycle-based method and past study indicators are also reviewed, followed by a systematic literature review on the monetisation of sustainability. Then, the chapter delves into the theory of this study, followed by the conceptual framework and conclusion of the literature review. The last part of Chapter 2 focuses on the monetisation of sustainability indicators.

In **Chapter 3**, the methodology and the research design are discussed to show how this study was conducted. The chapter starts with an overview of the developed LCSA method, followed by an explanation of the instruments used in the sustainability assessment.

Chapter 4 provides an analysis of the environmental, economic, and social impacts related to BEVs and GVs, followed by an evaluation of the sustainability of vehicles in monetary terms.

Chapter 5 discusses the conclusion and recommendations made based on the results of this study. The chapter ends with a discussion of the study's contributions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the current state and policy review of EVs in China. The life cycle method (LCC, LCA and S-LCA, LCSA) and past study indicators are reviewed, followed by the impact of EVs and their monetisation in terms of social and environmental impacts. The chapter also discusses LCSA monetisation and visualisation as a decision-making method. This study's underpinning theories that form the theoretical framework are also discussed. The chapter ends with a conclusion of the literature review.

2.2 Review of EVs

EVs operate with zero tailpipe emissions and are powered entirely or primarily by electricity (U.S. Department of Transportation, 2022). Global EV production has expanded steadily, accompanied by declining prices, making full electrification increasingly feasible. Governments in China, Europe, and North America actively promote EV adoption to improve air quality, combat climate change, and drive industrial growth (Kromydas, 2017). A global consensus on EV industry expansion has emerged, supported by national policies. China aims to halt sales of combustion-powered vehicles by 2035 and fully phase them out by 2050 (Hou et al., 2022b). As the world' s largest auto and EV market, China accelerates EV adoption through government incentives and long-term development plans (Gan et al., 2021). By 2020, China had 372 million motor vehicles, including 281 million cars, with 4.92 million new energy vehicles (NEVs), accounting for 1.75% of all vehicles. Of these, 4 million were fully electric, making up 81.32% of NEVs. NEV growth exceeded 1 million units annually for three consecutive years, indicating sustained high-speed expansion (China Road Traffic Safety, 2021).

Researchers find little international collaboration in EV research compared to other fields (Haghani et al., 2023). Generally, research with international collaboration is more impactful than purely domestic studies (Van Raan, 1998). The study by Barbosa et al. (2022) found a notable increase in the number of articles about EVs in the past 9 years. Further research could explore the geopolitical, economic, or proprietary barriers that contribute to this scenario and propose strategies for improvements.

This study focuses on China, the world's largest EV market and leading country in EV research, producing the highest number of EV-related publications. Since 2012, the number of scholarly papers on EV sustainability has shown slight variations, with the most linear growth occurring in 2020–2021, possibly influenced by General Secretary Xi Jinping's commitment to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 (National Department and Reform Commission of the People's Republic of China, 2021). While these efforts are commendable, a critical assessment of their effectiveness is necessary to determine whether they have led to sustainable EV adoption or merely short-term market boosts. As the field continues expanding rapidly, discussions on achieving long-term sustainable EV development and usage will become increasingly relevant.

China's leadership in EV research is driven by the active involvement of primary authors and research institutes within the country. Over the past decade, China has published more EV-related papers than the next five leading countries combined (Haghani et al., 2023). This dominance reflects not only academic interest but also the government's strategic push to position China as a global automotive leader (Altenburg et al., 2022). Despite its relative novelty and concentration in a limited number of publications, EV sustainability research is frequently cited due to its political significance. Given the global nature of EV development, its social, economic, and environmental impact will likely remain a key research focus in the future.

A keyword analysis, shown in **Figure 2.1** and supported by Barbosa et al. (2022), indicates that EV research over the past 20 years has focused primarily on energy storage and management, infrastructure and charging systems, and environmental concerns. This study finds that most EV sustainability research examines subsidies, charging costs, charging stations, batteries, and emissions, while fewer studies focus on the critical use stage, which is essential for assessing EVs environmental, social, and economic sustainability.

Similarly, Onat et al. (2019) highlight the lack of research on EVs' social and economic impacts. While LCA is the predominant method for assessing EV sustainability, it mainly evaluates environmental impacts. Scholars emphasize the need to integrate the three pillars of sustainability—environmental, economic, and social—under the same functional unit and system boundaries, preferably in quantitative terms (Kloepffer, 2008; Klöpffer, 2003; Reap et al., 2008). However, a notable research gap remains in fully integrating these three dimensions quantitatively and comparably, limiting the holistic assessment of EV sustainability.

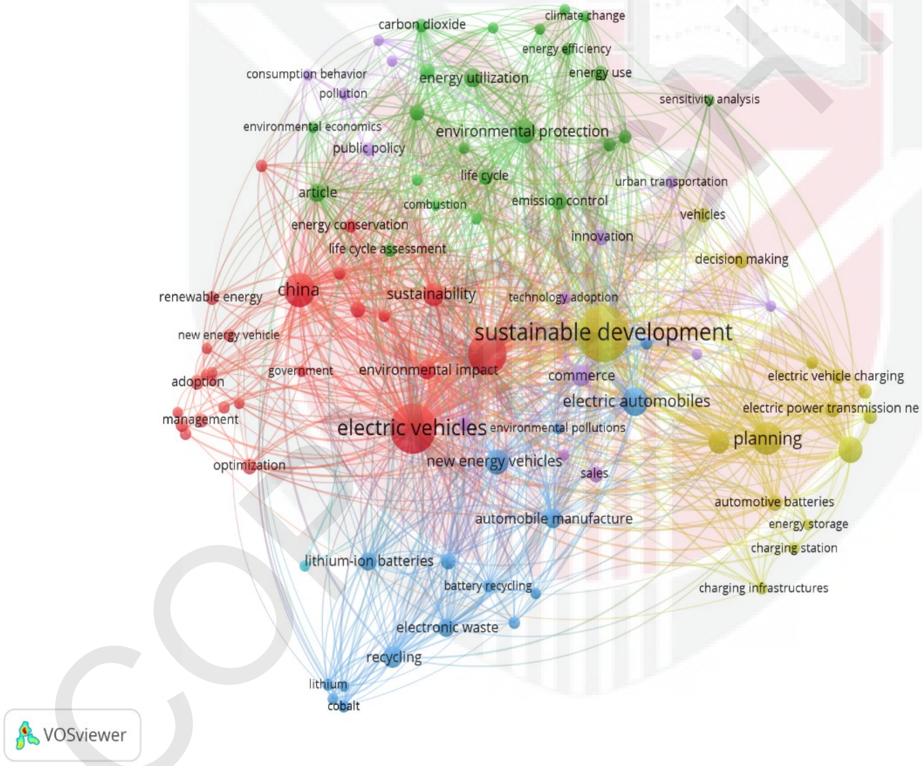

Figure 2.1 : Keywords Co-Occurrence of Past Evs Study

The automotive industry's core strategies for reducing oil consumption, pollutants, and greenhouse gas emissions focus on developing new energy vehicles (NEVs), advancing energy-saving technologies, and adopting clean, low-carbon alternative fuels. NEVs, including pure electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs), and fuel cell vehicles (FCVs), offer medium-to-long-term energy and environmental benefits, though challenges such as high costs and limited infrastructure remain. Hybrid electric vehicles (HEVs) and advanced technologies like 48V mild hybrid systems, engine optimization, and lightweighting provide effective short-term solutions for reducing fuel consumption. Alternative fuels such as natural gas, biofuels, and methanol serve as supplemental options, with natural gas widely used in trucks and taxis and biofuels mandated in many regions for reducing emissions. These combined efforts aim to transition the transportation sector toward sustainability. Summary of vehicle technologies and fuels has shown in **Table 2.1**

This study compares private vehicles, specifically BEVs and GVs, in Heilongjiang, China, while excluding all other vehicle types. The justification for this study is based on several key factors.

Firstly, China leads the global EV market, with 3.4 million EVs, accounting for 47% of the global market share (Paoli & Gül, 2022). China is projected to maintain its dominance, reaching 40% of total EV sales by 2030 (IEA, 2023). Additionally, car ownership in China is expected to rise from 200 million to 500 million vehicles, while EV sales surged by 80% in 2022 compared to 2021 (IEA, 2023). Meanwhile, gasoline consumption is projected to peak around 2025, whereas diesel consumption has stabilized. BEVs, which produce zero

GHG emissions, remain the preferred choice among new energy vehicles in China. Secondly, by 2040, all private vehicles in China are expected to transition to HEVs and BEVs, with traditional fuel vehicles becoming the alternative. As BEV costs decline and consumer awareness increases, vehicle replacements will shift from HEVs to BEVs.

Lastly, BEVs are projected to constitute approximately 85% of China’s total vehicle fleet by 2050 (An et al., 2019). This optimistic outlook is driven by rapid EV market growth and government initiatives to phase out traditional fuel vehicles. China’s EV market is dominated by BEVs in both private and public sectors (Xue et al., 2020). Reinforcing the focus on BEVs and GVs in this study.

Table 2.1 : Summary of Vehicle Technologies and Fuels

Category	Technology/Fuel	Characteristics
New Energy Vehicles	BEV	Pure electric drive, zero emissions, relies on charging infrastructure
	PHEV	Dual drive (electric + fuel), transitional technology
	FCV	Hydrogen fuel, no pollution, high energy density
Hybrid Vehicles	HEV	No external charging, combines combustion engine and electric motor
Internal Combustion Vehicles	ICV	Reliable and widely available, powered entirely by internal combustion engines
Advanced Energy-Saving Technologies	48V Mild Hybrid	Energy-saving through advanced powertrains and reduced engine friction
	Lightweighting	Reduces fuel consumption by decreasing vehicle weight (e.g., light alloys)

Table 2.1 : Continued

Category	Technology/Fuel	Characteristics
Alternative Fuels	Natural Gas	Stable combustion, low CO_2 emissions, good economy
	Biofuels	Lower carbon intensity, enhances fuel oxygen content
	Methanol	Alternative fuel with lower emissions than traditional gasoline

This study focuses on passenger vehicles (private cars) due to their growth potential following China' s second-child policy liberalization. Predictions from the China Society of Automotive Engineers, China Automotive Technology Research Center, and Tsinghua University estimate a future saturation of 300 passenger cars per 1,000 people. Unlike commercial vehicles, passenger car growth is constrained, and government policies prioritize EV adoption in taxis, time-share rentals, and official fleets. While fuel-powered official cars can be phased out quickly through government procurement, transitioning private cars to BEVs remains complex and time-consuming (An et al., 2019).Thus, private vehicles warrant greater research attention.

Policy Review

The Chinese government has implemented legislative and administrative initiatives to promote EV development and adoption as part of its broader environmental sustainability and economic strategy. These efforts focus on charging infrastructure expansion, financial incentives, and regulatory frameworks to enhance market readiness and environmental compliance. Although EVs have existed for decades, their significance grew in the 21st century due to their potential to mitigate environmental impacts (Barros & Pedro, 2012). Consequently, China has introduced numerous policies to encourage EV adoption (Zhang & Bai, 2017).

To reduce consumer costs and encourage adoption, China exempted EVs from car purchase taxes starting September 1, 2014, with extensions granted until December 31, 2023. The 2022 – 2023 tax exemptions are estimated to surpass CNY 200 billion, reflecting the government ’ s commitment to green transportation (Liu,2023) To maintain long-term support, China extended the vehicle purchase tax discount for new EVs until December 31, 2027. Additionally, EVs are exempt from vehicle and vessel taxes (Heilongjiang Provincial Tax Service, State Taxation Administration, 2021), and new EVs are not subject to exhaust gas environmental testing during annual inspections (Jiao, 2021).

Recognizing the importance of charging infrastructure, the government has committed to expanding the national EV charging network. The National Department and Reform Commission of the People's Republic of China (2021) the State Council the People’s Republic of China (2022) have set goals to build a high-quality, widely accessible charging infrastructure by 2030. This system aims to support over 20 million EVs, focusing on an advanced, efficient, and intelligent charging network. Additionally, all new residential parking spaces will include charging stations, targeting 100% coverage in urban areas. To optimize energy demand and encourage infrastructure expansion, a pricing strategy incorporating peak and valley rates will be introduced.

Given its vast territory and regional energy variations, China’s EV promotion strategy must ensure sustainability across diverse regions. The 2030 strategic directives emphasize integrating infrastructure development, regulatory policies, and local governance to support nationwide EV adoption. This approach is crucial for achieving long-term environmental and economic goals, ensuring that EV policies align with local conditions for sustainable mobility.

2.3 Review of Methods and Past Research Indicators

2.3.1 Life Cycle Costing (LCC) Past Research Indicators

The Life Cycle Cost (LCC) concept was first introduced by the U.S. Department of Defense in the 1960s for military asset evaluation, laying the foundation for its broader application (Sherif & Kolarik, 1981). However, its adoption in other industries has been slow (Lindholm & Suomala, 2004). with limited research on its frequency of use and mixed study results (Korpi & Ala-Risku, 2008). Despite this, LCC has been extensively applied in investment evaluations to compare different alternatives and support decision-making (Rebitzer & Seuring, 2003). LCC is guided by ISO 15686-5:2017(En), *Buildings and Constructed Assets — Service Life Planning — Part 5: Life-Cycle Costing* and National Institute of Standards and Technology Handbook 2022 Edition, *Life Cycle Costing Manual for the Federal Energy Management Program* (Kneifel & Webb, 2022).

LCC is critical in assessing total asset costs, considering both initial and future discounted costs by incorporating the time value of money. This economic valuation provides a comprehensive financial overview across an asset's lifespan (Kampf et al., 2016).Although widely used across industries, barriers to adoption persist (Bui et al., 2022; Woodward, 1997). However, LCC plays a key role in evaluating sustainable projects, ensuring alignment with SDGs (Gao et al., 2019; Maisham et al., 2019).

Life Cycle Cost Analysis (LCCA) extends LCC’ s utility by comparing cost-effectiveness across different options over their lifespans, aiding decision-making (Shabani et al., 2023). It accounts for acquisition, operation, maintenance, and disposal costs, making total cost of ownership a key consideration Elmakis & Lisnianski, 2006). In practice, LCC helps organizations evaluate asset acquisition and project feasibility, particularly in the automotive industry, where it informs EV vs. GV cost comparisons from a consumer perspective (Onat et al., 2014).

In summary, LCC is an essential tool for long-term economic assessment, particularly in sustainability-focused decision-making. However, further research is needed to enhance analytical techniques and expand its application across industries.

As Summary of past vehicle life cycle costing studies in **Table 2.2** Transitioning to battery electric vehicles (BEVs) is essential for reducing road transport emissions, but adoption lags behind ICEVs due to higher purchase prices, limited range, charging infrastructure, and battery life concerns (Anjos et al., 2020; Kim et al., 2017). Consumers also assess total ownership costs, including fuel, maintenance, repair, and insurance (Litman & Eric Doherty, 2011). LCC analyses show BEVs are less economically competitive than ICEVs due to high battery costs, though shorter-range BEVs can offset initial premiums more quickly (Liu et al., 2021: Weldon et al., 2018). Technological advancements and incentives may reduce these costs, enhancing BEVs' financial viability (Ayodele & Mustapa, 2020). Factors such as battery lifespan, annual driving distance, charge/discharge rates, and power grid composition also influence consumer choices (Yang et al., 2022). The European Union has implemented subsidies and reduced operating costs (e.g., parking, tolls, road tax) to promote BEV adoption (Stodola & Stodola, 2019).Stricter new EV credit goals may boost manufacturing while reducing ICEV sales (Zheng et al., 2018). However, Lyu et al. (2021) caution that excessive subsidies may undermine market functionality, emphasizing the need for balanced government support, especially for small EV companies (Li et al., 2019).

Wang et al. (2019) found BEVs have lower operational costs and higher resale values but higher initial costs, limiting their economic benefit compared to ICEVs. However, EVs offer societal and individual benefits, including reduced fuel costs and environmental impacts (Iken et al., 2019), . BEVs and ICEV-diesel are the most cost-efficient options, with BEVs being 5% cheaper than ICEV-petrol and 15% cheaper than HEVs (Petrauskienė et al., 2021). LCC analysis, using net present value (NPV), helps designers balance BEVs' higher upfront costs with lower ongoing costs (Mehta et al., 2023). Simões et al. (2016) highlight the benefits of integrating environmental and economic factors in sustainable design, while Witik et al. (2011) note that lighter components reduce fuel usage over a vehicle’s lifespan, despite higher production costs Vehicle’s materials are economically beneficial over the vehicle’s lifespan, although their sustainability can vary with cost considerations (Delogu et al., 2016; Pero et al., 2019).

Research on alternative fuels, such as hydrogen for HFCVs and bioethanol, explores LCC and environmental impacts. Centralized methane reforming is economically viable for hydrogen production, but HFCVs face high ownership and maintenance costs (Khzouz et al., 2020; Daylan & Ciliz, 2016). Comparative life cycle analyses by Cicconi et al. (2019) and Popien et al. (2023) highlight the advantages of emerging battery technologies like lithium-sulphur and all-solid-state batteries. Studies on natural gas and risk assessment methods emphasize cost optimization and emission reduction (Gabbar et al., 2016; Gorbea et al., 2010). The studies by Wilken et al. (2020) and Wulf et al. (2023)explore hydrogen mobility costs and sustainability, while Redpath et al. (2011) and Li et al. (2015) examine the examine solar photovoltaics and composite waste recovery. Rapa et al. (2020) find natural gas the most economical energy source, while solar is the costliest, underscoring the need for cost evaluations in energy production for vehicles.

Sensitivity analyses within uncertainties like inflation and fuel cost fluctuations are crucial for robust LCC assessments (Mehta et al., 2023).

Table 2.2 : Summary of Past Vehicle Life Cycle Costing Studies

Theme	Key Findings	References
Barriers to BEV Adoption	High purchase price, limited range, few charging stations, and battery life concerns hinder BEV adoption.	Anjos et al., (2020; Kim et al., (2017)
Consumer Cost Evaluation	Consumers evaluate total costs (fuel, maintenance, repair, insurance) before purchasing vehicles. BEVs are not yet economically competitive due to high battery costs, despite lower operational expenses.	Litman & Eric Doherty, (2011); Liu et al., (2021); Weldon et al., (2018)
Technological Advancements	Ongoing advancements and incentives could reduce BEV costs, improving financial viability.	Ayodele & Mustapa, (2020); Yang et al., (2022)
Policy Measures	EU policies (subsidies, reduced operating costs) encourage BEV adoption. Stricter EV credit goals may boost manufacturing but increasing subsidies alone could undermine market functionality.	Stodola & Stodola, (2019).;Zheng et al. (2018); Lyu et al. (2021)
Life Cycle Cost (LCC) Analysis	BEVs have lower operational costs and higher resale values but higher initial acquisition costs. LCC analysis helps compare upfront and ongoing costs, using NPV to determine profitable adoption scenarios.	Wang et al. (2019); Mehta et al., (2023)
Material Design and Costs	Simplified components and lightweight materials balance manufacturing costs and usage-phase savings. Lighter components reduce fuel usage over the vehicle’s life cycle.	Simões et al. (2016); Witik et al. (2011)
Alternative Energy Solutions	Hydrogen fuel cell vehicles (HFCVs) face high ownership and maintenance costs. Natural gas is economically viable, while solar electricity generation is costly.	Khzouz et al., (2020); Daylan & Ciliz, (2016); Rapa et al. (2020)
Battery Technologies	Lithium titanium oxide batteries offer financial and environmental advantages over lead-acid batteries. Emerging	Cicconi et al. (2019) and Popien et al. (2023)

Table 2.2 : Continued

Theme	Key Findings	References
	technologies like lithium-sulphur and all-solid-state batteries show potential.	
Regional and Economic Factors	Driving habits, fuel and electricity costs, and regional policies significantly influence ownership costs. Sensitivity analysis should account for inflation and fuel cost fluctuations.	Gorbea et al., (2010); Mehta et al., (2023)
Holistic Evaluation	Comprehensive LCC assessments are essential for evaluating economic and environmental impacts, aligning vehicle technology with energy systems, and promoting sustainable transportation.	Redpath et al. (2011); Li et al. (2015) Wilken et al. (2020); Wulf et al. (2023)

Research shows that the economic feasibility of EVs depends on factors such as initial acquisition costs, operational expenses, electricity sources, and generation costs. A comprehensive evaluation of vehicle lifespans and energy systems is crucial for assessing the viability of sustainable transportation options.

However, traditional LCC models need adjustments to account for regional factors like climate, policies, and discount rates, particularly in Heilongjiang Province. Incorporating local externalities and economic data can provide a more accurate assessment of BEV adoption costs and benefits.This study addresses gaps in prior research by enhancing LCC applicationthrough the inclusion of regional factors, such as climate and policy, which influence BEV and GV usage. It aims to provide a more tailored and accurate evaluation of sustainable transportation in Heilongjiang.

2.3.2 Life Cycle Assessment (LCA) Past Research Indicators

The concept of Life Cycle Assessment (LCA) emerged in the 1960s amid growing concerns about environmental degradation and resource scarcity (Bjørn et al., 2018). One of its earliest applications was Harold Smith’s 1963 analysis of energy requirements for chemical production (Brusseau, 2019). LCA evaluates the environmental impacts of products, processes, or services across their entire life cycle, from raw material extraction to disposal or recycling (Buchert et al., 2015). It is a standardized tool under ISO 14040, aimed at promoting sustainable consumption and production by addressing the triple bottom line of sustainability: people, planet, and profit (UNEP/SETAC Life Cycle Initiative, 2011).

LCA enables detailed comparisons to clarify sustainable products, technologies, and processes (Saranya & Ramachandra, 2020). It assesses both upstream (material and process choices) and downstream (use and disposal) impacts, providing a comprehensive view of environmental consequences (Khoshnevisan et al., 2020). Despite its strengths, LCA faces challenges, including uncertainties and incomplete coverage of all environmental impacts (Mayer et al., 2019).Nevertheless, it remains a vital tool for evaluating resource depletion and environmental effects (Rajaeifar et al., 2019).

The summarize of minly past study as **Table 2.3.** Electric vehicles (EVs) have shown significant potential in reducing greenhouse gas (GHG) emissions from the transportation sector. However, their environmental impacts are complexly affected by multiple factors. Studies have shown that the use phase of EVs consumes the most energy, water, and carbon, accounting for 85.3% of the total environmental impact (Onat et al., 2016). In China, due to the power structure, electric vehicles release a large amount of acidification gas and carbon dioxide during operation (Wang et al., 2019). Song et al. (2018), Petrauskienė et al. (2021), Bao et al. (2021), and Evtimov et al. (2020) Despite this, multiple studies have consistently concluded that EVs can significantly reduce GHG emissions and promote the transition to a greener transportation system. However, Shi et al. (2016), Boureima et al. (2009), and Abdul-Manan (2015) life cycle assessment (LCA) also points out that EVs may have greater negative impacts on certain environmental indicators, such as impacts on human health and atmospheric acidification.

Yu et al. (2018) assessed the environmental impacts of EVs and GVs in China, highlighting the role of coal in China's energy mix and suggesting cleaner energy sources could mitigate EV impacts. Their findings align with Yuksel et al. (2016), Meyer et al. (2018), Archsmith et al. (2015), and Holland et al. (2016), who emphasize the effect of ambient temperature on vehicle efficiency and emissions, advocating for region-specific EV promotion strategies.

The electricity power source is critical in determining EV environmental benefits. Coal power's prevalence and economic competitiveness hinder the full potential of EVs (Zhang & Han, 2017). As highlighted by Hsu (2013), notes that EV sustainability depends on grid cleanliness, while Luk et al., (2016) find that lower-efficiency compressed natural gas vehicles and heavier BEVs may have higher well-to-wheel GHG emissions than GVs. Moro & Lonza, (2018) report that EVs can reduce GHG emissions by ~60% in most EU Member States, with an average 50% savings compared to diesel, though some regions show no savings. EVs can only fully realize their environmental potential when powered by renewables, minimizing electricity production impacts Shafique & Luo, 2022).

Local factors like climate and geography affect EV performance, with the operating phase being most vulnerable to spatial variations (Onat, Kucukvar, & Afshar, 2019). Göhlich et al. (2015) and Ke et al. (2017), emphasize that ambient climate impacts EV range and market penetration, while effective policy and taxation influence consumer decisions and emissions reductions (Nonaka & Nakano, 2011).

EV-charging electricity sources significantly impact their environmental performance. Onat et al. (2019) highlight that 100% solar charging reduces water, energy, and carbon impacts, while Ivanov et al. (2020) show renewable-powered EVs reduce lifecycle emissions.. Moro and Lonza (2018) and Al-Buenain et al. (2021) stress diminished EV benefits in fossil fuel-reliant regions, underscoring the need for cleaner energy transitions..

Battery production significantly impacts EV sustainability. Thomitzek et al., 2019). find battery production is a major contributor to EV environmental impact, while Lombardi et al. (2017) emphasize the importance of efficient battery production and recycling to mitigate harmful effects.

Vehicle weight reduction is often seen as beneficial for environmental performance, but He et al. (2023) and Witik et al., (2011)note that lightweight materials like carbon fiber and magnesium may not always provide significant lifecycle benefits. Song et al. (2018) report EVs achieve significant GHG reductions, with emissions at 12.39 kg CO_2-eq/100 km in Macau.

The literature highlights the importance of technological and policy advancements in improving transportation sustainability. Lombardi et al. (2015), Candelaresi et al. (2022), Oliveri et al. (2023), and Trudewind et al. (2014) explore hybrid vehicle performance, efficient designs to reduce carbon footprints, and the use of captured CO_2 for fuel production, offering innovative solutions to minimize vehicle environmental impacts.

Comparative studies by Bekel and Pauliuk (2019) cshow BEVs outperform FCVs environmentally and financially, while Wang et al. (2015) highlight a 51-57% reduction in lifecycle energy consumption and 40-57% decrease in GHG emissions for advanced EVs compared to GVs.. Wu and Sun (2022) emphasize the long-term potential of BEVs in reducing fuel use and GHG emissions, stressing the need for cleaner energy and sustainable materials.

Research on water usage (Wang et al., 2020), car-sharing models (Ding et al., 2019), urban mobility (Jungmeier et al., 2012), catalytic converters (Islam et al., 2018), and water usage contribute to the discussion by addressing distinct aspects of the EV ecosystem.

Carbon emission reduction requires efforts from both producers and consumers, with each playing a role in achieving societal goals (Zhang et al., 2023). Nonaka and Nakano (2011) and Guo et al. (2023)emphasize the importance of policy and consumer behavior in driving emission reductions. Geographical variances, temperature effects, and the economic and social sustainability of EVs are critical, with personal EVs experiencing significant range reductions in winter (Hao et al., 2020; Reyes et al., 2016).

Despite higher lifecycle energy consumption and emissions due to battery production (Yang et al., 2020). Cai et al., (2017) find ICEVs have better lifecycle sustainability than BEVs in China, though Zeng et al., (2021). report BEVs and PHEVs reduce GWP by 23% and 17%, respectively, compared to ICEVs.

The lifetime energy consumption of a pure EV is 60.8% of a fuel vehicle, though fuel vehicles use 58.6% less energy in manufacturing but have higher emissions (Luk et al., 2019). Hou et al. (2022), project significant global GHG reductions from BEVs by 2030 and 2050, aiding the transition to a low-carbon transportation industry.. Cai et al. (2017) suggest using hybrid life cycle and multi-criteria decision analysis for city taxi fleets to assess environmental, financial, and political impacts. Reducing driving and adopting green consumption patterns, such as fewer car trips and energy-saving practices, can lower household GWP (Ding et al., 2019: Yu et al., 2020).

Table 2.3 : Mainly Past Study of Vehicle's LCA Study

Study	Methodology	Key Findings
Onat et al., (2016)	LCA	The operational phase of EVs accounts for 85.3% of their total environmental impact, primarily due to electricity consumption.
Wang et al., (2019)	LCA	In China's energy context, EVs emit significant amounts of acidifying gases and CO_2 during operation.
Song et al. (2018)	LCA	EVs significantly reduce greenhouse gas emissions but have a greater impact on human health and acidification.
Yu et al. (2018)	LCA	China's coal-dominated energy mix diminishes the environmental benefits of EVs; cleaner energy sources can improve this.
Moro & Lonza, (2018)	Well-to-Wheel (WTW) Analysis	In most EU countries, EVs reduce GHG emissions by approximately 50% compared to diesel vehicles, but in some countries, there are no savings.
Luk et al., (2016)	WTW Analysis	Even with lower carbon intensity of non-petroleum energy sources, low-efficiency compressed natural gas vehicles and heavier EVs may have higher GHG emissions per kilometer than gasoline vehicles.
Zhang & Han, (2017)	Energy Analysis	The prevalence and economic competitiveness of coal power hinder the full potential of EVs.
Hsu (2013)	Sustainability Analysis	The sustainability of EVs depends on the cleanliness of the energy grid.
Onat et al. (2019)	Scenario Analysis	100% solar charging significantly reduces water, energy, and carbon impacts of EVs, highlighting the importance of renewable energy.

Table 2.3 : Continued

Study	Methodology	Key Findings
Ivanov et al. (2020)	LCA	EVs powered by renewable energy sources have significantly lower life-cycle emissions.
Thomitzek et al., (2019)	LCA	The environmental impact of EVs is largely due to battery production; attention to battery system energy impacts is necessary for accurate LCAs and LCCs.
Lombardi et al. (2017)	LCA	Emphasizes the importance of effective battery production and recycling to reduce negative environmental impacts.
He et al. (2023)	Material Analysis	Investigates how vehicle materials affect environmental impact, finding that lightweight materials like carbon fiber and magnesium may not always provide significant environmental benefits over their lifecycles.
Bekel and Pauliuk (2019)	Comparative Study	Battery Electric Vehicles (BEVs) currently outperform Fuel Cell Vehicles (FCVs) in environmental and financial aspects, though they have shorter ranges. Fuel supply infrastructure also significantly affects life cycle impacts.
Wang et al. (2015)	GREET Model	Advanced vehicles show a 51% to 57% reduction in life-cycle total energy consumption and a 40% to 57% decrease in GHG emissions compared to conventional gasoline vehicles.
Wu and Sun (2022)	Long-term Impact Analysis	Highlights the importance of developing new technologies, producing cleaner energy, and using sustainable materials to enhance the sustainability of the EV industry.

Studies show EVs can reduce greenhouse gas emissions, but their environmental impact depends on electricity sources, battery production, and regional characteristics. Realizing their full potential requires addressing energy structure, technology, and policy implementation.

While existing research is extensive, a gap remains in assessing EV environmental impacts in regions with unique conditions. This study focuses on Heilongjiang Province's distinct climate and energy mix, integrating regional data to reduce uncertainties and provide clearer insights. It addresses limitations in prior research (LR) and fills the gap in region-specific EV sustainability analysis

2.3.3 Social Life Cycle Assessment (S-LCA) Past Research Indicators

Social Life Cycle Assessment (S-LCA) evaluates the social impacts of products throughout their life cycle, emerging in the mid-1990s as a complement to environmental assessments (McCabe & Halog, 2018). Initially integrated into E-LCA, it was later recognized as a distinct method to address social and socioeconomic impacts Ramos Huarachi et al., 2020). S-LCA is guided by the *Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA)*, *Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021*, and *Guidelines for Social Life Cycle Assessment of Products* (United Nations Environment Programme and SETAC, 2013, UNEP, 2009, 2021).

S-LCA examines organizational and stakeholder impacts, including workers, local communities, society, consumers, and value chain actors (Baumann et al., 2002; UNEP/SETAC Life Cycle Initiative, 2011). This study focuses on the use stage, where consumers are the primary stakeholders.

LCA aims to improve social conditions and socio-economic performance, recognizing both compliance with minimum benchmarks and positive impacts beyond them (UNEP, 2009, 2021). It uses social indicators to inform decision-making and enhance stakeholder well-being (Jørgensen et al., 2012). Key impact categories for EV and GV research include health and safety, feedback mechanisms, privacy, transparency, and end-of-life responsibility (United Nations Environment Programme and SETAC, 2013).

Health and safety focus on protecting consumers from harmful products, supporting SDG 3 (United Nations Conference on Trade and Development, 2018). Feedback mechanisms help businesses respond to consumer needs, driving innovation and sustainable consumption (Kuusisto, 2016). Privacy concerns, such as data protection, influence consumer trust and align with SDG 16 Wang, 2023) Transparency in product information supports informed consumer decisions and aligns with SDG 12.6 and 12.8 (Bibby et al., 2018; Wang et al., 2023). End-of-life responsibility, including recycling and waste reduction, supports SDG 12.5 by promoting sustainable disposal practices (Islam et al., 2021; UNEP, 2021).

The societal implications of EVs and FCEVs are critical for sustainable mobility. Springer et al. (2024) emphasize addressing labour rights and gender-based wage inequalities in FCEV production, though social impacts during usage and end-of-life remain under-explored. Governance issues, corruption, and legal inadequacies in industries like oil and sugar cane are relevant to EVs, leading to labour exploitation and environmental degradation (Ekener-Petersen et al., 2014). Workers' rights, including freedom of association and health and safety, are equally crucial in the EV supply chain (Osorio-Tejada et al., 2020)Vulnerabilities in the lithium-ion battery supply chain, such as child labour and poverty, highlight the need for geographical and risk-based assessments (Thies et al., 2019). Lighter batteries offer economic and social benefits, underscoring the importance of weight in sustainability efforts (Popien et al., 2023). Social Hotspots Database reveals risks in fossil fuels and biofuels, stressing the role of labour practices and human rights in long-term viability (Ekener-Petersen et al., 2014; Wilken et al., 2020).

Few studies assess consumer social impact during the use stage, despite its importance for satisfaction and adoption (Gonçalves & Silva, 2021). Vehicle safety, driving range, and winter performance are key consumer priorities (Featherman et al., 2021; Hanssen & Hasan., 2023; Sinha & Brophy., 2021). In the study by de Sousa and Castañeda-Ayarza (2022), many Brazilians believe that they would buy an EV when they increase their autonomy and when the availability of recharging points increases. Koppel et al. (2008) emphasise the importance of vehicle safety in influencing consumers' purchase decisions. It also significantly influences customer satisfaction, which in turn significantly affects customer loyalty (Susanto, 2013). Folkvord et al. (2020) highlight that Europeans prioritise factors such as price, safety, and performance over health and environmental impacts when making purchasing decisions.

Consumers' views on privacy are another significant aspect. Belanger et al. (2002) reported that trustworthiness, combined with web features such as security, privacy, and pleasure, influences purchasing intent and the willingness to disclose information. Privacy is an essential part of social well-being. Featherman et al. (2021) noted that consumers are concerned about the privacy of their driving information. These concerns are heightened by incidents like the NIO Automobile data breach (Jiang, 2023; Liu, 2022). GIP Digital Watch Observatory Team (2023) highlighted the vague security standards in the automotive industry. The increasing dependence on Internet of Things raises data security and privacy issues due to embedded sensors that collect personal, financial, health, and charging records; driving patterns; video and location coordinates; and car-related data (Malik et al., 2022). The addition of cameras, sensors, and monitoring devices to make EVs more sustainable also poses risks to user privacy (Saoudi et al., 2022). Thus, there is an urgent need to implement robust privacy measures to maintain consumer trust.

Transparency is also crucial. Yang and Battocchio (2020) examine the influence of product transparency on consumer brand attitudes, trust, and behavioural intentions. Kim et al. (2020) find that both price and production transparency positively affect overall brand equity and consumers' purchase intentions. Consumers are increasingly voicing their desire for transparent business practices and their willingness to support transparent brands (Gazzola et al., 2017; Su et al., 2019). Achtnicht (2012) advocates the use of ecolabelling to increase transparency and strengthen customer trust in environmental claims. Transparency significantly influences consumers' perceptions and attitudes (Cheng & Mugge, 2022; Ryan & Michael, 2021). In studies on environmental and ethical consumption, attitudes mediate the effects of various determinants (such as knowledge, values, concern, and affect) on behavioural intentions (Chan, 2001; Kang & Hustvedt, 2014). Featherman et al. (2021) highlight the influence of important individuals in younger consumers' EV evaluation and purchase decisions, indicating the need to consider social influences in understanding consumer behaviour. Vehicle buyers reflect the trend of younger customers (Hu, 2023).

Customer feedback is vital for quality improvement, new product success, and business profitability (Eiríksdóttir & Thorarensen, 2012). A customer feedback information system collects, summarises, and responds to client input to enhance products and services (Wang, 1996). Bjarklev et al. (2017) stress the importance of feedback mechanisms in meeting market demands, advocating for systematic collection to guide product enhancements and innovation. Fundin and Bergman (2003) argue that a structured approach to gathering customer feedback helps clarify areas for improvement in existing products and provides valuable insights for developing new ones. Tognazzini (2004) highlights that unclear information practices can discourage consumer purchases, arguing for increased transparency to improve society and maintain competitive marketplaces.

To address end-of-life and future concerns, customer satisfaction, which refers to the extent to which a product's perceived performance aligns with buyer expectations, is important (Kotler et al., 2012). Buyer decisions are heavily influenced by their satisfaction with the product or service (Park et al., 2010). According to Chan et al. (2015), support intentions, which include purchase intentions and future preferences, are the sole measure capable of predicting consumer behaviour. Therefore, addressing end-of-life and future concerns is essential for maintaining customer satisfaction and encouraging positive support intentions, ultimately predicting and influencing consumer behaviour towards more sustainable choices. Environmental concerns significantly influence consumers' attitudes towards purchasing eco-friendly products (Dutta & Hwang, 2021).

Wang et al. (2019) address customer concerns related to the adoption of EVs, highlighting issues such as driving range, availability of charging stations, and post-purchase support. Waiting time to access chargers and charging station availability also influence consumers' decisions (Xie et al., 2018). Insufficient public charging infrastructure can deter consumers from purchasing EVs (Mortimer et al., 2022). Additionally, the limited driving range of BEVs is a significant concern (Jiang et al., 2014). Social impact concerns vary across different geographic and cultural contexts (Masilela & Pradhan, 2021).

EVs are faced with uncertainty concerning battery costs (Inkpen & Baily, 2019; Egbue & Long, 201). Nonetheless, the maintenance and operating costs are lower for EVs than GVs because of current policy and technology (Bessenbach & Wallrapp, 2013). In China, policymakers have introduced policies to promote the replacement of GVs (Hu et al., 2021). Nonetheless, Al-Buenain et al. (2021) highlight the importance of considering social aspects in the transition to EVs, recommending motivational efforts like financial incentives, free parking, free charging, and lower registration fees to expedite the transition and align with infrastructure readiness. Moreover, Cordera et al. (2019) point out increasing concerns about the environmental perspective, which can increase the penalty cost per kilometre of GV usage. Summary of vehicles SLCA previous research shows in **Table 2.4.**

No research has explored the social impact of electric vehicle (EV) use on consumer stakeholders. This study addresses this gap by examining the use stage and considering consumers as key stakeholders. The identified social indicators reveal critical societal factors influencing EV adoption, emphasizing the need to enhance consumer well-being to promote sustainable vehicle choices. Integrating these indicators into policy and technology development is essential for a comprehensive sustainability assessment.

Table 2.4 : Vehicles SLCA Previous Research

Aspect	Key Findings	References
Labour Rights & Gender Equality	Addressing labour rights and gender-based wage inequalities in FCEV production is critical. Social impacts during usage and end-of-life stages remain under-explored.	Springer et al. (2024)
Governance & Legal Systems	Governance issues, corruption, and legal inadequacies in industries like oil and	Ekener-Petersen et al. (2014)

Table 2.4 : Continued

Aspect	Key Findings	References
	sugar cane are relevant to EVs, leading to labour exploitation, poor working conditions, and environmental degradation.	
Workers' Rights	Concerns in freight transportation (e.g., freedom of association, working hours, health and safety) are equally relevant to EVs, highlighting the need for comprehensive social assessments in supply chains.	Osorio-Tejada et al. (2020)
Battery Supply Chain Risks	Vulnerabilities in lithium-ion battery supply chains include child labour, corruption, occupational hazards, and poverty. Lighter batteries offer economic and social benefits.	Thies et al. (2019) ;Popien et al. (2023)
Social Hotspots & Fuel Types	Social Hotspots Database highlights risks in fossil fuels and biofuels, emphasizing the importance of social variables in sustainability assessments. Labour practices and human rights impact long-term viability.	Ekener-Petersen et al. (2014); Wilken et al. (2020)
Consumer Social Impact	Few studies assess consumer social impact during the use stage. Consumer satisfaction is influenced by product quality, safety, and transparency, which are critical for fostering sustainable consumption.	Gonçalves & Silva,(2021) ; Featherman et al.(2021); Hanssen & Hasan, (2023)
Vehicle Safety and Health	Safety, driving range, and winter performance are key consumer priorities. Similar ownership experiences to ICEVs are essential for EV adoption.	Sinha & Brophy, (2021); de Sousa and Castañeda-Ayarza (2022); Koppel et al. (2008)
Privacy Concerns	Privacy is a significant consumer concern, especially with IoT-enabled EVs. Data breaches and vague security standards in the automotive industry heighten these concerns.	Featherman et al. (2021); Jiang, (2023); Liu, (2022); Malik et al., (2022)
Transparency	Transparency in product information and business practices positively influences consumer trust, brand equity, and purchase intentions. Ecolabelling can enhance transparency and trust in environmental claims.	Yang and Battocchio (2020) ;Kim et al. (2020); Achtnicht (2012)

Table 2.4 : Continued

Aspect	Key Findings	References
Customer Feedback	Feedback mechanisms are vital for product improvement and innovation. Systematic collection of feedback helps meet market demands and guide sustainable product development.	Eiríksdóttir & Thorarensen, (2012); Bjarklev et al. (2017) ; Fundin & Bergman, (2003)
End-of-Life Concerns	Addressing end-of-life responsibilities and future concerns is essential for maintaining customer satisfaction and encouraging sustainable choices. Environmental concerns significantly influence consumer attitudes.	Kotler et al., (2012); Park et al., (2010); Dutta & Hwang, (2021)
EV Adoption Barriers	Consumer concerns include driving range, charging infrastructure, and post-purchase support. Policy incentives like financial benefits and lower registration fees can expedite EV adoption.	Wang et al. (2019); Xie et al., (2018); Al-Buenain et al. (2021)
Policy & Infrastructure	Policymakers in China promote GV replacement with EVs, but social aspects like infrastructure readiness and financial incentives must be considered. Environmental penalties for GV usage can further drive adoption.	Hu et al., (2021); Cordera et al. (2019)

2.3.4 LCSA Past Studies

LCSA integrates LCA, LCC, and S-LCA to assess the environmental, economic, and social sustainability of products within a unified framework (UNEP/SETAC Life Cycle Initiative, 2011). Rooted in ISO 14040, it enables a comprehensive evaluation of trade-offs in sustainability decision-making (Tarne et al., 2019). Given the increasing emphasis on sustainability in strategic product assessments (Kurka, 2013). LCSA provides a robust approach for early-stage evaluations. The methodology aligns with the triple bottom line (TBL) concept (Hoque et al., 2019). The three approaches that constitute the LCSA methodology are LCA, LCC, and S-LCA. The formula of the LCSA framework is LCSA = LCA + LCC + S-LCA (Klöpffer & Renner, 2008).

Among the literature reviewed in this paper are case study articles that used the LCSA approach. So, we categorized the case study articles by case product or case focused, and found ten categories in total: animal product, transportation, energy, plant, waste, building, chemical or biological product, mineral, industry, and others. **Table 2.5** contains a list of 67 published case studies that used the LCSA approach product category. From this part, it is easy to see that LCSA has already been applied in many different areas or products; in this study, the most popular area was discovered, but there is still room for further research.

This analysis should be shared with other authors. LCSA has been applied to illustrate what product or field has a gap, which product or field is currently more or less researched, and can help researchers to quickly find the research gap.

Table 2.5 : 67 Published Case Studies Used LCSA Approach Product Category and Reference

Product category	Reference
Animal products:	Pork (C. Valente et al., 2020), pork supply chains in Sweden(Zira et al., 2021), pork meat in Croatia(Josip Mesaric et al., 2016), cow´s milk (López et al., 2020), pork supply chains (Zira et al., 2021)
Transportation:	light rail transit system (Gulcimen et al., 2021), electricity or vehicle fuel (Masilela & Pradhan, 2021), pavement maintenance

Table 2.5 : Continued

Product category	Reference
	alternatives (Zheng et al., 2019), Transport Sector (Hoque et al., 2020)
Energy:	Solar Photovoltaic (Traverso et al., 2012), electricity generation (Akber et al., 2017), biogas production (Q. Jin et al., 2017), electricity scenarios (Stamford & Azapagic, 2014), electric mobility (Onat, Kucukvar, Aboushaqrah, et al., 2019), vegetable oil-based biodiesel (Nguyen et al., 2017), synthetic fuels from date palm waste (Ben Hnich et al., 2021), ground source heat pump in Shanghai, China (Huang & Mauerhofer, 2016), concentrated solar power (Corona & San Miguel, 2019), Solar Photovoltaic Development (M. Yu & Halog, 2015),Rice Husk Based Bioelectricity vs. Coal-fired Electricity (Luu & Halog, 2016), renewable and conventional hydrogen (A. Valente et al., 2021), crude oil in India(Shrivastava & Unnikrishnan, 2021), remanufactured alternators (Schau et al., 2011), electricity scenarios (Stamford & Azapagic, 2014).
Plant:	olive growing systems (De Luca et al., 2018), mangrove management (Moriizumi et al., 2010).
Waste:	Landfills, fertilizers (Martínez-Blanco et al., 2014), Municipal Solid Waste Management (J. Wang et al., 2018), Waste Recycling (Berardocco et al., 2022), agricultural and agro industrial wastes(Rizki Aziz et al., 2016), water sector (Bhambhani et al., 2022), remediation alternatives for contaminated lake sediments (Reddy et al., 2018), cooking oil waste management (Vinyes et al., 2013), different packaging waste collection systems (Yıldız-Geyhan et al., 2019), concrete recycling (M. Hu et al., 2013), crude oil(Shrivastava & Unnikrishnan, 2021), Bioenergy Development for Landfills(Ruiz & Diaz, 2022), Circular economy solutions for industrial wastes(Tóthné et al., 2020).
Building:	Residential building (Lin et al., 2021; Yıldız-Geyhan et al., 2019), construction product (López et al., 2020), Civil Engineering (Ek et al., 2020), Geotechnical Ground (Raymond et al., 2021), concrete structures in the tropics (Jahandideh et al., 2020), different concrete construction techniques for residential building(Balasbaneh & Sher, 2021).
Chemical or biological product:	High-Density Polyethylene Production (Hannouf & Assefa, 2017), polyethylene terephthalate (PET) bottles (Foolmaun & Ramjeawon, 2013), biorefinery placement(Zupko, 2021), wood derived drop-in biofuels(Bortsie-Aryee et al., 2012), Bioeconomy with algae (Hingsamer et al., 2017), ammonia process(Samaroo et al., 2020).
Mineral:	Rare Earth Permanent Magnets (Hingsamer et al., 2017), copper (Kuipers et al., 2018), mineral resource availability

Table 2.5 : Continued

Product category	Reference
	(Kuipers et al., 2018), Mineral resources (Drielsma et al., 2016), Rare Earth Permanent Magnets (Wulf et al., 2017)
Industry:	Additively Manufactured Products (AMP) (Drielsma et al., 2016), laminated veneer lumber production (Zeug et al., 2022), electric vehicles and dental X-ray equipment (Cimprich et al., 2018), Nanoscale Zerovalent Iron Production Methods (Visentin et al., 2022), cheese industry(Gosalvitr et al., 2021), sustainable nanotechnologies (D. E. Meyer & Upadhyayula, 2014), Concrete Plant Operations (Roh et al., 2018), Crucible Melting Furnace(Schutzbach et al., 2022), Used Lubricant Oil (Tsambe et al., 2021), Additively Manufactured Product(J. Ma et al., 2018), Ceramic District of Sassuolo (Settembre Blundo et al., 2019).
Others:	Trade off sourcing strategies for humanitarian relief items(Roh et al., 2018), culture (Pizzirani et al., 2018), annual global space activities (Wilson et al., 2022), travelling exhibition (Biedermann et al., 2021), Ceramic District of Sassuolo, sustainable city logistics (Nathanail et al., 2017, 2021).

Troullaki et al. (2021) argue that LCSA, in its current form, lacks comprehensiveness as a cross-disciplinary sustainability framework. To enhance its interpretation, decision-making models should be integrated (Furness et al., 2021). Berticelli et al. (2020) emphasize the need for systematic decision-support methods considering environmental, social, and economic factors. LCSA practitioners face methodological and practical challenges depending on the sustainability dimension assessed (Lassio et al., 2021). Wilken et al. (2020) propose an MCDM approach for comparing EVs and ICEVs, while Wang et al. (2019) used the GaBi software for environmental impacts and LCA indicators. Found that ICEVs are more sustainable in China due to BEVs' higher environmental impacts and costs.

Popien et al. (2023) analyzed ten battery types using LCSA, assessing climate change, toxicity, resource depletion, photochemical oxidants, costs, and social risks. Their results suggest lithium-sulphur batteries with solid electrolytes have lower impacts, especially with increased renewable energy use, though production energy demands remain high.. Wilken et al. (2020) further propose integrating multi-criteria assessments to help decision-makers implement sustainable vehicle technologies, noting that BEVs are more sustainable when charged with renewables.

Despite LCSA’s potential, discussions on social and economic factors remain limited (Zamagni et al., 2013). The complexity of S-LCA and LCSA, along with data limitations, hinders conceptual clarity. Future research should incorporate dynamic criteria to balance environmental, social, and economic issues, especially in emerging economies (Salim et al., 2022).

To further technological development and the understanding sustainability, more case studies are required. Further, there is a need to achieve equal weights for the three pillars and build sustainability on the same plane. The LCSA method needs to be improved so that decision-makers can better understand the LCSA results. The development and use of LCSA is anticipated to facilitate the assessment of SDGs and sustainability across various global locations, businesses, and products.

2.4 Review on Monetisation of Sustainability

Monetisation enables the costs of environmental problems to be perceived (Herendeen, 1998).By comparing these goals in monetary terms, it reduces subjectivity in environmental performance assessment (Farmani et al., 2005). It has been widely applied to measure the economic consequences of ecological effects (García-Gusano et al., 2018).

Despite their comprehensiveness, endpoint metrics are difficult to integrate due to interdependencies, making interpretation challenging for decision-makers (Valdivia et al., 2021).Weightings in LCA, LCC, and S-LCA are often contentious., Ekener, Hansson, Larsson et al. (2018) suggest using stakeholder profiles from cultural theory to determine sustainability weights instead of assuming equal distribution. Tarne et al. (2018) found that German automotive decision-makers assigned weights of 0.352 (environmental), 0.335 (economic), and 0.312 (social). Wulf et al. (2023) reported that energy system modellers prioritized environmental sustainability (0.385), significantly higher than social (0.320) and economic (0.295) factors. However, some studies advocate for equal weighting (Pope et al., 2004). Others argue that environmental concerns should be prioritized to safeguard future generations, aligning with the Brundtland principle (Kuhlman & Farrington, 2010). This study adopts equal weighting for sustainability dimensions.

Tamym et al. (2023)propose an LCSA-based monetisation approach combining the Environmental Priority Strategy (EPS) with big data analytics (BDA). The

EPS method evaluates five safeguard subjects: human health, ecosystem capacity, abiotic resources, biodiversity, and cultural values. Moslehi and Reddy (2019) develop a multi-criteria sustainability framework that monetises economic, environmental, and resilience factors across lifecycles but excludes social impacts.

2.4.1 Monetisation of Social Impact

Monetising social impacts in sustainability is crucial for engaging key stakeholders—consumers, citizens, companies, and governments—in the transition to a sustainable society. Vogtländer et al. (2002) stress the need for a common language among stakeholders to influence consumer behaviours, drive sustainable product development, advance this field by assigning monetary values to social variables (e.g., minimum wage, child labour, extreme poverty) using the s-eco-costs model. However, this method mainly addresses workers, neglecting other stakeholder groups defined by UNEP (2009), underscoring the challenge of applying socio-economic cost approaches broadly.

Ecological cost quantifies environmental impacts in monetary terms, aiding product sustainability comparisons (Vogtländer et al., 2002). Standardisation simplifies sustainability evaluation, bridging communication gaps among stakeholders.

Da Silva et al. (2023) introduce a new approach to monetising social impacts in supply chains, focusing on job creation, workplace accidents, and employee training. Their optimisation tool allows independent or simultaneous assessment of economic and social trade-offs in supply chain planning. Integrating social impact monetisation into sustainability fosters stakeholder engagement and sustainable production and consumption. However, challenges in broadening socio-economic cost approaches and ensuring inclusivity highlight the need for further research and methodological advancements.

2.4.2 Monetisation of Environmental Impacts

Monetising life cycle indicators is a significant advancement in environmental and social management, simplifying LCA interpretation and aiding policymakers (Kaenchan & Gheewala, 2017). Traditional impact representation often fails to convey trade-offs effectively, whereas monetisation standardises impact prioritisation based on public choice (Rabl & Holland, 2008). This approach translates life cycle indicators into monetary values to address environmental stressors, including health damage, ecosystem diversity, and resource availability (Algunaibet et al., 2019).

Assigning monetary values to environmental emissions enables economic evaluation of environmental harm, integrating external costs into decision-making (Krieg et al., 2013). Methods such as contingent valuation (CVM), hedonic pricing, and WTP link ecological impacts to economic value (Li et al., 2017). Monetisation enhances environmental policy by quantifying consequences for better prioritisation (Arendt et al.,2020).

Ecotaxes, introduced in Sweden in 1998, align societal values with environmental initiatives (Johansson, 1999). These taxes propose levies reflecting society's assessment of resource use and emissions (Finnveden et al., 2006). However, the subjective nature and jurisdictional differences create challenges in implementation (Zamagni et al., 2008).The complexity of converting environmental resources into monetary values within different tax systems highlights the need for tailored policies (Cao et al., 2012) China's green tax system exemplifies these challenges (Kong,2010).

The life-cycle impact assessment method based on endpoint modelling (LIME), a framework developed in Japan, assesses endpoint damages in human health and biodiversity to evaluate environmental impacts (Itsubo et al., 2004; Yi et al., 2011).The framework depends heavily on the selection of endpoints and protected subjects, which can introduce bias based on the subjective importance placed on certain impacts over others.

Discounting incorporates a time element into environmental impact assessments, ensuring inter-generational fairness (Zhang, 2017). This approach supports the use of a zero discount rate in evaluating environmental sustainability (Hellweg et al.,2003). The Brundtland principle reinforces this perspective, advocating that development should not compromise future generations (UN. Secretary-General & World Commission on Environment and Development, 1987). Selecting an appropriate discount rate is challenging and contentious. Different rates can significantly alter the outcomes of environmental evaluations, affecting decision-making processes.

The environmental priority strategies (EPS) method, developed in 1991–1992 and updated in 2000, facilitates product sustainability evaluation by assigning monetary values to emissions, resource use, and direct expenditures (Steen, 1999). Damages to essential insured objects are assessed based on WTP (Thi et al., 2016). It calculates the whole costs of developing renewable alternatives to fossil fuels, including the WTP for emissions, resource consumption, and direct expenditures (Zamagni et al., 2008). However, WTP has subjectivity and economic bias.

The social cost of carbon (SCC) assigns a monetary value to carbon emissions, but its applicability varies across regions due to economic, social, and climatic differences (United States Environmental Protection Agency, 2017). Even though it is a useful tool, SCC is not applicable universally due to different climatic, economic, and social conditions affecting how carbon impacts are valued. Different approaches to calculating the SCC can lead to vastly different outcomes, complicating international efforts to standardise climate change mitigation strategies.

Stepwise2006 integrates IMPACT 2002 and EDIP 2003 in SimaPro, categorising environmental impacts into human health, ecosystem quality, and resource scarcity. This enhances environmental cost – benefit analyses, particularly for future energy costs (Zamagni et al., 2008; Thi et al., 2016).

Monetising the environmental health impacts with the disability-adjusted life years (DALY) accounting system supports the systematic monetisation and selection of relevant health endpoints (Hofstetter & Müller-Wenk, 2005). Algunaibet et al. (2019) utilise DALY to analyse human health impacts, ecosystem impacts in species.yr (loss of species in a year) using the ReCiPe framework, and resource depletion by marginal cost increases, with the results monetised to quantify economic externalities objectively and avoid subjective weighting. Sadhukhan (2022) use Environmental Prices v1,consolidates environmental impact costs into a single value for decision-making This method requires comprehensive data for accurate health impact assessments.

Individual-revealed preference approaches assume market behavior reveals preferences, typically focusing on use values (Finnveden et al., 2006). Most methods for monetising environmental externalities include WTP, which is subjective and varies by region, people, organisation, and situation (Reap et al., 2008). External benefits and costs are often priced in environmental economics (Baracskay, 1998). There are various ways to estimate these virtual costs, such as WTP and willingness to accept (WTA) (Fenwick et al., 2004).

Monetising environmental externalities through revealed preferences and WTP offers a means to assess ecological effects' societal value (Finnveden et al., 2006; Reap et al., 2008). However, valuation varies by region, population, and context, reflecting its subjectivity (Baracskay, 1998; Fenwick et al., 2004). Economic development influences WTP for carbon mitigation (Lee et al., 2008; Zeng, 2011). Carbon taxes, though not widely implemented, are seen as effective tools for GHG reduction, yet comprehensive evaluations remain scarce (Baranzini & Carattini, 2014). WTP is highly subjective, shaped by socioeconomic factors.

Goh and Matthew (2021) found WTP was influenced by gender, age, income, education, household size, and marital status. Von Borgstede et al. (2013) noted income, attitude, and behaviour affected WTP, with tax opponents showing distrust in politicians and concerns over fairness, while supporters prioritised environmental solutions and social justice (Savin et al., 2020). Public perception of tax effectiveness influences support (Ewald et al., 2022), while unwillingness to pay often stems from low income, cost concerns, or lack of knowledge (Chang, 2018). Shaari et al. (2020) identified positive correlations between WTP and income, education, occupation, and age.. Ivanova and Moreira (2023) found EV purchase intention was driven by attitude, trust, WTP, experience, and economic benefits, while poor pre-sales services had a negative impact. Public support is crucial for effective environmental tax implementation (Klok et al., 2006; Wan et al., 2017).

This study employs WTP elicitation for LCA, justifying primary WTP studies (Hofstetter & Müller-Wenk, 2005). Although economic and social effects of carbon taxes are widely studied, research on WTP for policy calibration is limited (Rotaris & Danielis, 2019). Tsang and Burge (2011), suggested WTP may exceed actual carbon reduction costs, creating a social benefit. Countries impose fuel taxes to curb transport emissions, but China’s green tax system remains underdeveloped (Kong, 2010). Effective CO_2 policies must both charge for emissions and encourage behavioural change (Gupta, 2016). Carbon taxes are a cost-effective sustainability tool (Carattini et al., 2018).

WTP remains subjective across regions and contexts (Reap et al., 2008). CVM estimates individuals’ monetary valuation of CO_2reduction (Baker & Ruting, 2014). The complexity of monetising environmental value calls for systematic assessment, with gaps in S-LCA monetisation still to be explored (Rabl & Holland, 2008; Finnveden et al., 2006).

Limited research exists on socio-economic cost approaches within S-LCA. Methods such as ecotaxes, WTP, LIME, discounting, EPS, and stepwise are used, but monetisation of social and environmental sustainability remains underdeveloped. Integrating WTP into S-LCA can enhance sustainability evaluations, aiding consumers, businesses, and policymakers.

2.5 Underpinning Theories

2.5.1 Life Cycle Thinking (LCT)

There is a strong link between sustainable development and LCT, often referred to as the "cradle-to-grave" approach (Clift, 1998). It evaluates environmental, economic, and social impacts across a product's life cycle (Jacob-Lopes et al., 2021). while prioritising basic needs within environmental and technological constraints (United Nations, 1992). LCT supports decision-making by clarifying key interventions (Commission of the European Communities, 2003) and is operationalised through Life Cycle Management (LCM), encompassing LCA, LCC, and S-LCA (Toniolo et al., 2020; UNEP, 2012).

LCT originated in 1963 with Environmental Profile Analyses (REPA) and gained momentum with Coca-Cola’s 1969 comparative study. SETAC developed LCA impact assessment in 1991, and since the 1970s, LCT has evolved into a key tool for policy and business decisions (European Commission, Directorate-General for the Environment & European Commission, Joint Research Centre, 2010).A life cycle perspective ensures faster, more effective progress toward sustainability by addressing trade-offs between environmental, economic, and social factors (UNEP/SETAC Life Cycle Initiative, 2013).

Companies adopting LCT consider not only product design and functionality but also environmental and social impacts throughout manufacturing, use, and disposal. This enables them to calculate total life cycle costs, including procurement, transportation, storage, operation, and disposal (Hall, 2018).To support sustainable decision-making, businesses, consumers, and policymakers require comprehensive assessment tools, with LCT serving as the primary framework (Mazzi, 2020).

In the automotive industry, LCT assesses vehicle impacts from material extraction to disposal. Volvo's LCA aims to reduce emissions across all stages, including manufacturing and recycling (Volvo, 2024).

2.5.2 Sustainability Theory

The term “sustainability” first appeared in Karlowitz’s Afforestation and Economy (1713), discussing sustainable forestry. By 1809, it was defined as something reliable amid unsustainability (Shi et al., 2019). Early sustainable development concepts focused on resource use, later expanding to social and economic dimensions. The 1972 Stockholm Summit initiated discussions on sustainability (Sun, 2012), followed by Our Common Future (1987), which defined sustainable development as meeting present needs without compromising future generations (UN. Secretary-General & World Commission on Environment and Development, 1987). The 1992 Rio Summit established global sustainability frameworks (Sun, 2012),highlighted the green economy as a means to balance development and environmental concerns (Barbier, 2021). The 2015 UN Sustainable Development Summit adopted the 2030 Agenda after evaluating the Millennium Development Goals (United Nations General Assembly, 2015).

Debates persist on integrating sustainability ' s three pillars — social, economic, and environmental—often depicted as overlapping circles (Purvis et al., 2019). Some argue these pillars conflict, while others see them as synergistic (Cabezas et al., 2004). Environmental sustainability prioritises resource conservation for future generations (Huckle, 1993), but economic sustainability questions whether current growth models can achieve sustainability (Spangenberg, 2005). Social sustainability focuses on equity and human well-being, ensuring that sustainability policies do not worsen inequalities but promote social justice (Eizenberg & Jabareen, 2017). These three pillars must be balanced, with a healthy environment underpinning economic and social stability.

LCSA integrates sustainability ' s three dimensions into product lifecycle management, evaluating environmental, social, and economic impacts (UNEP, 2013).

Discussions on the best strategies to achieve sustainability range from technological innovation (techno-optimism) to changes in consumer behaviour and lifestyle (sufficiency and downsizing). Sustainable consumption is a key concept in society and the environment due to its direct relationship with sustainable development (Vargas-Merino et al., 2023). Economic, social, and environmental sustainability of any form of consumption requires a comprehensive understanding of all the potential impacts that could materialise throughout a product's production and consumption cycle (Jones et al., 2008). Therefore, consumption should not be understood as a purchasing activity but rather as a process of decision-making and action that includes the product purchase, use, and disposal of any remaining tangible product after use (Peattie & Collins, 2009).

Overall, sustainable development aims to promote human well-being, environmental protection, and economic stability (UNEP, 2020; UNEP/SETAC Life Cycle Initiative, 2011).

2.5.3 Welfare Theory

Welfare theory originated from Adam Smith' s invisible hand, suggesting self-interest drives societal benefits. It evolved with contributions from Jules Dupuit, who introduced consumer surplus, and Vilfredo Pareto, who established welfare improvement criteria. Alfred Marshall further developed consumer surplus, defining it as the difference between a consumer's maximum WTP and the actual price paid, reflecting economic benefit (Mankiw, 1998) This concept remains fundamental in assessing policy impacts on consumer and social welfare.

Arthur Cecil Pigou advanced welfare theory by addressing externalities and public goods, while later economists refined equilibrium models and welfare metrics, balancing efficiency and distribution (Aronsson & Löfgren, 2007). Welfare theory underpins public policy, taxation, environmental protection, and social security, guiding policymakers in addressing market failures through public goods provision and income redistribution (Bockstael & Freeman, 2005).

In sustainability assessments, welfare theory evaluates policy impacts on consumer and social welfare. For example, BEV subsidies enhance consumer surplus by lowering purchase costs, increasing consumer satisfaction. Additionally, EV adoption shifts market dynamics, influencing economic equilibrium in the automotive industry.

2.5.4 Utility Theory

Utility theory originated with classical economists and evolved through neoclassical thought, notably with Hermann Heinrich Gossen's law of diminishing marginal utility (Todorova, 2021). Jeremy Bentham introduced the quantification of pleasure and pain in the late 18th century, influencing 19th-century economists like Gossen, Jevons, and Marshall, who linked utility to consumer decisions and developed marginal utility. The 20th century saw a shift to ordinal utility, with Pareto emphasizing preference rankings over measurable utility, shaping modern consumer behaviour theories (Read, 2004).

Utility theory underpins microeconomics by assuming consumers aim to maximise total utility (Stigler, 1950). It describes how satisfaction (utility) depends on consumed goods and services, with marginal utility illustrating diminishing additional satisfaction (Bernoulli, 1954). WTP derives from utility maximisation, reflecting the marginal utility a product provides (Hanemann, 1991). It is closely linked to consumer surplus—the difference between actual payment and WTP (Brynjolfsson et al., 2019). Utility theory quantifies differential pricing effects on consumer preferences via consumer surplus and utility, benefiting both customers and retailers (Han et al., 2024).

The application of utility theory in environmental policy, especially in designing and implementing carbon tax schemes, provides a method to evaluate and balance economic and environmental goals. This method not only focuses on the economic motivations of consumer behaviour but also considers the social benefits of environmental protection, thereby promoting sustainable economic strategies.

2.5.5 Theoretical Framework

The study is grounded in a comprehensive theoretical framework, as illustrated in **Figure 2.2**. At its highest level, sustainability theory serves as the overarching foundation, guiding the evaluation of a system or process across environmental, economic, and social dimensions. This framework integrates established sustainability theories and Life Cycle Thinking (LCT) to ensure a holistic assessment of impacts.

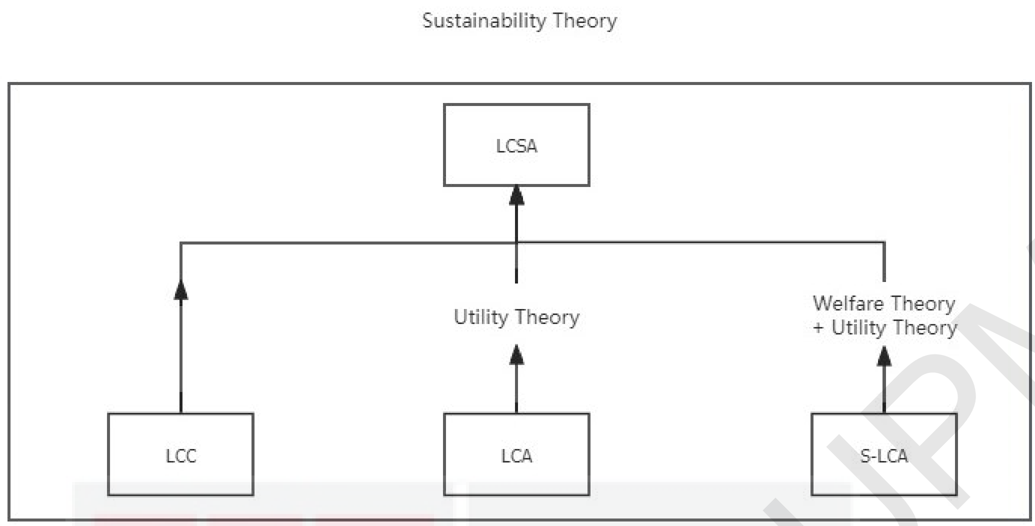

Figure 2.2 : Theoretical Framework of the Study

Life Cycle Costing (LCC) involves clarifying and managing costs throughout a product’ s life cycle, including acquisition, operation, maintenance, and disposal. It provides a long-term financial perspective beyond initial costs, ensuring informed decision-making.

Life Cycle Assessment (LCA) evaluates environmental impacts across a product ’ s life cycle and, in this framework, links to Life Cycle Sustainability Assessment (LCSA) through Utility Theory. Willingness to Pay (WTP) quantifies environmental impact by assessing how much consumers are willing to pay for carbon taxes on electric vehicles.

Utility Theory suggests consumers make decisions based on perceived satisfaction, seeking to maximize utility within budget constraints. WTP, an application of Utility Theory, expresses utility in monetary terms, allowing researchers to estimate the value consumers place on attributes like carbon emission reductions. By surveying WTP for environmental benefits, qualitative utility is translated into financial terms, facilitating the valuation of non-market goods.

Welfare Theory extends these concepts by examining consumer surplus—the gap between WTP and price paid—to evaluate social welfare impacts. Rational consumers purchase when perceived utility exceeds cost, creating surplus. Welfare Theory assesses how social impacts influence this surplus, shaping overall well-being. A social life cycle approach examines how social well-being mediates consumer decision-making. Social impact is quantified by comparing product satisfaction and purchase decisions with market prices. In the automobile market, consumer welfare is measured through questionnaires, capturing real surplus and utility. LCSA integrates LCA, LCC, and S-LCA, using Utility and Welfare Theories to comprehensively assess sustainability by monetizing product sustainability attributes.

2.6 Conceptual Framework

The conceptual framework in **Figure 2.3** outlines the analytical steps for evaluating the sustainability of EVs as replacements for GVs in economic terms. Social impact influences consumer well-being and decision-making, assessed by analyzing the correlation between social indicators and purchase decisions. These correlations determine indicator weights, which are applied in the monetization process.

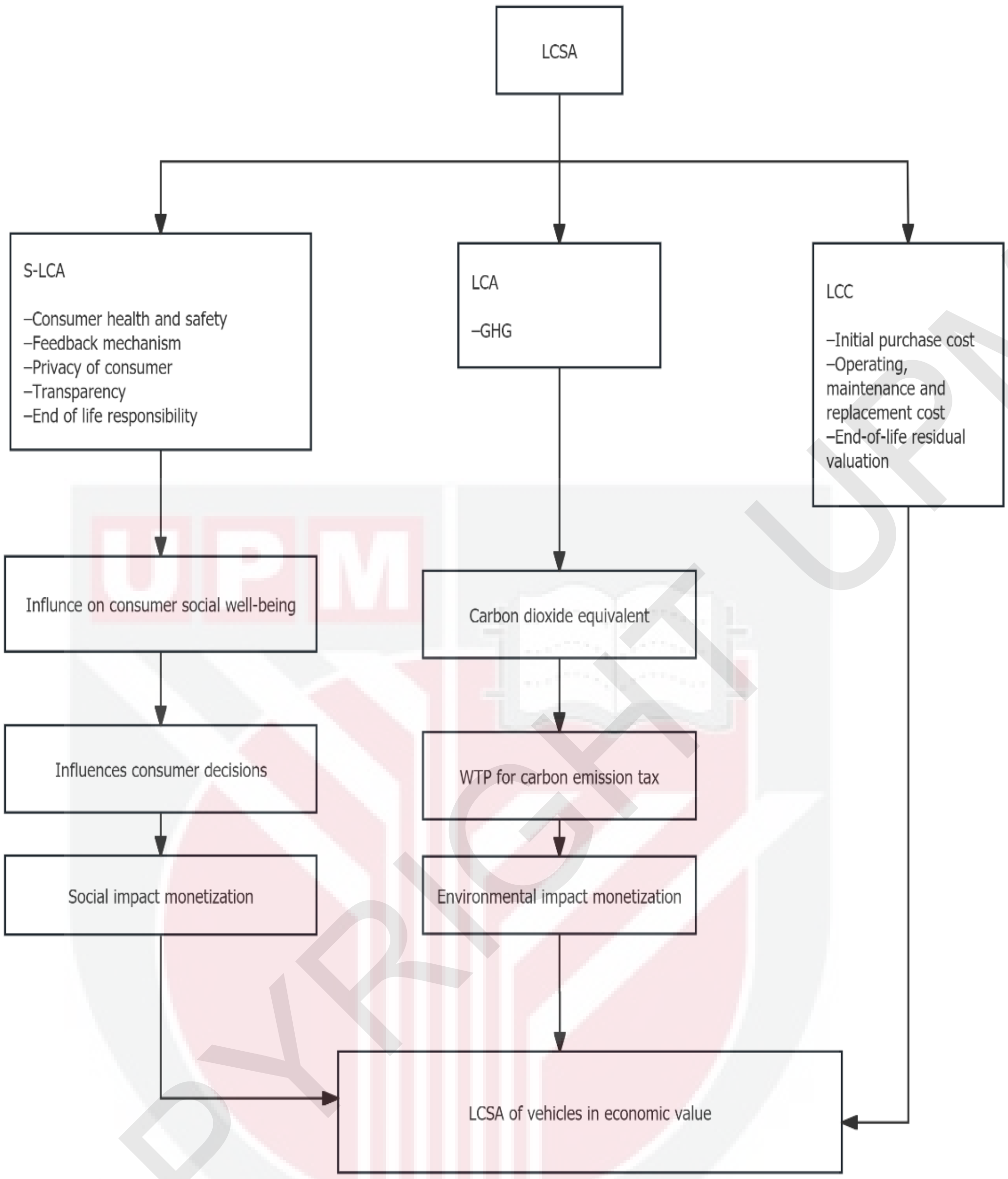

Figure 2.3 : Conceptual Framework of the Study on the Sustainability of EVs as a Replacement for GVs

2.7 Conclusion of Literature Review

Traditionally, sustainability studies using LCA have primarily focused on the environmental perspective. However, the interactions between social, environmental, and economic factors are essential to the sustainable development of EVs. These interdependencies shape the broader sustainability dynamics. This study addresses this gap by integrating all three dimensions—social, environmental, and economic—into the LCA of EVs.

Vehicle life cycle costs are a key consideration for consumers, yet existing research often overlooks how subsidy removal impacts the economic appeal of EVs. This study analyses subsidy removal effects and applies a real discount rate to provide a nuanced understanding of economic implications, filling a critical gap in the literature.

Although BEVs have zero tailpipe emissions, electricity generation emissions—particularly under varying grid structures—can reduce their environmental benefits. Additionally, regional temperature effects on EV emissions remain underexplored. This study examines emissions across different grids and temperature conditions to assess whether EVs genuinely outperform fuel vehicles in environmental impact.

Social impacts, including consumer health, safety, and privacy, are often underrepresented in sustainability studies. This research comprehensively evaluates these social factors, providing insights into how societal influences shape consumer decisions in the automotive market.

The integration of social, environmental, and economic sustainability results is another area where existing studies fall short. Monetisation simplifies result presentation, facilitating stakeholder decision-making. This study applies monetisation techniques to quantify sustainability impacts, enhancing understanding and policy communication.

The next chapter details the research methodology, outlining the study's holistic and integrated LCA approach. It highlights the inclusion and exclusion criteria, addressing research gaps and contributing to a more comprehensive understanding of sustainability in the automotive sector.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

LCSA studies are generally guided by ISO 14040:2006 and guidelines for LCSA (ISO, 2006; UNEP/SETAC Life Cycle Initiative, 2011). The present study is defined based on the procedure and recommendations of ISO 14040:2006 for LCA (ISO, 2006), which includes four main steps of goal and scope definition, inventory analysis, impact assessment, and result interpretation.

The LCSA methodology framework is shown in **Figure 3.1,** evaluates sustainability across three dimensions: environmental, social, and economic. In Phase 1, the research objectives and system boundaries are defined, followed by Life Cycle Inventory Analysis (LCI) to collect input and output data. Phase 2 employs three assessment methods: Social Life Cycle Assessment (S-LCA) to clarify social sustainability indicators, Life Cycle Assessment (LCA) to determine environmental sustainability indicators and collect secondary data, and Life Cycle Costing (LCC) to identify economic cost indicators and gather cost-related data. In Phase 3, the study assesses social, environmental, and economic impacts separately. Social impact (Objective 3) is evaluated through questionnaires covering consumer health and safety, feedback mechanisms, privacy, transparency, and end-of-life responsibility. Environmental impact (Objective 2) is analyzed using SimaPro software to assess GHG, carbon dioxide (CO_2), methane (CH_4) , and nitrous oxide (N_2O) emissions. Economic costing (Objective 1) considers initial purchase cost, operating, maintenance and replacement costs, and end-of-life residual valuations. Phase 4 focuses on monetization and interpretation. Social impact monetization is conducted by calculating the correlation between social impact and willingness to purchase, assigning impact category weights. Willingness to pay (WTP) for carbon emission tax is estimated using the average WTP, emission tax rates, and emission factors to determine total environmental costs. The final monetization model (Objective 4) integrates all factors for comprehensive interpretation. This framework provides a Life Cycle Sustainability Assessment (LCSA) by integrating social, environmental, and economic factors into a monetized sustainability evaluation.

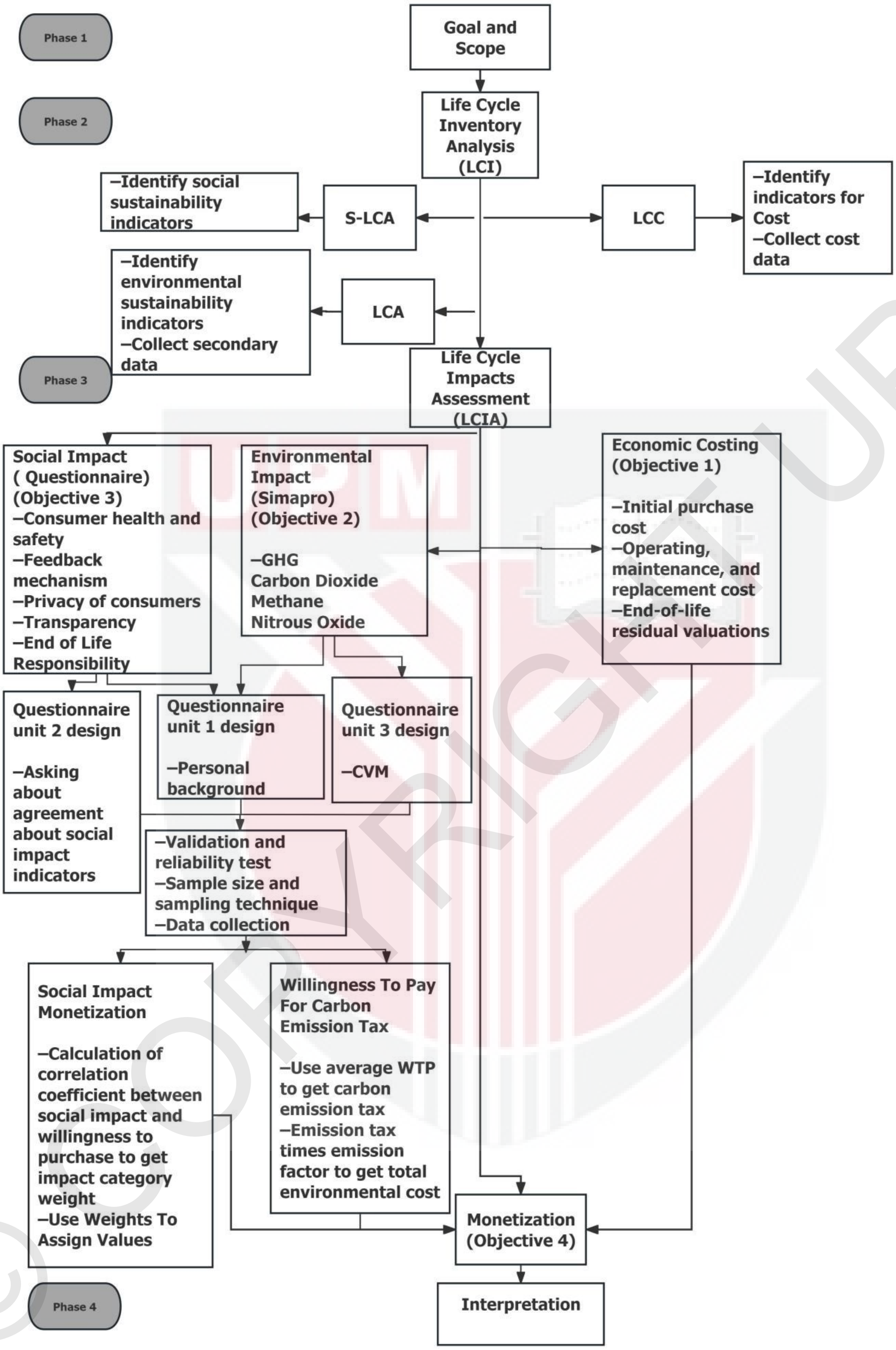

Figure 3.1 : LCSA Methodology's Framework

3.2 Goal and Scope

3.2.1 Goal

This study employed LCSA to analyse the social, environmental, and economic impacts of BEVs and GVs from consumers' perspective, specifically focusing on the use stage. The primary aim was to develop a monetisation method that translates the three pillars of sustainability into economic values. This method was applied to analyse decisions regarding replacing GVs with BEVs in the Northeast Regional Power Grid area, considering the specific regional characteristics of Heilongjiang Province, China.

The impacts of subsidy removal and discount rate on the economic attractiveness of BEVs compared to GVs are the central economic issue examined in this study. This aspect is crucial for understanding the financial implications for consumers and the broader market dynamics.

The study also evaluated the environmental benefits of BEVs in terms of emissions, taking into account the specific energy mix and regional variations in temperature, which may affect vehicle performance and emissions.

This study aimed to integrate social impact factors such as consumer safety and health, privacy, transparency, feedback mechanisms, end-of-life considerations, and future concerns into the overall sustainability assessment, reflecting their importance in consumer decision-making processes. To achieve this, the study selected one vehicle each to represent EVs and GVs based on their sales data. According to the sales data from Heilongjiang Province for the year 2022 and January to September 2023 (Source: December 2022 Retail Sales Ranking Quick Report, 2023), the study considered the top six highest-selling vehicle series .

3.2.2 Scope

The scope of this research was carefully selected to ensure it remains focused while comprehensively addressing the key aspects of sustainability. To represent BEVs and GVs in the regional context, the study focused on two specific vehicle models—BYD Dolphin and Volkswagen Lavida. These models were chosen based on their significant market presence and relevance to local consumers, allowing for a realistic and relevant sustainability performance comparison. The top six highest-selling vehicle series and total sales volume of EVs and GVs in Heilongjiang Province, China for the year 2022 and January–September 2023 shows in **Table 3.1 and 3.2**.

This study chose BYD Dolphin to represent EVs because it was the second highest-selling in the BEV series in Heilongjiang Province in 2023, with a price range of CNY116,800 to CNY139,800. Similarly, this study selected Volkswagen Lavida to represent GVs because its sales volume ranked second in the GV series in 2023, with a price range of CNY93,900 to CNY151,900.

The Wuling Hongguang Mini EV, priced between CNY32,800 and CNY99,900, was the highest-selling BEV in the year 2022 and from January to September

2023 (Automotive Industry Portal Mark Lines, 2023). However, BEVs generally sell at higher prices than traditional GVs with similar performance (IEA, 2022).

The selection of the BYD Dolphin Fashion Edition as the representative battery electric vehicle (BEV) and the Volkswagen Lavida 1.5L Automatic Wish Edition as the representative gasoline vehicle (GV) in this study is based on several key considerations. Firstly, these models are among the top-selling vehicles in their respective categories in Heilongjiang Province, ensuring they reflect common consumer choices. The BYD Dolphin ranked second in BEV sales in 2023, while the Volkswagen Lavida held the second position in GV sales during the same period. Secondly, their price comparability enhances the validity of the sustainability assessment, as the BYD Dolphin is priced at CNY123,800, closely aligning with the Volkswagen Lavida’s CNY110,000. Additionally, both models exhibit similar technical and performance characteristics, including vehicle size, power, and driving range, making them suitable for a balanced life cycle cost (LCC) and life cycle impact assessment (LCIA) comparison. Other vehicle models were excluded for specific reasons: high-end and luxury vehicles were not considered as they do not represent typical mass-market consumer choices, low-end mini EVs like the Wuling Hongguang Mini EV were excluded due to their significantly lower price range (CNY32,800 – 99,900), which does not align with mid-sized gasoline vehicles, and hybrid or plug-in hybrid vehicles (HEVs/PHEVs) were omitted due to the additional complexity in emissions calculations and cost structure. Moreover, commercial and public transport vehicles were excluded, as this study focuses on private vehicle adoption rather than taxis, ride-sharing services, or government fleets, which operate under different economic and policy conditions. By selecting the BYD Dolphin Fashion Edition and Volkswagen Lavida, this study ensures that its findings remain applicable to the average consumer in Heilongjiang Province, providing valuable insights for policymakers, industry stakeholders, and sustainability assessments.

Based on a survey conducted at an automobile sales service shop in Harbin, the capital of Heilongjiang Province, the best-selling model of the BYD Dolphin series is the Dolphin Fashion Edition, with a guide price of CNY123,800. The Volkswagen Lavida model with similar performance to the BYD Dolphin Fashion Edition is the 1.5L Automatic Wish Edition, with a guide price of CNY110,000 (California Primary Care Association, 2023). Information about BYD Dolphin Fashion Edition is shown in **Table 3.3**, and information on Volkswagen Lavida 1.5L Automatic Wish Edition is shown in **Table 3.4.**

The selection of the BYD Dolphin (EV) and Volkswagen Lavida (ICEV) isreal-world consumer choices within the same price range. Despite being different body types (hatchback vs. sedan), both vehicles serve the same primary function—personal transportation—making them functionally equivalent within the LCA framework. This comparison is also policy-relevant, as it assesses the environmental benefits of affordable EVs over conventional gasoline cars, providing insights for emission reduction strategies. Therefore, the selection remains scientifically valid, market-relevant, and impactful for sustainability policy.

Table 3.1 : The Top Six Highest-Selling Vehicle Series and Total Sales Volume of EVs in Heilongjiang Province, China for the Year 2022 and January–September 2023

Electric vehicle series	The volume of Sales for China in the year 2022 (Ranking)	Volume of Sales for China from Jan.-Sep. 2023 (Ranking)	Volume of Sales for Heilongjiang Province of the year 2022 (Ranking)	Volume of Sales for Heilongjiang Province from Jan.-Sep. 2023 (Ranking)	Guide price (Ten thousand)
Wuling Hongguang MINI EV	404,823 (1)	169,798 (2)	483 (1)	605 (1)	3.28-9.99
BYD Qin	341,943 (2)	151,078 (3)	177 (4)	330 (3)	12.98-20.99
BYD Han EV	272,418 (3)	74,972 (6)	136 (5)	164 (5)	20.98-33.18
BYD Dolphin	204,226 (4)	208,493 (1)	366 (2)	395 (2)	11.68-13.98
Tesla (Model 3)	124,456 (5)	113,172 (5)	214 (3)	201 (4)	25.99-29.26
AION.S	116,332 (6)	120,529 (4)	7 (6)	2 (6)	13.98-20.29

(Source: December 2022 Retail Sales Ranking Quick Report, 2023)

Table 3.2 : The Top Six Highest-Selling Vehicle Series and Total Sales Volume of GVs in Heilongjiang Province, China for the Year 2022 and January–September 2023

Gasoline vehicle series	The volume of Sales for China province in the year 2022 (Ranking)	Volume of Sales for China from Jan.-Sep. 2023 (Ranking)	The volume of Sales for Heilongjiang province in the year 2022 (Ranking)	Volume of Sales for Heilongjiang Province from Jan.-Sep. 2023 (Ranking)	Guide price (Ten thousand)
Nissan Sylphy	415,440 (1)	87,615 (5)	2,993 (4)	1,369 (6)	10.86-17.49
Volkswagen Lavida	350,923 (2)	177,105 (2)	8,177 (1)	2,161 (2)	9.39-15.19
Toyota Corolla	257,092 (3)	83,699 (6)	5,260 (2)	1,978 (3)	10.98-13.68
TOYOTA Camry	250,813 (4)	135,362 (3)	2,505 (5)	1,446 (5)	17.98-26.98
Honda Accord	223,200 (5)	87,818 (4)	2,428 (6)	1,528 (4)	16.98-25.98
Volkswagen Sagitar	222,961 (6)	192,762 (1)	4,843 (3)	4,521 (1)	12.79-17.99

Table 3.3 : Information on BYD Dolphin Fashion Edition

Model:	BYD Dolphin Fashion Edition
Suggested Retail Price (CNY):	123,800
Dimensions Parameters:	Length × Width × Height (mm): 4125 × 1770 × 1570
Pure Electric Range under Working Conditions (km):	420
Power Battery Capacity (KWh):	44.9
Fast Charging Time (min) (30%–80%):	30
Direct Current Charging:	60kW
Alternating Current Charging:	7kW
Torque	180
Top Speed	150
Horsepower	95
0-100 km/h Acceleration	10.9

(Source from: BYD Auto's Official Website)

Table 3.4 : Information on Volkswagen Lavida

Model:	Volkswagen Lavida
Suggested Retail Price (CNY):	110,000
Energy Type:	Gasoline
Environmental Standard:	National Standard VI (China)
Release Date:	June 2023
Dimensions (Length * Width * Height):	4561 * 1740 * 1494 mm
WLTC Combined Fuel Consumption	5.98 L/100km
Fuel tank capacity	55 L
Torque	145
Top Speed	190
Horsepower	110
0-100 km/h Acceleration	11.5

(Source: Saic Volkswagen)

The average annual mileage of passenger vehicles nationwide in 2013 was approximately 19,000 km (Zhao et al., 2017). The BYD Dolphin's owner manual shows that maintenance is at 20,000 km or 1 year (CarOBook, 2021). Therefore, this study assumed an average annual mileage of 20,000 km.

Survival and retirement rates reflect China's current situation and development of models, including vehicle preferences and end-of-life vehicle policies. In 1986, China began implementing mandatory scrap standards, officially called the Auto Scrap Standards in 1997 (Ministry of Commerce Standard for Compulsory Scrapping of Motor Vehicles, 2013). This standard specified the mandatory scrappage standard of 10 years (or mileage of 100,000 km) for passenger cars. With the rapid development of China's automobile industry, this limit was extended to 15 years in 2000. There were fewer scrapped vehicles in the first 8 years; the retirement rate reached a high level from the 9th to the 16th year and peaked in the 13th year, with an annual retirement rate of 8.09% and a survival rate of 49.53%. The survival rate in the 25th year was approximately 0%. In this study, the assumed number of service years is 15 years.

3.2.3 Study Area

China has six major regional power grids (General Office of the State Council of the People’s Republic of China, 2006). And Appendix E shows the proportion of power generation sources in various regions (Source: China Electricity Statistical Yearbook 2022). The Northeast, Northwest, and Southwest grids act as sending ends, while North China, East China, and Central China are receiving ends (Wang, 2020). Northeast China relies heavily on coal-fired power, leading to high fuel consumption and carbon emissions (Cai et al., 2023). Furthermore, EV sales in the Northeast Power Grid region are the lowest nationwide, with Heilongjiang ranking at the bottom. **Figure 3.2** illustrates China ' s EV sales volume in 2022 (Passenger Car Market Information Joint Branch of China Automobile Dealers Association, 2023).

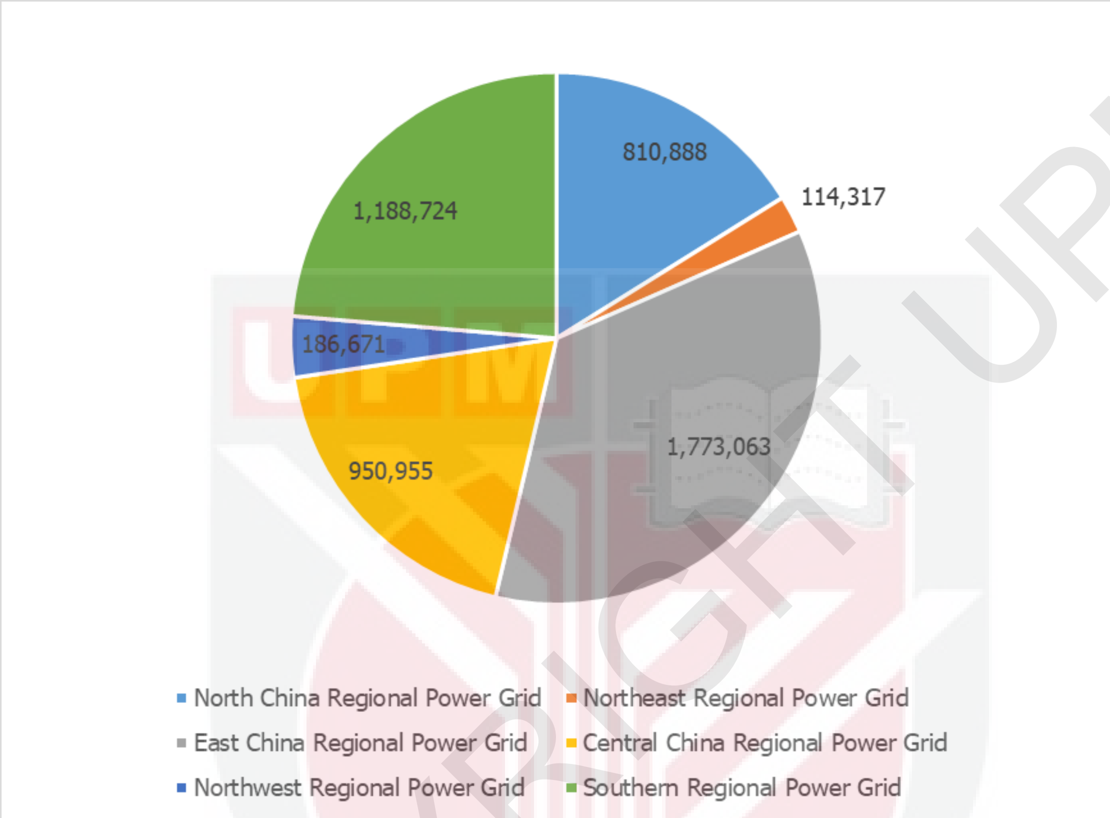

Figure 3.2 : Electric Vehicle Sales Volume in China in 2022 (in 10 Thousand)
(Source: New Car Compulsory Traffic Insurance Data)

The geographical scope was confined to Heilongjiang Province, utilising data pertinent to the Northeast China Power Grid. This regional focus helped tailor the analysis to specific environmental conditions and policy frameworks, enhancing the applicability of the findings.

Heilongjiang has the lowest sales volume of EVs in the Northeast Power Grid region, since China plans to fully replace the use of fuel vehicles with EVs, the country needs to pay special attention to regions where EVs have low sales vvolume and power compositions record high unclean energy. This study also examines the Northeast Regional Power Grid in Heilongjiang Province, where regional energy structures significantly affect EV sustainability assessments. Most LCAs rely on average energy data from developed regions, yet power generation and energy mix vary, impacting evaluation outcomes (Liu & Xu, 2016).

According to the Ministry of Ecology and Environment of the People's Republic of China (2020), the Northeast Regional Power Grid covers Liaoning Province, Jilin Province, and Heilongjiang Province. This study only considered Heilongjiang Province, which consists of a total of 13 cities, namely, DaHinganLing, Heihe, Qiqihar, Daqing, Suihua, Yichun, Harbin, Hegang, Jiamusi, Shuangyashan, Qitaihe, Jixi, and Mudanjiang. The study area is illustrated in **Figure 3.3**.

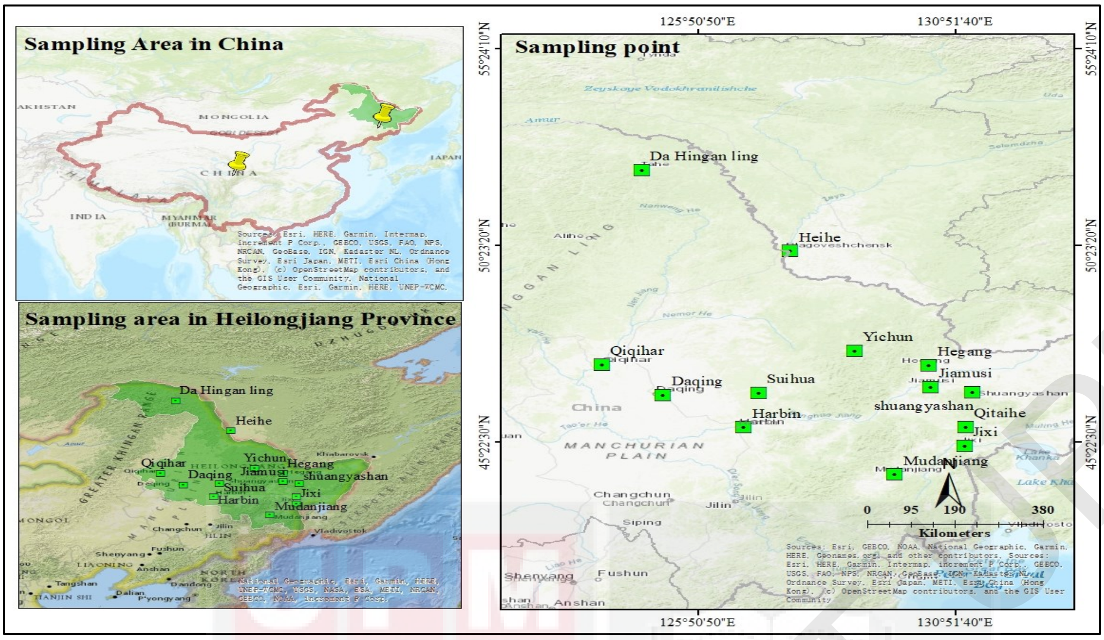

Figure 3.3 : The Study Area of Heilongjiang Province, China
(Source: The Ministry of Ecology and Environment of the People's Republic of China 2020)

Figure 3.4 Temperature, Climate graph for Heilongjiang Province. The average temperatures in Heilongjiang Province, as reported by the Heilongjiang Meteorological Bureau (2021), vary according to the season. For instance, the average temperatures were −16.3°C during the winter months (December 2019–February 2020), 6.0°C in spring (March–May 2020), 20.5°C during summer (June–August 2020), and 5.1°C in autumn (September–November 2020).

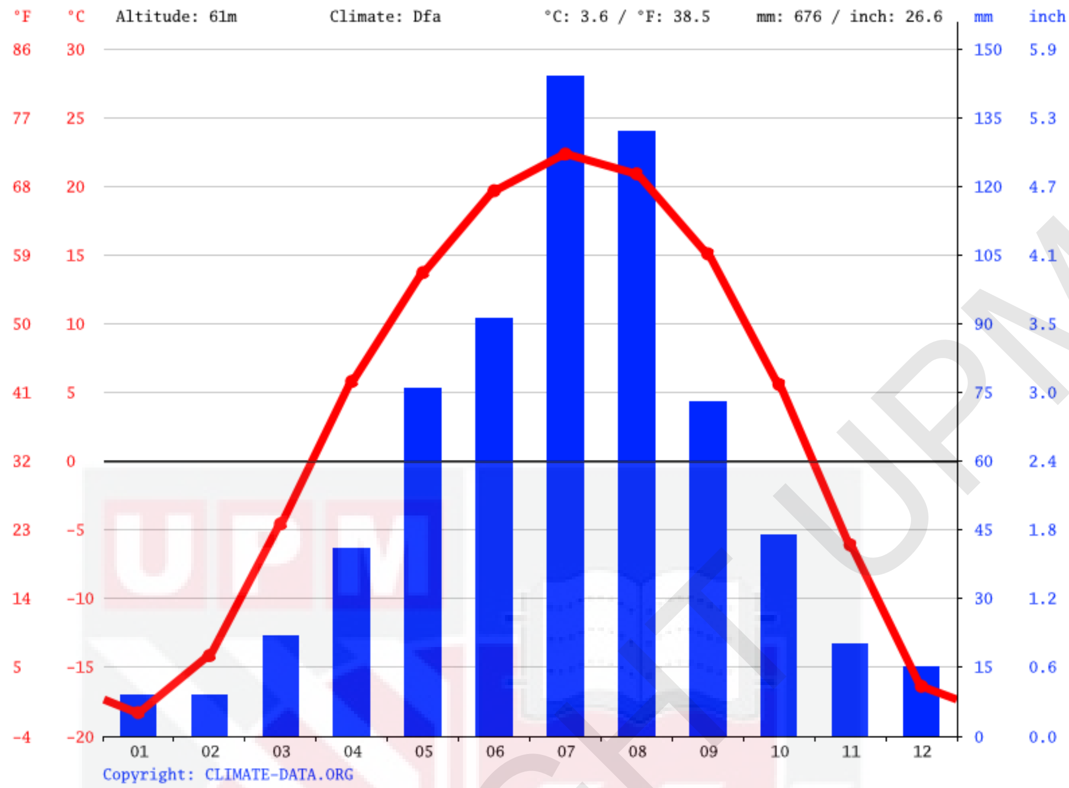

Figure 3.4 : Temperature, Climate Graph for Heilongjiang Province
(Scouces: https://en.climate-data.org/asia/china/heilongjiang-893/)

This study considered the unique four-season climate of Heilongjiang Province, where temperature significantly affects power consumption and the number of charges, which in turn affects battery life. Most studies exclude the battery use phase due to the variability of battery usage conditions and the complexity of technical indicators such as performance and lifespan. However, since the battery use phase accounts for a substantial part of the vehicle's life cycle and is a significant source of carbon emissions, it should not be overlooked (Wu et al., 2023).

Lithium battery energy consumption during the use phase has two primary aspects. Firstly, EVs require more energy to carry the battery weight while being driven. Secondly, there is power loss because the power battery does not achieve 100% efficiency during charging and discharging (Feng et al., 2022). According to Burke and Miller (2011), the maximum usable power density of lithium-ion batteries may be higher than the power density corresponding to 95% efficiency. The best charging and discharging efficiency is 100% (Feng et al., 2014).

The average temperatures in Heilongjiang Province, as reported by the Heilongjiang Meteorological Bureau (2021), vary according to the season. For instance, the average temperatures were −16.3°C during the winter months (December 2019–February 2020), 6.0°C in spring (March–May 2020), 20.5°C during summer (June–August 2020), and 5.1°C in autumn (September–November 2020).

When temperatures fall below 10°C, power consumption per 100 km increases, and the predicted cruising range decreases with decreasing temperatures. The average energy consumption is lowest around 10°C. When temperatures exceed 10°C, there is a slight increase in power consumption per 100 km and a slight decrease in cruising range with rising temperatures. Trips in temperatures below 10°C or above 30°C show more significant variances (Liu et al., 2018). Therefore, 10°C–30°C is considered the optimal operating temperature range.

“A report on the actual driving performance, energy consumption, cruising range, and charging mode of China's pure electric passenger vehicles” (June 2023) selected 10 private EVs in five cities. It found that at high temperatures (30°C–35°C), energy consumption increased by about 4%, while at low temperatures (0°C or below, excluding ≤−7°C), energy consumption per 100 km increased by 40%. At extremely low temperatures (≤−7°C), energy consumption per 100 km increased by 70%. Moreover, energy consumption increased by 40% when the temperature dropped from 10°C to 0°C, equivalent to a 4% increase for every 1°C drop (L. Jin et al., 2023).

Based on past studies, this research assumed significant temperature variances across the four seasons in Heilongjiang Province and assigned energy consumption accordingly. In winter (−16.3°C), energy consumption per 100 km increases by 70%, with a charge and discharge rate of 59%. In spring (6.0°C), energy consumption per 100 km increases by 24%, with a charge and discharge rate of 81%. Summer (20.5°C) is considered the optimal operating temperature, with a charge and discharge rate of 100%. In autumn (5.1°C), energy consumption per 100 km increases by 20%, with a charge and discharge rate of 83%. The annual average energy consumption per 100 km is 13.52 KWh/100km, which aligns with Feng et al. (2014) regarding available capacity at different temperatures in Harbin.

3.2.4 Functional Unit and System Boundary

A functional unit is defined as the quantified performance of a product system used as a reference unit (ISO, 2021). In this LCA, a single vehicle was used as the functional unit to compare the effects of various parameters on the sustainability of BEVs and GVs.

The system boundary included the use stage's input and output. The most significant difference between GVs and EVs is that EVs do not produce vehicle exhaust. In the environmental dimension, impacts were assessed using the ISO standardised LCA. Since the main resource consumption during the use phase is either electric energy or gasoline, this study included both energy generation and gasoline extraction. To obtain the possible sustainability impacts within the system boundary, this study conducted a survey to collect relevant information and used secondary data. For all the data collected during the use phase, the only stakeholder type involved was the consumer. **Figure 3.5** illustrates the system boundary of the EV sustainability analysis study, detailing the included and excluded elements.

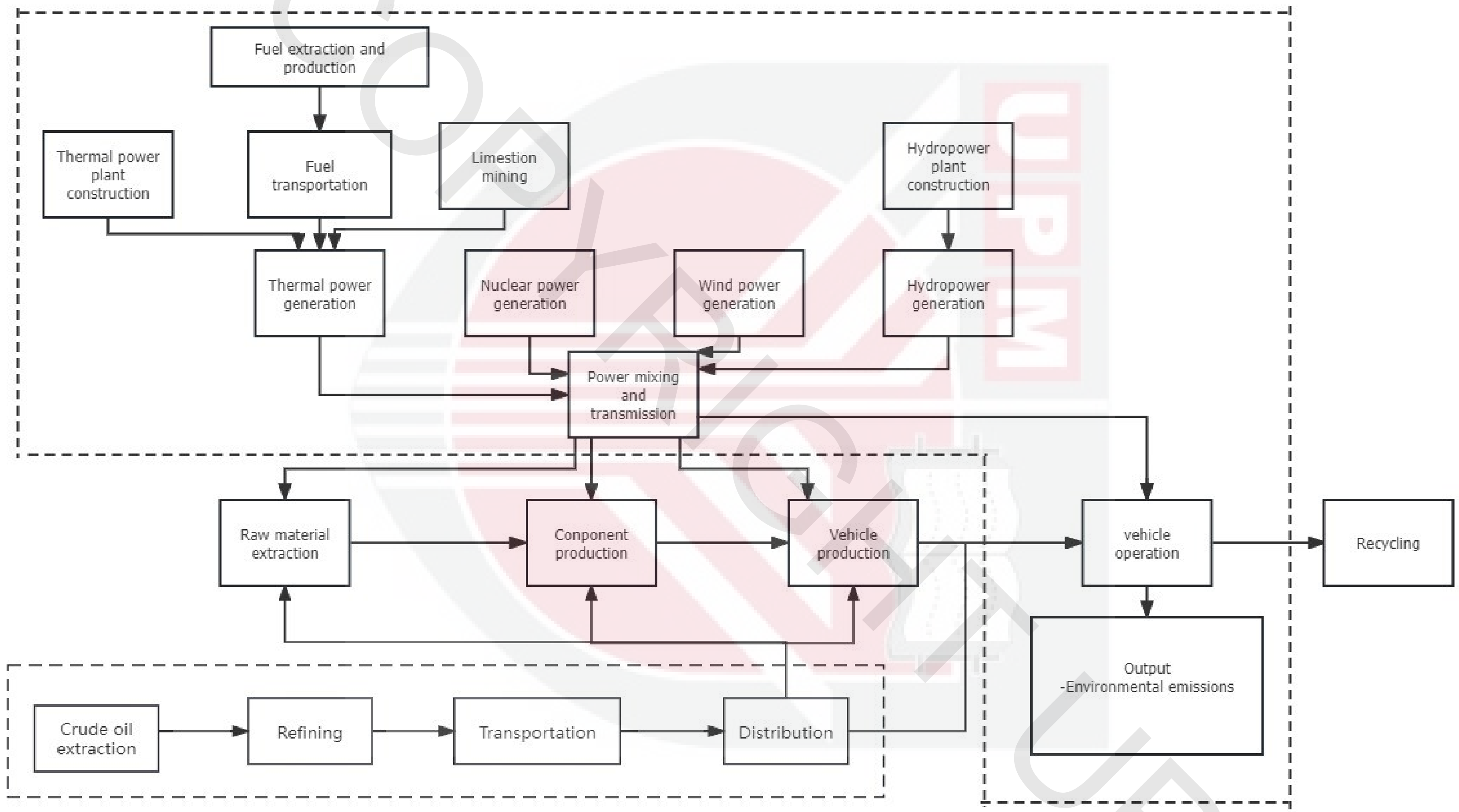

Figure 3.5 : System Boundary of the Vehicle Sustainability Analysis Study

3.3 Life Cycle Inventory and Impact Assessment

The Life Cycle Inventory (LCI) is a comprehensive approach to data collection and analysis, essential for evaluating the sustainability of BEVs and GVs in Heilongjiang Province, China. The inventory analysis follows the guidelines established under ISO 14040:2006, ensuring a systematic and standardised methodology. The reliability of data sources is paramount in conducting a credible LCI. In this study, data was gathered from multiple reliable sources including:

Ecoinvent Database: The main source of environmental data, utilising Ecoinvent v3.9.1. This database is acknowledged for its comprehensive and up-to-date LCI data, which is crucial for ensuring the accuracy of the environmental impact assessment.

Literature and government reports: Supplementary data was obtained from published research papers, government reports, and official statistics, such as the climate data from the Heilongjiang Provincial Meteorological Bureau and vehicle emission standards from the Ministry of Environmental Protection.

Manufacturer Data: Specific information on vehicle specifications, energy consumption, and maintenance requirements was sourced from the official documents provided by manufacturers such as BYD Auto and SAIC Volkswagen.

Questionnaires: Detailed surveys were conducted to gather primary data, including information on user perceptions, from vehicle users in Heilongjiang Province. The surveys were carefully designed to minimise bias and maximise response accuracy. Details of the data sources and data collection method are provided in the following subsections.

3.3.1 Life Cycle Costing (LCC) Inventory and Analysis

3.3.1.1 Inventory

LCC is an economic analysis used to assess the total cost of ownership over the life of an asset. The LCC study takes into account the initial purchase cost, operating cost, maintenance cost, replacement cost, and end-of-life residual valuations (recycling cost), as per ISO 15686-5:2017(En), *Buildings and Constructed Assets — Service Life Planning — Part 5: Life-Cycle Costing* and National Institute of Standards and Technology Handbook 2022 Edition titled *Life Cycle Costing Manual for the Federal Energy Management Program* (Kneifel & Webb, 2022).

During the LCC study, all the economic data collected during the inventory phase was classified into specific cost categories, as shown in **Table 3.5**. The initial purchase cost is the cost incurred by the consumer in purchasing the vehicle. It includes purchase tax, which is payable when buying a car for the first time, subsidies from merchant promotions or government policies, charging pile installation fees paid when purchasing an EV, and license plate fee.

Operating costs include insurance cost, vehicle and vessel tax, and annual vehicle inspection cost. These are recurring expenses necessary for the daily functioning and legal compliance of the vehicle. Charging costs were also considered, noting that private charging piles, though cheaper, are less common in Heilongjiang Province. Public charging piles incur higher fees, comprising commercial electricity charges and service fees. According to a field survey in Harbin, the average service fee for charging piles is CNY 0.40. This study used the average electricity price for household and commercial electricity plus service fee, resulting in an average charging cost of CNY0.92/KWh for EVs.

Maintenance and replacement costs include the costs for energy, cleaning, and essential maintenance and replacement services based on the vehicle's maintenance manual. Accidents and other exceptional circumstances are covered by insurance and thus not considered separately.

For EVs, battery degradation is a significant factor. According to Zhou (2020), when battery attenuation reaches 20%, the cruising range fluctuates significantly, and further attenuation beyond 30% affects daily use. However, to ensure quality, new EV manufacturers provide warranties for critical components such as power battery, drive motor, and motor controller for no less than 8 years or 120,000 km (Ministry of Industry and Information Technology of the People’s Republic of China, 2015). Additionally, BYD offers free lifetime battery replacement and charging pile installation (BYD Auto's official website). Therefore, this study did not consider battery replacement costs.

This study considered the costs associated with resale or recycling at the end of the vehicle's life, including the resale price minus any disposal or decommissioning costs. The data collection and analysis methods for these costs are detailed in **Appendix B &C**. This comprehensive approach ensured that the LCC analysis was thorough and reliable, providing valuable insights into the total cost of ownership for BEVs and GVs in Heilongjiang Province.

Table 3.5 : Classification of LCC Indicators

Impact category	Indicators	Sources
Initial purchase cost	Purchase price	BYD Auto Official Website (n.d.) and Saic Volkswagen (n.d.)
	Purchase tax	*Tax Service and Advocacy Center* (2023) and The state council of the People's Republic of China (2019)
	Subsidy	BYD Auto Official Website (n.d.) and Saic Volkswagen(n.d.)
	Charging pile fee	BYD Auto Official Website (n.d.)
	License plate fee	Auto Baodian (2023)
	Insurance Cost	007 Car Bond (2023), *Jiaoqiangxian* (2023) 2024 and Da xijie shuo che, 2023
Operating and maintenance cost	Vehicle and vessel tax	Heilongjiang Provincial Tax Service, State Taxation Adiministration, 2021; State Council (2011)
	Annual Vehicle Inspection Cost	Car Owners Guide (2022) and Jiao (2021)
	Energy Cost (For EV consider four seasons average temperature effect of energy consumptions)	*Jinri heilongjiang qiyou jiage* (2023) and Heilongjiang power grid staff
	Replacement Cost and Service Cost	BYD Auto Official Website (n.d.), vehicle Owner's Guide (2018, 2022), JD.com

Table 3.5 : Continued

Impact category	Indicators	Sources
End of life	Resale price	Calculate based on Vehicle Depreciation Rate
	Resale cost	China Pacific Insurance (Group) Co., Ltd. (2021)
Inflation rate	2%	Xinhua (2023)
discount rate	5%	Biolek and Hanák (2019)
Energy consumption	5.98L/100km 44.9 KWh/420 km	BYD Auto Official Website (n.d.) and Saic Volkswage (n.d.)
Everage electricity fee	0.9192583125 CNY/KWh	State grid Heilongjiang electric power company limited
Everage gasoline fee	8.312083333 CNY/L	*Jinri heilongjiang qiyou jiage* (2022)

3.3.1.2 LCC Analysis

In LCC analysis, applying an appropriate discount rate is crucial for evaluating future costs such as maintenance and repair costs. The discount rate significantly affects the accuracy of the analysis; the lower the discount rate, the higher the present value (PV) of future costs, and vice versa.

PV refers to the current value of a future sum of money or a stream of cash flows given a specified rate of return (refer to **Eq 3** for the PV equation). In addition, net present value (NPV) is the difference between the PV of cash inflows and the PV of cash outflows over some time (Beers, 2022). The NPV metric should be used to evaluate investments in the project (Biolek & Hanák, 2019). NPV is the PB of the cash flows at the project's required rate of return compared to the initial investment (Gallo, 2014). It is a method for assessing the financial viability of an investment project based on the time value of money principle, and it is used to calculate the sum of the current values of future cash inflows minus the initial investment cost of the project (Shou, 2022).

The core idea of NPV is to discount future cash flows to their current values to account for the time value of money (Ross, 1995; Gallo, 2014). The NPV equation is a per **Eq 1**. The cumulative PV (CPV) equals the current year's PV plus last year's CPV **Eq 2**.

$$LCC_{NPV} = CPV_n - RV \times (1 + I_{rd})^{-n} \quad \textbf{Eq 1}$$

$$CPV_n = PV_n + CPV_{n-1} \quad \textbf{Eq 2}$$

$$PV_n = (OC_n + MRC_n) \times (1 + I_{rd})^{-n} \quad \textbf{Eq 3}$$

where:

LCC_{NPV}: Net present value of life cycle cost
n: Current year
CPV: Cumulative present value
RV: Residual valuation
I_{rd} : Real discount rate
PV: Present value
OC: Operating cost
MRC: Maintenance and replacement cost

The initial purchase cost is the sum of purchase price, purchase tax subsidy, charging pile (if applicable), and license plate fee (refer to **Eq 4**). Any LCC analysis must include operation and maintenance costs. Operation cost includes insurance cost, vehicle and vessel tax, and annual vehicle inspection fee (refer to **Eq 5**). Maintenance and replacement cost include energy, cleaning, replacement, and service costs (refer to **Eq 6**). The findings of the LCC analysis can be used to determine the strategy for the created asset. Inaccuracies and uncertainties in operating phase expenses are caused by several variables, including anticipated inflation rates, the availability of new technology, changes to the law, inspection fees, insurance, local taxes, and labour prices (Lazzarin et al., 2008).

$$IPC = P + PT - MD + C + L \quad \textbf{Eq 4}$$

$$OC = IC + VVT + VIC \quad \textbf{Eq 5}$$

$$MRC = EC + CC + RC + SC \quad \textbf{Eq 6}$$

where:

IPC: Initial purchase cost
P: Purchase price
PT: Purchase tax
MD: Merchant discount
C: Charging pile fee
L: License plate fee
IC: Insurance cost
VVT: Vehicle and vessel tax
VIC: Annual vehicle inspection cost
EC: Energy cost
CC: Cleaning cost
C: Replacement cost
SC: Service cost

Residual valuation at the end of the vehicle's life is calculated as the resale price minus any resale costs. **Eq 7** is a hybrid of basic valuation methods adopting a combined revenue and cost approach (Kupec & Dlask, 2020). The residual value is equal to resale price minus resale cost.

$$RV = RP - RC \quad \textbf{Eq 7}$$

where:

RV: Residual valuation
RP: Resale price
RC: Resale cost

Resale cost (**Eq 10**) is the sum of transfer fee and administrative fee. This study used an administrative fee of CNY58. Transfer fee, which is the handling fee for the car transfer, was calculated as the resale price multiplied by 2.5%. This study did not include the additional costs arising from uncertainties (China Pacific Insurance (Group) Co., Ltd., 2021). It can be challenging to determine a vehicle's trade-in or salvage value because different car models deteriorate at different rates and future material prices fluctuate. This study referred to Raustad (2017) for the depreciation rate (**Eq 9**). Resale price is the purchase price multiplied by one minus vehicle depreciation rate (**Eq 8**).

$$RP = P \times (1 - I_{vd}) \quad \textbf{Eq 8}$$

$$I_{vd} = 6 \times 10^{-5} \times n^3 - 0.0038n^2 + 0.093n + 0.1384 \quad \textbf{Eq 9}$$

$$RC = RP \times 2.5\% + 58 \quad \textbf{Eq 10}$$

where:

I_{vd}: Vehicle depreciation rate

A suitable discount rate should be applied to future expenses like maintenance and repair. The value of the discount rate is crucial; the lower the discount rate, the greater the impact, and vice versa (Biolek & Hanák, 2019). A discount rate of 5% was used in this study. A country's economy is dependent on several factors, including inflation (Musarat et al., 2021). It is believed that inflation is a key determinant of future economic conditions, in which every country's main objective is sustainable economic growth (Feldkircher & Siklos, 2019; Oikawa & Ueda, 2018). This study used an escalation rate of 2%. It was based on China's consumer price index (CPI), which increased by 2% in 2022 (Xinhua, 2023). The real discount rate is the factor or rate used to relate present and future money values in comparable terms. The real discount rate was calculated using Fisher's equation (**Eq 11**).

$$I_{rd} = \frac{1+r}{1+e} - 1 \qquad \textbf{Eq 11}$$

where:

r: Discount rate

e: Escalation rate

Sensitivity Analysis 1: Real Discount Rate

The classic form of NPV regards future cash flows as fixed or with deterministic amounts. Most NPV calculations are based on the premise that facts are ambiguous, which is very reasonable since the incomes and expenditures related to the project concern the future. One of the methods designed for incorporating uncertainty in such calculations is sensitivity analysis (Gaspars-Wieloch, 2019). Sensitivity analysis is necessary to predict the outcome of a decision given a set of variables (Naseb, 2020). This study investigated the sensitivity of the NPV of EVs and GVs to discount rates and subsidies over different service life durations. There needs to be a consensus on which discount rate should be used for LCC (UNEP/SETAC Life Cycle Initiative, 2011). Therefore, conducting a sensitivity analysis for various discount rates is recommended (Marenjak & Krstić, 2010). The traditional calculation methods are LCC and discounting, including setting different discount rates depending on the period. Discount rates of 3%, 5% (or 7%), and 10% per year are often used for sensitivity analysis (Yuan et al., 2021). The research conducted by Fregonara and Ferrando (2023) on the sustainability of environmental-economic projects used a 5% discount rate. To determine the impact of economic indicators on the time value and purchasing power of money, this study's analysis used real discount rates of 1% to 10% (Yuan et al., 2021) and service life of 1 to 15 years. The number of years of service life is also one of the essential components of the NPV calculation.

Sensitivity Analysis 2: Subsidy Policy

Subsidies for EVs are gradually being reduced and have been extended several times. At present, it has been extended to the year 2027. From 1 January 2024 until 31 December 2025, vehicle purchase tax exemptions are applicable for new energy passenger vehicles. The vehicle purchase tax will be halved from 1 January 2026 until 31 December 2027. After 2027, there will be no more vehicle purchase tax exemptions (People's Republic of China State Council Information Office, 2023). The subsidy policy may also affect the conditions for the cost competitiveness of EVs (Bubeck et al., 2016; Parker et al., 2021).

Hence, this study considered the effect of changes to the subsidy policy from the current subsidy to 50% subsidy and eventually zero subsidy over a 15-year period. This was done to analyse how subsidy affects the economic benefit of EVs compared with GVs.

3.3.2 Environmental Life Cycle Inventory and Analysis

3.3.2.1 Environmental Life Cycle Inventory

EVs generate almost zero exhaust emissions during the operating phase. However, researchers have different perspectives on the EVs reducing CO_2 emission. Even though BEVs do not use fossil fuels and emit no emissions, these vehicles transfer pressure to the power grid when they use electricity for energy consumption. Power generation consumes non-renewable energy and causes emissions. Some studies highlight that electricity generation has a significant effect during the EV use phase (Shafique et al., 2021). Hence, given China's current power structure, is BEV an environmentally friendly product compared with GVs? This question needs to be considered.

LCA, a system of assessment developed under ISO 14040, is one of the most effective ways for exploring the resource and environmental impact of a life cycle (ISO, 2006a). This study aimed to establish a comprehensive monetisation framework based on the LCA framework and clarify the environmental impacts of BEVs and GVs by using four phases, namely, goal and scope definition, inventory analysis, impact assessment, and interpretation. It is crucial that each of these phases is clearly defined and followed to ensure a comprehensive and systematic assessment.

This study (LCC, LCA, S-LCA and LCSA) are shares the same goal and scope, functional unit and system boundary, and study area. Thus, all the basic information about the type of vehicle and the functional unit of this study is as per **Section 3.2**.

The LCI stage details out the data collection process for all relevant inputs and outputs associated with the vehicle's life cycle. It includes energy consumption, emissions, and resource use from production to disposal (International Reference Life Cycle Data System [ILCD], 2010). Therefore, its accuracy is closely connected to how reliable and easy it is to obtain LCA results (Yin et al., 2019). Emissions from fossil fuel and energy production must be reported, according to ISO 14064 *Greenhouse Gas Reporting Standard* (Chan & Boehmer, 2006). Indirect emissions can be directly linked to the reporting organisation, and they may occur in all life cycle stages, accounting for a substantial proportion of the overall life cycle emissions (Martínez-Blanco & Finkbeiner, 2017).

Data collection ensured high-quality, region-specific data was used, particularly for the electricity mix in Heilongjiang Province. The data was derived from the latest database compiled in January 2023, Ecoinvent 3.9.1 data, as unit processes with links to other methods (*Ecoinvent v3.9.1 -*

Ecoinvent, 2022). Data was also obtained from publications in the literature or government policy. The LCI summary is shown in **Table 3.6**. Environmental impacts are often highly region-specific. Specific power grids in the database were selected to analyse the environmental impacts of different power compositions in regional power grids. In addition, this study specifically considered the climate characteristics of Heilongjiang Province, especially in terms of the impact of power grid mix and temperature on EV performance. By conducting sensitivity analysis of temperature and power composition, the study could evaluate the effects of changes in key parameters on the results, thereby enhancing the reliability of the conclusions. The details are discussed as follows.

Ecoinvent 3.9 has been updated to reflect China's power structure in 2020. The power structure of the State Grid Corporation of China (SGCC) has been divided into six zones and now better reflects local conditions (*Ecoinvent v3.9.1 - Ecoinvent*, 2022). This dataset includes the electricity inputs produced in the country and from imports and transformed to medium voltage, the transmission network, direct emissions to air (SF6 from the insulation gas in the high voltage level switchgear is allocated to the electricity demand on medium voltage), and electricity losses during transmission.

Low-sulphur petrol, in the global geography, is the inventory for distributing petroleum products to the final consumer (household, car, power plant, etc.), including all the necessary transports. This activity ends with the supply of low-sulphur petrol to consumers. Product losses during transportation are assumed to be negligible and therefore not included (*Ecoinvent v3.9.1 - Ecoinvent*, 2022). This database does not include gasoline consumption emissions; vehicles emit methane (CH_4) and nitrous oxide (N_2O) with CO_2 through their tailpipes, while hydrofluorocarbon (HFC) emissions are released from air conditioners that are leaking. It is more challenging to estimate the vehicle emissions of CH_4, N_2O, and HFCs compared to CO_2. The emissions of CH_4 and N_2O depend on the engine design and emission control system rather than the fuel usage per kilometre.

The extent of HFC emissions from air conditioners depends on system design, level of usage, and maintenance. Considering the GWP of other GHGs, the average percentage of CO_2 emissions to total GHG emissions from a passenger vehicle is approximately 95%–99%. The remaining 1%-5% comprises CH_4, N_2O, and HFC emissions (United States Environmental Protection Agency, 2016a).

This study did not consider air conditioner leakages and N_2O emissions according to the emission standard titled *Limits and Measurement Methods for Emissions from Light-Duty Vehicles (China 6)* (Ministry of Environmental Protection General Administration of Quality Supervision, Inspection, and Quarantine, 2016). Vehicles can meet the most stringent National VI B emission standards. It is reasonable to expect that car emissions are precisely equal to those specified in this standard because no car company will impose stricter requirements on itself at the expense of increased costs (Mei, 2022). Since National VI B emission standards do not mention CH_4, this study did not consider CH_4 in combustion emissions.

Table 3.6 : LCI Summary

Vehicles	Components	Location	Reference
GV	Petrol, low-sulphur, in the Global geography	Global geography	Ecoinvent version 3.
	One litre of gasoline emits approximately 2,339 grams of carbon dioxide from vehicle exhaust.	China	He and Bandivadekar (2010)
	N_2O 20mg/km	China	Ministry of Environmental Protection General Administration of Quality Supervision, Inspection and Quarantine (2016)
BEV	State Grid Southwest (SWG) China Branch input and output	The inventory is modelled for CN-SWG	Ecoinvent version 3.9.1
	State Grid Northwest China Branch (NWG) China Branch input and output	The inventory is modelled for CN-NWG	Ecoinvent version 3.9.1
	State Grid Northeast China Branch (NECG)China Branch input and output	The inventory is modeled for CN-NECG	Ecoinvent version 3.9.1
	State Grid North China Branch (NCGC)China Branch input and output	The inventory is modeled for CN-NCGC	Ecoinvent version 3.9.1
	State Grid East China Branch (ECGC)China Branch input and output	The inventory is modeled for CN-ECGC	Ecoinvent version 3.9.1
	State Grid Central China Branch (CCG)China Branch input and output	The inventory is modeled for CN-CCG	Ecoinvent version 3.9.1

Environmental impacts of vehicles from gate to gate were constructed using SimaPro v9.0.0.48. The SimaPro LCA software, created in the 1990s by the Dutch PRé Sustainability consultant firm, has an extensive data repository and is presently utilised globally (Lai et al., 2022). In selecting the impact categories and indicators, the methodology should identify and evaluate the potential environmental impacts using appropriate indicators and categories, such as GWP and endpoint impact.

3.3.2.2 LCA analysis

According to ISO 14040 (2006), life cycle impact assessment step involves five steps, namely, classification and characterisation of indicators, normalisation, grouping, and weighting. While classification and characterisation are mandatory steps, normalisation and weighting are optional. This study specifically focused on the classification and characterisation of GHG emissions, particularly CO_2 equivalents (CO_2-eq).

Classification entails organising the environmental impacts into relevant impact categories. In this study, emissions were classified under the GWP category. This categorisation allowed the study to systematically group the data related to GHG emissions, ensuring that all relevant emissions were considered in the analysis.

Characterisation study entails accounting for GHG emissions, which contribute to global warming, and adjusting based on their GWP. The impacts are expressed in kilograms of CO_2-eq (ISO, 2006a). The GWP method developed by the Intergovernmental Panel on Climate Change (IPCC) is widely applied in LCA to assess the impact of climate change. The IPCC GWP factors are based on the most up-to-date and scientifically robust consensus model (Hauschild et al., 2013). GWP was calculated on a 100-year (GWP 100a) time scale to consider impact assessment characterisations. IPCC GWP 100 V1.2 was used in this study.

IPCC 2021, developed by the IPCC, is the successor to the IPCC 2013 method. It consists of the Global Temperature Potential (GTP) climate change factors of IPCC with a timeframe of 100 years. According to the Database & Support team at PRé Sustainability (2021), the characterisation factors are based on Table 7.15 of Chapter 7 (Intergovernmental Panel on Climate Change [IPCC], 2021) and Table 7.SM.7 in the Supplementary Materials of Chapter 7 (IPCC, 2021).

All the characterisation factors listed in Table 7.SM.7 of the IPCC 2021 report have been implemented in SimaPro 9.4 June 2022 v1.01 adaptations. The GWP formula (**Eq 12**), which uses the unit of measurement of kg CO_2 equivalent (kg CO_2-eq), is from the *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards* (Guinée, 2002).

$$GWP = \sum GWP_i \times m_i \qquad \textbf{Eq 12}$$

Where:

GWP: Global warming potential

GWP_i: Global warming potential for substance i
m_i: The quantity of substance i emitted

Endpoint impact assessments in LCA are derived by applying constant factors to translate midpoint characterisation results into endpoint damages. This process quantifies the ultimate effects on specific damage categories, such as human health, ecosystem quality, and resource availability, providing a more tangible basis for evaluating the potential environmental and health outcomes of products and processes. This phrasing more clearly distinguishes the roles of classification and characterisation at both the midpoint and endpoint levels, emphasising the transformation from environmental impact data to assessments of actual damage based on the methodologies discussed by Huijbregts et al. (2017), with a constant midpoint to endpoint factor per impact category (**Eq 13**).

Based on the ISO standard on LCA impact assessment, the ReCiPe 2016 endpoint, the Hierarchist perspective was selected to consider the environmental impact on the endpoint—human health, resources, and ecology (Goedkoop et al., 2009). For human health damage, the unit of measurement is disability adjusted life years (DALY), representing the number of years lost or a person's disability duration due to a disease or accident. Ecosystem quality is measured in terms of local relative species loss across terrestrial, freshwater, and marine ecosystems, integrated over space and time. It is expressed as the potentially disappeared fraction of species per square meter per year (species·m²·year) or per cubic meter per year (species·m³·year) to aggregate the impacts from terrestrial, freshwater, and marine ecosystems into a single unit (species.year). Resource scarcity is quantified in monetary terms (dollars, $), representing the additional costs required for future extraction of mineral and fossil resources. Endpoint characterisation factors (CFe) are derived from midpoint characterisation factors (CFm) using a constant mid-to-endpoint factor for each impact category (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al., 2017).

$$CFe_{x,a} = CFm_x \times F_M \rightarrow, E, a \qquad \textbf{Eq 13}$$

where:

CFe : Endpoint characterisation factors
a: The area of protection, i.e., human health, terrestrial, freshwater, and marine ecosystems, or resource scarcity
x: The stressor of concern
CFm: Midpoint characterisation factors
$F_M \rightarrow, E, a$: The midpoint-to-endpoint conversion factor for area of protection a

Scenario LCA - Comparing BEVs' Emissions in Different Power Grids

This study performed a scenario LCA to compare the emissions of BEVs and GVs over a period of 1 year, covering a mileage of 20,000 km. The analysis focused on emissions in different power grids without factoring in temperature effects.

The energy source of electricity is crucial in determining the environmental benefits of EVs. According to the research conducted by Zhang and Han

(2017), the prevalence of coal power and its significant economic competitiveness compared to other forms of energy generation hinder the generation mix from fully realising the potential of EVs. Yu et al. (2018) assessed the environmental impacts of EVs and GVs in China, considering the role of coal in China's energy mix and suggesting that cleaner energy sources could mitigate the environmental impacts of EVs. As highlighted by Hsu (2013), the sustainability of EVs depends on the cleanliness of the energy grid. This highlights the need for region-specific approaches in promoting EVs.

This study examined BEVs within these different power grids and compared their emissions with those of GVs. The analysis used ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A damage assessment method to assess and compare the emissions associated with the different power grids over 1 year and a driving distance of 20,000 km. The formula for the comparative process is expressed in **Eq 13**.

By focusing on different power grids, this study aims to provide a comprehensive understanding of how different energy structures affect the emissions associated with BEVs and GVs, contributing to a more nuanced evaluation of the environmental benefits of EVs.

Scenario LCA - Temperature Effect

This study conducted a scenario LCA to analyse the emissions of BEVs and GVs over the course of 1 year (20,000 km) in Heilongjiang Province with a particular focus on the effects of temperature. The analysis considered the different charge and discharge rates of BEVs—59%, 86%, 100%, and 83%—across different temperatures, as outlined in **Section 3.1**. Simapro used IPCC 2021 GWP 100 V1.02/Characterisation to compare for each season and four seasons (1 year) of BEV and GV emissions (**Eq 12**). Assessing EVs' environmental impacts requires knowledge of local conditions like energy structure and ambient temperature, as these conditions influence battery efficiencies (Zhang et al., 2010; Huo et al., 2015). Geographical variances and temperature affect the overall sustainability of EVs (Hao et al., 2020; Reyes et al., 2016).

The inclusion of temperature effects in this analysis is crucial to accurately reflect the real-world performance of BEVs under different climatic conditions. By incorporating these factors, the study aims to provide a more comprehensive understanding of the environmental impacts of BEVs compared to GVs, tailored specifically to the context of Heilongjiang Province.

3.3.3 Social Life Cycle Inventory Analysis

In this study, the S-LCA approach was used to evaluate the social impacts of BEVs and GVs from the consumer's perspective. As defined by UNEP, the impact categories in S-LCA are "logical groupings of S-LCA outcomes relevant to social issues of concern to stakeholders and decision-makers" (UNEP, 2009). The methodology for performing the life cycle inventory phase in S-LCA involves several revised operational steps, including preparing for the main data collection, executing the main data collection, gathering data for impact assessment, validating data, linking data to functional units and unit processes (when applicable), refining the system boundary, and aggregating data when applicable (UNEP, 2009).

In the data collection phase, according to the UNEP (2009), the five indicators of consumer social impact are health and safety, feedback mechanisms, privacy, transparency, and end-of-life responsibility. Each of these indicators is critical for understanding the broader impacts of vehicle usage on consumers, ensuring a comprehensive evaluation of the social dimensions associated with automotive technologies.

The study aims to develop a methodology to quantify social well-being during the use stage in monetary terms from the consumer's perspective. This approach aligns with the characterisation methods available and emphasises stakeholder experience and concern, which are critical for effectively assessing the impact on human well-being. Such a methodology supports decision-making by providing valuable insights into how different aspects of vehicle use affect consumer satisfaction and social well-being (Subramanian et al., 2018). S-LCA plays a crucial role in evaluating the social impacts of production and guiding more socially sustainable purchasing and consumption decisions (Parent et al., 2013). Positive social impacts are recognised as key factors that influence consumers' attraction to products (Ekener, Hansson, & Gustavsson, 2018).

S-LCA guidelines categorise consumer social impacts into five dimensions, namely, health and safety, privacy, transparency, feedback mechanisms, and end-of-life responsibility (United Nations Environment Programme and SETAC, 2013). Each category is described by aspects that affect consumer decision-making. To capture these dimensions accurately, the study designed a questionnaire reflecting these definitions. Details on the questionnaire design and its implementation are discussed in the subsequent subsections. This refined approach ensures a comprehensive and systematic evaluation of the social impacts of BEVs and GVs, providing actionable insights for stakeholders and informing more socially responsible decisions regarding automotive technologies.

3.3.3.1 Social Life Cycle Inventory Analysis: Questionnaire Design

This study employed the S-LCA approach to evaluate the social impacts associated with EVs and GVs, specifically focusing on consumer perceptions and behaviours. The primary objectives are to understand the relationship between vehicle purchase intentions and perceived social impacts, as well as to assess consumers' WTP for CO_2 tax initiatives as a component of environmental responsibility.

A comprehensive questionnaire was developed to achieve these objectives. This questionnaire was meticulously designed to be clear and precise, facilitating quick and accurate responses from participants. It was made available in both Chinese and English to ensure accessibility and understanding among a diverse respondent pool.

The survey is structured in three parts. Part I - The background information of respondents gathers demographic and personal information from respondents. It includes questions on driving license status, gender, age, location, highest academic qualifications, monthly income, experience with various vehicle types, and vehicle purchase preferences. This background data is essential for contextualising the responses and analysing them in relation to different demographic factors.

Part II - Social impact assessment is divided into five sections, each addressing a specific social impact category. The sections consist of Section A: Health and Safety, Section B: Consumer Privacy Security, Section C: Basic Information Transparency, Section D: Feedback Mechanism, and Section E: End of Life and Future Concerns. This part was designed to analyse the social impacts of EVs and GVs on consumers, as well as the relationship between vehicle purchase intention and the socials impact of vehicles, with the overall aim of gathering insights into the social dimensions of vehicle use and ownership.

Part III explores consumers' WTP for CO_2 tax initiatives as a measure of their commitment to environmental responsibility. Quantification in social sciences often involves dealing with subjective variables that may be challenging to measure directly (Anjaria, 2022). This part aims to translate consumer attitudes (WTP) towards emission tax for environmental impact into measurable monetary terms.

According to United Nations Environment Programme and SETAC (2013), S-LCA data consists of three types, namely, quantitative, semi-quantitative (yes/no or rating scale responses), and qualitative (descriptive text). This study implemented a descriptive statistical analysis using the Likert scale for the social impact questions. Rating scales, along with attitude scores, are commonly used in the social sciences. This type of scale was developed by Rensis Likert (Likert, 1932), who described and then developed this technique for attitude assessments. Such instruments often use a Likert-type scale. A Likert-type scale "requires an individual to respond to a series of statements by indicating whether he or she strongly agrees, is undecided, disagrees, or strongly disagrees" (Croasmun & Ostrom, 2011). According to Preston and Colman (2000), 5 to 10 categories are easy to rate. Further, five categories are short enough to select an answer quickly, and 3 or 4 categories are complete enough for participants to express their feelings satisfactorily. Thus, a maximum of 5 categories is adequate for most scales (Yang et al., 2014). This study used a 5-point Likert scale, with 1 representing strongly disagree and 5 representing strongly agree.

The inclusion of negative statements, intended to overcome several causes of common method biases in survey questionnaires, has been discussed widely by academic scholars (Jamadin & Noordin, 2016). In designing questionnaires, positive and negative statements are often combined in the set of questions. Conventionally, including negative statements in survey instruments is intended to prevent response bias that affects the validity of research findings (van Sonderen et al., 2013) and produces errors (Colosi, 2005). It is also intended to interrupt response (Roszkowski & Soven, 2010) and reduce the problem of acquiescence, affirmation, or agreement bias made by respondents. Acquiescence refers to a situation where respondents have a tendency to agree with items irrespective of the content (DeVellis & Thorpe, 2021). Respondents tend to provide extreme answers, either agreeing or disagreeing with all statements (van Sonderen et al., 2013).

3.3.3.2 Part I Personal Background

Part I (personal background) comprises eight questions designed to capture the demographic details of respondents. This section is crucial for understanding the context within which respondents make their vehicle-related decisions and for analysing how different demographic factors might influence these decisions.

One of the initial questions in this part addresses whether respondents possess a driving license. Despite the introductory instructions clearly stating that respondents should have experience with vehicles to participate, this question serves as a confirmation of their practical experience with vehicle use. It helps to ensure that respondents are either current or potential consumers, thereby enhancing the relevance of their responses.

The remaining questions in Part I collect detailed demographic information, including gender, age, residential location, academic qualifications, and monthly income. These variables are critical for analysing the influence of personal background on respondents' WTP for CO_2 tax initiatives and their purchase decisions regarding EVs and GVs. Previous studies have shown that factors such as gender, age, education level, and income significantly influence consumers' purchasing behaviour and attitudes towards environmental issue (Che In & Ahmad, 2018; Witek & Kuźniar, 2020).

Furthermore, the inclusion of these demographic questions ensures logical consistency in the analysis. For example, discrepancies such as a very young respondent with high educational attainment but low income may indicate inconsistencies or anomalies in the data. By capturing these details, the study can better understand and account for variations in consumer preferences and behaviours based on demographic characteristics.

Overall, Part I provides a foundational context for interpreting the responses in subsequent parts of the questionnaire, allowing for a more nuanced understanding of how personal background influences social impact perceptions and purchase decisions related to EVs and GVs.

3.3.3.3 Part II Social Impact

Section A (Consumer Health and Safety) is concerned with consumers' fundamental right, ensuring that products and services do not pose hazards to health or life (International Organization for Standardization, 2010). Customers (end users) expect products and services to perform the intended functions satisfactorily and not pose a risk to their health and safety. The aim and approach of this subcategory is to help identify the existence and scope of systematic efforts to address consumer health and safety across the organisations involved in the life cycle of a product and service (United Nations Environment Programme and SETAC 2013). This section aims to assess how well organisations in the vehicle life cycle address these concerns. It includes 10 questions designed to gauge consumer perspectives on how EVs and GVs affect public health and the environment. Understanding these perspectives helps to identify consumers' concerns and needs, thus supporting decision-making by governments and automakers. The insights gathered can lead to improved environmental policies, increased availability of EVs, and better safety standards. For instance, stable vehicle performance, including safety, reliability, and mileage per charge, is a primary concern for consumers considering EVs (She et al., 2017).

Section B (Consumer Privacy Security) consists of 14 questions to obtain understanding of consumers' privacy concerns and views on EVs and GVs and how concerned consumers are about their personal information being leaked during the car purchase process. By understanding these concerns, researchers and policymakers can develop better privacy policies and security measures, enhancing consumers' trust and ensuring a safer buying experience. Effective privacy protection is crucial for maintaining consumer confidence and ensuring that the car-buying process remains secure (Martin, 2018).

Section C (Basic Information Transparency) has 18 questions to understand consumers' perceptions and experiences with the transparency of information provided during the car buying process. The section also seeks to obtain an understanding of whether consumers feel that the information provided by car sellers and manufacturers is sufficiently transparent during the car purchase process, including information on vehicle specifications, prices, fees, and quality, and whether they feel that the policies are transparent, clear, easy to understand, and easy to obtain. The purpose is to understand consumers' views, satisfaction, and need for information transparency in the car purchase process. This helps promote a more transparent and trustworthy car-buying experience while providing consumers with the information they need in order to make informed decisions. The results of the questionnaire can provide essential insights into consumers' perspectives and needs, helping to improve the car buying experience and policy development. According to Willmott (2003), transparency is essential to the consumer–company relationship built by brand trust, communication, and perceived good citizenship. The relationship between consumers and companies is influenced not only by the transparent actions of the company but also by the consumer's subjective assessment of how the company behaves in situations where actions cannot be transparent (Kitchin, 2003). Moreover, consumers' awareness and knowledge are important for promoting sustainable product choices (Hasanzade et al., 2018).

Section D (Feedback Mechanism) has 16 questions to determine whether consumers know how to provide feedback to car manufacturers or service providers. It explores whether consumers are aware of how to provide feedback, their experiences with feedback processes, and the feasibility of existing mechanisms. By understanding these aspects, the study aims to enhance feedback systems, thereby improving product innovation and consumer satisfaction. Effective feedback mechanisms are crucial for capturing consumer experiences and adapting market strategies (Panwar et al., 2019).

Section E (End of Life and Future Concern about Electric Vehicles and Gasoline Vehicles) contains 25 questions. The main aim is to understand consumers' perceptions and preferences regarding end-of-life disposal and future sustainability of EVs and GVs. It also seeks to better understand consumers' needs and considerations, as well as the level of consumer awareness of the responsibilities and obligations of EV and GV manufacturers at the end of their vehicle life. Moreover, the section seeks to determine whether the vehicle's environmental performance and sustainability are considered when buying a car and whether consumers think EVs have advantages.

The summary of the social impact part of the questionnaire is shown in **Table 3.7**. The questionnaire can support decision-making by government agencies, car manufacturers, and related companies to develop better environmental policies, provide more sustainable car scrapping and reuse options, and meet the future needs of consumers.

Table 3.7 : Summary of Social Impact Indicators in the Questionnaire

Category	Indicator	Number of questions	
		BEV	GV
Health and Safety of GV/EV (HSGV/HSBEV)	Consumer perspectives on how electric and gasoline vehicles impact the environment and public health	6	4
Consumer privacy of GV/EV (CPGV/CPBEV)	Consumer Concerns and Perceptions of Privacy in These Two Types of Vehicles	7	7
Transparency (TGV/TBEV)	Consumers' perceptions and experiences with transparency of information provided	9	9
Feedback mechanism (FMGV/FMBEV)	Respondents' satisfaction with the provided feedback.	8	8
End of life and future concern (EFGV/EFBEV)	Perceptions and preferences regarding end-of-life disposal and future sustainability of vehicles	15	10

Note: Including all sub-questions

3.3.3.4 Part III Willingness to pay (WTP) for Carbon Tax Initiative

This part of the questionnaire aims to gauge the value of the GHG discharge fee. Economists commonly regard carbon pricing as the most efficient and effective climate mitigation policy through carbon taxes or emission trading systems (Baranzini et al., 2017). The value of the carbon tax fee in this study can be a benchmark for policymakers who are concerned about the carbon tax or GHG tax. The objective is to protect the environment by slowing down global warming via CO_2 emission reductions. The open-ended CVM method uses the WTP elicitation technique. Furthermore, this part seeks to understand how much consumers willing to pay for carbon emissions and to determine the social characteristics affecting WTP. The findings can inform policymakers of the various stakeholder social characteristics affecting WTP that they should consider when formulating a policy or regulation (Ali & Ali, 2020).

The scenario model provided before the WTP question seeks to provide respondents with full understanding of China's energy component and energy consumption emissions between gasoline and electricity. Coal, China's main energy source, is widely used for heating, power generation, and steelmaking (He, 2023). The electricity used for living and producing is relevant to everyone. In short, respondents were made aware of the climate change problem in general and their contribution to it as residents.

Open-ended questions were used in this questionnaire. Open-ended elicitation is straightforward, simple to deal with in terms of statistical techniques, not prone to anchoring or a starting point bias, and very informative as the maximum WTP can be identified for each respondent (Abedini et al., 2016).

3.3.3.5 Questionnaire Validity

Validity refers to the degree to which the empiric measurement correctly reflects the true sense of the definition in the conversion process (Mohajan, 2017). Validity also concerns the accuracy and meaning of the deductions based on the collected information. This research employed a variety of approaches to improve its validity. To validate the survey questionnaire, the study conducted questionnaire validity testing to ensure that the number of items in each category appropriately represented the category. Content validation was also conducted. In doing so, this study ensured that the expert review panel had clear expectations and an understanding of the task.

In selecting the expert review panel, this study set several criteria: (1) social, S-LCA, or economic experts; and (2) questionnaire design experts. A non-face-to-face validation strategy was used, whereby an online content validation form was sent to the experts and clear instructions were provided. The experts were requested to score each item based on a relevance rating scale independently. These experts have extensive experience and knowledge in social sciences and economics. The content validation period was 1 month, and using the snowball method, this study tried to obtain the highest participated during the period. Finally, six experts participated in validating the questionnaire. The minimum acceptable number of experts is two (Lynn, 1986). However, most studies recommend a minimum of six experts (Yusoff, 2019). Considering the recommended five to eight experts and the researcher's experience, the number of experts for content validation should be at least six and not more than ten (Yusoff, 2019).

The content validation was conducted based on a relevance rating scale, where 1 = *the item is not relevant*; 2 = *the item is somewhat relevant*; 3 = *the item is quite relevant*; and 4 = *the item is highly relevant*. Most studies report the item-level content validity index (I-CVI) or the scale-level content validity index (S-CVI), but not both. This study conducted I-CVI because the S-CVI is an average score that can be skewed by outliers (Rodrigues et al., 2017). I-CVI is the proportion of content experts giving an item relevance rating of 3 or 4 , and the formula is as per **Eq 14** (Yusoff, 2019).

$$I - CVI = \frac{N_a}{N_e} \quad \textbf{Eq 14}$$

where:

$I - CVI$: Item-level content validity index
N_a: Number of experts who agree that a particular item is valid
N_e: Total number of experts consulted

I-CVI is calculated as the number of experts providing a score of 3 or 4 divided by the total number of experts (Lynn, 1986). Items with an I-CVI of .78 or higher for three or more experts could be considered evidence of good content validity (Polit et al., 2007). In this study, all items in the questionnaire were scored between .9 and 1. **Table 3.8** shows the I-CVI results for the questionnaire items.

Table 3.8 : I-CVI Results for Questionnaire Items

Type of variables	Number of Questions	Item content validity index (I-CVI)
Personal background	8	0.9
Health and Safet	10	1
Consumer privacy	14	0.9
Transparency	18	0.9
Feedback mechanism	16	0.9
End of life and future concern part	25	0.9
Willingness to pay for a carbon tax initiative	17	0.9

Note: Including all sub-questions and combining the questions for EVs and GVs

3.3.3.6 Pilot Study for Reliability Test

A pilot study was conducted to ensure that respondents understood the questions and to establish the accuracy and reliability of the instruments. A pilot study assesses the possibility of a study's success and the necessary steps to be taken. It has a particular feature; it is conducted on a small sample rather than the main or full sample of the study. The pilot study is crucial for improving the consistency and efficiency of the main research (In, 2017).

When using a questionnaire as a data collection method, it is essential to determine whether the questions and directions are transparent to the respondents and whether they understand what is required of them. The purpose of conducting a pilot study in survey research is to verify the instrument of the questionnaire, the suitability of the constructs to assess the target variables, and the appropriateness of the wording used to ensure that the respondents understand the content of the instrument well (Hazzi & Maaldaon, 2015).

The pilot study was conducted before distributing the final questionnaire in the Northeast China Regional Power Grid region. A generally recognised guideline for reliability is that pilot studies should target 10% of the overall sample (Gabel & Shindledecker, 1990; Vassar & Holzmann, 2013). This pilot study was conducted on 10% of the actual research sample size, as shown in **Table 3.9**. The reliability test was measured using Cronbach's alpha. Cronbach's alpha offers an inter-item correlation coefficient, that is, the correlation of each item with the sum of all other relevant items that are useful for multi-item scales. According to Cortina (1993), checked by Taber (2018), a value of .7 is an appropriate coefficient of reliability. This study's reliability test results are shown in **Table 3.9**. Five variables with Cronbach's alpha coefficients above .7 are considered acceptable in the reliability test results.

Table 3.9 : Reliability Test Results

Type of variables	Number of questions	Cronbach's Alpha coefficient
Health and Safety	10	.736
Consumer privacy	14	.891
Transparency	18	.964
Feedback mechanism	16	.849
End of life and future concern	25	.935

Note: Including all sub-questions and combining the questions for EVs and GVs

3.3.3.7 Sample Size and Sample Technique

The estimated population of Northeast Regional Power Grid area at the end of 2022 was 34.9 million. In this study, the sample size was determined using Cochran's sample size. Four methods to determine the sample size for research. These methods are: (1) using a census for a small population, (2) replicating the sample size of similar studies, (3) using the sample size from published data, and (4) applying formulas to calculate the sample size (Nanjundeswaraswamy & Divakar, 2021). In a normal distribution, approximately 95% of the sample values are within 2 standard deviations of the actual population values. This confidence interval is also known as the risk of error in statistical hypothesis testing. There is always a possibility that the sample obtained by the researcher does not represent the actual population value. This risk is reduced at 99% confidence levels and increased at 90% or lower levels of confidence. Following Cochran's formula (Singh & Masuku, 2013), the present study chose a 99% confidence level to reduce the risk of error and increase the reliability of the study.

Cochran's formula enables an estimation of the optimal sample size, providing the required level of precision, the required confidence level, and the approximate proportion of the attribute present in the population (**Eq 15** and **Eq 16)**. Based on Cochran's sample size formula (Israel, 2003), the margin of error is 5%; in social research, a 5% margin of error is acceptable (Taherdoost, 2016). The sample size in this study was determined to be 666 respondents.

$$n_0 = \frac{Z^2 pq}{e^2}$$ **Eq 15**

where:

e: The desired level of precision (i.e. the margin of error),

p: The estimated proportion of the population that has the attribute in question,

q: $1 - p$,

Z: The z-value (from the Z table), and

n_0: Cochran's recommended sample size.

$$n = \frac{n_0}{\frac{(n_0 - 1)}{N}} \qquad \textbf{Eq 16}$$

where:

n: The sample size, and

N: The population size.

Sampling is a crucial methodology in research, enabling researchers to observe characteristics representative of a larger population by carefully selecting a smaller, manageable sample (Mohsin, 2016).

This study used proportional stratified random sampling as the sampling technique. In large-scale surveys, stratified sampling is particularly advantageous due to its ability to provide precise estimates not only for the entire population but also for distinct subpopulations (Arnab, 2017). This technique involves dividing the population into homogeneous subgroups known as strata, typically based on defining characteristics like geographical location. In stratified sampling, each subgroup is sampled proportionally to its size in the overall population, ensuring that all segments are adequately represented, which is crucial in populations with significant variability (Simkus, 2023).

Following the stratification of the population and the determination of the proportions, the next step typically involves random sampling within each stratum. This method is highly effective because it maintains the impartiality of random sampling while ensuring that all segments of the population, including minority or under-represented groups, are adequately represented in the study (Elfil & Negida, 2017). Stratified random sampling ensures that every subgroup of the population is adequately reflected in the overall sample of the research study (Taherdoost, 2016). The advantage of this method is it assesses the effect size within each stratum independently, akin to conducting a separate study for each subgroup. This clarity helps highlight differences between groups and enhance the representation of minority or under-represented populations (Elfil & Negida, 2017).

The Northeast China Regional Power Grid area has 13 cities. The sample size for each city (stratum) is proportional to its size in the entire population. The sample size is shown in **Table 3.10**.

Table 3.10 : Northeast China Regional Power Grid Sample Size

Region	Total Population (10000 persons)	Percentage	Sample size with 95% confidence level	Pilot study	Real sample size with 99% confidence level
Total	3491.1	100.00%	385	41	666
Harbin	943.2	27.02%	104	10	180
Qiqihar	516.5	14.80%	57	6	99
Jixi	164.7	4.72%	18	2	31
Hegang	95.7	2.74%	11	1	18
Shuangyashan	137.0	3.92%	15	2	26
Daqing	271.8	7.78%	30	3	52

Table 3.10 : Continued

Region	Total Population (10000 persons)	Percentage	Sample size with 95% confidence level	Pilot study	Real sample size with 99% confidence level
Yichun	108.4	3.10%	12	1	21
Jiamusi	227.9	6.53%	25	3	43
Qitaihe	75.1	2.15%	8	1	14
Mudanjiang	244.2	6.99%	27	3	47
Heihe	153.8	4.41%	17	2	29
Suihua	513.3	14.70%	57	6	98
Daxinganling	39.7	1.14%	4	1	8
Suihua	513.3	14.70%	57	6	98
Daxinganling	39.7	1.14%	4	1	8

Confidence Level: 95%/99%
Margin of Error: 5%
Population Proportion: 50%

3.3.3.8 Data Collection

Data collection is an essential step in inventory analysis. This study's data was collected from 1 November 2023 to 1 February 2024. Enumerators with good academic backgrounds were selected to help distribute and collect questionnaires in various regions in China. Specific training for this study was provided to the enumerators and the researcher explained the issues to the enumerators. A total of 666 questionnaires were distributed to respondents. All participants were assured that their anonymity and confidentiality would be upheld throughout the study process. When differences in sample characteristics are considered, face-to-face and online survey preferences may be comparable (Saloniki et al., 2019). In the study conducted by Touvier et al. (2010), 92.2% of the respondents preferred web-based questionnaires. High levels of agreement were found between the paper and web-based versions. Thus, Touvier et al. (2010) concluded that the web-based questionnaire's information quality was at par with or superior to that of the paper version, in addition to possessing significant logistical and financial advantages (Touvier et al., 2010). Dodou and De Winter (2014) reported the same results. No distinction in social desirability was discovered between polls conducted on paper and online (Dodou & De Winter, 2014). However, some researchers still view face-to-face surveys as producing the most accurate findings (Szolnoki & Hoffmann, 2013). Hence, due to the extensive coverage of the study area, both web-based and face-to-face methods were used to

Descriptive statistics and correlation analysis were applied to the survey data to draw meaningful conclusions about the social impacts of EVs and GVs. The results are expected inform stakeholders and guide future vehicle policy and consumer engagement strategies.

3.3.3.9 Social Impact Assessment Analysis

This study conducted an analysis of respondents' demographic information and scores for inventory to determine how consumers' perceptions of social impacts (health and safety, privacy, transparency, feedback mechanism, and end-of-life) differ between EVs and GVs in Heilongjiang Province. The analysis was also aimed at determining how consumers' perceptions of the social impact categories influence their purchasing decisions regarding BEVs and GVs in Heilongjiang Province. Correlation coefficient was used to determine the relationship between social impact and consumer purchase decision-making.

The respondents' demographic information was collected using questionnaire surveys. Frequency analysis (frequencies and percentages) was used to summarise and present the demographic characteristics of the respondents, as per the formula in **Eq 17**. Frequency analysis is a key statistical method that focuses on the number of occurrences (frequency) and the corresponding percentage of those occurrences (Mishra et al., 2019).

Respondents were asked to score each social impact category based on a five-point Likert scale. The aim was to identify trends in vehicle preferences. Arithmetic mean was used to calculate the average score (**Eq 18**) of different vehicle types for each social impact category, and high and low scores were compared.

Correlation analysis based on Spearman's correlation coefficient was used to assess the strength and direction of the association between social impact evaluation and vehicle preference. Spearman's rank correlation coefficient is a nonparametric statistical measure used to assess the strength and direction of the monotonic relationship between two ranked variables or between one ranked variable and one measurement variable. Because the data were non-normally distributed, they were analysed using Spearman's rho correlation coefficient. This distribution-free method evaluates how well the relationship between variables can be described using a monotonic function without assuming any specific distribution for the data (Xiao et al., 2015). The present study used the correlation component of non-parametric correlation, Spearman's rho correlation coefficients (**Eq 19**). This is because non-parametric correlations are used to investigate the relationship between two variables if any one or both the variables are categorical (Verma, 2019). While a correlation greater than .8 is generally considered as high, a correlation less than .5 is generally regarded as weak (Smith, 1969). In this study, Spearman's correlation coefficient and its significance level (*p*-value) was generated for the relationship between each social impact category and vehicle preference.

$$\text{Freq\%} = \frac{Freq_i}{N} \times 100\% \qquad \textbf{Eq 17}$$

where:

$Freq\%$: The frequency percentage of individual questions;
$Freq_i$: The frequency of individual questions; and
N: The total number of answers for an individual question.

$$Average\ Score = \frac{\sum_{i=1}^{n} x_i}{n} \qquad \textbf{Eq 18}$$

where:

x_i: Each individual question score in a specific part of the questionnaire; and
n: The total number of answers in a specific part of the questionnaire.

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \qquad \textbf{Eq 19}$$

where:

r_s: Spearman's rank correlation coefficient;
d_i: The difference between the ranks of corresponding variables; and
n: The number of observations.

3.4 Evaluating Vehicle Sustainability

This study's evaluation of vehicle sustainability comprehensively assessed EVs and GVs across their life cycles, encapsulating environmental, economic, and social dimensions. This section delineates the evaluation criteria and introduces a structured framework to guide the analysis, ensuring that the criteria are not only clearly defined but also robustly justified based on stakeholder concerns and policy implications.

The LCSA method employs a monetisation approach to integrate these three dimensions for informed decision-making. The inclusion of stakeholders is necessary to validate decision-making processes (Wulf et al., 2023). To avoid bias and keep the assessment feasible, neither stakeholder representatives nor experts were involved in the study's criteria weight-making (Wilken et al., 2020). Additionally, each pillar of sustainability—environmental, economic, and social—was accorded equal weight.

The evaluation criteria were selected based on their relevance to key stakeholder concerns and their ability to offer a comprehensive assessment of sustainability. Environmental criteria address direct and indirect ecological impacts and are essential for regulatory compliance and environmental management. Economic criteria ensure that the cost impacts of vehicle ownership and operation are clear, thereby facilitating consumer decision-making and policy development. Social criteria reflect the broader impact on community well-being and consumer satisfaction, consistent with global SDGs and local social priorities. The results are quantified in monetary terms to provide comprehensive sustainability insights for regulators and consumers, enhancing the practicality of the findings in policy-making and market behaviour.

3.4.1 Environmental Impact Monetisation

This study used the WTP elicitation technique to estimate the environmental impact monetarily. For LCA purposes, conducting new primary WTP studies may be justified and beneficial (Hofstetter & Müller-Wenk, 2005). The WTP assessment for CO_2-eq was included in the same questionnaire section as the social impact assessment. This approach allows for a comprehensive analysis of the environmental costs associated with respondents' WTP for carbon emissions reduction. The questionnaire design, pilot study, sampling size and sampling technique, and data collection are described in **Subsection 3.2.3**. The questionnaire asked respondents' WTP for CO_2-eq; the average WTP indicates the environmental cost.

The mean WTP is easily changed by the assumed distribution end formation (Li et al., 2009). Honu (2007)'s formula (**Eq 20**) was used to measure the mean WTP by establishing no negative response from respondents for the carbon emission tax price. This formula provides a straightforward metric for assessing the economic valuation of environmental impacts as perceived by the respondents. The carbon emission tax per year for a BEV is 1 year's CO_2-eq for BEVs multiplied by the mean WTP (**Eq 21**). The same formula was used for GVs (**Eq 23**). For the entire life usage of BEVs/GVs, the carbon emission tax is 15 times of 1 year carbon emission tax (**Eq 22**/**Eq 24**). By implementing these enhancements, the study aims to provide a reliable and actionable understanding of the public's WTP for reducing CO_2 emissions. This information is essential for designing effective environmental policies and interventions that are both socially acceptable and economically justifiable.

$$Mean\ WTP = \frac{1}{N}\sum_{i}^{N} WTP \quad \textbf{Eq 20}$$

$$BEV_{Tax/year} = BEV\ emission/year\ \times mean\ WTP \quad \textbf{Eq 21}$$

$$BEV_{Tax\ 15} = 15 \times BEV_{Tax/year} \quad \textbf{Eq 22}$$

$$GV_{Tax/year} = GV\ emission\ \times mean\ WTP \quad \textbf{Eq 23}$$

$$GV_{Tax\ 15} = 15 \times GV_{Tax/year} \quad \textbf{Eq 24}$$

$MeanWTP$: Mean WTP value for all respondents
N: Total number of respondents
i: Individual respondent's response
$WTPi$: Individual respondent's WTP value
$BEV_{Tax/year}$: One year of BEV's CO_2-eq emission tax
$BEV\ emission$: Amount of BEV's CO_2-eq emissions in a year
$BEV_{Tax\ 15}$: BEV's CO_2-eq emission tax within 15 years
$GV_{Tax/year}$: One year of GV's CO_2-eq emission tax
$GV\ emission$: Amount of GV's CO_2-eq emissions in a year
$GV_{Tax\ 15}$: GV's CO_2-eq emission tax within 15 years

3.4.2 Social Impact Monetisation

Most of the current studies focus on EV technology and emission reduction, and little attention is given to WTP or willingness to buy (WTB). The WTP approach has been used in LCA studies to quantify non-market values such as environmental and social impacts (Murakami et al., 2018; Wang et al., 2018). Few studies have focused on residents' WTB, an essential factor affecting EV sales (Zhang et al., 2023). WTP and WTB (whether one is willing to buy something at a given price) are two standard methods to elicit valuations that normally yield the same valuation order between two options (Lu & Hsee, 2019). This study wants to explore the influence of social impact on purchase decisions and monetise the results. The social impact indicators affect WTB. The social WTP approach is used to quantify the relative severity levels across different impact categories (Wu et al., 2005). It reveals through societal decisions that WTB has the same function because social impact may affect consumer decision-making.

Consumer decision-making is the dependent variable, and it is affected by the independent and intermediary variables and represents the consumer's final purchase or behavioural decision (Oke et al., 2016).

Well-being should be considered a critical area of protection for assessing the social impact of products based on the principles of social life-cycle calculation. Social inventory indicators have a direct effect on the categories of midpoints and endpoints (Neugebauer et al., 2014). Hence, social well-being can be regarded as the mediating variable to comprehensively evaluate the effect of products or services on consumers' attitudes and decisions throughout the life cycle of the products or services, thereby affecting sustainable purchase decision.

The impact pathway approach uses cause-effect chains and implements the assessment from a different angle, which could potentially lead to other results (Springer et al., 2024).

The WTB approach entails calculating consumers' WTB affected by consumer social well-being issues. Among the weighing methods, implicit equal weighing employed in most studies might result in discrepancies. All sub-categories cannot be given equal significance, and each has its own weak or strong effect according to its relevance in the life cycle stages. For the environmental impact, weighting factors are usually used to identify different significance among sub-categories. The weighting criteria for ecological damage and resource depletion categories were developed based on the green tax imposed on emissions and natural resources (Wu et al., 2005; Li et al., 2011).

In the study by Yang et al. (2017), the WTP value of each grade of ready-mixed concrete unit volume was determined using the revised environmental impact monetisation weight factor after the environmental profile of ready-mixed concrete was studied and defined. Utilisation routes were subjected to thorough evaluation from both economic and environmental standpoints based on the idea of environmental efficiency. The environmental evaluation was carried out using LCA principles, and a monetisation-weighting method was used to determine social WTP as a reflection of damage.

Assigning different weights to the indicators and subcategories with strong and weak relationships and further using those weights as factors to aggregate the results at the subcategory level is a possible approach (Ofori et al., 2017). This study conducted an inventory analysis to integrate the indicators in the use stage. The impact of indicators in the use stage was the distribution of WTB to each indicator of the use stage. Weight was used to monetise the social impact. The price of a social impact indicator equals the selling price of the vehicle multiplied by the indicator's weight. Weighting the five indicators of consumers' social well-being impact on total purchase intention by using correlation coefficients between the indicators and purchase intention enables the quantification of the total impact on consumers. The higher the correlation, the higher the weight. This is because consumers' attitude and satisfaction affect consumers' purchase and intention, leading to sustainability behaviour (Ahamad & Ariffin, 2018; Roth & Bösener, 2015).

Both WTP and WTB provide insights into how much consumers value certain social aspects of EVs and GVs, reflecting their direct impact on market behaviour. Converting social impacts into monetary values allows policymakers and businesses to understand the economic implications of social preferences and plan accordingly. The weighting approach ensures that all the relevant social factors are considered according to their significance in affecting consumer decisions, thereby avoiding biases that might arise from unequal consideration of impacts. In practice, the study calculated the WTB affected by consumer social well-being issues. This involved determining the correlation coefficients between social well-being impacts and consumers' WTP, and then using these correlations to assign weights to each social impact indicator. The final monetisation of these social impacts involved multiplying the selling price of the vehicle by the weighted value of each social impact indicator. This method effectively quantifies how much each social aspect contributes to the total purchase intention and, ultimately, to the market valuation of EVs and GVs.

This approach allows for a nuanced understanding of how different social factors influence consumer behaviour and the overall market dynamics for vehicles. By detailing the methodology, providing practical applications, and comparing different approaches, this study aims to provide a robust framework for monetising the social impacts of EVs and GVs, facilitating informed decision-making by stakeholders and contributing to a broader understanding and promotion of sustainable consumer behaviours in the automotive industry.

Firstly, this study calculated the correlation coefficient between social well-being impact category and purchase decision. This step was done in the social impact assessment and will continue it to do willingness to purchase and obtain the impact category’s weight (**Eq 25**). By dividing the correlation coefficient of a specific social impact category by the correlation coefficient of the overall social impact, the relative weight of that social impact category in the overall social impact could be calculated. Then, the value of the impact category was obtained by multiplying the weight of the impact category by the vehicle's selling price (**Eq 26**). To calculate the real social value of the impact category, the correlation coefficient of the social impact category was first divided by 3 (mid-point of a 5-point Likert scale) to derive the true value rate of the category, which is the degree of social contribution of that category (**Eq 28**). Finally, the true value rate of the category was multiplied by the value of the category to obtain the real value of that category, which is the monetisation result of the impact category (**Eq 29**).

By calculating the real value of each impact category, the actual contribution of each social impact category to the overall social welfare was obtained. If the value of the impact category is greater than the real value of the impact category, is means that EVs have a negative social impact in this category. If the real value of the impact category is greater than the value of the impact category, it indicates a positive social impact of EVs in this category. If the sum of all real values are greater than the vehicle's selling price, it can be concluded that promoting EVs is beneficial to stakeholders. In other words, the more EVs sold, the greater the positive social impact. Conversely, if the total real value is less than the selling price, it indicates that EVs do not contribute positively to social welfare.

$$W_i = \frac{1}{\sum C_r A-i} \times C_{ri}$$ **Eq 25**

$$P_v \times W_i = P_i$$ **Eq 26**

$$\overline{X} = \frac{\sum X_i}{N}$$ **Eq 27**

$$ID_i = \frac{\overline{X_i}}{3} \times 100\%$$ **Eq 28**

$$\overline{X} \times P_i = Real\ P_i$$ **Eq 29**

where:

W_i: Weight of impact category i

$\sum C_{rA-i}$: Total correlation coefficients of impact categories

C_{ri}: Correlation coefficient of impact category i

P_V: Vehicle selling price

$\overline{X}$: Average score of impact category i

$\sum X_i$: Total score of impact category i

N: Total number of respondents

P_i: Value of impact category i

ID_i: Degree of social contribution of category i

3: Mid-point of a 5-point Likert scale

$Real\ P_i$: Real value of impact category i

By detailing the methodology, providing the practical applications, and comparing different approaches, this study aims to provide a robust framework for monetising the social impacts of EVs. The goal is to facilitate informed decision-making by stakeholders and contribute to the broader understanding and promotion of sustainable consumer behaviours in the automotive industry.

3.4.3 Monetisation of Vehicle Sustainability

Sustainability results should be used in decision-making when choosing the energy technology to be implemented in a geographical location (Hake et al., 2017). The authors stress that choosing the concept of weighting impact indicators has a substantial influence on the sustainability performance results.

The sustainability of replacing GVs with EVs in Heilongjiang Province, China was evaluated by combining the social, economic, and environmental impacts. Then, the monetisation results of each dimension of EV sustainability were subtracted from the monetisation results of each dimension of GV sustainability to obtain the impact of replacement. The percentage change in sustainability after replacement was then calculated.

Economic sustainability was calculated by subtracting the NPV of BEVs from the NPV of GVs (based on LCA for 15 years for both BEVs and GVs), dividing the result by the NPV for GVs, and then multiplying by 100 to express it as a percentage (**Eq 30**). Environmental sustainability was calculated by subtracting the environmental tax for BEVs from those for GVs, dividing the result by the tax for GVs, and then multiplying by 100 to convert this figure into a percentage (**Eq 31**). Social impact was measured by summing up the real values of impact categories and subtracting the vehicle selling price (**Eq 32**). Social sustainability was assessed by subtracting the social impact of BEVs from that of GVs, dividing by the social impact of GVs, and multiplying by 100 to convert it into a percentage (**Eq 33**).

To enable the public or policymakers to make better use of this research, this research monetised sustainability and used radar charts to visualise sustainability.

$$ECO_S = \lfloor (GV\ LCC_{NPV\ 15} - BEV\ LCC_{NPV\ 15})/GV\ LCC_{NPV\ 15} \rfloor \times 100\% \qquad \textbf{Eq 30}$$

$$Env_s = [GV_{Tax\ 15} - BEV_{Tax\ 15}/GV_{Tax\ 15}] \times 100\% \qquad \textbf{Eq 31}$$

$$SI = \sum Real\ P - P_V \qquad \textbf{Eq 32}$$

$$Sco_s = [(SI_{GV} - SI_{BEV})/SI_{GV}] \times 100\% \qquad \textbf{Eq 33}$$

where:

ECO_S: Economic sustainability

$GV\ LCC_{NPV\ 15}$: NPV of GVs based on 15 years' LCA

$BEV\ LCC_{NPV\ 15}$: NPV of BEVs based on 15 years' LCA

Env_s: Environmental sustainability

SI: Social impact

Sco_s: Social sustainability

SI_{GV}: Social impact of GVs

SI_{BEV}: Social impact of BEVs

3.5 Summary

Chapter 3 has outlined the methodologies used to assess the sustainability of transitioning from GVs to BEVs in the Northeast Regional Power Grid area of Heilongjiang Province, China. This evaluation spans economic, environmental, and social dimensions, reflecting a holistic approach to understanding the impacts of such a transition. Results were monetised to facilitate understanding and decision-making.

To provide these insights, the next chapter discusses the analysis of multiple facets of vehicle sustainability, contributing to informed discussions on policy development and market strategies for the promotion of BEVs in Heilongjiang Province.

CHAPTER 4

INTERPRETATION OF RESULTS AND DISCUSSION

4.1 Life Cycle Cost Results

Section 4.1 answers research questions 1 and 2 to achieve objective 1. The first research question is how do the life cycle costs of GVs compare to those of BEVs in the Northeast Regional Power Grid of Heilongjiang Province, China?

Details of the estimated LCC pertaining to BEVs and GVs in Heilongjiang Province, China, are shown in Appendix 1 and Appendix 2. NPV is the sum of all the PVs of future cash flows determined using a discount rate. Future cash flows consist of future inflows and future outflows (Bora, 2015).

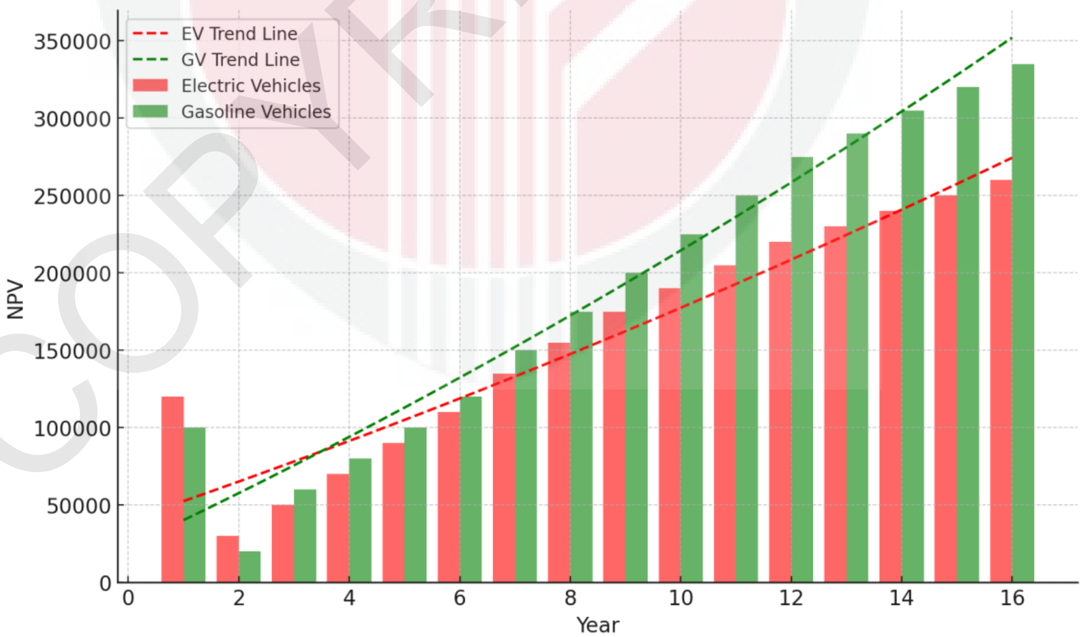

Figure 4.1 : LCC's NPV Result (EVs vs GVs)

Figure 4.1 illustrates the NPV trajectory from year 1 to year 15, demonstrating how initial costs and residual values shape the economic landscape of vehicle ownership. BEVs start with a higher NPV, indicative of greater initial costs, but lower operational and maintenance expenses over time. GVs show a cost advantage in the initial 2.5 years due to lower upfront costs. However, as operational costs accrue, BEVs become more economically viable, especially beyond the 2.5-year mark. This is because the initial purchase cost of a vehicle accounts for a relatively high proportion in the early stages of use. The corresponding residual value also constitutes a large proportion. As the service life increases, NPV also increases. However, the NPV of EVs increases more slowly than that of GVs. The gap between the two NPVs increases as the service life increases. This means that before the crossover point at 2.5 years, it is more cost-effective to choose a GV due to the lower purchase cost, as a lower purchase cost means lower losses at the same depreciation rate. In the chart, the cost change curve of GVs was also lower than the cost change curve of EVs in the first 2.5 years. However, for long-term use, EVs are more cost-effective because their operating costs are lower than those of GVs. Based on the trend shown in the chart, the longer the time passes under the same true discount rate, the more significant the advantage of low operating costs becomes. Therefore, consumers should seriously consider the usage time, current interest rates, and policies related to purchase costs when making purchase decisions.

BEVs show a consistent increase in nominal costs from CNY162,155.64 at 5 years to CNY251,657.66 at 15 years. Meanwhile, GVs experience a more substantial increase from CNY180,254.53 at 5 years to CNY 366,244.28 at 15 years.

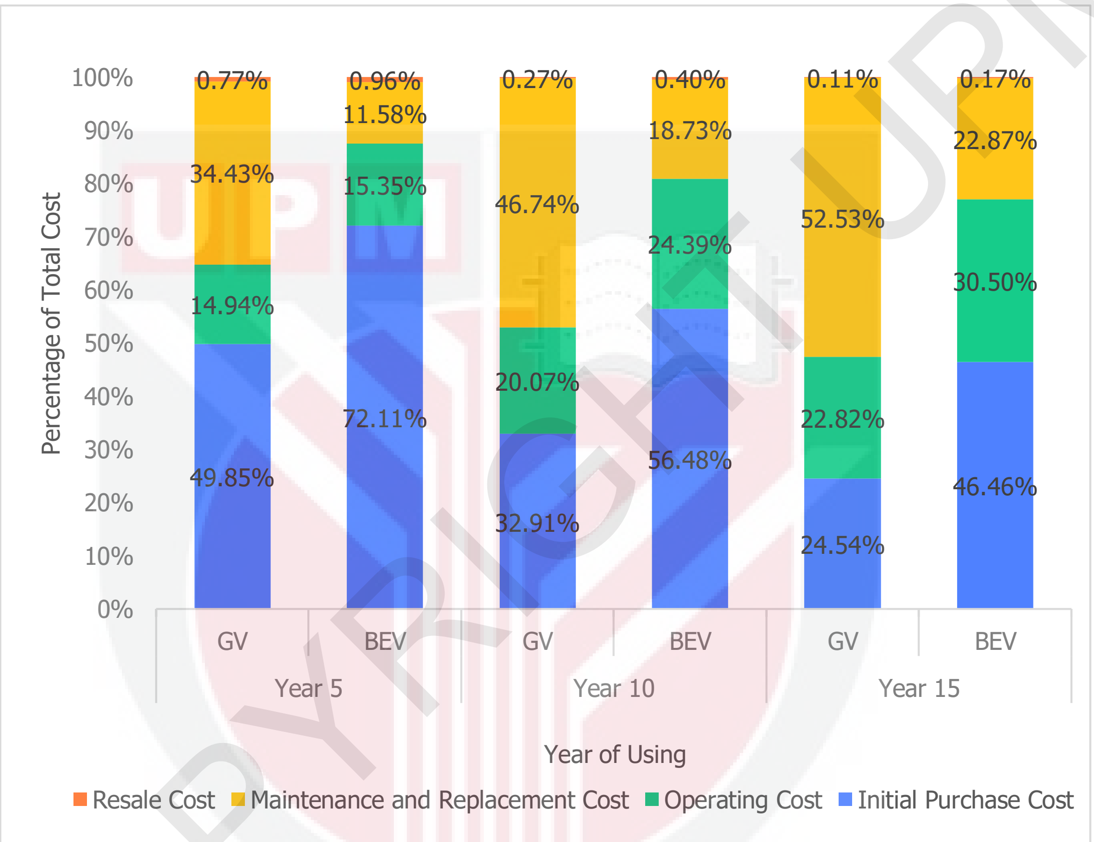

Figure 4.2 : Total Cost of BEVs vs GVs by Service Life (Years)

Figure 4.2 shows a comparison of the total costs for BEVs and GVs by service life years. The visual comparison of these costs highlights the shift in cost dynamics as the service life progresses. Notably, the proportion of initial costs decreases over time for both vehicle types, but the reduction is more pronounced for GVs due to the higher operational and maintenance costs compared to BEVs.

BEVs are currently not as economically competitive as ICEVs due to high battery costs (Ayodele & Mustapa, 2020). However, advancements in technology and various incentives could reduce these costs, making BEVs more financially viable. Subsidy programmes and reductions in operating costs, including parking, tolls, and road taxes, promote the adoption of BEVs (Stodola & Stodola, 2019). Although the proportion of operating cost to total cost is lower for GVs than for BEVs, GVs have a higher total operating cost than BEVs. It may because even though the purchase cost of BEVs is higher than that of GVs, the operational cost for BEVs is lower than that of GVs as a result of the current policy where EVs are not subjected to vehicle and vessel taxes (Heilongjiang Provincial Tax Service, State Taxation Administration, 2021). During annual vehicle inspections, new EVs are not included in exhaust gas environmental testing (Jiao, 2021). Hence, BEVs' operating costs are cheaper than GVs' operating costs.

EVs' maintenance and replacement costs increase slightly from 5 years to 15 years of service, but GVs' maintenance and replacement costs increase substantially as a proportion of the total costs from 34.43% in 5 years to 52.53% in 15 years. Due to the varying gasoline and electricity costs, usage levels significantly affect the cost comparison between EVs and GVs. Long-term maintenance and repair costs have a secondary effect (Weldon et al., 2018). Some researchers have found EVs to be more expensive than GVs. However, such a conclusion would change with changes in battery lifetime, annual driving kilometres, battery charge and discharge rates, and power grid structure (Yang et al., 2022). Nonetheless, currently, some brands provide free lifetime battery replacement and free installation of charging piles; BYD is one of the brands (BYD Auto's official website). Based on this study's results, it can be concluded that under current policies, the maintenance and replacement costs of EVs are lower than those of GVs.

Resale price decreases with an increase in service life. The resale price of BEVs is higher than that of GVs. Higher battery costs result in a purchase price premium relative to equivalent ICEVs; BEVs with shorter driving ranges (shorter service life) will recoup the initial premium more quickly (Liu et al., 2021).

EVs usage 15 years net present value is CNY 214,814.24 and GVs usage 15 years net present value is CNY 301,467.71. If the service life is less than 2.5 years, it is more cost-effective to choose GVs; however, if the service life is more than 2.5 years, it is more cost-effective to choose BEVs. BEVs have a higher resale value than GVs, because a higher purchase price. Due to merchant promotions and supportive government policies, the maintenance and replacement costs of BEVs are lower than those of GVs. Additionally, BEVs benefit from lower operating costs due to current subsidies and exemptions, enhancing their economic appeal over GVs. However, according to the study by Wang et al. (2019), BEVs currently do not hold an economic advantage over ICEVs. This is primarily due to the initial cost of BEVs being approximately higher which increases purchase tax and insurance costs . The key reasons include the high development costs of battery technology and reduced government support, such as decreased subsidies and expired preferential tax policies (Wang et al., 2019). However, in Wang's study, the initial cost of BEVs was approximately 1.69 times higher than that of ICEVs. This could be due to vehicles chosen for the study. For the LCC, vehicles with similar performance and initial costs should be used to minimise bias.

This study's analysis provides a comprehensive view of the life cycle costs associated with BEVs and GVs. Despite the higher initial costs associated with BEVs, their long-term economic benefits are clear, especially when considering their lower operating and maintenance costs and higher resale values. These findings are crucial for stakeholders and policymakers as they consider the broader implications of transitioning to EVs within the framework of sustainable development in Heilongjiang Province.

4.1.1 Analysis of the Real Discount Rate Affecting the Overall Cost for Consumers in Using BEVs and GVs

Section 4.1.1 and **4.1.2** is to answer research question 2, how does the sensitivity of real discount rate and subsidies affect the overall cost for consumers in the utilization of BEVs and GVs within the Northeast Regional Power Grid of Heilongjiang Province, China?"

LCC calculations consider the time value of money. NPV is often used to calculate NPV (Lu et al., 2021). The NPV discount rates usually range from 2% to 6.1% or based on local bank rates (Liu & Ning, 2019). During the 15-year vehicle life cycle, variables that determine the discounted value, such as interest rates and inflation rates, may change. Because interest rates have a profound impact on company investments, different discount rate scenarios are compared (Wouterszoon Jansen et al., 2020).

Sensitivity analysis is an investigation into how projected performance varies with changes in the key assumptions on which the projections are based. It also enables the examination of how uncertainty, for example in international prices, can alter project outcomes (Ong et al., 2012). The discount rate is a key factor in assessing the economic feasibility of a project. In this study, the LCC analysis was conducted based on a 5% discount rate and a real discount rate, but changes in this value can significantly affect the LCC analysis results. Therefore, a sensitivity analysis is needed to determine how changes in the discount rate affect the cost to consumers in the use stage to accommodate investors of different categories and needs (Kumar, 2017).

Based on **Figure 4.3** and **Figure 4.4**, a comparison of the cost curves of GVs and EVs shows that GVs have a larger slope, which means GVs are more sensitive to the discount rate than EVs in the 15-year use cycle.

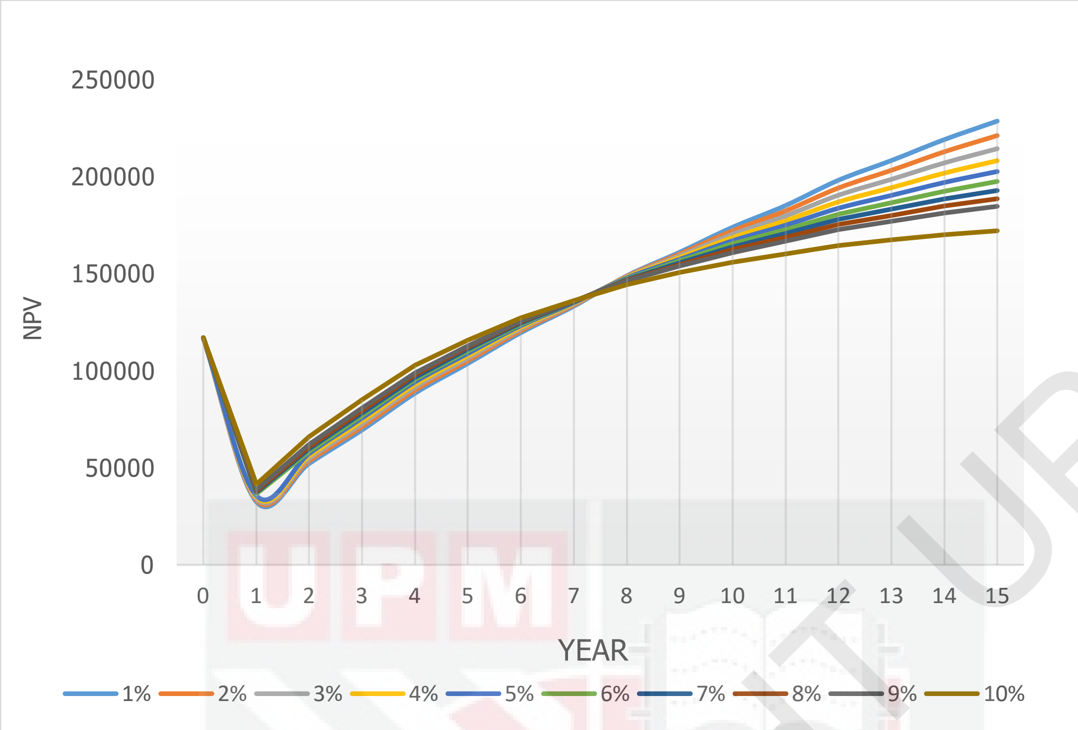

Figure 4.3 : Sensitivity Analysis of EVs' LCC Results (Adjusted Real Discount Rate of 1%–10%)

Figure 4.3 depicts the sensitivity analysis of EVs' LCC results with adjusted real discount rates. First, high depreciations due to high real discount rates will lead to higher life cycle costs. This is because a high depreciation rate results in a lower vehicle resale price, that is, a lower residual value. Therefore, the higher the real discount rate in the first 7 years, the higher the NPV result, which means higher life cycle costs. Over time, the NPV cost curve becomes smoother and the slope becomes flatter. When the vehicle's residual value continues to decrease and accounts for a smaller proportion of the total cost than other costs, the NPV result changes. Starting from the 7th year, the higher real discount rate, the lower the change in NPV, which means that other costs are significantly affected by changes in the real discount rate. A high real discount rate means higher life cycle costs in the first 7 years, but the opposite is true after 7 years when a high real discount rate means lower life cycle costs.

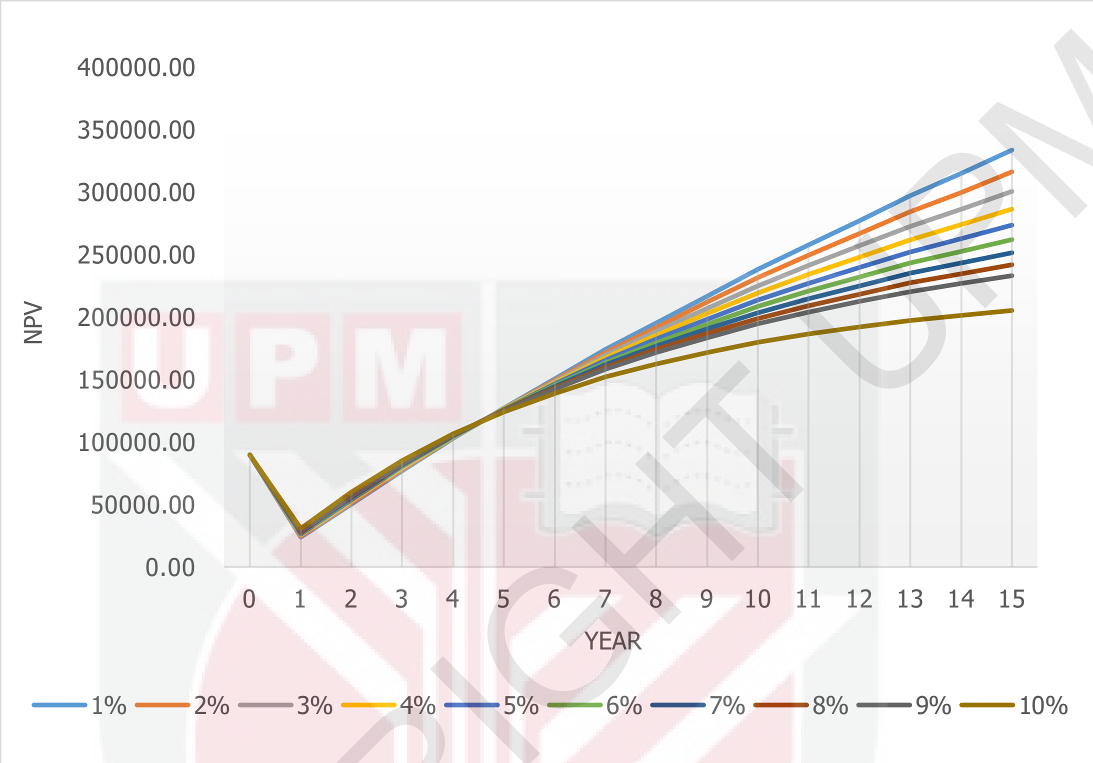

Figure 4.4 : Sensitivity Analysis of GVs' LCC Results (Adjusted Real Discount Rate of 1%–10%)

Figure 4.4 shows a similar pattern to the EV sensitivity analysis. Initially, a higher real discount rate is accompanied by a higher NPV. However, after 4.5 years, a higher real discount rate lowers the NPV. Furthermore, GVs' LCC results are more sensitive than EVs' LCC results to the actual discount rate. This is because GVs incur higher operating costs than EVs. The slope of the cost curve in **Figure 4.4** also shows that higher costs will respond significantly to the discount rate. However, EVs' LCC results are more sensitive than GVs' LCC results to real discount rates at the early stage.

The value of the vehicle depreciates rapidly over time. The depreciation pressure will be more significant at a high real discount rate in a shorter period. If a high discount rate results in a more significant discounting effect on the upfront secondary sales price, the short-term NPV may be lower. If the value of the vehicle in the later stages of purchase (for example, the secondary sales price) contributes more to the overall cost, then at a high discount rate, more emphasis on the impact of later cash flows may lead to a relatively high short-term NPV. Under high discount rates, more emphasis is placed on the value of immediate cash flows. If other expenses (e.g., maintenance, fuel costs, etc.) are relatively low in the short term, then the NPV at a high discount rate may be less affected by the discounting impact of these expenses. The results of the discount rate sensitivity analysis are aligned with the study by J. Li et al. (2021). While the operating costs of GV are more sensitive to changes in discount rates, EVs still have cost advantages over GVs at different discount rates.

4.1.2 Sensitivity Analysis of Consumers' Overall Cost in Using BEVs and GVs–Changes in Subsidies

Figure 4.5 shows that the cost difference between EVs with and without subsidies is primarily reflected in the initial purchase cost. Subsidies help lower the upfront cost and improve consumer acceptance. However, from the sixth year onward, EVs remain more cost-effective than GVs even without subsidies, as they have lower long-term operating costs. While subsidies can accelerate market penetration, long-term dependence may hinder technological innovation. Therefore, gradually phasing out subsidies and implementing policies such as a carbon tax or a reward – penalty mechanism would be more beneficial for promoting the sustainable development of the EV market. This finding is important for policymakers because it suggests that while subsidies are critical in the initial adoption phase, they may become less necessary in the long term as BEVs become more economical due to lower operating and maintenance costs. Subsequently, while the cost of GVs increases linearly with service life, the cost EVs increases more slowly than that of GVs. EVs still have advantages even with zero subsidies. Hence, it is appropriate and timely to consider eliminating the subsidy for EVs (Z. Li et al., 2021).

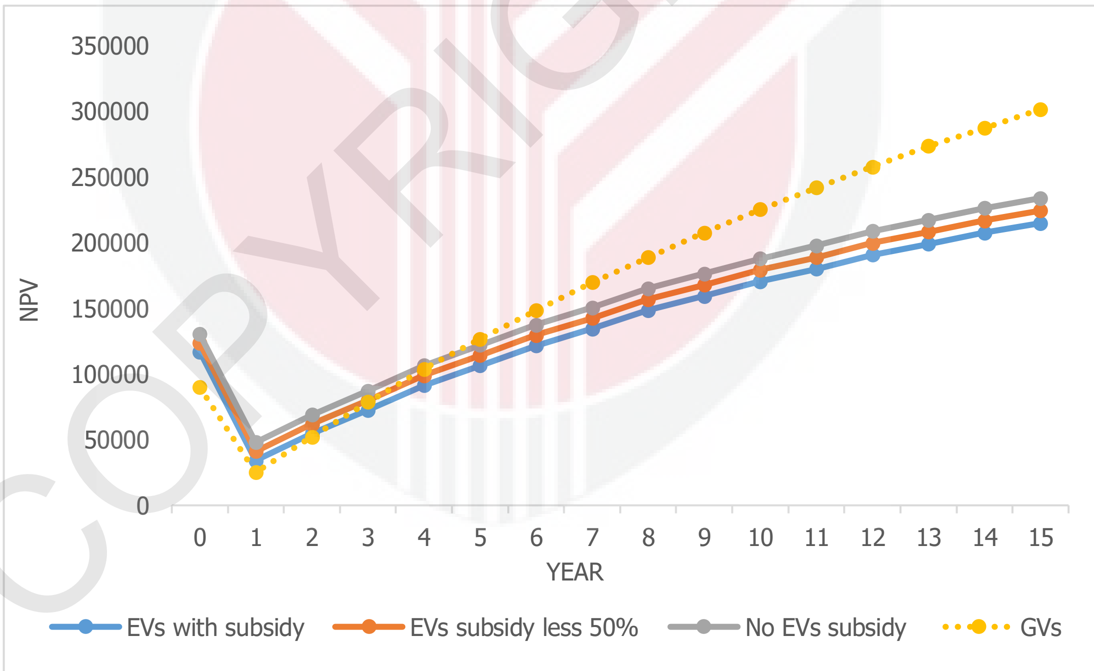

Figure 4.5 : Sensitivity Analysis of LCC Results (Changes in Subsidy Policy)

The analysis highlights the risk of relying on subsidies for the industry, which could stifle innovation and market competitiveness. A shift away from direct fiscal incentives towards mechanisms that promote technological advancement and cost reductions could ensure continued industry growth and consumer acceptance without the need for long-term fiscal support (Wang et al., 2019). Increased overall emissions and the requirements for continued technological advancement indicate that promoting technological progress is a more sustainable alternative than maintaining subsidies (Guo et al., 2021; Zhou et al., 2020). Effective policy implementation and taxation, as outlined by Nonaka and Nakano (2011), further influences consumers' decisions and contribute to emission reductions.

Compared with the subsidy mechanism, the reward–penalty mechanism presents more significant effects on the recycling rate and social welfare (Tang et al., 2019). A combination of subsidy and supervision, or phased regulation, should be adopted. Increasing subsidies is likely to weaken the function of the market and have a counterproductive effect (Lyu et al., 2021). Also, stricter credit targets for new EVs could increase production while curbing the sales of ICEVs (Zheng et al., 2018).

According to the results, despite the elimination of subsidies, EVs still have economic benefit if the usage is maintained for more than 5 years. More subsidies are not always more beneficial. Thus, subsidies may be phased out and replaced by a penalty or compensation mechanism (such as a carbon tax) to encourage consumers to buy EVs. By understanding the impact of subsidies on the economic positioning of BEVs relative to GVs, policymakers can design more effective strategies that not only promote initial adoption but also support sustainable growth of the EV market.

4.2 Environmental Impact Results

Section 4.2 and **Subsections 4.2.1** and **4.2.2** answer research questions 3, 4, and 5, respectively, to achieve the second objective. Section 4.2 answers the research question of "What is the comparative environmental impact of GVs and BEVs in Heilongjiang Province, focusing on total emissions during their use stage?"

Characterisation and end-point damage results of GV and BEV emissions over 1 year (20,000 km) in Heilongjiang province were examined. The temperature effect was not considered. Impact assessment characterisation was used to compare between GVs and BEVs.

Impact Assessment Characterization

Based on **Table 4.1**, GHGs absorb energy and impede energy loss to space, warming the Earth like a blanket. Different GHGs affect Earth's warming differently. These gases differ in their radiative efficiency and lifetime in the atmosphere. GWP is used to compare the global warming consequences of gases, typically over 100 years (United States Environmental Protection Agency, 2016b). GWP and energy consumption are the two largest environmental impacts of the EVs studied (Onat, Kucukvar, & Afshar, 2019). GWP indicators are GWP of fossil (GWP-fossil), GWP of biogenic carbon (GWP-biogenic), and GWP arising from land use and land use change (GWP-land use) (Dodd et al., 2020).

Table 4.1 : Impact Assessment of GV and BEV Emissions in Heilongjiang Province (20,000 km usage)

Impact assessment	Damage category	Unit	GV	BEV
Impact assessment characterization	GWP100 - fossil	kg CO_2-eq	4148.85	3099.88
	GWP100 - biogenic	kg CO_2-eq	0.43	0.32
	GWP100 - land transformation	kg CO_2-eq	0.35	0.72
End-point damage assessment	Human health	DALY	0.01	0.01
	Ecosystems	species. yr	0.00	0.00
	Resources	USD2013	652.26	58.06

For the effect of fossil emissions on GWP over 100 years (GWP 100-fossil), GVs have a significantly higher impact at 4148.85 kg CO_2-eq compared to 3099.88 kg CO_2-eq for BEVs. BEVs emit 25.3% less fossil-based CO_2-eq than GVs due to the lack of direct fuel combustion.This is largely attributed to the combustion processes in GVs, which utilise gasoline, a major source of fossil fuel emissions.

For the effect of biogenic carbon emissions on GWP over 100 years (GWP100-biogenic), BEVs (0.322 kg CO_2-eq) are associated with lower biogenic emissions compared with GVs (0.433 kg CO_2-eq). Biogenic carbon emissions refer to the GWP of CO_2 emissions originating from biomass, as well as the quantity of such emissions (Liu et al., 2020). GVs are associated with higher biogenic emissions compared to BEVs because the exploration, extraction, development, and production activities in petroleum industries produce huge amounts of waste materials (Asim et al., 2021). The energy activities inventory mainly covers emissions of CO_2 and N_2O from the combustion of fossil fuels, emissions of CH_4 from coal mining and post-mining activities, fugitive emissions of CH_4 from oil and natural gas systems, and emissions of CH_4 from the burning of biomass fuels (United Nations Framework Convention on Climate Change, 2004).

GWP100-land transformation quantifies the environmental consequences of converting land throughout the whole lifespan of vehicles, expressed in kg CO_2-eq. The GWP 100-land transformation of a BEV is significantly greater at 0.722 kg CO2-eq, in contrast to a GV, which emits only 0.348 kg CO2-eq. BEVs increase land transformation emissions by 105.7%, highlighting the environmental impact of battery production.Land transformation refers to the change from one land use category to another; for example, forest plantation on land previously used for agriculture (Mattila et al., 2011). A widely used synonym for land transformation is land use change, which, according to the definition by IPCC 2007, refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land use change may affect the surface albedo, evapotranspiration, sources and sinks of GHGs, or other climate system properties. It may thus have a radiative forcing and other impacts on climate, locally or globally (Metz et al., 2007). Land transformation emissions are higher for BEVs than GVs, with the highest contribution coming from electricity production, which is hydro-pumped storage.

For the total emissions for 1 year consumption, GVs exhibit higher overall emissions than BEVs primarily due to their reliance on fossil fuel. The analysis illustrates that while BEVs do generate emissions, particularly from electricity production, their total emissions are consistently lower than those of GVs over the same distance. GVs emit 4149.63 kg of CO_2-eq, and BEVs emit 3100.92 kg of CO_2-eq.

Ignoring the effect of temperature, the BEV's energy consumption is 10.69 KWh per 100 km (battery capacity of 44.9 KWh/100 km of cruising range [cruising range 420km/100km] = 10.69 KWh per 100 km). Assuming that consumers drive 20,000 km a year, the energy consumption for the entire year is 10.69 × 200 = 2,138 KWh. The total annual carbon emission is 3100.92 kg of CO_2-eq divided by 2,138 KWh = 1.45 kg of CO_2-eq. Hence, 1 kW of electricity consumption will emit approximately 1.45 kg of CO_2-eq.

The GV's consumption of gasoline is 5.98 L/100km, and the average annual fuel consumption is 200 × 5.98 = 1196 L. The total annual carbon emission is 4149.63 kg of CO_2-eq divided by 1196 L = 3.47 kg CO_2-eq. Therefore, 1 L of gasoline consumption will emit approximately 3.47 kg of CO_2-eq.

To standardise the electricity and gasoline consumption emissions, the emissions are based on 10 kg of CO_2 in Part III of the questionnaire on respondents' WTP for the carbon emission tax initiative. For gasoline, 10 kg of CO_2-eq are emitted by 3 L of gasoline. For electricity in China's Northeast Power Grid, 10 kg of CO_2-eq are emitted by 7 KWh of electricity.

The findings shows that EVs can substantially reduce GHG emissions, consistent with the results of the studies conducted by Song et al. (2018), Petrauskienė et al. (2021), Bao et al. (2021), and Evtimov et al. (2020). However, Wang et al. (2019) found that BEVs' emissions and climate change impacts were significantly higher than those of the ICEVs. Nonetheless, the study had a limitation in that it used foreign data, which might lead to errors in the conclusions (Wang et al., 2019).

End-Point Damage Assessment

The endpoints damaged by emissions include global warming; stratospheric ozone depletion; ionizing radiation; ozone formation; fine particulate matter formation; ozone formation; land acidification; eutrophication of freshwater and marine environments; toxicity in land, freshwater, and marine environments; toxicity in humans, carcinogenic toxicity in humans, and noncarcinogenic toxicity in humans; land use; and mineral resources. All 18 middle-point damages were converted to three endpoint damages, namely, human health, ecosystems, and resources (Rashedi et al., 2022). **Table 4.1** shows the results of end point damage assessment in Heilongjiang Province for GV and BEV emissions over a 20,000 km driving distance.

For human health, disability-adjusted life years (DALY) quantify the amount of healthy life lost due to a specific health condition or disability (World Health Organization [WHO], 2023). It is a result of the effects of global warming, depletion of stratospheric ozone, ionizing radiation, creation of ozone, formation of delicate particulate matter, toxicity to humans (both carcinogenic and non-carcinogenic), and water usage (Bałdowska-Witos et al., 2023). The impact on human health measured in DALY is relatively low for both vehicle types, with negligible differences between them. This suggests that while vehicle emissions have health impacts, the difference between BEVs and GVs is minimal in this regard.

For ecosystems, when measured in terms of the possible impact on species per year (species.yr), both vehicles have a comparable impact (Huijbregts et al., 2017). GVs' impact is 0.000013848643 species.yr, and BEVs' impact is 0.000013089429 species.yr. There is no significant difference in DALY (human health impact) or species loss between BEVs and GVs.

For resources, 2013 US dollars were used as a reference in the monetary evaluation of reduction in resources (De Bruijn et al., 2002). GVs have a substantially greater impact, with a cost of 652.69 in USD 2013, compared to the BEVs, with a cost of 58.06 in USD 2013. BEVs significantly reduce resource consumption costs (91.1% lower than GVs), indicating long-term economic benefits.The highest contributor to resource damage in GVs is petroleum and gas production process; for BEVs, it is hard coal mine operation and hard coal preparation.

To summarise, the results in **Table 4.1** The transition from GVs to BEVs provides a clear environmental benefit in reducing fossil-related emissions and resource consumption, but comes with trade-offs in land transformation emissions. Future sustainability improvements should focus on cleaner energy sources and reducing battery production impacts. However, if the power industry continues to follow the conventional trajectory, a significant amount of the electricity needed to meet the demand for EVs that are replacing GVs will have to be supplied by conventional coal-fired power plants. This, in turn, may have another effect on humans (China Electricity Council, 2011). The studies by Shi et al. (2016), Boureima et al. (2009), and Abdul-Manan (2015) provide valuable insights into the broader environmental impacts of EVs through LCAs. While these assessments confirm the positive impacts of EVs on global warming and other aspects, they also highlight the complex trade-offs, for example, the greater impact of BEVs on human health and atmospheric acidification.

4.2.1 Scenario LCA-Comparing BEV Emissions Across Different Power Grids

Subsections 4.2.1 and **4.2.2** discuss a range of scenarios devised to shed light on the environmental impact of BEVs under diverse operational scenarios and climatic conditions. **Subsection 4.2.1** answers the question of "How do emissions vary across different power grids of BEVs during the use stage?". To answer this question, this study analysed GV and BEV emissions over 1 year (20,000 km) in different power grids and did not consider the temperature effect.

In the use stage, carbon emission results could be uncertain. Yu et al. (2018) assessed the environmental impacts of EVs and GVs in China, considering the role of coal in China's energy mix and suggesting that cleaner energy sources could mitigate the environmental impacts of EVs. Carbon emissions are linked to power usage, which is affected by the energy structure. As renewables grow, battery carbon emissions will shift. Countries also differ in energy structures, and the results differ (Wu et al., 2023). In the present study, damage assessment was used to compare the emissions associated with various power grids for BEVs and GVs across 1 year (20,000 km). The results shown in **Figure 4.6** compare the environmental impacts of BEVs and GVs across three impact categories, namely, human health, ecosystems, and resources. The analysis used the ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A damage assessment method.

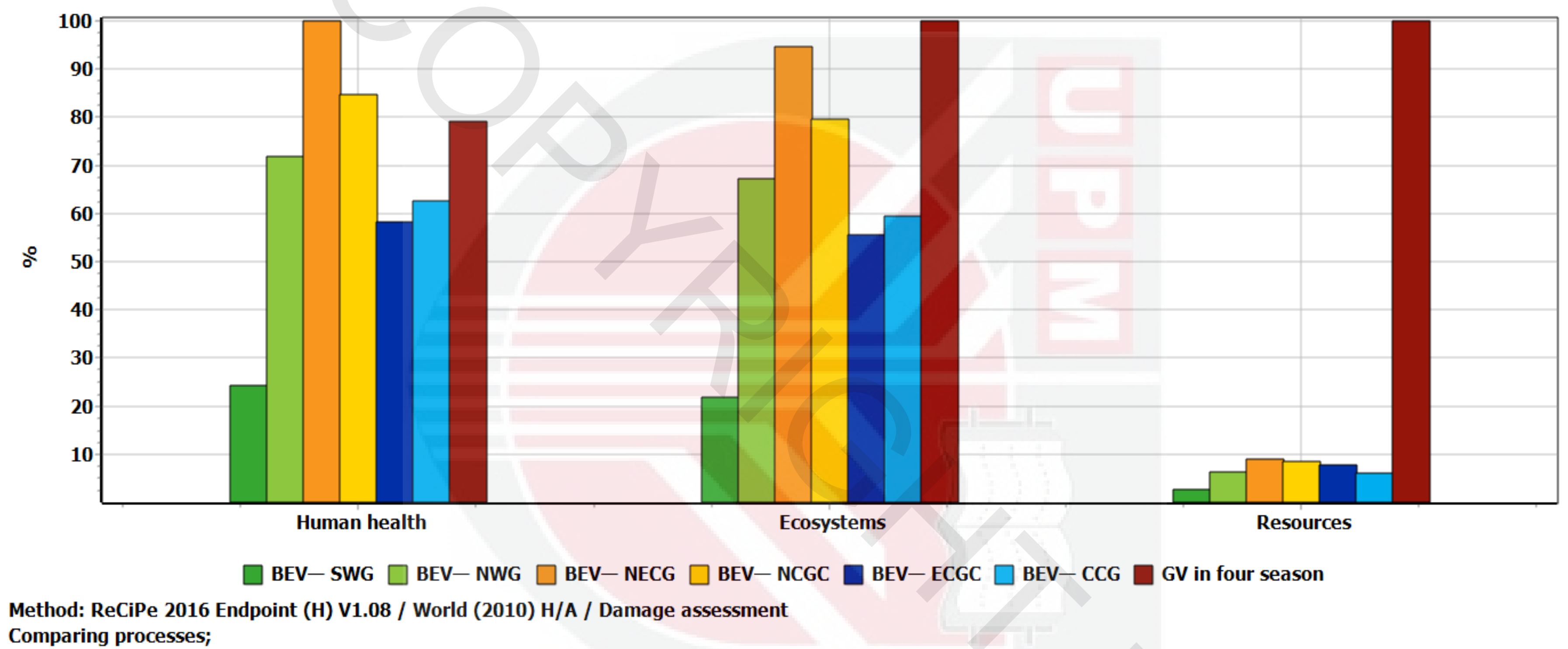

Figure 4.6 : Comparison of the Impacts of BEV and GV Emissions across Power Grids (20,000 km mileage)

For human health, BEV-SWG (Southwest Power Grid) has the shortest bar (dark green bar), indicating the lowest impact on human health. This finding suggests that this grid, likely powered by a higher share of renewable energy, is the most favourable for BEVs in terms of health impacts. BEV-NWG (Northwest Power Grid) has a slightly taller bar (light green bar), indicating a higher health impact than SWG but still lower than most other grids and GVs. BEV-NECG (Northeast China Grid) has the tallest bar (orange bar) for BEVs, indicating the highest health impact, possibly due to high coal dependency. For BEV-NCGC (North China Grid), the yellow bar indicates that this grid has the second-highest health impact for BEVs. For BEV-ECGC (East China Grid), the blue bar indicates moderate health impacts, suggesting a balanced energy mix. For BEV-CCG (Central China Grid), the light blue bar indicates moderate impacts which are slightly better than ECGC and NWG.

For ecosystems, BEV-SWG again has the shortest bar, indicating the lowest impact on ecosystems. BEV-NWG, BEV-CCG, and BEV-ECGC have bars of varying heights but all are significantly lower than GVs, indicating better performance than traditional vehicles. BEV-NECG has the highest impact on ecosystems for BEVs. This is similar to the human health category, which is likely due to high coal usage. GV in four seasons has the highest impact on ecosystems, depicted by the tallest brown bar.

For resources, BEV-SWG, BEV-NWG, BEV-CCG, BEV-ECGC, BEV-NECG, and BEV-NCGC all have relatively short bars that are similar in height, indicating that BEVs have lower resource impacts compared to GVs.

Overall, BEVs have significantly lower impacts than GVs across all categories, regardless of the power grid. The environmental benefits of BEVs are most pronounced when powered by grids with higher shares of renewable energy (e.g., SWG). The source of electricity power significantly affects EVs' environmental benefits. Hsu (2013) highlights that the sustainability of EVs hinges on the cleanliness of the power grid. Moro and Lonza (2018) and Al-Buenain et al. (2021) emphasise that the benefits of EVs are reduced in regions that are dependent on fossil fuels. They stress the importance of transitioning to cleaner energy sources to fully harness the potential of EVs in lowering emissions.

SWG has the best performance in all categories, suggesting a high share of renewables and efficient power generation. NECG has the worst performance for BEVs, indicating reliance on coal and higher usage of fossil fuel. NWG, NCGC, ECGC, CCG have intermediate performance, better than the performance of GVs but still varying based on the energy mix of their respective grids. Performance varies according to differences in energy composition among the grids, such as the share of electricity generated from coal, natural gas, hydropower, or wind. A grid that relies on coal for power generation has relatively high carbon emissions. The findings are similar to

Wilken et al. (2020), which conclude that BEVs that are powered by renewable energy seem more sustainable than ICEVs and BEVs that are powered by a combination of sources.

A grid that uses more renewable energy, such as wind or hydropower, has relatively low emissions. Thus, different types of vehicles are suitable for different regions. While hybrids are more cost-effective and environmentally friendly than other types of vehicles, in developed regions, EVs are more likely than hybrids to reduce carbon emissions and the associated costs. Hybrid vehicles are the most cost-effective and environmentally friendly transportation in northwest, northeast, and southern China. In addition, the dominance of coal power and its sheer economic competitiveness relative to other forms of power generation prevent the generation mix from realising the true potential of EVs (Zhang & Han, 2017).

To maximise the benefits of BEVs, it is essential to transition power grids to cleaner energy sources. This would significantly reduce the environmental impacts associated with BEVs. Different regions should adopt tailored strategies to optimise their energy mix and improve the sustainability of BEVs. For example, areas that are heavily reliant on coal should prioritise renewable energy investments.

China's power structure is predominantly reliant on thermal power generation, resulting in a phase of electric energy acquisition that is marked by significant energy consumption (Wang et al., 2021). Therefore, it is crucial to alter China's coal-fired power generation structure and reduce power consumption throughout the operating phase (Wang et al., 2019). Based on the study's results, EVs have a significant advantage in reducing the environmental impact across all categories, even in a state where power production primarily depends on fossil fuels. GVs exhibit more significant direct emissions during the usage period than all other types of vehicles (Shafique et al., 2021). Thus, it is important to optimise the regional power generation structure for the future advancement of EVs in China (Zhang & Han, 2017).

The findings highlight the critical role of grid cleanliness in determining the environmental benefits of EVs. Policies aimed at enhancing grid sustainability, such as increasing investment in renewable energy and upgrading grid infrastructure, are crucial. Additionally, moving away from coal-based energy production will greatly enhance the environmental advantages of EVs. In summary, although pure EVs have significant advantages over GVs in terms of emissions, the extent to which these advantages can be realised is largely affected by the energy structure of the power grid. Thus, future policies should focus on supporting clean energy to ensure that the shift to EVs produces the desired environmental improvements.

4.2.2 Scenario LCA-Temperature Effect

This subsection answers the question of "How does ambient temperature affect the emissions of EVs compared to GVs in the Northeast Regional Power

Grid of Heilongjiang Province, China?” This subsection discusses the analysis of GV and BEV emissions over 1 year (20,000 km) in Heilongjiang Province by considering the temperature effect.

The studies by Yuksel et al. (2016), Meyer et al. (2018), Archsmith et al. (2015), and Holland et al. (2016) examined the effect of ambient temperature on vehicle efficiency and emissions, highlighting the necessity of region-specific approaches to EV promotion. GHG emissions are influenced by the choice of primary fuel and the associated emissions throughout the value chain until electricity is generated. Additionally, EV efficiency is affected by driving patterns, weather conditions, and land geography (Al-Buenain et al., 2021). As discussed in **Section 3.1**, the energy consumption, charge, and discharge rate in Heilongjiang Province vary across the four seasons, the charge and discharge rates are 59% (winter), 81% (spring), 100% (summer), and 83% (autumn). These rates reflect the decreased battery efficiency during cold weather due to increased energy demands for heating and decreased battery chemical activity. Winter conditions lead to higher electricity consumption for BEVs due to heating needs, resulting in increased emissions during this season. However, emissions are lower in other seasons when the battery operates more efficiently.

Simapro used IPCC 2021 GWP 100 V1.02/Characterization to compare BEV and GV emissions across the four seasons and in one full year. The results are shown in **Figure 4.7**. The figure illustrates the comparison of seasonal emissions between GVs and BEVs powered by the Northeast China Grid (NECG) over a range of 20,000 km (1 year).

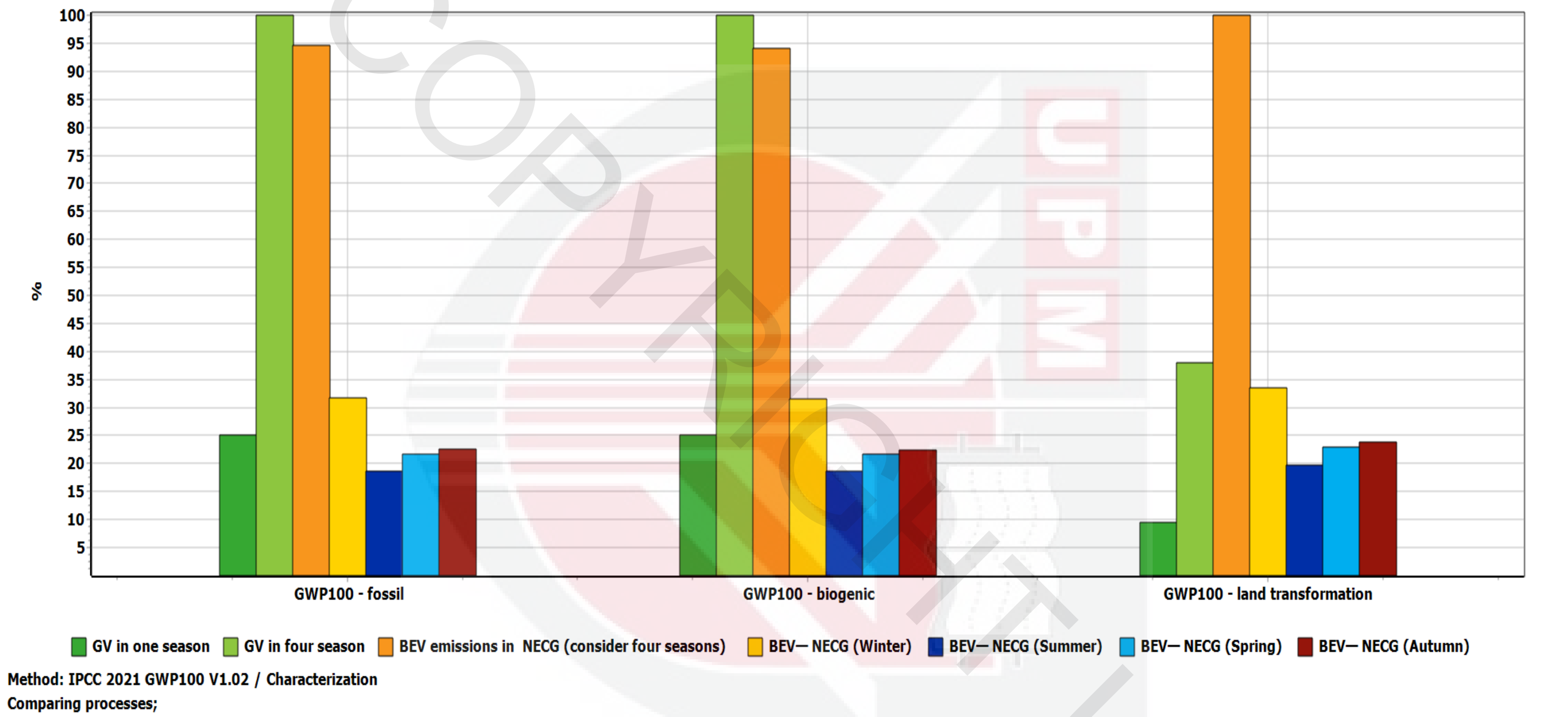

Figure 4.7 : Comparison of BEV and GV Emissions across Seasons (20,000 km mileage)

GWP100-fossil measures the GHG emissions from fossil fuel sources, expressed in percentage. GVs, represented by green bars, have a notably higher percentage of GHG emissions from fossil fuel sources in four seasons (1 year). During winter, BEVs are associated with higher fossil fuel GHG emissions than GVs (one season). BEVs' GHG emissions from fossil fuel depend on energy consumption. In winter, more electricity is consumed due to the cold weather, which causes more emissions compared with other seasons. EVs for personal use undergo a significant decrease in driving range during winter months (Hao et al., 2020). According to Reyes et al. (2016), using the heater at its highest setting results in a significant decrease in range (68%–80%), due to subpar battery performance. However, when emissions in NECG for 1 year (20,000 km) usage are compared, BEVs (3923.30 CO_2-eq) have lower emissions than GVs (4145.85 CO_2-eq). If use BEVs to replace GVs representing a 14.2% reduction of GWP-100 fossil. The study by Zeng et al. (2021) indicates that BEVs fuelled by the current average Chinese energy mix can achieve a 23% reduction in GWP. The lower percentage in NECG may be because of the temperature effect and electricity mix, making EVs less advantageous in this region.

For biogenic carbon GHG emissions, the results for seasonal and 1 year are both the same as the results for fossil fuel. During winter, BEVs have higher emissions than GVs (one season). However, for usage over 1 year (20,000 KM) or all seasons, BEVs are associated with lower GHG emissions than GVs.

For land transformation, regardless of whether one season or one full year is considered, BEVs' emissions are always higher than those of GVs. When the entire year is considered, BEVs are associated with 2.6 times more emissions than GVs.

Göhlich et al. (2015) and Ke et al. (2017) highlight the significant effect of ambient climate on the daily operational range of EVs and their market penetration. The overall interpretation is that from the seasonal perspective, BEVs are associated with higher emissions than GV emissions during winter. However, in other seasons, BEVs are mostly associated with lower emissions than GVs. When all four seasons (1 year or 20,000 km range) are considered, while BEVs are associated with lower fossil fuel emissions and biogenic emissions than GVs, the emissions from land transformation are higher for BEVs than GVs. Additionally, GVs are consistently associated with higher emissions from fossil fuel and biogenic carbon sources, highlighting the potential benefits of transitioning to BEVs from the emission standpoint, particularly when the electricity is generated from cleaner sources.

After factoring the temperature effect, BEVs may be associated with higher emissions than GVs during winter. However, after considering the emissions for 1 full year (four seasons), the study finds that BEVs have advantages over GVs in Heilongjiang Province, China. BEV is a promising technology for reducing the environmental impacts of the transport sector (Koroma et al., 2022). Therefore, the Chinese government needs to promote the use of BEVs and at the same time reduce coal power consumption and restructure the regional power systems (Shafique & Luo, 2022).

To minimise the automotive sector's climate impact effectively, policy instruments should therefore adopt a life cycle perspective on GHG emissions and be technology-neutral. Phasing out of subsidies and increasing the CO_2 taxes on fossil fuel would improve the prospects for renewable alternatives. Reducing the CO_2 taxes on renewable fuel in proportion to their GHG reduction potential would serve the same purpose. The current definition of zero emission poses an imminent risk that this pathway will lead to emissions that approach zero only on paper (Andersson & Börjesson, 2021). This is because of the significant amount of electricity consumed, which means the goal of zero pollution has not been achieved (Wang et al., 2019).

4.3 Social Impact Results

This section aims to achieve the third research objective by assessing the social impacts (health and safety, privacy, transparency, feedback mechanism, and end-of-life) on consumers using BEVs and GVs, particularly in the Northeast Regional Power Grid of Heilongjiang Province.

Welfare theory and the weight assignment method were used to establish the S-LCA monetisation method. Utility theory was combined with social factors to determine the relationship between social factors and consumer decision-making. Then, correlation weighting was used to determine the impact of each social factor on purchase decision. Through weighted summation, the true value of the product, that is, the monetised value of social impact, was obtained.

4.3.1 Descriptive Analysis

This subsection answers the research question of "How do consumer perceptions of social impact (health and safety, privacy, transparency, feedback mechanism, and end-of-life) differ between EVs and GVs in Heilongjiang Province?"

The descriptive analysis of the respondents' profiles is provided in **Table 4.2**. All 666 participants possess a driving licence. About 20.72% of the respondents are using or have used BEVs, 49.70% are using or have used GVs, and 29.58% are using or have used both types of vehicles. The sample has more men (55.41%) than women (44.59%). In terms of age, the 18–32 years old group has the highest number of respondents (37.30%). About 38% of the respondents are under 30 years, reflecting the trend of younger customers (Hu, 2023). Harbin city has the highest number of respondents (27.03%). As highlighted in **Subsection 3.2.3**, Harbin is the most populous city Heilongjiang Province. Daxinganling, which has the smallest population in the province, is the least represented (1.20%). About 38.44% of the respondents have a bachelor's degree, and another 29.58% are college graduates. About 0.40% never went to school. In terms of monthly income, the CNY5,001–CNY8,000 income group has the highest number of respondents (47%), followed by the CNY5,000 or below income group (28.53%). Few (1.8%) earn CNY30,001 or above per month. The results are aligned with the wage standard in Heilongjiang Province, where the average annual salary of full-time employees is CNY77,160.00 (CNY6,430.00 per month) (People's Government of Heilongjiang Province, 2023). Assuming that EVs and GVs have equivalent performance and pricing, 38.40% of the respondents would select BEVs and 61.50% would choose GVs. EVs are popular, but GVs are more common. The reasons for preferring GVs to EVs among Heilongjiang Province residents are analysed and discussed next.

Table 4.2 : Descriptive Statistics of Respondents

Demographic Variables	Categories	Frequency	Proportion %
Driving license	Yes	666	100.00
	No	0	0.00
Type of vehicle being used or has been used before	BEV	138	20.72
	GV	331	49.70
	Both	197	29.58
Gender	Male	369	55.41
	Female	297	44.59
Age	18–22	49	7.30
	23–27	111	16.60
	28–32	124	18.60
	33–37	99	14.80
	38–42	79	11.80
	43–47	52	7.80
	48–52	64	9.60
	53–57	45	6.70
	58–62	26	3.90
	63 years old and above	17	2.50
The current city of residence	Harbin	180	27.03
	Qiqihar	99	14.86
	Suihua	98	14.71
	Daqing	52	7.81
	Mudanjiang	47	7.06
	Jiamusi	43	6.46
	Jixi	31	4.65

Table 4.2 : Continued

Demographic Variables	Categories	Frequency	Proportion %
	Heihe	29	4.35
	Shuangyashan	26	3.90
	Yichun	21	3.15
	Hegang	18	2.70
	Qitaihe	14	2.10
	Daxinganling	8	1.20
Highest education qualification	No formal education	3	0.40
	Primary school	12	1.80
	Secondary school or equivalent	94	14.10
	High school or equivalent	69	10.36
	College degree or equivalent	197	29.58
	Bachelor's degree or equivalent	256	38.44
	Master	19	2.85
	Ph.D.	16	2.40
Monthly income (CNY)	5,000 and below	190	28.53
	5,001–8,000	313	47.00
	8,001–17,000	143	21.47
	17,001–30,000	8	1.20
	30,001–40,000	4	0.60
	40,001–60,000	3	0.45
	60,001–85,000	3	0.45
	85,001 and above	2	0.30
Similar performance and price, EVs or GVs which would you give more priority	BEV	256	38.40
	GV	410	61.50

To understand the social impacts of these vehicles from the consumer's perspective, the inventory results are presented in **Table 4.3**. The table shows consumers' perceptions of various social indicators related to EVs and GVs.

Table 4.3 : Inventory Results of Consumers' Perceptions of EVs and GVs

Category	Indicator	Mean Score	
		EV	GV
Health and Safety of GV/EV (HSGV/HSBEV)	Consumer perspectives on how electric and gasoline vehicles impact the environment and public health	3.3048	3.3855
Consumer privacy of GV/EV (CPGV/CPBEV)	Consumer Concerns and Perceptions of Privacy in These Two Types of Vehicles	3.5187	3.5624
Transparency (TGV/TBEV)	Consumers' perceptions and experiences with transparency of information provided	3.2065	3.2239
Feedback mechanism (FMGV/FMBEV)	Respondents' satisfaction with the provided feedback.	3.3476	3.4219
End of life and future concern (EFGV/EFBEV)	Perceptions and preferences regarding end-of-life disposal and future sustainability of vehicles	3.3113	3.3699

Health and Safety

GVs (mean = 3.3855) are perceived as slightly safer than BEVs (mean = 3.3048), possibly due to their longer market presence and familiarity among consumers. Moreover, concerns about BEVs' safety, particularly regarding battery fires, may influence perceptions negatively. Consumers believe that ICEVs are more mature and safer than pure EVs because of their long-term use and familiarity with ICEVs (Wang et al., 2019). According to statistics from the emergency management department, in the first season of 2023, the spontaneous combustion rate of new EVs increased by 32%, with an average of 8 new EV fires per day (Meng, 2023). Consumers may worry about their safety because EVs pose a fire risk (Featherman et al., 2021).

Consumer Privacy

BEVs (3.5187) score slightly lower than GVs (3.5624) for privacy due to increased data connectivity, which raises concerns about data security and privacy. This may indicate that EV users are more anxious or experience less privacy, though the difference is negligible. The study by Featherman et al. (2021) found that EV users' adoption could result in a loss of privacy of consumers' personal, finance, and driving information. Technology is gradually advancing intelligent transportation systems and smart cities. With technological advancements, human reliance on Internet of Things has grown dramatically. However, embedded sensors that collect personal, financial, and health information; charging records; driving patterns; video; location coordinates; and car-related data raise users' data security and privacy concerns (Malik et al., 2022). Introducing cameras, monitoring devices, and sensors to make EVs sustainable puts users at confidentiality and privacy risk (Muhammad et al., 2023; Saoudi et al., 2022). According to statistics, since 2020, there have been more than 2.8 million malicious data attacks on related companies, such as vehicle manufacturing and vehicle information service providers in China. Further, from 2023 to date, there have been more than 20 data leaks related to car companies in China (Hylender et al., 2024).

The results indicate consumers have low tolerance for various types of information leakage related to EVs and GVs. The mean score of 3.74 for personal information leakage indicates that, on average, consumers have a relatively high concern about personal information leakage, with the majority scoring it as a 4 (median and mode), signifying a high level of concern. Financial information leakage has the highest mean score (3.90), indicating that it is a major concern among consumers. The mode of 5 indicates that many consumers rate their concern at the maximum level. Vehicle information leakage has a mean score of 3.60, which is slightly lower than the mean score of personal information leakage. This finding suggests that consumers are somewhat less concerned about vehicle information leakage. However, the median and mode of 4 still indicate significant concern. Itinerary information leakage has the lowest mean score of 3.17, indicating relatively low concern compared to other types of information leakage. The median and mode of 3, with 25% scoring it as a 2, suggest that while there is concern, it is not as high as for personal or financial information.

The analysis indicates that vehicle consumers are highly concerned about leakages to their personal, vehicle, and financial information, with financial information leakage being the highest concern. Itinerary information leakage, although still a concern, is perceived as less critical by consumers. Consumers' private information is also exposed elsewhere. Some 4S stores install high-tech facial recognition systems and various monitoring systems which record the consumer's image and every move as soon as they enter the store. If the customer leaves their contact information, they will be inundated by a large number of strange calls (Wang, 2023). Along the same line, the People's Daily reported that "Consumers believe that personal financial information is the most important, and personal communication information is the most leaked"

(X. Chen, 2015). According to survey data from satisfaction survey agency J.D. Power, 90% of users prefer car brands with high data security protection (Hylender et al., 2024). Thus, it is crucial for manufacturers and policymakers to address the privacy concerns in order to increase consumer trust and acceptance of EVs. Implementing robust privacy measures and ensuring transparent communication about these measures could mitigate consumers' concerns and potentially increase the adoption rate of EVs.

Transparency

Both vehicle types are rated similarly. GVs (3.2239) score marginally higher than BEVs (3.2065), suggesting that consumers find traditional vehicle manufacturers and sellers to be slightly more transparent. In other words, consumers believe GV information is slightly more transparent than EV information. Tognazzini (2004) argues that unclear information practices can discourage consumer purchases, and the author emphasises the need for greater transparency to enhance societal welfare and maintain competitive markets. Transparency entails publishing product information about supplier traceability, sustainability, lifecycle, and company purchasing procedures (Ospital et al., 2023). According to Willmott (2003), communication, perceived good citizenship, and brand trust all contribute to the development of relationships that depend on transparency. In addition to the transparent acts of the company, consumers' subjective assessment of a company's behaviour in circumstances where transparency is not possible influences the connection between the company and its customers (Kitchin, 2003). Hasanzade et al.

(2018) identified customer awareness, knowledge, and information as elements that motivate them to choose sustainable products.

Feedback Mechanism

In terms of feedback mechanism, consumers' report better satisfaction with GVs (3.4219) than BEV (3.3476), indicating a maturity gap in how feedback is handled between the two vehicle types. This may indicate that GV manufacturers are more attentive to customer feedback or that EV makers must be more mature. Customer feedback is crucial to quality improvement, new product success, business profitability, and input to drive product improvements and foster innovation (Eiríksdóttir & Thorarensen, 2012; Bjarklev et al., 2017). Feedback mechanism helps companies identify the necessary enhancements for current products and provides crucial insights for the development of new products (Fundin & Bergman, 2003). Featherman et al. (2021) highlighted the role of influential individuals in shaping younger consumers' evaluations and purchase decisions regarding EVs, pointing to the importance of social influences in understanding consumer behaviour.

End of Life and Future Concerns

For concerns about disposal and sustainability, BEVs (3.3113) score slightly lower than GVs (3.3699). This shows that under vehicle's end-of-life process and responsibility GVs are higher than those of EVs. End-of-life BEVs and their components, especially batteries, contain substantial amounts of toxic chemicals that might harm the environment and humans, making them harder to manage than their fossil-fuelled counterparts (Prates et al., 2023). For future concerns, GVs have a higher score than BEVs, which means consumers are more likely to buy GVs than EVs in the future.

Consumers find EVs relatively easy to maintain (mean = 3.43) and have low repair costs (mean = 3.16). GVs also receive favourable views for ease of maintenance (mean = 3.45) and low repair costs (mean = 3.56). In fact, GVs score slightly higher than EVs in both categories, indicating that consumers perceive GVs as having a slight edge in terms of maintenance and repair. A major barrier to the adoption of EVs is uncertainty about the battery cost (Inkpen & Baily, 2020). In addition, Egbue and Long (2012) highlighted that although the environmental benefits and sustainability factors of EVs have a major positive impact on their adoption, they still rank lower in factors such as battery replacement costs. However, past research and the current study find that EVs incur lower maintenance and operating costs than GVs (Bessenbach & Wallrapp, 2013). This is due to subsidies such as those on inspection tax and free battery replacements (Heilongjiang Provincial Tax Service, State Taxation Administration, 2021; Jiao, 2021;). Hence, the advantages of EVs' maintenance and operating costs should be promoted.

Satisfaction with EVs' charging time is relatively low, with a mean score of 2.99. EV users' satisfaction is also influenced by the waiting time to access chargers and the likelihood of finding an available charging station (Xie et al., 2018), indicating that this is a significant area for improvement. Conversely, GVs have a high satisfaction rate for refuelling time, with a mean score of 3.56. This stark difference highlights a major convenience factor favouring GVs.

Respondents rated highly for the cost of electricity for EVs, resulting in a mean score of 3.68. They also perceive the gasoline prices for GVs as moderately reasonable, with a mean score of 3.18. This finding suggests that while gasoline costs are not seen as prohibitive, they do not offer as strong an advantage as the lower electricity costs for EVs (*Jinri heilongjiang qiyou jiage,* 2022, 2023).

The ease of obtaining license plates and exemption from traffic control measures are viewed positively for EVs, with mean scores of 3.37 and 3.31, respectively. This category was not directly measured for GVs, but EVs clearly have an advantage here due to favourable regulatory conditions. Recently, Chinese policymakers exempted BEVs from traffic restrictions to promote BEVs as replacements for GVs (Hu et al., 2021).

The rationality of the tiered pricing mechanism for EV charging costs and the location of public charging stations are positively viewed, with mean scores of 3.33 and 3.38, respectively. However, the adequacy of charging infrastructure is still seen as having room for improvement, with a mean score of 3.36. The lack of public charging infrastructure may prevent residents and companies in these areas from purchasing EVs (Mortimer et al., 2022). Clearly, the limited driving range of BEVs imposes some constraints on the travel behaviours of BEV drivers, at least for a considerable time until the recharging infrastructure is sufficiently widespread (Jiang et al., 2014). For GVs, the locations of gas stations and the sufficiency of refuelling infrastructure have mean scores of 3.18 and 3.49, respectively, indicating a positive perception of infrastructure sufficiency. The change in traffic flow for the BEV segment is more significant than that for the GV segment. This result is easy to understand: BEV travel choices are directly limited by distance constraints (Jiang et al., 2014).

EVs are strongly recognised for their environmental benefits, including alignment with carbon peaking goals (mean = 3.39) and contributions to sustainable development (mean = 3.40). The environmental impact of GVs was not directly measured in this study, but it is generally understood that EVs have a significant advantage in this area due to lower emissions and alignment with sustainability goals. Environmental concerns significantly influence consumers' attitudes towards purchasing eco-friendly products. This awareness is shaped by the information disseminated through mass media sources like the internet, social media, and television, which also affects the decisions to buy innovative eco-friendly EVs. Mass media plays a crucial role in educating and shaping positive consumer perceptions, especially among millennials who are highly active online (Dutta & Hwang, 2021).

Thus, it seems both EVs and GVs are perceived as easy to maintain, with GVs being slightly favoured in terms of repair costs. GVs have a significant advantage in refuelling time, and EVs lag in charging time satisfaction. EVs are preferred for lower electricity costs compared to GVs. EVs have a clear advantage in terms of easier licensing and fewer traffic restrictions. Both EVs and GVs have adequate infrastructure, but EVs need improvements in the charging infrastructure. EVs are also highly favoured for their environmental benefits, aligning with carbon reduction and sustainability goals.

In conclusion, while GVs are still favoured for their perceived refuelling convenience and slightly better maintenance, EVs stand out for their operational cost advantages, regulatory benefits, and significant environmental impact. To further increase the attractiveness of EVs, addressing the charging time and enhancing the charging infrastructure are key areas for improvement. Assuming BEVs and GVs have equal performance and pricing, more consumers prefer GVs to BEVs.

BEVs have substantial room for improvement, particularly in increasing consumers' trust and addressing safety and privacy concerns. Addressing these issues through targeted policies and improved manufacturer practices can help increase the adoption and acceptance of BEVs in Heilongjiang Province.

4.3.2 Correlation between Social Impacts and Consumer Purchase Decisions towards BEVs and GVs

This subsection delves into how consumers' perceptions of social impacts influence their purchasing decisions towards BEVs and GVs in Heilongjiang

Province. Spearman's rank correlation coefficient was used to explore this relationship, providing a robust statistical foundation to guide marketing strategies and policy-making.

The study used Spearman's correlation to measure the strength and direction of the association between ranked variables, specifically the link between consumers' perceptions of social impacts and their vehicle purchase decisions. This non-parametric measure was chosen due to its ability to handle non-normally distributed data and ordinal variables.

Table 4.4 shows Spearman's correlations, significance level (sig. 2-tailed), and sample size (*N*). The Pearson correlation coefficient values range from −1 to +1, where +1 means a perfect positive correlation, −1 means a perfect negative correlation, and 0 means no correlation (Nettleton, 2014). Researchers set a significance level threshold (such as 0.05) in standard hypothesis testing. The significance level indicates the likelihood that the observed correlation occurred by chance, and typically, a *p*-value less than 0.05 (or 5%) is considered statistically significant (Andrade, 2019).

The study explored the relationship between consumer purchase decisions and social impacts, explicitly focusing on BEVs and GVs. Code 1 was assigned for BEVs and code 2 for GVs to provide the basis for interpreting Spearman's correlation coefficient. A positive correlation coefficient means a positive correlation with GVs, and a negative correlation coefficient means a positive correlation with BEVs. The analysis considered health and safety, consumer privacy, transparency, feedback mechanisms, and end-of-life and future concerns.

For health and safety (HSBEV/HSGV), the coefficient of BEV (0.328, $p<0.01$) indicates a strong association between prioritising health and safety and the intention to purchase BEV. The positive coefficient of GV (0.234, $p<0.01$) indicates that consumers consider safety and health more when purchasing GVs, which means that the safety and health aspect of GVs positively correlates with GV purchase intention. When choosing a car, EV owners prioritise instrumental elements such as driving range, battery recharge time, safety, energy efficiency, winter driving quality, and environmental impact (Hanssen & Hasan, 2023). Since EVs are new, there are concerns regarding their performance and safety. Undoubtedly, among the most significant elements influencing consumers' decisions to buy EVs is stable performance (She et al., 2017). According to Koppel et al. (2008), vehicle safety has a significant influence on consumers' purchase decisions. Folkvord et al. (2020) point out that Europeans emphasise criteria like price, safety, and performance over the health and environmental aspects of automobiles when making purchase decisions. Safety and health are important elements influencing consumers' purchasing decisions. This suggests that BEV makers should focus on improving the health and safety aspects of BEVs.

For consumer privacy (CPBEV/CPGV), BEV correlation coefficient (0.1, $p<0.01$) and GV has a positive coefficient (0.126, $p<0.01$). Consumer privacy is positively related to consumer purchase intention. However, the study finds that the correlation coefficient of GVs is slightly higher than that of EVs. According to Belanger et al. (2002), the combination of trustworthiness with web features such as security, privacy, and user enjoyment significantly influences purchase intention and the willingness to share personal information. Privacy is a crucial element of social well-being. When privacy expectations are breached, consumer trust diminishes, making it challenging for companies to regain confidence in their services and products (Martin, 2018). Consumers in this sample also expressed worries about the privacy of their driving records. In the study by Featherman et al. (2021), privacy emerged as a major concern. Investigation highlights vague security standards within the automotive industry, leading to concerns about cyberattack vulnerability (GIP Digital Watch Observatory Team, 2023). This may reflect concerns about data security for more technologically advanced BEVs. Clearly communicating privacy measures and data security can help ease consumers' concerns and boost EV sales.

In terms of transparency (TBEV/TGV), BEV has coefficient (0.265, $p<0.01$). Conversely, GV has a coefficient (0.268, $p<0.01$), indicating that higher transparency issues are related to consumer purchase intention. Product transparency influences consumers' brand attitudes, trust, and behavioural intentions (Yang & Battocchio, 2020). Both price and production transparency positively affect overall brand equity and consumer purchase intentions (Kim et al., 2020). Consumers increasingly express their desire for transparent business practices and willingness to support such brands (Gazzola et al., 2017; Su et al., 2019). Transparency significantly influences consumers' perceptions and attitudes (Cheng & Mugge, 2022; Ryan & Michael, 2021). In environmental and ethical consumption studies, attitudes mediate the impact of various determinants (e.g., knowledge, value, concern, and affect) on behavioural intentions (Chan, 2001; Kang & Hustvedt, 2014). This suggests that consumers may be sceptical of the information provided by BEV manufacturers. Regulators may impose stricter transparency guidelines on EV manufacturers to ensure clear and honest communication of vehicle performance and environmental impact.

Regarding the feedback mechanism (FMBEV/FMGV), the correlation coefficient of BEVs (0.139, $p<0.01$). The coefficient of GVs (0.079, $p=0.041$) indicates that, under the social influence of the feedback mechanism, BEVs have a stronger relationship with purchase intention than GVs. According to Bjarklev et al. (2017), feedback mechanisms are crucial for meeting consumer needs. A systematic approach to consumer feedback helps identify areas where current products need to be improved and provides crucial information for the development of new products (Fundin & Bergman, 2003). Tognazzini (2004) highlighted the demotivating effects of imprecise information practices on consumer purchases. Featherman et al. (2021) stressed the necessity of considering social impacts when attempting to understand consumer behaviour. Prioritising responsive customer service and a strong feedback mechanism in marketing campaigns can enhance consumers' trust and favourability toward BEVs.

Regarding end-of-life and future concerns (EFBEV/EFGV), the coefficient for BEVs (0.215, $p<0.01$) indicates that concerns about vehicle end-of-life and future impacts are associated with BEVs. The positive coefficient of GVs (0.134, $p<0.01$) indicates that when consumers consider more end-of-life and future concerns, it means a greater possibility of choosing EVs. Buyers' decisions are significantly influenced by their satisfaction with the product or service (Park et al., 2010). Deemed support intentions (purchase intentions and future preference possibilities) are the only measure that can predict consumer behaviour (Chan et al., 2015). Policies promoting sustainable end-of-life practices for BEVs, such as battery recycling programmes, can address these consumer concerns and support environmental sustainability.

The analysis revealed different consumer preferences in relation to social impact categories. Consumers' purchase intention towards pure EVs is positively related to EV health and safety, feedback mechanism, and end-of-life issues. These social impact categories have more influence on consumers' intention to purchase EVs, indicating that EV makers should focus on addressing these social issues. Further, privacy and transparency have similar effects on consumers' purchase intention towards GVs and EVs. However, EVs have smaller positive social impacts than GVs. Social influence has a significantly positive impact on purchase intention towards EVs (Ivanova & Moreira, 2023). According to Aslam et al. (2018), a significant positive correlation exists between price and customer satisfaction. Furthermore, they believe the industry's success depends on price fairness and customer satisfaction. Susanto (2013) found that purchase decisions were significantly affected by customer satisfaction across all indicators. Increasing consumers' choice as more manufacturers debut attractive EV products by expanding car varieties and buying pricing will encourage adoption. Driving and ownership experience comparable to ICE vehicles is also crucial. A traditional refuelling station model will appeal to consumers who are unwilling or unable to adopt an EV charging model (Sinha & Brophy, 2021). The study by de Sousa and Castañeda-Ayarza (2022) found costs and infrastructure dampened consumers' purchase intentions. Complete infrastructure is also critical. When promoting EVs on a large scale, it is necessary to ensure that the infrastructure is adequately supplied.

This study concludes that all five social impact categories positively affect consumers' purchase intention. However, EVs have smaller positive social impacts than GVs, which means that if Heilongjiang Province plans to aggressively promote EVs to replace GVs, the country and automobile manufacturers need to strengthen the positive social impact of EVs and increase consumers' WTP towards them.

Table 4.4 : Correlations between Consumer Purchase Intention and Social Impact Categories of BEVs and GVs

		I-8. With similar performance and price, BEV or GV which more priority	HSBEV	HSGV	CPBEV	CPGV	TBEV	TGV	FMBEV	FMGV	EFBEV	EFGV
I-8. With similar performance and price, BEV or GV which more priority	Spearman's Correlation	1	0.328	0.234	0.1	0.126	0.265	0.268	0.139	0.079	0.215	0.134
	Sig.(2-tailed)	.	0	0	0.01	0.001	0	0	0	0.041	0	0.001
	N	666	666	666	666	666	666	666	666	666	666	666

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

4.4 Evaluation of Vehicle Sustainability

4.4.1 Monetisation of Environmental Impact

The study asked about consumers' WTP for a carbon emission tax and obtained the possible value of the carbon emission tax to convert the environmental impact of vehicle use into economic terms. The amount was added to the cost of each refuelling or charging of the car. The more consumers use the car, the more they will have to pay the carbon tax, thereby encouraging consumers to reduce their use of private cars and choose more environmentally friendly transportation.

From a total of 666 respondents, 296 (44.2%) respondents are willing to pay the CO_2 emission tax and 371 (55.6%) respondents are not willing to pay. The average WTP is CNY2.67 per 10 kg CO_2-eq or CNY0.267 per kg CO_2-eq. Based on this study's environmental impact results, 1 L of gasoline emits 3.47 kg CO_2-eq, and 1KWh emits 1.45 kg CO_2-eq. Therefore, if a carbon emission tax is imposed, 1 L of gasoline will cost an extra CNY0.93 and 1KWh will cost an extra CNY0.39. From past research, the monthly WTP for 30% carbon mitigation in Suzhou, China is CNY26.20 (Yang et al., 2014). However, this study considers monthly WTP as unfair for the people who produce lower carbon emissions and also not conducive to motivating the public to think and choose sustainable lifestyles. Moreover, the monthly WTP in Suzhou is much lower than in Chongqing (CNY37), Beijing (CNY130), and Jiujiang (CNY130) (Zeng, 2011), but higher than in Seoul (about CNY19.60) (Lee et al., 2008).

Shenzhen's WTP pertaining carbon emissions is estimated to be ¥37.96 per ton CO_2-eq (Wang et al., 2018). It is equal to ¥0.03796 per kg CO_2-eq or almost CNY 0.25 per kg CO_2-eq, which is almost the same as this study's finding of CNY0.267 per kg CO_2-eq. Shenzhen is a large city and its population's income and education may be higher than those in Heilongjiang Province. However, the study by Wang et al. was conducted in 2018. Hence, the slightly higher WTP obtained in the current study is reasonable.

The vehicle information selected for this study shows that combined fuel consumption is 5.98 L per 100 km. For a total mileage of 20,000 km in 1 year, 1196 L per year (5.98 L × 200) of gasoline is needed. Due to carbon tax, one litre of gasoline will incur an extra cost of CNY0.93 (3.47 kg CO2-eq × CNY 0.267). The current average gasoline price is CNY8.31/L. If carbon emission tax is imposed, the gasoline price will be CNY9.24/L. Hence, for a total mileage of 20,000 km/year, the annual gasoline cost will increase from CNY9938.76 (CNY8.312/L × 1196 L) to CNY11051.04 (CNY9.24/L × 1196 L).

In this study, the range of working conditions for pure EVs was 420 km. and the power battery capacity was 44.9 KWh. For a total mileage of 20,000 km a year (considering temperature, effective charge, and discharge efficiency), the EV needs to be charged 60.22 times (2704 KWh). Since 1KWh emits 1.45 kg of CO_2-eq, the extra cost caused by carbon tax for 1KWh will be CNY0.39. Based on the current average electric price of around CNY0.919/KWh, with the addition of carbon emission tax, the electric price will be around

CNY1.31/KWh. Thus, the annual charging fee for 20,000 km will increase from CNY2,485 (CNY0.919/KWh × 2,704 KWh) to CNY3,542 (CNY1.31/KWh × 2,704 KWh).

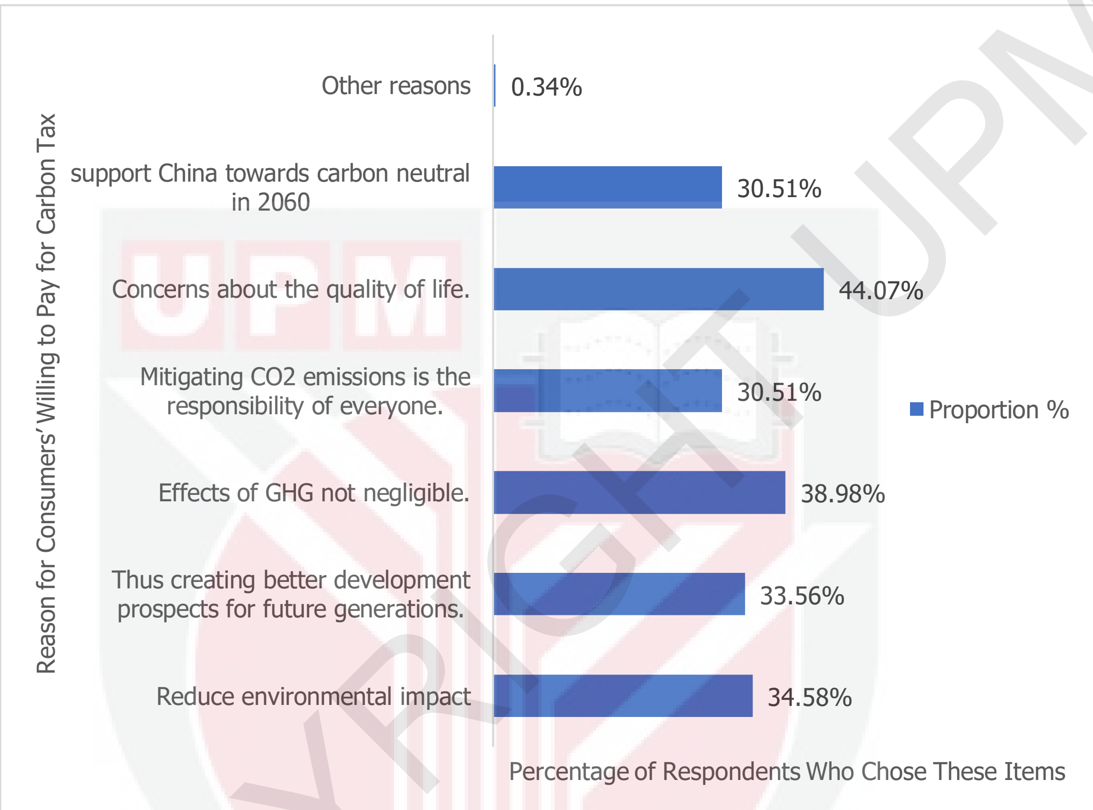

Figure 4.8 : Reasons for Consumers' Willingness to Pay for Carbon Tax

Figure 4.8 depicts the factors that motivate consumers to accept the imposition of a carbon tax. The main factor, selected by 44.07% of the respondents, is "Concerns about the quality of life". This suggests that customers who are prepared to pay a carbon tax are primarily motivated by their desire to preserve or enhance their standard of living, most likely by benefiting from the environmental improvements that the tax is intended to accomplish. Climate change has raised health concerns among consumers, making them aware of environmentally friendly consumption practices (Le Quéré et al., 2020).

Following that, 38.98% of the respondents acknowledge that the "Effect of GHG not negligible". This indicates that a substantial proportion of consumers know and are apprehensive about the serious impacts of GHG emissions, motivating them to support initiatives like carbon tax that seek to mitigate these emissions. People's perceptions of climate change influence their level of concern and, ultimately, their motivation to take action (Swim et al., 2009). Past research has also shown that concerns about climate change increase consumers' willingness to change their behaviour (Semenza et al., 2008). The level of environmental awareness determines how much consumers take into consideration the environmental cost of the product (Gupta, 2016).

The respondents are also willing to pay carbon tax to "Thus creating better development possibilities for future generations" (33.56%) and "Reduce environmental impact" (34.58%). These factors indicate that consumers are driven by a future-oriented outlook, taking into account the long-term benefits for future generations and the overall well-being of the planet. The same results were obtained by Gupta (2016), where people remained aware and concerned about environmental pollution and wanted to protect the environment for future generations.

Two factors are ranked similar, each receiving 30.51% responses from the respondents: “Support China towards carbon neutrality by 2060” and “Mitigating CO_2 emissions is responsibility to everyone”. These factors indicate a shared sense of accountability and dedication to national objectives. Consumers who choose these reasons acknowledge the importance of communal efforts in tackling climate change and view the carbon tax as a measure towards accomplishing broader environmental goals. The amount of total emissions determines the consumer’s responsibility. People pay a carbon tax because they feel responsible for climate change (Goh & Matthew, 2021). Society's direct carbon emissions can be controlled by controlling their consumption (Zhang et al., 2023).

Only a tiny fraction (0.34%) mentioned 'Other reasons' as their motivation to support a carbon tax, which might include many undefined variables. For example, respondents mentioned, “Taxes could help reduce CO_2 emissions while encouraging people to use public transport”.

To summarise, the figure demonstrates that the individuals willing to bear the cost of a carbon tax are primarily driven by their concerns about improving their quality of life and preserving the environment. They acknowledge the great impacts of GHGs and share a collective obligation to address this issue, in line with the national objectives and a commitment to protect the welfare of future generations. Further, a minority of the individuals have other reasons for supporting the imposition of carbon tax.

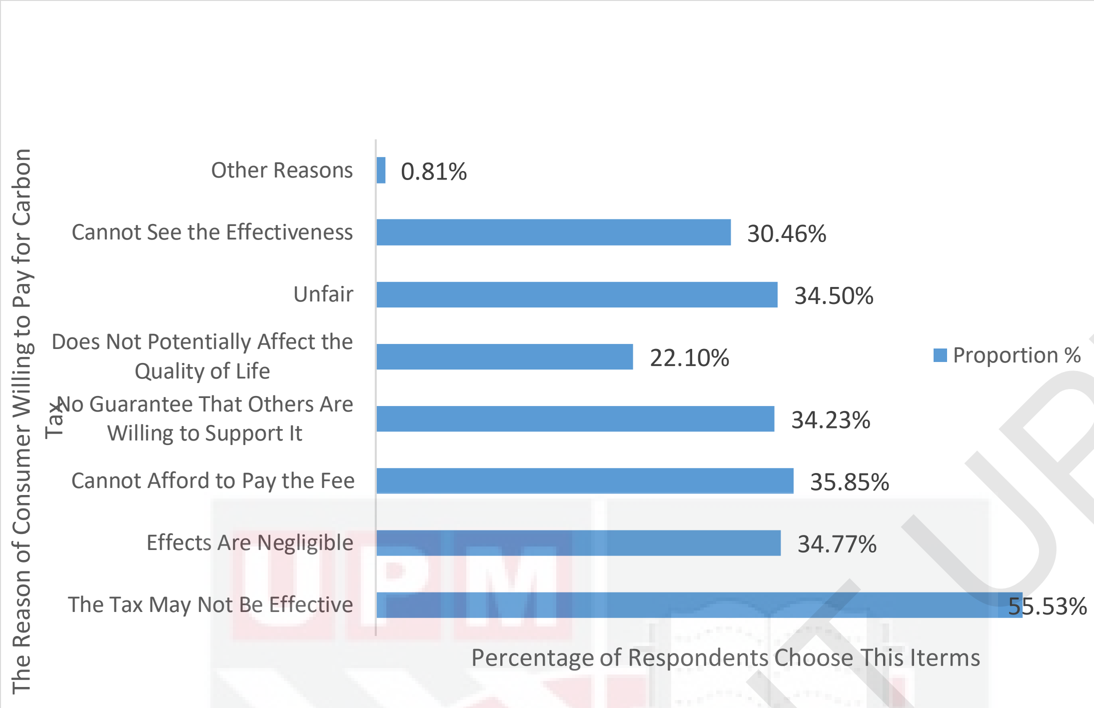

Figure 4.9 : Reasons for Consumers' Unwillingness to Pay for Carbon Tax

Figure 4.9 summarises the respondents' reasons for their reluctance to pay a carbon tax. There are seven main reasons, with different percentages of respondents selecting them. The reasons given are "Tax may not work" (55.3%), "The effects are negligible" (34.77%), "I cannot afford to pay the fee" (35.85%), "No guarantee others are willing to support" (34.23%), "No potential effect on the quality of life" (22.1%), "Not fair" (34.5%), "Cannot see the effectiveness" (30.46%), and "Other reasons" (0.81%).

Upon further analysis of the data, the study finds that the biggest concern is doubt about the effectiveness of carbon tax, where more than half of the respondents believe that carbon tax may not work. Individuals do not view carbon tax as an effective strategy to reduce the high-carbon emission behaviour. People oppose carbon tax in polls and actual ballots because they expect carbon tax not to work (Carattini et al., 2018). According to Wan et al. (2017), individuals' WTP is positively influenced by procedural and distributive justice and political trust. Thus, distrust will reduce WTP. One of the most critical determinants of opinion on WTP is trust in government (Ewald et al., 2022). A study by Savin et al. (2020) compared those who accepted and rejected carbon tax, had less trust in politicians, believed the rich should pay more taxes than the poor, and believed specific CO_2 tax as unfair. Moreover, many people think that the impact of climate change may be negligible, and environmental knowledge about and attitudes affect individuals' WTP (Goh & Matthew, 2021). People cannot afford to pay the tax, and people's reluctance to pay higher prices to address global warming may be linked to their low income (Chang, 2018). There are also concerns that others will not support the measure and scepticism about the fairness and effectiveness of a carbon tax. The respondents stated, "The carbon dioxide produced by cars is much less than that caused by industrial production" and "National taxes are already hefty. Consumers ultimately pay all the indirect taxes. We strongly oppose raising taxes on ordinary people".

There is a significant relationship between income and WTP (von Borgstede et al., 2013). More educated, higher-income individuals exhibit a stronger propensity to support and financially contribute to a carbon tax (Wan et al., 2017). The education level component shows the change in the proportion of respondents willing to pay a carbon tax as their education level increases.

According to the data, a higher proportion of people with undergraduate degrees are unwilling to pay carbon taxes. In comparison, more people with master's and doctorate degrees are willing to pay. The higher the education level, the higher the WTP for a carbon tax. This is because educated people know more about environmental issues (Shaari et al., 2020). Education level plays an important role in determining respondents' WTP for a carbon tax (Goh & Matthew, 2021). Carbon taxes are generally well accepted in countries with significant experience, yet public resistance to increasing them remains. Opinions on carbon taxes are correlated with educational level, rural versus urban residence, political orientation, and particularly trust in government (Ewald et al., 2022).

These results provide insights into how carbon tax policies may be designed and implemented, considering the socioeconomic factors to ensure policy effectiveness and fairness. This study's result on the monetisation of environmental impacts shows a price of CNY 0.267/kg of CO_2-eq.

The CO_2 emission tax may be included in the refill or charging fee to encourage consumers to save energy, turn to cleaner production, and use public transportation. Governments and policymakers also need to educate the public, especially among those from lower education background, about the long-term benefits of carbon taxes. Financial subsidies or other incentives may need to be considered for low-income groups to reduce their financial pressure. Also, public concerns need to be addressed before the carbon tax is implemented, for example, by providing more evidence of its effectiveness or introducing alternative measures so as to reduce or eliminate the financial burden faced by low-income groups. With balancing measures, carbon taxes could positively impact low-income stakeholders (Baranzini & Carattini, 2014). There is also a need to increase confidence that carbon taxes are fair and generally supportive (Carattini et al., 2018). Government legitimacy, the tax's perceived effectiveness, climate change information, and the extent to which human activities contribute to climate change all affect the acceptance of a carbon tax. Providing all the necessary information would lessen voters' doubts about carbon pricing's effectiveness (Carattini et al., 2018). The tax's objective and the predicted environmental and economic effects should be clearly stated before implementation. The final basis for opposition is that people distrust government motives. They anticipate a carbon price to increase government revenues rather than reduce GHGs (Klok et al., 2006). Effective awareness campaigns may reduce early reluctance to embrace a carbon fee (Rotaris & Danielis, 2019). Carbon tax revenue should always be used efficiently and transparently, and different countries will probably choose different combinations of earmarking and refunding (Ewald et al., 2022).

Table 4.5 : Monetisation of Environmental Impacts of GVs and BEVs

	GV	BEV
CO_2 eq emission per year	4149.63 kg CO_2 eq	3100.92 kg CO_2 eq
Usage (15 year) CO_2 eq emission	62244.45 kg CO_2 eq	46513.80 kg CO_2 eq
CO_2 eq emission tax per year	1107.95 CNY	827.95 CNY
Usage (15 year) CO_2 eq emission tax	16619.27 CNY	12419.18 CNY

The monetisation of GVs' and BEVs' environmental impacts are shown in **Table 4.5**. Carbon emission tax is used to quantify the social impact of usage. Different amounts of CO_2-eq are generated by GVs and BEVs. In 1 year (20,000 km distance), consumers need to pay additional CNY1,107.95 for GVs and CNY827.95 for BEVs. In a lifespan of 15 years, consumers will need to pay additional CNY16,619.27 for GV usage and CNY12,419.18 for BEV usage. Thus, EVs can save 25.27% of the cost of carbon emission tax, which means a 25.27% reduction in the environmental impact caused by CO_2 emissions. With BEVs producing 25.3% fewer emissions and incurring 25.3% lower CO_2 taxes than GVs. Over a 15-year lifespan, this translates into a substantial environmental and economic advantage. These findings highlight the importance of carbon taxation and policy incentives in making BEVs a more viable and sustainable alternative to GVs. However, the effectiveness of BEVs in reducing emissions depends on the cleanliness of the electricity grid, reinforcing the need for renewable energy expansion alongside EV adoption.The implementation of a carbon tax as part of the cost of refuelling or charging encourages consumers to reduce their reliance on private vehicles and consider more sustainable transport options. Education and awareness campaigns are critical to enhancing consumers' understanding of the benefits of carbon taxes and their role in combating climate change.

4.4.2 Monetisation of Social Impacts

This analysis quantifies the social impacts of EVs in monetary terms based on consumers' perceptions and their WTB. Social impact categories such as health and safety, consumer privacy, transparency, feedback mechanisms, and end-of-life concerns were evaluated for their influence on purchase decisions. The non-parametric measure assesses the strength and direction of the association between social impacts and purchase intentions, providing a robust analysis of the data. Each social indicator was assigned a correlation weight based on its influence on purchase decision, helping to translate the impacts into monetary terms.

Table 4.6 : Monetisation Analysis of Social Impacts and Price-Related Indicators for EVs

Electric Vehicle Weight			Electric Vehicle Price (CNY123,800)		
Social indicator	Correlation coefficient	Correlation weight	Partial value (weight proportional distribution) (CNY)	True value rate (evenly divided according to indicators)	True value (true value rate * fractional value) (CNY)
SHBV	0.328	31%	38784	110.15%	42722
PSBV	0.1	10%	11824	117.28%	13868
ITBV	0.265	25%	31334	106.89%	33493
FMBV	0.139	13%	16436	111.66%	18353
EFBV	0.215	21%	25422	110.38%	28061
Total	1.047	100%	123800	110.26%	136496

Social benefit = Real value - partial value = CNY12,696

Table 4.6 summarises the evaluation of EVs' societal impacts in monetary terms based on the vehicle price of CNY123,800. The strength of the association between each of the five social well-being impact variables and WTB is measured by the correlation coefficients of Spearman's Rho in **Section 4.3**.

The total correlations' weights distribute the EV price into partial values, and an equal division of the EV price by the indicators yields the true value rate. The true value (CNY) is calculated by multiplying the partial amount by the actual value rate. The BEV's social value beyond its purchase price is CNY12,696 after deducting the partial value.

In **Table 4.7**, the same procedure was applied to GVs with a base price of CNY110,000. Similar social indicators were used with slightly different abbreviations and correlation coefficients. The calculation resulted in a social value of CNY13,256 for the GV.

By summing up the correlation coefficients of all subcategories with purchase decisions, a comparison of the calculations for EVs and GVs shows that EVs (1.047) have a greater overall correlation coefficient than GVs (0.841), because the strength of the relationship can be anywhere between −1 and +1. The stronger the correlation, the closer the correlation coefficient to ±1 (Mukaka, 2012). The results mean that the social indicators are more strongly linked to EVs' impacts over time. EVs have a smaller monetary social benefit (CNY12,696) than GVs (CNY13,256). The analysis reveals that while EVs may have stronger associations with certain positive social outcomes, GVs sometimes offer a slightly higher monetary social benefit.

There is a need to strengthen the positive social impacts of EVs to increase consumers' WTB, which may be supported by targeted marketing strategies and policy incentives. Increasing consumers' awareness about the social benefits of EVs may help mitigate some of the scepticism and resistance observed. The social impact analysis indicates a need for better alignment of EV attributes with consumers' expectations and societal values. Future policies should aim to enhance the perceived and actual social benefits of EVs to support a more sustainable transition in vehicle usage.

Table 4.7 : Monetisation Analysis of Social Impacts and Price-Related Indicators for GVs

Gasoline vehicle weight			Gasoline vehicle price (CNY110,000)		
Social indicator	Correlation coefficient	Correlation weight	Partial value (weight proportional distribution) (CNY)	True value rate (evenly divided according to indicators)	True value (true value rate * fractional value) (CNY)
SHGV	0.234	28%	30606	112.85%	34539
PSGV	0.126	15%	16480	118.75%	19571
ITGV	0.268	32%	35054	107.46%	37670
FMGV	0.079	9%	10333	114.15%	11795
EFGV	0.134	16%	17527	112.30%	19682
Total	0.841	100%	110000	112.05%	123257

Social benefit = Real value - partial value = CNY13,256

4.4.3 LCSA Monetisation

This section answers the research question of "What are the economic, environmental, and social impacts, as quantified through monetisation, of replacing GVs with EVs in Heilongjiang Province, and how do these impacts collectively influence the overall sustainability of such a transition?"

The steps entailed evaluating the social, environmental, and economic impacts of GVs and BEVs and calculating the difference. The sustainability of replacing GVs with BEVs is shown in **Table 4.8**. The LCC shows that BEVs cost significantly less than GVs over a 15-year period, resulting in a total saving of CNY86,653.47 (28.74%). This substantial economic benefit underscores the potential cost-effectiveness of adopting BEVs from a long-term ownership perspective.

Table 4.8 : Sustainability Impact Analysis of Replacing GVs with BEVs

Impact category	Economic impact	Environment impact	Social impact
Difference in impact when replacing GV with BEV	86653.47	4200.08	-560
Percentage change in sustainability impact when replacing GV with BEV	28.74%	25.27%	-4.23%

In terms of carbon emission reduction, annually, BEVs emit significantly less CO_2 than GVs (3,100.92 kg vs 4,149.63 kg of CO_2-eq). Over 15 years, adopting BEVs would save consumers CNY4,200.08 in carbon tax, further enhancing the environmental justification for transitioning to BEVs, with a 25.27% reduction in carbon emission cost (CNY2.67/10kg of CO_2 eq).

The social impact brought about by replacing GVs (CNY13,256) with EVs (CNY12,696) is negative CNY560, equivalent to a change in social benefits of −4.23%. It means replacing GVs with BEVs will reduce the social well-being of consumers. This might explain why Heilongjiang Province consumers are reluctant to buy EVs. Hence, if the Chinese government plans to fully replace

GVs with BEVs, they should increase consumers' social well-being from using BEVs to encourage consumers to purchase BEVs.

These findings align with previous studies, such as Wang et al. (2019) and Guo et al. (2021), which also highlight that BEVs become more cost-effective over time due to lower operational and maintenance costs. Similar conclusions were drawn by Zhou et al. (2020), who found that the economic viability of BEVs improves significantly beyond five years of ownership, even in regions with higher electricity prices. Additionally, Nonaka and Nakano (2011) emphasized that policy interventions, including taxation and infrastructure development, play a crucial role in enhancing BEV adoption. The results also support the conclusions of Tang et al. (2019)., who found that a reward–penalty mechanism is more effective than direct subsidies in increasing adoption rates.

To encourage greater BEV adoption, the government should enhance the social well-being of EV users through targeted policies and incentives. This may include improving EV infrastructure, increasing public awareness, and ensuring social benefits such as convenience, safety, and data privacy. Additionally, policymakers should emphasize the long-term cost advantages of BEVs to consumers, reinforcing the economic incentives for transition.

Automakers can also contribute by enhancing the perceived value of BEVs through effective marketing strategies, improved vehicle safety, and technological advancements. Public awareness campaigns emphasizing the environmental and economic benefits of BEVs can further encourage consumer confidence and support for sustainable transportation.

Overall, while the economic and environmental advantages of BEVs are evident, addressing the social impact concerns remains critical for achieving a balanced and sustainable transition from GVs to BEVs in Heilongjiang Province.

To encourage greater BEV adoption, the government should enhance the social well-being of EV users through targeted policies and incentives. This may include improving EV infrastructure, increasing public awareness, and ensuring social benefits such as convenience, safety, and data privacy. Additionally, policymakers should emphasize the long-term cost advantages of BEVs to consumers, reinforcing the economic incentives for transition.

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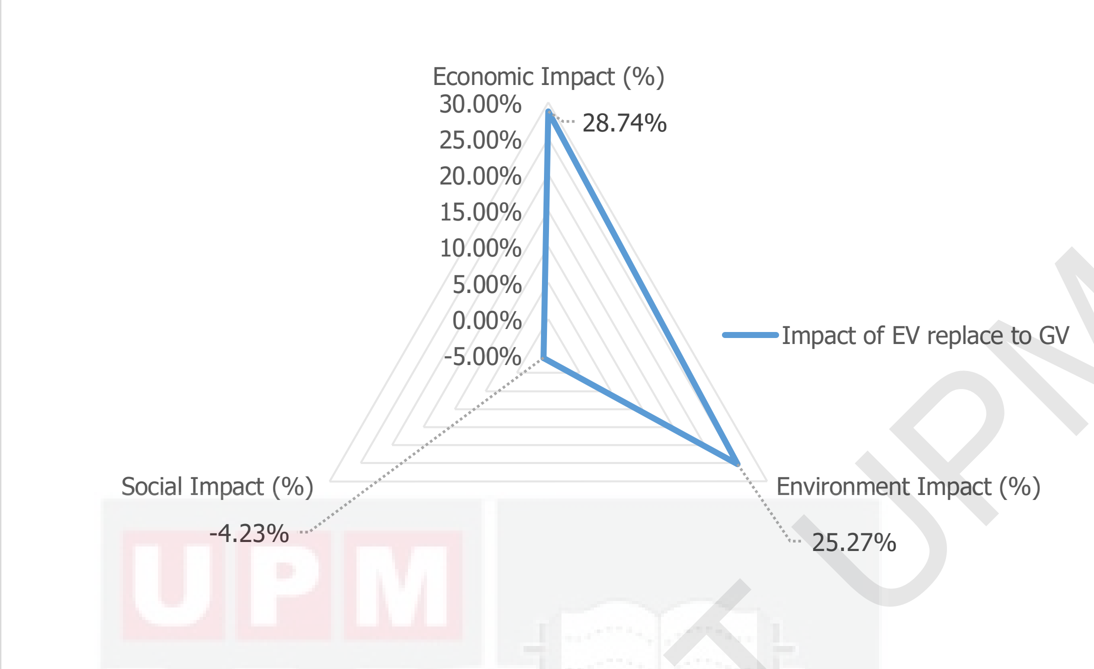

Figure 4.10 : Visualisation of the Sustainability of Replacing GVs with EVs in Heilongjiang Province, China

Figure 4.10 provides the visualisation of the sustainability of replacing GVs with EVs in Heilongjiang Province, China. In this province, replacing GVs with EVs has a positive impact on the economy and environment but harms the social well-being of consumers. Hence, if the government plans to replace GVs with EVs in the province, they need to improve the social well-being of consumers to encourage the consumers to purchase the cleaner product.

The government should also highlight the long-term cost–benefit of using BEVs to consumers. In promoting the environmental benefits, carmakers can market BEVs as a key solution to reducing one's carbon footprint, tapping into the public's growing environmental awareness. Clear, transparent information about EVs' technology, safety, and performance should be provided to improve society's perceptions.

4.5 Summary

This chapter provides a detailed analysis of the sustainability of replacing GVs with BEVs in Heilongjiang Province, offering insights into the economic, environmental, and social impacts. Additionally, the chapter includes sensitivity and scenario analyses to explore how economic factors, such as discount rates and subsidies, influence the cost-effectiveness of BEVs and GVs. Also, the effects of temperature and grid structure on EV emissions in comparison with GV emissions are discussed. The assessment highlights the seasonal variability of BEV emissions, emphasising the need for region-specific strategies to optimise their environmental performance. The next chapter will conclude all the findings and offer recommendations based on the findings. Finally, a discussion of this study's contributions concludes the thesis.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study compares the three dimensions of sustainability (environmental, social, economics) by converting all indicators into monetary values. These three dimensions are assumed to have equal weights. Still, the selected indicators of these three dimensions contribute different percentages to the sustainability of vehicles. Monetisation facilitates the assessment and interpretation of the impact categories and subcategories, providing a comprehensive evaluation of the sustainability of vehicles. This approach offers transparency and decision support in determining a product's sustainability.

The LCC results show that BEVs are more cost-effective for a long-term use exceeding 2.5 years. Due to the relevant policies on subsidies and exemptions, the BEV has a lower operating cost than the GV, making it more economically attractive. From a short-term perspective, high discount rates accelerate vehicle depreciation, resulting in a reduced residual value. This significantly affects the short-term NPV by emphasising the importance of immediate cash flows. When secondary sales prices and residual values account for a large portion of the total costs, higher discount rates can significantly affect the financial estimates and purchasing decisions. Additionally, when operating expenses such as maintenance and fuel costs are low, a high discount rate can minimise the PV of these costs, potentially making long-term vehicle ownership more economically attractive. If pure EVs are used for more than 5 years, even if all the current subsidy policies are cancelled, pure EVs would still have an economic advantage over pure GVs. Based on the results and discussions, China may phase out subsidies and replace them with other ways to encourage people to buy EVs, and increase carbon emissions taxes or other punitive measures.

For the environmental dimension, BEVs are associated with lower overall CO_2 emissions than GVs. From the impact assessment characterisation, BEVs' emissions related to fossil and biogenic carbon are lower than those of GVs. However, for land transformation, BEVs emit higher CO_2 than GVs. From the analysis, 3 L of gasoline or 7 KWh of electricity may generate around 10 kg of CO_2-eq. For the end-point damage, GVs and BEVs are not much different in terms of their effects on human health and ecosystems, but BEVs can save more resources. Heilongjiang Province is located on the Northeast Power Grid, which has the least environmental advantages among all power grids because of the high reliance on non-clean energy. Nonetheless, BVs still have environmental advantages compared with GVs in this region. When the impact of regional characteristics (four seasons) pertaining to temperature is considered in this power grid region, BEVs' have higher CO_2-eq emissions than GVs during winter. However, when the whole year is considered, BEVs have lower emissions than GVs. Although the Northeast Power Grid has a high reliance on non-clean energy and the region has large temperature differences across the four seasons, BEVs still offer the benefit of reducing emissions, indicating the feasibility and advantages of promoting BEVs in China.

Regarding the social impact, consumers believe that GVs have better social impacts than BEVs, and they are more likely to purchase GVs given the same performance and price. From the analysis, consumers' purchase decisions are correlated with the sub-categories of social impact (health and safety, consumer privacy, transparency, feedback mechanisms, and end-of-life), which can explain why consumers are more willing to purchase GVs.

Monetisation was successfully applied in this study. The monetisation of environmental impact shows that respondents' WTP for CO_2 emission tax is CNY0.267/kg of CO_2-eq. The main reason for respondents' WTP is related to concerns about their quality of life. However, most respondents are not willing to pay because they think tax might not achieve its objective. If CO_2 emission tax is imposed, using BEVs (CNY12,419.18 emission tax for 15 years of usage) would save the consumer 25.27% compared with using GVs (CNY16,619.27 emission tax for 15 years of usage). It would also mean a 25.37% reduction in CO_2-eq emissions.

For the social impact monetisation, the monetary social impacts of BEVs are GVs are CNY12,696 and CNY13,256, respectively. The correlation coefficient between social impact and consumer decision-making is greater in the case of

BEVs. Thus, the study finds that respondents perceive BEVs as offering lower social benefits than GVs. Hence, more respondents prefer GVs to BEVs.

For the sustainability monetisation, replacing GVs with BEVs in Heilongjiang Province would result in a saving of CNY86,653.47 (28.74%) for the consumer from the economic perspective. From the environmental perspective, the consumer would save CNY4,200.08 on CO_2-eq emissions, which means a 25.27% reduction in emissions. However, from the social perspective, replacing GVs with BEVs would reduce the consumer's social benefit by CNY560 (4.23%). In addition, adaptive radar charts were used to visualise the results, allowing the researcher to assess the sustainability level of vehicles based on the degree of regularity of the sustainability triangle's shape. Based on the monetisation and visualisation results, replacing GVs with BEVs will result in higher sustainability from economic and environmental perspectives. However, BEV makers need to improve their vehicles' social impact to improve sustainability.

5.2 Recommendations

This study makes the following recommendations:

(1) Cancel the current subsidy policy and introduce a penalty for higher-emission vehicles. This approach can incentivise a market-driven approach towards adopting BEVs. Further, the quality and durability of BEVs need to be improved to ensure their long-term economic benefits are realised. Infrastructure development, particularly at

charging stations, needs to be strengthened to support a more widespread use of BEVs.

(2) Use reforestation and other methods to offset the emissions from land use changes. The government should transition to renewable energy sources to reduce the overall emissions. The efficiency of BEV charging and discharging should be increased, especially in low-temperature conditions.

(3) To aggressively promote BEVs, car makers should improve BEVs' social impact benefits. The quality and technical aspects of BEVs should be enhanced, and safety risk issues such as spontaneous combustion should be addressed. The government should improve consumer privacy protection and promulgate relevant privacy protection policies. Information transparency should be increased, especially concerning BEVs' environmental, economic, and social sustainability. By strengthening the feedback channels, manufacturers can communicate with consumers more directly. The end-of-life pathways and impacts of BEVs should also be clarified. Finally, public education should be strengthened to increase understanding of the sustainability of BEVs and the global impact of CO_2 emissions.

(4) Utilise monetisation and visualisation of sustainability data to educate the public and inform policy decisions. The findings can be used to guide the formulation of policies that support sustainable practices and BEV adoption.

(5) To be able to evaluate the applicability of the monetisation of LCSA method to various products, further application of the proposed technique across multiple case studies is recommended. Expanding the geographical scope of the research could provide insights into regional differences in BEV adoption and the effectiveness of different incentive mechanisms. Longitudinal studies to track changes in

consumer perceptions and actual BEV performance over time could provide deeper insights into the long-term sustainability of EVs.

5.3 Contributions of the Study

This study specifically contributes to the understanding of vehicle sustainability in Heilongjiang Province, China, particularly by incorporating regional temperature characteristics that influence product efficiency. The study was conducted by comprehensive analysing across the three dimensions of sustainability—environmental, social, and economic dimensions.

The results show that even without subsidies, BEVs have long-term economic benefits over GVs, supporting the case for a policy shift toward penalising high-emission vehicles. This economic analysis is critical for policymakers and stakeholders aiming to promote sustainable transportation.

This study highlights the importance of considering regional climate conditions (especially the low temperatures in Heilongjiang Province) and energy composition, thus enriching the body of knowledge. Climate conditions affect the efficiency of pure EVs. Also, since energy composition directly affects EV emissions, region-specific strategies should be formulated when promoting the transition to pure EVs.

By improving understanding of the influence of social impacts on consumer decision-making, this research helps to improve social acceptance of BEVs.

The study highlights the importance of public education and transparency of sustainability data to make consumers more informed and supportive of sustainable practices. These measures help to improve consumers' confidence and public awareness.

An immense innovation of this study lies in the introduction of a monetisation method that quantifies the three dimensions of sustainability, mainly contributing to SDG 12 and SDG 13. This method simplifies the interpretation of LCSA results, making them more accessible to stakeholders. It helps policymakers make more informed decisions by clearly understanding the impacts of products from a sustainability perspective. It also aids in consumer education, enabling easier and more sustainable purchasing decisions. The tested applicability of this monetisation method can extend beyond BEVs to other products, providing a versatile tool for evaluating and promoting sustainability in various sectors.

These contributions highlight the significance of this study in advancing the understanding of vehicle sustainability and informing policy and practice. By addressing regional specificities and introducing innovative methodologies, the research provides valuable insights and tools for promoting sustainable transportation and achieving broader sustainability goals.

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APPENDICES

Appendix A

Questionnaire

附件 A

使用可持续评估方法分析中国纯纯电动汽车和汽油汽车的社会影响和缴纳碳税的意愿

Analysing the Social Impact and Willingness to Pay Carbon Tax on Chinese Battery Electric Vehicles and Gasoline Vehicles Using a Sustainable Assessment Methodology

您好！

感谢您对我们的调查感兴趣。年满 18 岁、有驾驶执照、汽油汽车和纯电动汽车的中国受访者均可参与本次研究。 回答所有问题预计需要三十分钟左右。

该调查分为三个部分：

·第一部分是关于受访者的个人背景信息。
·第二部分探讨纯纯电动汽车和汽油汽车的社会影响。
·第三部分是受访者是否愿意缴纳二氧化碳排放税。

这项研究的目的是深入了解纯电动汽车和传统汽油汽车的社会影响，以及这些影响如何影响消费者的决策以及他们通过支付碳税将环境影响转化为货币的意愿 。 研究成果将应用到我的博士研究中。

请放心，您的答案将被严格保密。 您的参与完全是自愿的，不受任何形式的强迫。 请提供真实、真诚的回答。 如果您发现任何敏感问题，您有权随时退出调查。

非常感谢您参与本研究。

Hello!

Thank you for your interest in our survey. Respondents who are Chinese of 18 years old and above and have a driving license and gasoline and battery electric vehicle user can participation in the study. It is expected to take about thirty minutes to answer all the questions.

The survey is divided into three sections:

- The first section is about the respondents' personal background information.
- The second section explores the societal impacts of electric vehicles and gasoline vehicles.
- The third section is about whether the respondents are willing to pay for carbon dioxide emissions tax.

The objective of this research is to gain an in-depth understanding of the societal impacts of battery electric and gasoline vehicles, as well as how these impacts influence consumer decisions and their willingness to pay to convert environmental impacts into currency through payment of a carbon tax. The research findings will be applied in my doctoral study.

Rest assured that your answers will be kept strictly confidential. Your participation is entirely voluntary and not subject to any form of coercion. Please provide truthful and sincere answers. If you find any questions sensitive, you have the right to withdraw from the survey at any time.

Thank you very much for your participation in this study.

Part I: PERSONAL BACKGROUND

请提供您的个人背景信息。 请在相关方框内填写或打勾[√]：
Kindly provide the information about your personal background. Please tick [√] in the correspond in boxes:

您有驾驶证吗？Do you have a vehicle driving license？ Yes [ ] No [ ]
（如果没有，您不需要继续填写此问卷：If no, you don't need continue this questionnaire)

您正在使用或使用过哪种车辆？
What type of vehicle do you being used or has been used before?
纯电动汽车 Battery Electric vehicles [ ]
汽油汽车 Gasoline vehicle [ ]
两种车型都有使用 Both types of vehicles [ ]
（如果没有，您不需要继续填写此问卷：If no, you don't need continue this questionnaire)

性别 Gender： 男 Male [ ] 女 Female [ ]

年龄 Age：
18-22 岁 18–22 years old [ ]
23-27 岁 23–27 years old [ ]
28-32 岁 28–32 years old [ ]
33-37 岁 33–37 years old [ ]
38-42 岁 38–42 years old [ ]
43-47 岁 43–47 years old [ ]
48-52 岁 48–52 years old [ ]
53-57 岁 53–57 years old [ ]
58-62 岁 58–62 years old [ ]
63 岁以上 63 years old and above [ ]
现居住城市 Current city of residence：______________________________

最高学历 Highest education qualification：未受过教育 No formal education [ ]
小学 Primary school [ ]
初中或同等学历 Secondary school or equivalent [ ]
高中或同等学历 High school or equivalent [ ]
专科学历或同等学历 College degree or equivalent [ ]
本科或同等学历 Bachelor's degree or equivalent [ ]
硕士 Master [ ]
博士 PhD [ ]

月收入 Monthly income：

5000 人民币以下	5,000 CNY and below	[ ]
5001-8000 人民币	5,001–8,000 CNY	[ ]
8001-17000 人民币	8,001–17,000 CNY	[ ]
17001-30000 人民币	17,001–30,000 CNY	[ ]
30001-40000 人民币	30,001–40,000 CNY	[ ]
40001-60000 人民币	40,001–60,000 CNY	[ ]
60001-85000 人民币	60,001–85,000 CNY	[ ]
85001 元以上人民币	85,001 CNY and above	[ ]

在性能和价格接近的条件下,你会优先考虑纯电动汽车还是汽油汽车？
With similar performance and price, Electric vehicles or gasoline vehicles which would you give more priority?
Electric vehicles [ ] Gasoline vehicles [ ]

Part II：SOCIAL IMPACT FOR ELECTRIC VEHICLES AND GASOLINE VEHICLES
对于 Section A - Section F，请根据您的真实使用经历、个人看法或基于公共媒体信息和周围人的反馈的感受来回答。 对于以下每个观点陈述，请圈出最能代表您观点的选项。 采用 5 分制，其中 [1] 表示"强烈不同意"，[5] 表示"强烈同意"。 您可以选择这些端点之间的任意数字。 请回答**两种**类型的车辆

For Section A to Section F, please provide your answer based on your actual usage experience, personal perception, or feelings based on mass media information and feedback from people around you. For each of the following perspective statements, please circle a level of agreement that best describes your opinion. Use a 5-point scale, where [1] signifies 'strongly disagree' and [5] signifies 'strongly agree.' You can choose any number between these points. Please answer for both **two types** of vehicles.

部分 A：使用纯纯电动汽车/汽油汽车的消费者健康与使用安全
Section A: Consumer Health and Use Safety through the use of Battery Electric Vehicles and Gasoline Vehicles

No	问题/汽车种类 Items/ Types of vehicles	纯电动汽车 Battery Electric vehicles	汽油汽车 Gasoline Vehicles
1	我觉得**纯电动车/汽油车**可以安全使用。I think **battery electric vehicles/gasoline vehicles** are safe to use.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
2	我认为**纯电动汽车**充电桩不安全。 I believe **battery electric vehicles** charging stations are not safe.	[1] [2] [3] [4] [5]	---------------------------
3	我认为**汽油汽车**加油站不安全。 I believe **gasoline vehicle** filling stations are not safe.	----------------------------	[1] [2] [3] [4] [5]
4	我认为**纯电动汽车**电池并不安全。 I think batteries for **electric vehicle** are not safe.	[1] [2] [3] [4] [5]	---------------------------
5	我认为**汽油汽车**内燃机并不安全。 I think combustion engines for **gasoline vehicles** are not safe.	----------------------------	[1] [2] [3] [4] [5]

6	我认为**纯电动汽车**的电磁辐射对人体健康没有危害。 I believe that electromagnetic radiation from **battery electric vehicles** not harmful to human health.	[1] [2] [3] [4] [5]	___________________
7	我认为**纯电动汽车**没有发动机的噪音，驾驶起来更加愉快。 I think **battery electric vehicles** don't make engine noise, which make driving more pleasant.	[1] [2] [3] [4] [5]	________________
8	我相信使用**纯电动汽车**不会导致温室气体排放，减缓全球变暖。 I believe that using **battery electric vehicles** does not contribute global greenhouse gas emissions, slowing down global warming.	[1] [2] [3] [4] [5]	__________________
9	我相信使用**汽油汽车**不会导致全球气候变暖。 I believe that using **gasoline vehicles** does not contribute to global climate warming.	____________________	[1] [2] [3] [4] [5]

部分 B：关于纯电动汽车/汽油汽车的消费者隐私安全调查

Section B: Consumer Privacy Security in Using Battery Electric Vehicles and Gasoline Vehicles

No	问题 Item	Type of information leakage	5-point scale
1	我对购车和使用过程中的信息**泄露零容忍**（个人信息、车辆信息、财务信息、行程信息）	个人信息（姓名、地址、电话号码等） Personal information (name, address, phone	[1] [2] [3] [4] [5]

	I have **zero tolerance** for information（personal information、vehicle information、financial information、itinerary information) leakage during the car purchasing and usage process	number, etc.）	
		车辆信息（车辆型号、品牌、年份等） Vehicle Information (vehicle model, brand, year, etc.)	[1] [2] [3] [4] [5]
		财务信息（信用卡号、银行账户信息等） Financial Information(credit card numbers, bank account information, etc.)	[1] [2] [3] [4] [5]
		行程信息 Itinerary information（(Such as driving route, parking location, etc.)	[1] [2] [3] [4] [5]

No.	问题/汽车种类 Items/ Types of vehicles	纯电动汽车 <u>Battery Electric vehicles</u>	汽油汽车 <u>Gasoline Vehicles</u>
2	据我了解，消费者在购买**纯电动汽车/汽油汽车**阶段商家<u>会保护</u>客户的隐私信息 According to my understanding, the seller <u>will protect</u> customers' personal private information when purchasing **battery electric vehicles/gasoline vehicles**	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]

3	我不担心我的个人信息在购买**纯电动汽车/汽油汽车**过程中被泄露。 I never worry about my personal information being leaked during the process of buying **battery electric vehicles/gasoline vehicles**	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
4	我认为车主在购买**纯电动汽车/汽油汽车**后不会收到关联推销信息 I think vehicle owner will not receiving an affiliate marketing message after purchasing a **battery electric vehicles/gasoline vehicles**	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]

部分 C：购买汽车基础信息透明度

Section C：Basic Information Transparency in Buying a Vehicle

No.	问题/汽车种类 Items/ Types of vehicles	纯电动汽车 Battery Electric vehicles	汽油汽车 Gasoline Vehicles
1	当前居住地的**纯电动汽车/汽油汽车**准入政策清晰易懂 Current city of residence policies on access to **battery electric vehicles/gasoline vehicles** are clear.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
2	购买**纯电动车/汽油汽车**企业提供的优惠政策清晰易懂。 The (company's) purchasing policy for purchasing **battery electric/gasoline vehicles** is clear and easy to understand.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
3	**纯电动汽车/汽油汽车**销售公司提供报价是透明的，无隐藏收费。	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]

	Companies selling **battery electric/gasoline vehicles** offer transparent pricing and no hidden fees.		
4	我发现很容易获取**有关车辆**基本信息的信息。 I find it easy to access the information provided about basic information of the **vehicles**.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
5	获取**有关车辆**使用功能的全面信息会影响我的车辆购买决策。 Having access to comprehensive information about the **vehicle's** performance characteristics will influences my vehicle purchasing decision.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
6	纯电动汽车/汽油汽车企会公布环保数据。 **Battery electric vehicles/gasoline vehicles** companies will publish environmental protection data	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
7	**纯电动汽车/汽油汽车**整个生命周期（"从摇篮到坟墓"）的相关数据对消费者公开透明。 Relevant data throughout the life cycle（"Cradle-to-Grave"） of **battery electric/gasoline vehicles** is transparent to consumers.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
8	**纯电动汽车/汽油汽车**对环境的影响将影响我的车辆购买决定 Being informed about the environmental impact of **battery electric/gasoline vehicles** will influence my	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]

	vehicle purchasing decision		
9	我对**纯电动汽车/汽油汽车**公司信息透明度感到满意。 I am satisfied with the information transparency of the **battery electric vehicles/gasoline vehicles** company.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]

部分 D：纯电动汽车和汽油汽车使用阶段的反馈机制（在产品在运营过程中，通过渠道建立和用户之间的联系）：

Section D: Feedback Mechanism（During the operation of the product, establish contact with users through channels） for use of Electric Vehicles and Gasoline Vehicles

NO.	问题/汽车种类 Items/ Types of vehicles	纯电动汽车 Battery Electric vehicles	汽油汽车 Gasoline Vehicles
1	我会向 4S 店反馈**纯电动汽车/汽油汽车**使用过程中遇到的任何问题。 I will provide feedback to the automobile sales service shop regarding any problems encountered while using the **battery electric vehicles/gasoline vehicles**	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
2	我认为**纯电动车/汽油汽车**的反馈渠道是多种多样的。 I think feedback channels for **battery electric vehicles/gasoline vehicles** are very diverse.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
3	访问**纯电动汽车/汽油汽车**的消费者反馈机制非常简单。 Accessing the consumers feedback mechanism of **battery electric vehicles/gasoline vehicles** is straightforward.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
4	纯电动汽车/汽油汽车的 4S	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]

	店工作人员积极主动的帮助解决问题。 **Battery electric vehicles/gasoline vehicles** Automobile Sales Service Shop the staff proactively solves the problem.		
5	我认为目前**纯电动汽车/汽油汽车**消费者反馈机制完善不需要改进 I think the customer feedback mechanism of **battery electric vehicles/gasoline vehicles** no needs any improvement at the moment.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
6	我认为**纯电动车/汽油汽车**销售公司缺乏有效的消费者反馈机制。 I believe that companies selling **battery electric/gasoline vehicles** are lack effective feedback mechanisms.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
9	消费者反馈机制在提高**纯电动汽车/汽油汽车**质量方面发挥着至关重要的作用。 Feedback mechanisms play an important role in improving the quality of **battery electric/gasoline vehicle** supply.	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
10	消费者反馈机制增强了我使用**纯电动车/汽油汽车**时的整体体验。 The feedback mechanism helps improve my overall experience using an **battery electric/gasoline vehicle.**	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]

E 部分：纯电动汽车/汽油汽车的报废责任和对未来的考虑

E: End of Life and Future Concern about Battery Electric Vehicles and Gasoline Vehicles.

No	问题/汽车种类 Items/ Types of vehicles	纯电动汽车 Battery Electric vehicles	汽油汽车 Gasoline Vehicles
1.	我关心纯电动汽车/汽油汽车的转售价值。 I care about the resale value of **battery electric vehicles/gasoline vehicles**	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]
2.	我不了解**纯电动汽车**的报废流程。 I do not understand the end-of-life process for **battery electric vehicles.**(Choose 4 or 5 will not answer question 4.)	[1] [2] [3] [4] [5]	————————
3.	我不了解**汽油汽车**的报废流程。 I do not understand the end-of-life process for **gasoline vehicles.**(Choose 4 or 5 will not answer question 5.)	————————	[1] [2] [3] [4] [5]
4.	我认可当前纯电动汽车的报废流程。 I approve the current scrappage process for **battery electric vehicles**.	[1] [2] [3] [4] [5]	————————
5.	我认可当前汽油汽车的报废流程。 I approve the current scrappage process for **gasoline vehicles.**	————————	[1] [2] [3] [4] [5]
6.	我认为**纯电动车/汽油汽车**报废后有助于减少对环境的污染。 I think **battery electric vehicles/gasoline vehicles** contribute to	[1] [2] [3] [4] [5]	[1] [2] [3] [4] [5]

	less pollution to the environment after they are scrapped.		

No.	问题 Item	原因 Reasons	5-point scale
7	未来倾向于购买**纯电动汽车**的其他主要原因 Some other primary reasons lean towards purchasing an **battery electric vehicle** in the future	易于维护 Easy to maintain	[1] [2] [3] [4] [5]
		维修成本低 Low repair costs	[1] [2] [3] [4] [5]
		对充电时间很满意 Satisfied with the charging time	[1] [2] [3] [4] [5]
		与汽油相比，电力成本低廉 Low-cost of electricity compared with gasoline	[1] [2] [3] [4] [5]
		不受车牌交通管制措施的限制。 Not restricted by license plate-based traffic control measures.	[1] [2] [3] [4] [5]
		与汽油汽车相比，更能轻松拿到车牌 It's easier to get a license plate than a gasoline vehicle	[1] [2] [3] [4] [5]
		电动汽车充电费用分级定价机制合理 The tiered pricing mechanism for electric vehicle charging costs is rational	[1] [2] [3] [4] [5]
		电动汽车充电桩位置合理 Reasonable location for installing public charging stations for electric vehicles.	[1] [2] [3] [4] [5]
		电动汽车充电基础设施充足 The infrastructure for electric vehicles' charging is sufficient	[1] [2] [3] [4] [5]
		使用纯电动汽车符合碳	[1] [2] [3] [4] [5]

		达峰目标。 Using electric battery vehicle is in line with the goal of carbon peaking.	
		使用纯电动汽车有利于可持续发展 Using battery electric vehicle is helpful for sustainable development	[1] [2] [3] [4] [5]
8	Some other primary reasons I lean towards purchasing a **gasoline** vehicle in the future. 我未来倾向于购买汽油车的其他主要原因。	易于维护 Easy to maintain	[1] [2] [3] [4] [5]
		维修成本低 Low repair costs	[1] [2] [3] [4] [5]
		我对汽油汽车的平均加油时间感到满意。 I am satisfied with the average refuelling time of gasoline vehicles.	[1] [2] [3] [4] [5]
		汽油价格合理。 The gasoline prices for gasoline vehicles are reasonable.	[1] [2] [3] [4] [5]
		汽油汽车公共加油站布局合理。 The locations of public gas stations for gasoline vehicles are reasonable.	[1] [2] [3] [4] [5]
		汽油汽车加油基础设施充足。 The infrastructure for gasoline vehicles' refuelling is sufficient.	[1] [2] [3] [4] [5]

III 单元： 支付意愿
Part III: Willingness to Pay for Carbon Emission Tax Initiative

碳达峰和碳中和是一个充满挑战的旅程，在汽车行业实现碳中和的道路上必须考虑到这一点。 因为燃烧 3 升汽油会产生 10 公斤二氧化碳排放。东北电网平均生产 7 千瓦时电将产生 10 公斤二氧化碳。

想象一下，如果政府启动一项针对能源消耗产生的碳税税倡议，旨在减少二氧化碳排放并减少化石燃料和其他不可再生资源的使用。 每次为车辆充电或加油时征收二氧化碳排放税，针对使用电力的纯电动汽车排放的二氧化碳，或燃烧车辆燃烧化石燃料产生的二氧化碳。 意味着纯电动汽车充电成本和汽油成本会随着二氧化碳排放量的增加而增加，这意味着能源消费者将需要支付额外的碳排放税。

税可分配给以下项目：
能源工厂和设施的更新和开发
温室气体减排技术的进步
城市绿色改造
扩大森林面积、保护现有森林、促进林业可持续发展等项目。
环境教育和意识提高项目

Carbon peaking and carbon neutrality is a challenging journey that must be considered in the automotive industry’s path to carbon neutrality. This is because burning 3 litre of gasoline will produce 10 kg CO_2 eq of carbon dioxide emissions. China north east power grid average produce 7 KWh electricity will generate 10 kg CO_2 eq .

Imagine if the government initiated a carbon emissions initiative on energy consumption, aiming to reduce carbon emissions and curtail the use of fossil fuels and other non-renewable resources. The carbon emissions tax is incurred every time you charge or fill up the vehicle. This is for the carbon emissions from your electric vehicles that use electricity, or the carbon emissions produced by burning fossil fuels by your gasoline vehicles. This means the electric vehicles’ charging costs and gasoline costs increase with carbon emissions . This implies that energy consumers would need to pay additional carbon emission taxes. This tax could be allocated towards the followings project:

Renewal and development of energy plants and facilities
Green house gas emissions mitigation technological advancement
Green development transformation of cities
Expanding forest area, protecting existing forests, and promoting sustainable forestry development
Funding environmental education and awareness-raising projects

基于以上场景：
您愿意为拟议的碳税倡议付费吗?

Based on the above scenario:
Would you be willing to pay for the proposed carbon emission tax initiative?

□ 愿意 yes (请回答问题 2 和 3 ；please go for question 2 and 3)
□ 不愿意 no (请回答问题 2 和 4 ；please go for question 4)

最多愿意为 10 kg 碳当量排放支付__________________人民币（约消耗 3 升汽油或 7 千瓦时电将产生 10 千克碳当量，碳税将包含在每次充电或加油费用中）
The maximum WTP is _______________________CNY for CO_2 eq/10 kg (approximately consuming 3 liters of gasoline or 7 KWh of electricity will produce 10 kg of carbon equivalent, and the carbon tax will be included in the cost of each charge or refueling)

如果您愿意付款，请说明原因。（你可以选择多于一个）
Choose the reasons if you want to pay (you may choose more than one option)

□ 通过调整税收体系来可以励环保行为以减少对环境的负面影响。
Adjusting the tax system to encourage environmentally friendly behaviour can reduce environmental impact

□碳税助于平衡经济增长与环境保护之间的关系，为未来世代创造更好的发展前景。
Carbon tax can contribute to balancing the relationship between economic growth and environmental protection, thus creating better development prospects for future generations.

□ 能源生产产生的温室气体不能忽略不计。
The effects of green house gas from energy production are not negligible.

□ 减缓二氧化碳排放是每个人的责任。
Mitigating carbon dioxide emissions is the responsibility of everyone.

□担心二氧化碳对地球的影响可能会影响到个人生活质量。
Concerns about the impact of carbon dioxide on the Earth could potentially affect the quality of life.

支持中国在 2060 年实现碳中和
support China towards carbon neutral in 2060

□ 其他原因（请注明） ________。
Other reasons (Please specify) ________.

4. 如果您不想付款，请说明原因。（你可以选择多于一个）
Choose the reasons if you don’t want to pay (you may choose more than one option)

□ 税收可能无法按照场景中提到的分配给项目来发挥作用。

Tax may not be working as the tax allocated to the project as mentioned in the scenario

□能源生产产生的温室气体的影响可以忽略不计。
The effects of green house gas from energy production are negligible.

□ 付不起这笔费用。
I cannot afford to pay the fee.

□不保证其他人会支持。
There is no guarantee that others are willing to supported.

□ 二氧化碳对地球的影响不会影响到个人生活质量。
The impact of carbon dioxide on the Earth could not potentially affect the quality of life.

□不公平
not fair

□看不到碳税对环境保护的有效性
cannot see the effectiveness of carbon taxes towards environmental protection

□ 其他原因（请注明） ________。
Other reasons (Please specify) ________.

Appendix B

Life Cycle Inventory Cost Results for BEV

Option 1: Electric Vehicles

Disscount Rate: 5%

Escalation Rate: 2%

Real Disscount Rate: 2.94%

Year	Purchase Price	Purchase Tax	Merchant Discount	Charging Pile Fee	License Plate Fee	Insurance Cost	Vehicle and Vessel Tax	Annual Vehicle Inspection Cost	Energy Cost	Cleaning Cost	Replacement and Service Cost	Resale Price	Resale Cost	Present Value	Cumulative Present Value	Net Present Value	Year
0	123,800.00	0.00	7,000.00	0.00	130.00									116,930.00	116,930.00	116,930.00	0
1						4,979.00	0.00		2,485.67	240.00	240.00	95,615.69	2,448.39	7,717.68	124,647.68	34,142.30	1
2						4,979.00	0.00		2,485.67	240.00	1,463.00	85,461.62	2,194.54	8,651.29	133,298.97	54,722.04	2
3						4,979.00	0.00		2,485.67	240.00	240.00	76,159.28	1,961.98	7,282.97	140,581.94	72,564.43	3
4						4,979.00	0.00		2,485.67	240.00	2,963.00	67,664.13	1,749.60	9,499.77	150,081.71	91,383.53	4
5						4,979.00	0.00		2,485.67	240.00	240.00	59,931.58	1,556.29	6,872.74	156,954.45	106,455.38	5
6						4,979.00	0.00	230.00	2,485.67	240.00	1,463.00	52,917.07	1,380.93	7,897.42	164,851.87	121,542.97	6
7						4,979.00	0.00		2,485.67	240.00	240.00	46,576.04	1,222.40	6,485.63	171,337.50	134,313.09	7
8						4,979.00	0.00	230.00	2,485.67	240.00	2,963.00	40,863.90	1,079.60	8,642.13	179,979.63	148,429.67	8
9						4,979.00	0.00		2,485.67	240.00	240.00	35,736.11	951.40	6,120.31	186,099.94	159,302.94	9
10						4,979.00	0.00	230.00	2,485.67	240.00	1,463.00	31,148.08	836.70	7,032.81	193,132.75	170,449.03	10
11						4,979.00	0.00	230.00	2,485.67	240.00	240.00	27,055.25	734.38	5,942.78	199,075.53	179,940.91	11
12						4,979.00	0.00	230.00	2,485.67	240.00	2,963.00	23,413.06	643.33	7,695.98	206,771.52	190,691.43	12
13						4,979.00	0.00	230.00	2,485.67	240.00	240.00	20,176.92	562.42	5,608.05	212,379.56	198,923.48	13
14						4,979.00	0.00	230.00	2,485.67	240.00	1,463.00	17,302.29	490.56	6,262.86	218,642.42	207,438.64	14
15						4,979.00	0.00	460.00	2,485.67	240.00	240.00	14,744.58	426.61	5,441.06	224,083.48	214,814.24	15

Appendix C

Life Cycle Inventory Cost Results for GV

Option 2: Gasoline Vehicles

Disscount Rate: 5%

Escalation Rate: 2%

Real Disscount Rate: 2.94%

Year	Purchase Price	Purchase Tax	Merchant Discount	Charging Pile Fee	License Plate Fee	Insurance Cost	Vehicle and Vessel Tax	Annual Vehicle Inspection Cost	Energy Cost	Cleaning Cost	Replacement and Service Cost	Resale Price	Resale Cost	Present Value	Cumulative Present Value	Net Present Value	Year
0	110,000.00	9,734.50	30,000.00	0.00	130.00									89864.50	89864.50	89864.50	0
1						4,906.00	480.00		9,938.76	240.00	504.00	84,957.40	2,181.94	15609.65	105474.15	25063.70	1
2						4,906.00	480.00		9,938.76	240.00	1,771.00	75,935.20	1,956.38	16359.30	121833.45	52021.60	2
3						4,906.00	480.00		9,938.76	240.00	3,290.00	67,669.80	1,749.75	17284.37	139117.82	78688.16	3
4						4,906.00	480.00		9,938.76	240.00	3,196.00	60,121.60	1,561.04	16706.82	155824.65	103675.32	4
5						4,906.00	480.00		9,938.76	240.00	2,404.00	53,251.00	1,389.28	15544.35	171368.99	126504.65	5
6						4,906.00	480.00	310.00	9,938.76	240.00	2,576.00	47,018.40	1,233.46	15505.28	186874.27	148398.45	6
7						4,906.00	480.00		9,938.76	240.00	3,829.00	41,384.20	1,092.61	15832.09	202706.35	169814.33	7
8						4,906.00	480.00	310.00	9,938.76	240.00	1,771.00	36,308.80	965.72	13993.53	216699.89	188671.93	8
9						4,906.00	480.00		9,938.76	240.00	3,290.00	31,752.60	851.82	14525.09	231224.98	207420.02	9
10						4,906.00	480.00	310.00	9,938.76	240.00	3,196.00	27,676.00	749.90	14271.73	245496.71	225346.38	10
11						4,906.00	480.00	310.00	9,938.76	240.00	2,404.00	24,039.40	658.99	13288.21	258784.92	241787.93	11
12						4,906.00	480.00	310.00	9,938.76	240.00	2,576.00	20,803.20	578.08	13030.01	271814.93	257531.86	12
13						4,906.00	480.00	310.00	9,938.76	240.00	3,829.00	17,927.80	506.20	13517.32	285332.24	273380.55	13
14						4,906.00	480.00	310.00	9,938.76	240.00	1,771.00	15,373.60	442.34	11759.60	297091.84	287141.26	14
15						4,906.00	480.00	620.00	9,938.76	240.00	3,290.00	13,101.00	385.53	12607.68	309699.52	301467.71	15

Appendix D

Ethics Approval Letter from the UPM Ethics Committee

Ref. no: UPM/TNCPI/RMC/JKEUPM/1.4.18.2 (JKEUPM)
Date: 11 July 2024

Dear Prof./Dr./Mr./Ms.,

APPLICATION FOR JKEUPM ETHICAL CLEARANCE: APPROVED

With reference to the above, I am pleased to inform you that your application for ethical clearance for the research project entitled **'ANALYZING THE SUSTAINABILITY OF A CASE STUDY IN HEILONGJIANG PROVINCE CHINESE ELECTRIC VEHICLES AND GASOLINE VEHICLE USING SUSTAINABLE ASSESSMENT METHODOLOGY',** has been approved.

The approval is **valid from 11 July 2024 until 10 July 2025.**

Please note that the official letter of approval will be issued as soon as possible. However, the ethical clearance is considered effective from the date of this email, and you may now proceed with your research.

Kindly remind the ethical approval is required in the case of amendments/ changes to the studydocuments/ study sites/ study team.

Researchers should also complete a Study Final Report upon study completion. The form can be obtained from the Ethics Committee for Research Involving Human Subjects (JKEUPM) website (http://www.tncpi.upm.edu.my/faildokumen).

If you have any enquiries, please contact at number 03-97691244/1602/**1421**. Note: Please use this reference number for any transaction:- **JKEUPM-2023-1319.** Thank you.

Yours faithfully,

Prof. Dr. Johnson Stanslas
Chair
Ethics Committee for Research Involving Human Subjects
Universiti Putra Malaysia

Appendix E

The Proportion of Power Generation Sources in Various Regions
(Source: China Electricity Statistical Yearbook 2022)

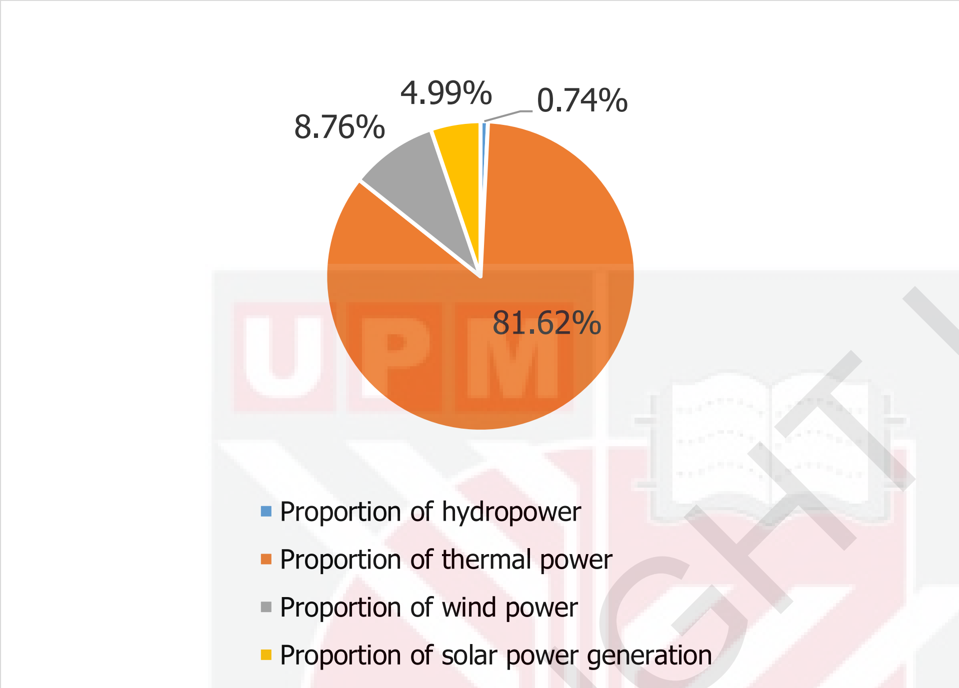

Figure 1: State Grid North China Branch

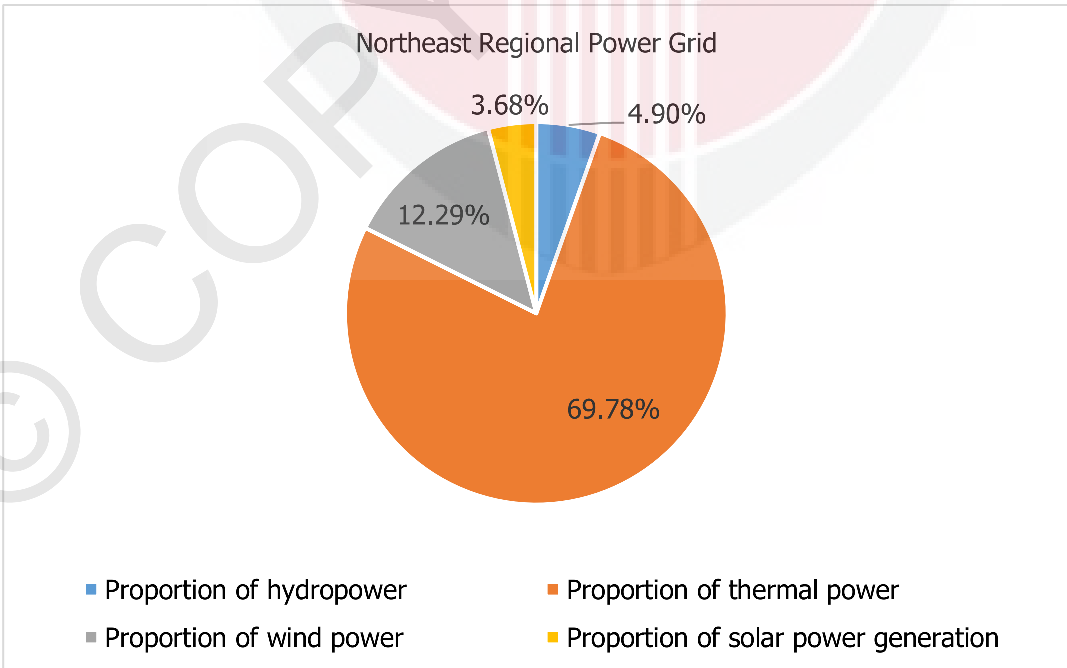

Figure 2: State Grid Northeast China Branch

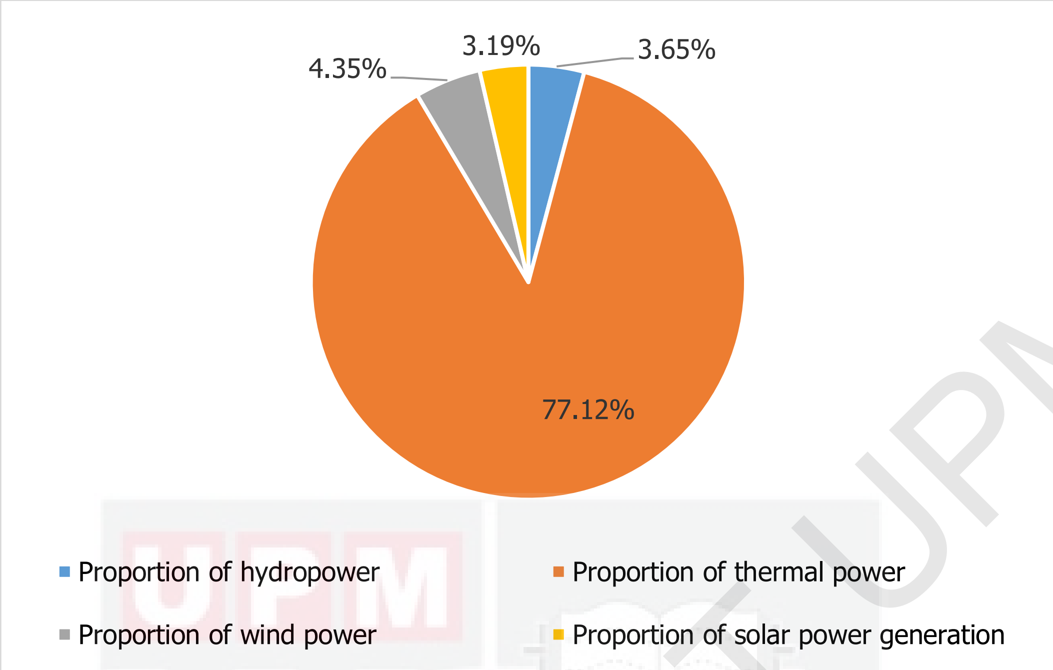

Figure 3: State Grid East China Branch

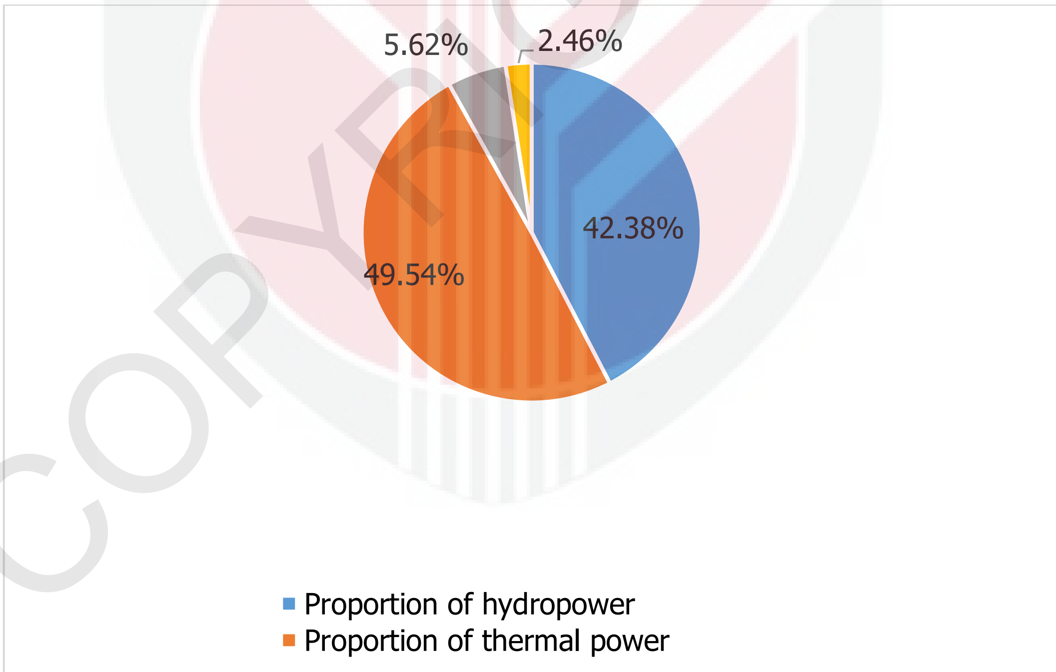

Figure 4: State Grid Central China Branch

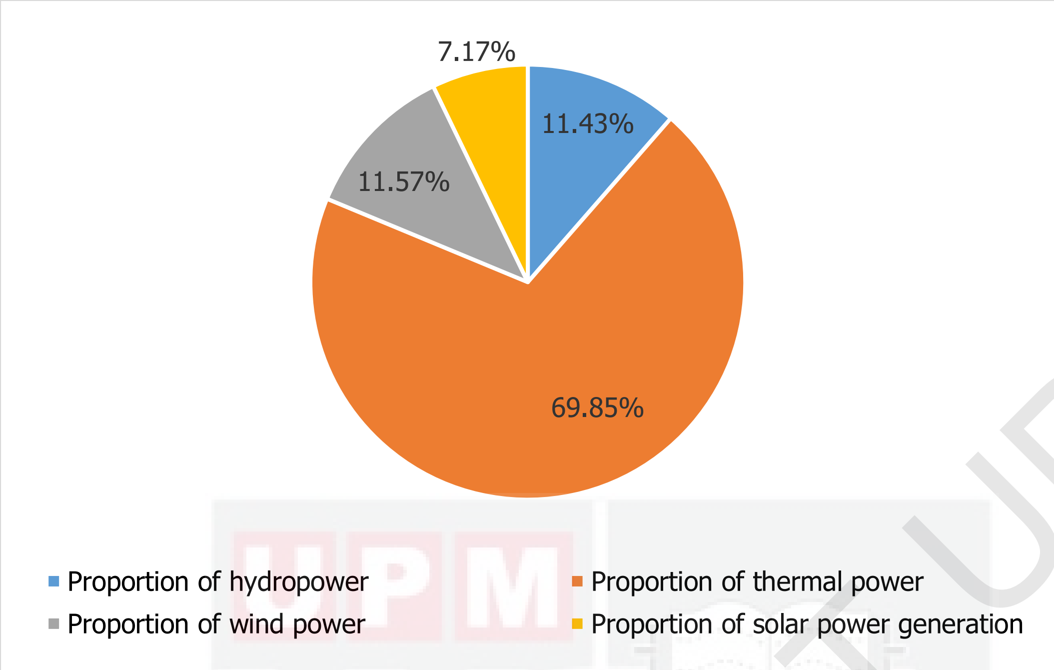

Figure 5: State Grid Northwet China Branch

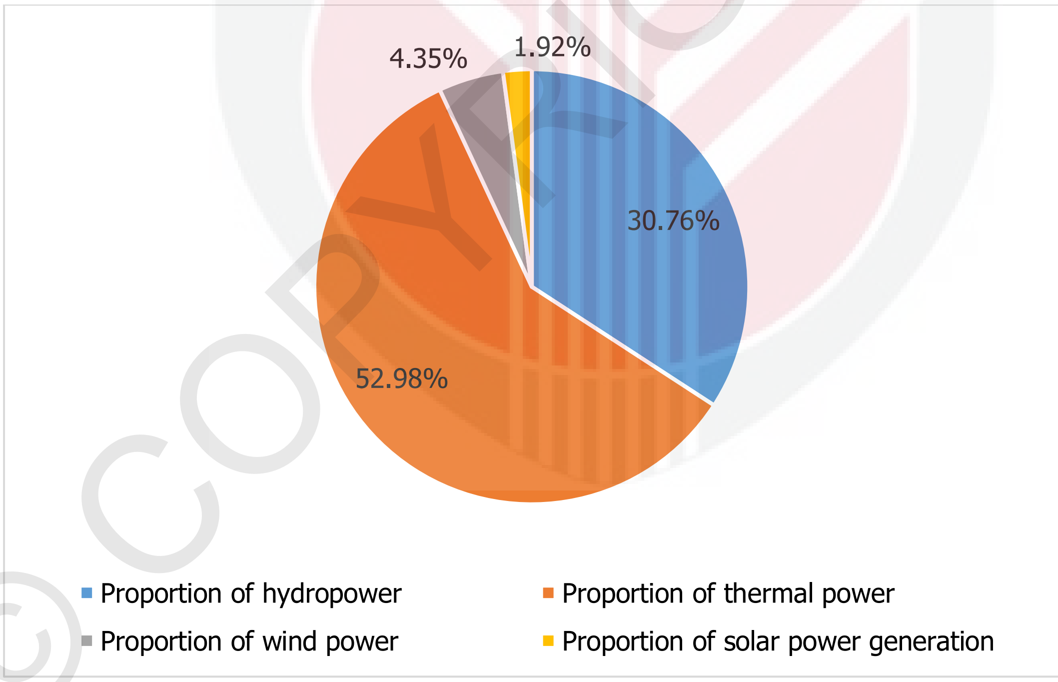

Figure 6: State Grid Southwest China Branch

BIODATA OF STUDENT

Ma Sining was born in China. She earned a bachelor's degree in environmental science from University Malaysia Sabah by 2018. She has continued her master's degree in 2019 and graduate in 2020, major in environmental studies from Universiti Putra Malaysia. She worked as administration and lecture at Southwest Jiaotong University Hope College science 2021.

LIST OF PUBLICATIONS

Ma, S., Sharaai, A. H., He, Z., Matthew, N. K., Zainordin, N. S., & Wafa, W. (2023). Exploring the Research Frontier of Life Cycle Sustainability Assessment—A Systematic Literature Review of Applied Bibliometric Analysis. Chemical Engineering Transactions, 106, 547–552. https://doi.org/10.3303/CET23106092

Ma, S., Sharaai, A. H., & Wafa, W. (2022). A study of social well-being among university students. The International Journal of Life Cycle Assessment, 27(3), 492–504. https://doi.org/10.1007/s11367-022-02029-w

Sining, M., Sharaai, A. H., Matthew, N. K. a/l, & Zainordin, N. S. (2024a). Monetization of Sustainability Indicators Integrating Willingness to Pay into Life Cycle Sustainability Assessment. International Journal of Academic Research in Economics and Management Sciences, 13(4), 155–168. https://hrmars.com/index.php/IJAREMS/article/view/23037/Monetization-of-Sustainability-Indicators-Integrating-Willingness-to-Pay-into-Life-Cycle-Sustainability-Assessment

Sining, M., Sharaai, A. H., Matthew, N., & Zainordin, N. (2024b). Sustainable development of electric vehicles in China: A bibliometric analysis and systematic review, 2011 onward. Edelweiss Applied Science and Technology, 8, 2252–2260. https://doi.org/10.55214/25768484.v8i6.242 2