Environmental Assessment of Road Transport in Qatar and its Policy Implications: Current Emissions and Future Reduction Projections

By Abdulla Alishaq

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Faculty of Natural Sciences

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Declaration of Originality

I, Abdulla Alishaq, hereby declare that this thesis is entirely my own work with the exception of that which has been referenced appropriately.

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PhD Supervisors

Principal Supervisor: Professor Jeremy Woods

Assistant Supervisor: Dr Daniel Mehlig and Dr Onesmus Mwabonje

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Abstract

This thesis evaluates Qatar's road transport sector, its policies and their effectiveness in reducing greenhouse gas (GHG) emissions. It aims to facilitate a transition to a sustainable, low-carbon transport system by 2050. The study is structured around three principal components: an analysis of existing road transport policies in Qatar and the projected impact of internal combustion engine vehicle (ICEV) ban scenarios enacted in 2030, 2035, and 2040; a comparative life cycle assessment (LCA) of battery electric vehicles (BEVs) versus ICEVs; and, the application of a carbon calculator to evaluate the potential CO2-equivalent (CO2-eq) impact of a range of mitigation measures and initiatives.

Utilizing a multifaceted methodological approach that includes scenario analysis, dynamic LCA, and the strategic use of a carbon calculator tool, this research assesses the implications of Qatar's road transport policies on GHG emissions. The scenario analysis reveals that an early 2030 ICEV ban would reduce cumulative CO2-eq road emissions by 34% in 2050 compared to the business-as-usual (BAU) scenario, while delays until 2035 and 2040 would result in 28% and 23% reductions, respectively. The LCA findings highlight the advantages of BEVs in terms of global warming potential and fossil resource consumption, although they currently face challenges related to mineral resource scarcity. The carbon calculator analysis shows that maintaining current practices in Qatar's transportation sector would lead to a 54% increase in emissions by 2050 compared to 2022 levels. In contrast, implementing the highest ambition scenario could result in an 89% reduction in emissions over the same period.

Contributing to the global dialogue on sustainable development and climate change mitigation, this thesis offers strategic insights and recommendations for policymakers, researchers, and practitioners. It emphasizes the need for an integrated strategy that addresses the intricate interactions between policy, technology, and social behaviour in pursuit of a sustainable, low-carbon future.

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1 Introduction

Extending from its east coast northwards into the Arabian Gulf, the Qatar peninsula is an icon of oil production in the Middle East. With a long history in both oil and natural gas production and consumption, Qatar is in a unique position to transition the state's energy system away from fossil fuels (Al-Siddiqi & Dawe, 1999). Decarbonization is at the forefront of the global community's push to mitigate the impacts of climate change, and Qatar is no exception. Facing distinct challenges to decarbonization on a nationwide scale, Qatar should explore potential ways to shift its energy economy away from fossil fuels. To do so, it is crucial to understand the history of oil and natural gas production, as this provides insights into areas of opportunity. As a parallel consideration, the impacts of climate change on Qatar must also be recognized. Understanding the specific ramifications of this global phenomenon on the nation is pivotal. Such understanding allows for delineating bespoke mitigation strategies tailored to Qatar's unique environmental, economic, and socio-cultural contexts.



Figure 1.1: Map of the State of Qatar

The world's shift towards cleaner energy sources presents Qatar with difficult economic choices, especially in light of the recent COP28 report, which emphasizes the need to phase out fossil fuels (Climate Change Committee, 2024). Notably, Liquefied Natural Gas (LNG) is considered by some to be an energy transition fuel (Gürsan & de Gooyert, 2021; International Trade Administration, 2022). This means demand for it is currently high, but there could be a risk that it may decrease as the world moves entirely away from carbon-intensive fuels. This was evidenced at the end of 2014 when oil prices dropped dramatically, leading to a 20.2% decline in the nominal GDP growth rate (Ministry of Development Planning and Statistics, 2018).

Qatar is characterized by a high and sustained dependence on hydrocarbons, with the hydrocarbon sector being more prominent here than in other GCC countries. Qatar has surpassed Australia to be recognized as the largest LNG exporter in 2022. The recent surge in oil prices in 2021 further strengthened LNG markets, mainly as oil-linked contracts performed better than anticipated (World Bank, 2022).

The conflict between Qatar's dependence on hydrocarbons and the impacts of climate change provides challenges for its growth and development. The rise in economic development observed in Gulf nations, notably Qatar, can largely be attributed to the expansion of the oil and gas industry. This dependency on hydrocarbon resources, however, has triggered an increase in CO2 emissions (Shannak & Contestabile, 2022). Central to decarbonization are two primary energy sectors: electricity and transportation. Both sectors depend on long-term policymaking strategies and direct government involvement to advance technological, social, and economic programs that enhance energy transition. To implement practical sustainable development within transportation specifically, Qatar will need to optimize the sector by analyzing future scenarios, outlining blueprints and policies to meet transportation demand, and incentivizing vehicle electrification.

The road transport landscape in Qatar has evolved significantly over the past few decades. Initially, the nation's transport infrastructure and policies were primarily focused on accommodating the rapid economic and population growth, with less emphasis on environmental sustainability. This growth phase saw a substantial rise in the number of internal

combustion engine vehicles (ICEV), leading to increased greenhouse gas (GHG) emissions. However, recognizing the environmental implications, Qatar shifted its focus towards more sustainable transport solutions.

A crucial factor that must be considered in tandem with transportation development is urban planning. The relationship between transport and urban planning is fundamental, as the layout and design of urban areas directly influence transport efficiency and emissions. Qatar's urban expansion, driven by economic growth, has led to increased urban sprawl, which in turn has escalated reliance on private vehicles. Historically, urban planning in Qatar, like in many Gulf countries, has prioritized the construction of highways and expansive road networks, accommodating a car-centric lifestyle. This has reinforced the dominance of ICEVs and increased the transportation sector's carbon footprint. To transition to a sustainable transport system, urban planning must play a pivotal role in reshaping how cities are structured and how people move within them. Compact city designs, mixed-use developments, and public transport integration can significantly reduce transport-related emissions.

The transportation sector, predominantly reliant on ICEVs, greatly contributes to GHG emissions. Recognizing this, Qatar has initiated policies to transition towards more sustainable transport systems (Al Mamun et al., 2021). Understanding the environmental impact of these road transport policies is crucial. It informs the effectiveness of current measures and guides future policy-making to align with international environmental standards and commitments.

1.1 Research significance

This study assesses the effectiveness of Qatar's existing policies towards accomplishing its goals for mitigating GHG emissions within the transport sector. Additionally, it delves into prospective future scenarios, offering strategic insights into potential avenues for Qatar to reduce GHG emissions. This is particularly important for a country which is evaluating strategies for evolving its economy beyond its traditional hydrocarbon dependence, aiming to achieve a balance between economic growth and sustainability.

Globally, the findings of this research have broader implications. Many countries face similar challenges in balancing economic growth with environmental sustainability, especially those with economies reliant on fossil fuels. The scenarios and strategies explored in this study could serve as a model for other nations with similar contexts, providing valuable lessons in policy formulation, implementation, and evaluation. The research contributes to the global discourse on sustainable development, particularly in mitigating climate change through decarbonizing the transport sector.

Furthermore, this research contributes to the field of road transport decarbonization. Assessing the effectiveness of various policies and initiatives adds to the understanding of what works and what does not in the transition towards a low-carbon transport system. The study's detailed approach, which includes evaluating electrification policies and vehicle ban scenarios, provides a nuanced understanding of the complex interplay between policy, technology, and environmental impact. This contribution is vital for policymakers, researchers, and practitioners, offering evidence-based insights and guidance for future actions in the quest for sustainable and environmentally responsible transport systems.

1.2 Research aim and questions

The aim of this research is to evaluate Qatar's road transport policies and strategies for GHG emission reduction. This will involve an in-depth analysis of the current and projected impacts of Qatar's road transport policies on GHG emissions, the potential effect of different ICEV ban scenarios, the comparative life cycle assessment (LCA) of ICEVs and battery electric vehicles (BEV), and the effectiveness of various GHG mitigation measures and initiatives using the carbon calculator approach. The ultimate objective is to provide strategic insights and recommendations for achieving Qatar's national targets of reducing GHG emissions from road transport by 2030 and facilitating a sustainable transition to a low-carbon transport system by 2050.

The research is structured around a main question and a set of sub-questions, each aimed at exploring different facets of the environmental impact of road transport policies in Qatar. The main research question addresses the overall effectiveness of Qatar's current policies and future strategies in meeting national targets and sustaining reductions through 2050. The sub-questions are organized into three key areas: policy impacts and scenarios, life cycle assessment, and long-term mitigation strategies. This structure clarifies the specific focus and expected outcomes of the research, ensuring a thorough examination of Qatar's road transport policies and their potential to achieve GHG emission reductions.

Main Question: How effective are Qatar's current road transport policies in reducing GHG emissions to meet the national target for 2030, and what strategies can sustain and enhance these reductions through 2050?

Sub-question 1: What are the impacts of Qatar's current road transport policies to reduce GHG emissions and how will ICEV ban scenarios affect GHG emissions?

- Sub-question 1.a: How would vehicle ban scenarios in 2030, 2035, and 2040 impact on GHG emissions trajectory for Qatar?
- Sub-question 1.b: What would be the impact of Qatar's policy towards the electrification of 10% of the road fleet by 2030?

- Sub-question 1.c: What fleet configuration of road vehicles would achieve the national goal of reducing 25% of GHG road transport emissions by 2030?

Sub-question 2: What is the dynamic LCA for a cradle to grave system boundary of a BEV in comparison to an ICEV operating in Qatar?

Sub-question 3: Using the carbon calculator approach, how would different mitigation measures and initiatives affect the decarbonization of road transport in Qatar by 2050?

1.3 Conclusion

The mounting challenges presented by climate change necessitate that nations cultivate radical strategies to mitigate GHG emissions, with the transportation sector emerging as a primary focal point. Qatar, distinguished for its rapid economic evolution and infrastructural prowess, discerns that its road transport policies are integral in realizing emission reductions.

The assessment of current transport policies provides an initial understanding of Qatar's current environmental positioning concerning GHG emissions. This foundational methodology is not merely an evaluative tool; it sets the stage for forecasting future policy trajectories, offering a measure against the intended sustainable outcomes.

The lifecycle emissions analysis of BEVs and ICEVs, tailored to Qatar's unique environmental and infrastructural context, presents another pivotal methodology. While global narratives frequently herald BEVs as environmentally superior, local studies are essential to understand how these vehicles fare, specifically in Qatar. This method delivers insights into the environmental footprint of vehicles from inception to decommissioning, underpinning policy decisions regarding vehicular adoption in alignment with the nation's sustainability efforts.

The third and final methods chapter uses the carbon calculator approach which stands out as a tool designed to project Qatar's environmental path to 2050. By feeding different initiatives into this calculator, it can show the potential environmental benefits or challenges. This tool is especially useful for policymakers. It allows them to foresee the results and adjust strategies to ensure the best outcomes.

While each method has unique attributes, they are designed to be used together. They are not siloed in their operation but form a symbiotic relationship. The insights derived from the lifecycle analysis can influence and refine the parameters utilized within the carbon calculator. Conversely, the understanding generated by assessing existing transport policies can shape the contextual system boundaries for the lifecycle study. These methods are utilized in this study

serve as Qatar's navigational tools, steering the nation towards a sustainable and decarbonized future for road transport.

1.4 Structure of the thesis

This thesis is organized into seven chapters, each focusing on a distinct aspect of the research and collectively contributing to an all-encompassing understanding of the environmental impact of road transport policies in Qatar.

Chapter 1: Introduction

This chapter sets the stage for the research, introducing the context, significance, aim and objectives of the study. It provides an overview of the environmental challenges related to road transport in Qatar and outlines the research questions and methodology. This chapter lays the foundation for the subsequent analysis.

Chapter 2: Background and Literature Review

This chapter serves a dual purpose. It begins by exploring the background information concerning the energy and transport sector in Qatar, laying the foundational context for the research. After that, the literature review section systematically examines existing academic literature on road transport policies, their environmental impacts, and the global trends in transport towards GHG reductions. This review establishes a theoretical and empirical basis for the research. It identifies gaps in the existing knowledge, which this thesis aims to fill, highlighting the unique contributions and significance of the study.

Chapter 3: Scenario Analysis for Road Transport

This chapter investigates and evaluates the effectiveness of Qatar's existing road transport policies on mitigating GHG emissions and explores the potential long-term implications of banning ICEVs and the adoption of BEVs.

Chapter 4: Life Cycle Assessment (LCA)

The focus in this chapter is on conducting a thorough LCA for BEVs compared to ICEVs in the Qatari context. This chapter evaluates the cradle-to-grave environmental impacts of these

vehicle types, offering insights into their respective roles in the nation's transport sector decarbonization.

Chapter 5: Carbon Calculator

In this chapter, the carbon calculator method is applied to quantify the potential impact of various measures and initiatives on the decarbonization of Qatar's road transport sector by 2050. This quantitative analysis provides a grounded assessment of different decarbonization strategies.

Chapter 6: Discussion

This chapter synthesizes the key findings from the preceding analyses, integrating scenario analysis, LCA, and carbon calculator modeling to evaluate the effectiveness of Qatar's road transport policies in reducing GHG emissions. It emphasizes the importance of policy implementation, the integration of vehicle electrification, and the necessity of considering a wide range of environmental impacts.

Chapter 7: Conclusions

The final chapter synthesizes the findings from the previous chapters, discussing their implications for Qatar's road transport policies and broader environmental goals. It also addresses the research questions, reflects on the limitations of the study, suggests directions for future research, and includes recommendations. This chapter concludes the thesis by summarizing the key contributions of the research to the field of transport decarbonization.

2 Background and literature review

2.1 Introduction

This chapter presents a foundation for understanding the evolving dynamics of road transport technologies and their environmental implications. The Background section examines key components of Qatar's development, including its energy sector, transportation policies, and the impact of climate change and population growth. It highlights the economic significance of oil and gas, assesses mobility needs, and reviews advancements in vehicle technology. Subsequently, the literature review summarizes previous work applying analytical tools to compare ICEVs and BEVs. This includes studies using scenario analysis to model different possible futures for BEV adoption depending on technological and policy developments. LCA studies are also reviewed which estimate the various environmental impacts from ICEVs versus BEVs over their full life cycles. Furthermore, the literature review also examines studies that have utilized the Carbon Calculator to model various levers that influence GHG emissions from LDVs and HDVs in order to identify and detail the factors impacting transport emissions now and leading up to 2050.

Together, the background and literature review establish current knowledge on the challenges and uncertainties involved in transitioning the vehicle fleet to BEVs. They also review the analytical approaches used to date to model this transition and its emissions implications. Insights from this background and review of past analytical approaches provide an essential foundation for the original analysis and modeling presented in later chapters. This thesis also identifies gaps in current research on Qatar's road transport, which it aims to address through its analysis and modeling efforts.

2.2 Background

The Background section provides an overview of Qatar's energy sector, transportation system and policies, the effects of climate change, growth, and development challenges, population growth, and a technical overview of vehicle technologies. It explores the role of oil and natural gas in Qatar's economic growth, the nation's mobility demands, the interplay between environmental factors and strategic objectives, the implications of population growth, and the advancements and challenges in passenger vehicle technologies. This section sets the context for understanding the complexities and interconnections of these elements in Qatar's progression.

2.2.1 The Energy Sector

Qatar has long relied on its substantial fossil fuel resources to power its economy and meet its energy needs. Both the electricity and transportation sectors are dominated by fossil fuels, providing reliable power and heat year-round. However, Qatar is well-positioned to harness solar power photovoltaic systems, despite the intermittency issues and large storage costs associated with renewable generation (IEA, 2022a). Natural gas has been recognized as a "transition fuel" due to its role in scaling up hydrogen production and transport (Gürsan & de Gooyert, 2021).

To reduce its reliance on fossil fuels, Qatar's energy policymakers must implement long-term planning solutions (Al-Aali & Modi, 2022; Al-Noaimi et al., 2023; Bohra & Shah, 2019). While domestic energy consumption can transition to clean energy, this does not significantly change Qatar's economic forecast, as domestic resource consumption is a small fraction of the energy infrastructure (Bohra & Shah, 2019).

Qatar's focus is on natural gas, with a relatively small oil production of 1.46 million barrels per day, 78% of which goes to exports. Renewables proved only a marginal fraction of energy in Qatar at the time of the study (Okonkwo et al., 2021). Qatar's solar potential is high, with Global solar horizontal irradiance (GHI), Diffuse Horizontal Irradiance (DHI), and Direct Normal Irradiance (DNI) determined to be 2,163 kWh/m2, 1,855 kWh/m2, and 897 kWh/m2 over a 10-year average

(Okonkwo et al., 2021). However, proposed solar plants of 800MW are not expected to significantly impact production mixes or the overall carbon footprint.

Qatar's power market is governed by the state-owned Qatar General Electricity and Water Corporation (KAHRAMAA) (Bayram et al., 2018; Mahmood et al., 2021). The Umm Al Houl Power (UHP) mega project aims to enhance energy security, while the Al Kharsaah solar power plant, an 800 megawatt facility, will be the first large-scale solar power plant in Qatar (Abdmouleh et al., 2018; Mahmood et al., 2021).

The primary regulatory authorities for Qatar's electricity sector include KAHRAMAA and the Minister of State for Energy. Qatar Electricity and Water Company holds approximately 55% of the 10,000 megawatt hours of power generation capacity. Electricity is transmitted solely by KAHRAMAA, and Qatar does not import or export any electricity. However, a regional treaty regulates electricity trade between Gulf Cooperation Council member countries (Mahmood et al., 2021).

2.2.2 The Transportation System and Policy

Transportation ranks as the third largest emission generator globally (Kamal et al., 2020), with GHG emissions contributing to a global temperature increase of approximately 0.85°C between 1880 and 2015 (IPCC, 2015). Qatar's transportation system consists of over 760 miles of paved roadway, a metro, ports, and an international airport (Encyclopedia Britannica, 2019), with a demand for gasoline or diesel fuels in freight and passenger transportation (Bohra & Shah, 2019).

The country launched the Qatar National Environment and Climate Change Strategy (QNE) to improve citizens' well-being, enhance environmental health, and ensure economic resilience. The Qatar National Development Framework (QNDF) serves as a regulatory substructure for addressing transportation system demands and achieving sustainable development goals from 2017 to 2032. The QNDF outlines key development objectives, focusing on education, health, environment, energy, infrastructure, industry, and tourism. The Qatar National Vision 2030, parent legislation to the QNDF, outlines five main challenges and four pillars of sustainable development: human, social, economic, and environmental. These strategies and policies aim to

achieve sustainable development goals (Ministry of Development Planning and Statistics, 2018; Ministry of Municipality, n.d.).

Land transportation is crucial for the Qatari economy and growth. The Ministry of Transport is responsible for sanctioning transportation infrastructure projects, aiming to build an integrated, effective, and sustainable transportation system that serves local needs and links regional and international economies. The Transportation Master Plan for Qatar 2050 (TMPQ) exemplifies this mission and is expected to provide significant economic returns (Ministry of Transport, 2023).

The TMPQ aims to reduce fuel consumption, GHG emissions, improve safety and security, and result in QR300 billion in savings through reduced operating expenses, energy and fuel consumption, travel durations, emissions, and accidents. Launched in 2022 with collaboration from various ministries and stakeholders, the TMPQ 2050 emphasizes sustainability as critical for economic and environmental integrity. Ensuring financial stability in land transportation can be achieved through demand management policies and public-private partnerships. Long-term planning initiatives like the TMPQ 2050 can potentially transition Qatar to a sustainable transportation system. Focusing on sustainability, the TMPQ 2050 aims to harmonize environmental concerns with economic growth and reduce climate change impacts through enduring initiatives that facilitate the shift toward sustainable transportation (Ministry of Transport, 2023).

The TMPQ 2050 is expected to lead to economic returns due to revenue increases and cost-saving benefits from decreased vehicle-operating costs, consumption, trip time, fuel and energy use, accidents, and carbon emissions. However, Qatar's electric vehicle market has yet to materialize, and legislation has not been launched to promote the adoption. The Ministry of Transport's Green Car Initiative aimed to reach 4% electric vehicles by 2022 and 10% by 2030, while the BEV Strategy targeted electrifying 25% of the public transport bus fleet by 2022. The 4% target was not achieved, but the 25% public transport fleet electrification was met (Ministry of Transport, 2022).

The number of vehicles worldwide is expected to double by 2050, which means higher emissions from the transport sector globally (Creutzig et al., 2015). Qatar is no exception, and transportation plays a crucial role in hydrocarbon development, consumption efficiency, and production projects. Factors such as vehicle numbers, usage, fuel efficiency, age, and fuel type impact the environment, oil reliance, and energy consumption. To move towards a sustainable transportation system, the complexity of the transport system must be evaluated, and vertical and horizontal policy connections across administrative levels must be established. Throughout history, adopting fuel-efficient and low-carbon transportation technologies has faced challenges due to misunderstandings between fuel and vehicle sectors, extensive infrastructure demands, and consumer behaviour (Kamal et al., 2020).

2.2.3 The Effects of Climate Change, Growth & Development, and Challenges

The effects of climate change transverse boundaries and generations, necessitating long-term problem solving and cumulative outcomes. Climate change has a worldwide effect, yet its impacts will vary by region. Based on 2021 values, the Arabian Gulf countries are not the largest GHG emitters in the world, however, their citizens rank among top 10 GHG emitters per capita (Qader et al., 2022).

The effects of global climate change on Qatar will be far-reaching. Elevated population numbers in addition to higher temperatures mean heightened water scarcity and food insecurity, while other issues such as human health, economic opportunities, and the environment are all threatened. Qatar is particularly exposed to rising temperatures as it has very little agricultural land and water resources available to develop carbon sinks, forests, or green spaces. Also, it is a hyper-arid country in the northeastern coast of the Arabian Peninsula. It has a hot, long summer, and a mild winter. Qatar has no surface water and a precipitation average of 80 millimeters per year, making freshwater resources limited. If sea levels were to rise, Qatar's coastline and aquatic life may suffer from coastal erosion and freshwater supplies would be depleted. Additionally, higher temperature levels could cause underground water salinity and lower the efficiency of desalination plants that are a major factor in Qatar's water security. Statistics even point out that the state of Qatar ranks number 10 in terms of vulnerability and risk of sea level rise in terms of

percentages of land area and wetlands affected. Furthermore, due to its reliance on revenue generated from oil and gas production, Qatar could suffer economically if GHG are successfully curtailed worldwide as this would inevitably result in reduced fossil fuel consumption, with a subsequent knock-on impact for the region's primary economic activity (Meltzer et al., 2014).

For instance, according to the national climate records of Qatar, the annual temperature has increased by 0.3 °C over the last 40 years. In addition, 62 million tons of GHGs and over 90% CO2 were emitted in 2017. The danger these emissions pose to the citizens by ruining the ambient environment and the ecosystem has forced the government to develop plans to reduce the emissions (Meltzer et al., 2014).

The transport sector globally emits substantial amounts of GHGs, contributing to climate change. In 2022, global emissions from the transport sector reached approximately 8 Gt of CO2-equivalent (CO2-eq) (IEA, 2022a). This global pattern is mirrored in the Middle East, where fossil fuel reliance for transportation plays a critical role. The region's energy-related CO2 emissions totaled 1,092 Mt, with 471 Mt CO2-eq coming from the transport sector, representing 43% of the region's energy-related emissions. Countries in the Middle East hold pivotal roles in global energy markets, yet they face rising pressure to reduce their carbon footprints. For example, the region accounted for over 40% of global oil exports in 2022 (IEA, n.d.-b).

Within the Middle East, the emissions profiles of the Gulf Cooperation Council (GCC) countries—the United Arab Emirates (UAE), Kuwait, and Saudi Arabia—offer a detailed view of the transport sector's contributions at the national level. For instance, the UAE emitted 243 Mt CO2-eq in 2022, ranking 28th globally and 3rd in the Middle East. Its transport sector is an important focus for future decarbonization strategies, contributing 35.6 Mt CO2-eq, or 20.5% of the country's total emissions (IEA, n.d.-e). Kuwait, like its Gulf counterparts, is also heavily reliant on fossil fuels for energy. In 2022, Kuwait's total CO2-eq emissions stood at 109 Mt CO2-eq, ranking 38th globally. The country emitted 94 Mt CO2-eq from fuel combustion, placing it 5th in the Middle East. The transport sector contributed 17.2 Mt CO2-eq, representing 18.3% of Kuwait's overall emissions (IEA, n.d.-a).

On the other hand, Saudi Arabia, with a significantly larger economy and population, presents a contrasting profile. In 2022, the kingdom's total emissions were 662 Mt CO2-eq, representing 1.6% of global emissions and ranking it 9th globally. The transport sector contributed 138 Mt CO2-eq, making up 26% of Saudi Arabia's total emissions (IEA, n.d.-d). The disparities in emissions reflect the varying economic sizes, population densities, and energy consumption patterns of these countries. Despite Qatar and Kuwait being relatively smaller contributors to global transport emissions, their national totals highlight the significance of the transport sector in their overall carbon footprints.

Qatar's National Emission Inventory Report shows the surge in transport CO2-eq emissions, marking a 428% increase from 1998 to 2019, with the transport sector accounting for 6.6% of the nation's total net emissions. In 2019, over two-thirds of these emissions originated from passenger transport, highlighting the sector's high environmental footprint. Additionally, while Qatar's production-based emissions stood at 116.2 Mt CO2-eq yr^{-1} in 2019, the consumption-based emissions (CBE) were much lower, at 45 Mt CO2-eq yr^{-1} for the same year. This discrepancy highlights a notable rise in CBE by 416% since 1998, with domestic electricity consumption representing the largest share at 41%, followed by manufacturing at 19%, and transport at 17% (S. Mohammed, 2021).

Furthermore, Qatar's total CO2-eq emissions in 2022 were 101 Mt CO2-eq, ranking it 40th globally and 6th in the Middle East for CO2-eq emissions from fuel combustion. Although Qatar's share of global emissions is relatively small at 0.3% of CO2-eq, its transport sector remains a key component of the country's emissions profile. The IEA reports that the transport sector in Qatar emitted 12.2 and 11.6 Mt yr^{-1} of CO2 in 2021 and 2022 respectively (IEA, n.d.-c). Moreover, Qatar, as the country, has the highest CO2 emissions per capita that year, at 31.69 tonnes of CO2 per capita (IEA, n.d.-c). This data emphasizes the need for Qatar to address its carbon footprint, particularly in the transport sector, to mitigate its environmental impact.

In terms of air pollution, Qatar's Second National Development Strategy (2018-2022) established a target of reducing incidences of high ozone levels through better control of air quality (Ministry of Development Planning and Statistics, 2018). As in many highly populated cities, PM and ozone

levels surpassed the safety cap more often than ever before, hence this aim was not met. By use of initiatives such as advanced air quality monitoring, reporting and verification programs, air pollution levels have since been reduced. From those efforts, necessary data was collected, critical to updating air quality standards and procedures for pollution reduction while simultaneously increasing adherence to environmental guidelines. The major pollutants of concern are PM10 and PM2.5, corresponding with their diameter expressed in micrometers. Based on a study by the Institute of Health Metrics and Evaluation, 250 premature deaths were recorded in Qatar caused by exposure to PM2.5 and ozone in 2015 (Ministry of Development Planning and Statistics, 2018). However, as a result of large quantities of natural dust in the atmosphere, these estimates are susceptible to error, requiring more research on this topic.

The Middle East has few regulations on ambient air quality, but Qatar is one of the exceptions. Even with regulations in place, norms for air pollution are frequently exceeded, both in Qatar and around the world. For Qatar, national air quality regulations are more stringent than those established by the World Health Organization (WHO, 50 g/m3 and 20 g/m3 for PM10 and PM2.5 respectively). The established 24-hour average of PM10 is roughly 150 g/m3, while the yearly average concentration is around 50 g/m3 (Lanouar et al., 2016). With poor air quality as one of the main causes of heart disease, strokes and lung cancer, it is a gap that no official study in Qatar has linked air pollutants to changing rates of diseases. Kuwait, a country with similar conditions to Qatar, conducted such studies in which it was stated that annual PM2.5 concentrations ranged between 38 μg/m3 and 75.2 μg/m3, posing the urgent need to implement air pollution control strategies (Al-Hemoud et al., 2019).

This finding is further supported by a study conducted in Shizuoka, Japan, which found positive associations between NO2 levels, a marker for traffic-related air pollution, and increased risk of mortality from all-cause, cardiopulmonary disease, and lung cancer (Yorifuji et al., 2013). The study also provided evidence for adverse effects on intracerebral hemorrhage and ischemic stroke. An expert position paper on air pollution and cardiovascular disease highlighted that numerous manifestations of cardiovascular disease have been associated with air pollution, involving both the arterial and venous circulations (Newby et al., 2015). The paper also

emphasized that air pollution not only exacerbates existing heart conditions but also appears to have a role in the development of the disease. Moreover, another study found that long-term exposure to PM2.5 was associated with elevated hazard ratios for mortality from ischemic heart disease and incident stroke. The study also found associations between exposure to nitrogen oxides and elevated risks for ischemic heart disease and all cardiovascular mortality (Lipsett et al., 2011). Furthermore, a review by Schraufnagel et al. (2019) estimated that air pollution may account for 19% of all cardiovascular deaths and 21% of all stroke deaths globally. The review also linked air pollution to other malignancies, such as bladder cancer and childhood leukemia (Schraufnagel et al., 2019). When it comes to addressing air quality concerns, BEVs hold appeal due to their capacity to operate without direct emissions, thereby offering the potential to reduce GHG emissions, mitigate local air pollutants, and lower overall energy consumption (The International Council on Clean Transport, 2020).

However, with its heavy reliance on oil and gas, the aforementioned shifts in response to climate change can introduce significant uncertainty. The sharp decline in revenue for countries that see a peak followed by a rapid decline in oil demand could be extremely detrimental to them. Energy transitions can be halted if economic constraints are introduced, delaying necessary change and putting the achievement of future transition targets at risk (Al-Saffar & Van der Beeuren, 2020).

2.2.4 Population growth

The escalating quantity of vehicles is a substantial contributor to Qatar's national GHG emissions stemming from the road transportation sector. Qatar boasts one of the world's highest rates of car ownership due to the affordability of some vehicles, even for low-income households (S. S. Mohammed, 2017). Factors such as the relatively low gasoline prices, the absence of vehicle taxes, inexpensive registration costs, the presence of modern road infrastructure, and a well-established highway network all contribute to the elevated levels of car ownership. The accessibility of affordable energy has discouraged the use of public transportation and renewable energy in Qatar, further exacerbating the high GHG emissions in the transportation sector.

The growth of the population, coupled with the swift urbanization process, leads to an increase in fossil fuel-based energy consumption on both a collective scale (total energy consumption) and an individual scale (such as road transportation energy consumption and electricity usage (Lee et al., 2016). Between 1970 and 2010, the population of the Arab region increased almost threefold, going from 128 million to 359 million. In 1970, Arab nations represented a mere 4% of the world's population, but by 2010, this proportion had risen to 5%. If the current pace of population growth persists, the Arab region is projected to make up 7% of the global population by 2050. From 2000 to 2010, Qatar experienced a population growth rate of around 10.75%. Subsequently, between 2010 and 2020, the annual average population increase reduced to 6.11% (Mirkin, 2010). Given the strong link between population growth, especially in urban areas, and increased resource consumption and GHG emissions related to energy, Qatar's emissions from key sectors like transportation and power have been on the rise.

In Qatar, pedestrian facilities are extremely restricted, with few or no sidewalks along key metropolitan thoroughfares. Intersections were not designed with pedestrian crossings in mind. Wide junction spacing, large volumes of traffic, and high vehicle speeds made it impossible for people to crossroads safely. In most cities, low-density single-use horizontal development predominates over compact mixed-use vertical growth. Consequently, the gaps between residential zones and commercial, educational, and office facilities, as well as other essential services, tend to be beyond reasonable walking distances. Furthermore, the severe weather conditions, particularly during the summer months, make walking nearly unfeasible. This leads to an increased dependence on vehicles for mobility, thereby contributing to the growth of GHG emissions in the transportation sector.

The public transportation system in Qatar is somewhat limited. In the major cities of Qatar, the only available forms of public transportation are intercity bus services and school bus services. These meagre services fall far short of meeting the fundamental mobility needs of people who do not own or drive a car. According to research, more than 89% of Qataris own at least one personal automobile (S. S. Mohammed, 2017).

2.2.5 Technical overview of vehicle technologies

This section provides a technical overview of the fundamental differences between ICEVs and BEVs in their operation and environmental impacts. It explores the technological promise and uncertainty surrounding the potential for emissions reductions in both vehicle types. The analysis then narrows in on the prospects for battery innovations to improve the environmental performance of BEVs. Key factors including tailpipe emissions, manufacturing impacts, electricity generation, and battery chemistry are examined to understand variability between studies and inform a dynamic model across the timeframe 2022-2050.

Technical differences between ICEVs and BEVs

The operation mode of an ICEV can vary based on the type of fuel and ignition system used. Most commonly, gasoline engines use a spark ignition system. In these engines, fuel from the storage tank is transported to the engine where it's mixed with air. This mixture is then ignited by a spark from the spark plug. The combustion that results pushes the piston, turning the crankshaft, which in turn operates the gearbox and ultimately moves the wheels. As the piston moves back down, fresh air enters the engine, allowing for another combustion cycle while simultaneously expelling exhaust gases. There are variations within gasoline engines. While Port Fuel Injection (PFI) systems introduce fuel before the combustion chamber, Gasoline Direct Injection (GDI) systems inject fuel directly into the combustion chamber. Some GDI systems use a combination of compression ignition and spark ignition, somewhat resembling diesel engines in their operation (Muneer & García, 2017).

Diesel engines, on the other hand, rely on compression ignition. Air in the combustion chamber is compressed to a point where its temperature rises significantly. Diesel fuel is then injected directly into this highly compressed and hot air, leading to spontaneous ignition. This form of ignition creates a flame front with higher temperatures, leading to increased NOx emissions. However, diesel engines typically have a higher compression ratio than gasoline engines, leading to better fuel efficiency. Comparatively, BEVs have a more straightforward mechanism. The battery pack serves as the power source, converting stored electric energy into kinetic energy via

brushless motors. The torque and speed are directly regulated by the electric supply. Electric vehicles often do not require traditional transmissions or gearboxes, simplifying their design and potentially reducing in-use operating costs and maintenance needs (Vattanapuripakorn et al., 2022).

From literature databases (Ecoinvent) and manufacturer data, a general trend of battery weight compared to empty weight can be observed. For electric cars, this ranges from 18-25%, depending on the brand (Renault, Tesla, VW, BMW manufacturer data and technical sheets, n.d.). The Tesla Model S has a battery weight of ca. 545 kg with a total weight of around 2,100 kg, while the Renault Zoe as an example of a smaller BEV sedan has a battery weight of around 320 kg with a total of 1,500 kg. This trend is seen in larger HDV and bus vehicles as well. With the implementation of higher voltage and battery chemistry alternatives, the same weight fraction just results in a lower driving range. This is less of an issue as both HDV and bus transport is highly mapped with fixed stops and charging locations. The studied electric Proterra bus has a gross mass of 19,800 kg and a 738 kWh battery weighing ca. 4,100kg still similar battery to total weight dimensions.

Moreover, some studies have examined the comparative heaviness of BEVs against traditional ICEVs using different methodologies. One approach involves assessing the mass of BEVs within each vehicle category, matching these with the segment's average (mini, small, lower medium, etc.). This was done for 20 BEVs using data from the manufacturers. The findings reveal that these BEVs are have a typically weight of about 22% more than the average vehicle in their respective categories (Timmers & Achten, 2018).

A different angle taken for this comparison uses a direct weight comparison between BEVs and their corresponding non-electric models, circumventing the need for vehicle categorization and focusing on matching similar models as closely as possible. In a study by Timmers and Achten (2016), 9 pairs of BEVs and their ICEV equivalents were compared. The authors noticed an average weight increase of 280 kg in BEVs, marking a 24% rise over their ICEV versions (Timmers & Achten, 2016).

The weight differential between BEVs and ICEVs is anticipated to evolve, considering advancements in battery technology and the increasing use of lighter materials in vehicle production. However, projections and analyses of theseis weight difference remain scarce. One of the few studies to explore this was by C. Bauer et al. (2015), who utilized a midsize vehicle simulation to compare the 2012 weights of ICEVs and BEVs and forecasted these weights for 2030. In 2012, they recorded an average weight of 1,567 kg for ICEVs against 1,944 kg for BEVs, indicating BEVs were 24% heavier. Their forecasted estimate for 2030 predicted an average weight of 1,383 kg for ICEVs and 1,613 kg for BEVs, which means a predicted weight difference narrowing down to 17% (C. Bauer et al., 2015).

Technological promise and uncertainty

This analysis provides an overview of current electric vehicle technologies, with a focus on their potential environmental influences between 2022-2050, including intermediate time points in 2030 and 2040. There is variance among the literature regarding the future performance and environmental impact of BEVs, attributable to discrepancies in assumptions about future technological developments, electricity grid decarbonization, and global supply chain dynamics. Such variability in input data is important, as it forms the basis for sensitivity and uncertainty analyses.

BEVs reduce tailpipe emissions compared to ICEVs, leading to decreased CO2-eq emissions and air pollution, particularly in urban and enclosed settings (Del Pero et al., 2018; Gebrehiwot & Van Den Bossche, 2015; Plötz et al., 2022). However, BEVs aren't entirely without environmental impact. They run on electricity, which may produce emissions during its generation, making BEVs susceptible to the emission profile of the electrical grid. While ICEVs primarily emit CO2-eq through operation, including direct tailpipe emissions and background processes, BEVs shift these impacts to the manufacturing, electricity generation, and disposal stages.

Existing literature suggests that without advancements in battery technology, BEVs might strain mineral resources, particularly at the end-of-life stage. It's essential to incorporate recycling and circularity to minimize this impact, especially since the industry is relatively new, and there's

uncertainty surrounding its long-term effects. LCA studies often cannot give definitive answers about emerging technologies because of their nascent stages and the fact that alternatives may not always be universally better. This limitation shows the importance of using a prospective LCA approach.

Prospective LCA adopts a futuristic viewpoint to scrutinize developing technologies' environmental implications before their extensive dissemination. Unlike conventional LCA methodologies that focus on evaluating current technologies or products, prospective LCA attempts to forecast forthcoming shifts in technological innovation, consumption patterns, and policy frameworks. This methodology is particularly vital for industries undergoing swift technological evolution, such as the development of battery technology in electric vehicles (Sacchi et al., 2022).

Prospects on Battery innovations

The realm of battery innovation, particularly for BEVs, continues to evolve. Not only are these advancements pertinent to grid-scale energy storage, but they are also manifesting in the production of higher-density lithium-ion batteries. Leading research groups and manufacturers, such as Contemporary Amperex Technology Co. Ltd (CATL), Panasonic, and LG, are at the forefront of this progress. In addition to enhancing current battery compositions, they are also delving into novel chemical types and compositions. However, despite the advancements to date, some contend that these technological strides may be approaching their limits (Barchasz et al., 2012; Benveniste et al., 2018).

Lithium-ion batteries (LIB) have been in research and use since the 1990s as part of the push to mobile devices, but initially had low energy density and low efficiencies (Deng, 2015). After large investments and the long development cycle of the automotive industry, there is consensus in the industry that lithium batteries will not be replaced by other technologies any time soon (Schmuch et al., 2018). This limits the amount of other battery chemical compositions that could be assessed in the sensitivity analysis of this report. This also means that all other chemical compositions that are mentioned in this report and the results are linked to lithium chemistries.

Currently, the main battery composition implemented in BEV is the Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminum (NCA) and prismatic Lithium Iron Phosphate (LFP). Similarly, the NCA battery uses Nickel, Cobalt, and Aluminum. The LFP battery still uses lithium, yet its main share is iron and phosphate ions to transfer the energy of the battery. With more than 4,000 cycles, LFP is more stable yet has a lower energy density of around 170Wh/kg compared to NMC811 with ca. 275Wh/kg but only 2,000 cycles. Real-life data is still lacking as most novel chemistries are still in low Technology Readiness Level (TRL) and have not yet been available on the market for a long enough time. The difference between those types in use is the cycle lifetime, cost, and its energy density. The impact these chemistries have on this thesis is both the lifetime of the battery as well as the battery weight. The latter one not only reduces the weight that has to be carried by the vehicle but also influences the maximum distance travelled (R. Kumar & Chavan, 2022). For this thesis, the different chemistries and characteristics are important to distinguish the production of the vehicle, the impact of the battery and the lifetime of the components. The results can thus be framed as if a different technology would be included as part of the sensitivity analysis.

2.3 Literature review

This literature review provides the context for a broader study aimed at evaluating the environmental impacts of Qatar's road transport policies vis-à-vis national and global climate change mitigation targets. The review is structured around three key areas of focus. First, it will analyse current GHG emissions from road transport in Qatar and model future scenarios based on bans on ICEVs by 2030, 2035, and 2040 respectively. Second, as the global automotive landscape is experiencing a paradigm shift towards BEVs, it's imperative to question and understand the environmental trade-offs, thus, the review will include life cycle impacts studies of BEVs and ICEVs in the global as well as the Qatari context through a C2G analysis. Finally, it will assess the influence of different decarbonization measures and initiatives on GHG emission reduction by 2050 using a Carbon Calculator modeling approach.

Collectively, these three dimensions will inform evidence-based pathways for sustainable road transport policy in Qatar consonant with the urgent global need for deep decarbonization. The literature review section covers the most recent studies in literature, identifies area gaps that this thesis can fill once completed. The ultimate goal of this thesis is to eventually support Qatar's evolving leadership in advancing ambitious climate action through sustainable transport policies.

2.3.1 Scenario analysis for road transport

This sub-section begins with a brief introduction to scenario analysis and its application to modeling potential road transport futures. It then provides an overview of previous literature utilizing the Vehicle Stock Model (VSM) to conduct scenario analysis of road transport systems. The intention is to outline the background and current state of the field in order to situate the methodology and findings that will follow in the thesis. By reviewing relevant applications of VSM, this section establishes the context for the unique contribution made in the following sections.

Exploring the VSM in the context of Qatar's unique geographic and socio-economic factors, such as its small landmass, high population density in urban areas, and high reliance on road

transportation, presents specific challenges. These challenges also offer opportunities for innovative solutions in the realm of transportation planning and environmental sustainability.

Generally, road transport models have been used to estimate the emissions associated with the penetration of alternative fuel technologies in the road fleet (Krause et al., 2020). Economic models gauge the adoption of specific technologies based on vehicle cost and features, while more detailed transport models outline every decision from the beginning to the end of a journey, making road transport models cover an extensive array of topics. VSMs are based on the stock-flow model typically used in economics; in these models, a fund's inflow and outflow in the market enable insights into the evolution of individual or market actors for a given case. This modeling framework can also be applied to road transportation because vehicle stock exhibits steady activities of inflows through new vehicle sales and outflows through vehicle end of life. When used to address pertinent issues, these models improve the efficiency of policy choices (H. Wang et al., 2017). For instance, road transport models can assess the impact of a BEV fleet on GHG emissions and air pollution, evaluate the potential of the road fleet to realize a net zero carbon footprint, and determine the extent of BEV adoption required to achieve net zero emissions. The incorporation of the most up-to-date technology into the fleet is a complex issue, and VSMs are a well-suited tool to answering these concerns. These models describe how the introduction and development of new and old vehicle technologies have helped in the evolution of fleets. In general, VSMs are utilized to calculate future GHG releases for a road transport, but they are less commonly employed to estimate releases from air pollution (Baptista et al., 2012; Craglia & Cullen, 2020; He et al., 2021; Hill et al., 2019; Trofimenko et al., 2020).

In the IEA's Stated Policies Scenario, the number of BEVs, surges from roughly 30 million in 2022 to an estimated 240 million by 2030. This reflects an approximate 30% yearly growth rate. By 2030, BEVs make up more than 10% of vehicles on the road. Furthermore, by 2025 BEV sales are projected to exceed 20 million and by 2030 they're expected to surpass 40 million. These figures equate to more than 20% of total vehicle sales in 2025 and over 30% in 2030 (IEA, 2023). Modeling these trends using the VSM is vital for understanding the future impact of BEV

penetration on potential emissions reductions, achieving climate targets, and informing strategic environmental policymaking.

The transition towards sustainable transportation is acknowledged as an imperative part of the global move to decarbonisation, yet poses distinct challenges and opportunities across different regions. With an increasing urgency to address global climate change, urban congestion and energy conservation, the transportation sector is perceived as a critical determinant in any sustainability goal or strategy due to its impact on many aspects of daily life. However, the dynamics of transportation vary considerably across continents, largely due to differences in socio-economic conditions, infrastructural developments and current policy frameworks.

Regional disparities underscore the necessity for research that is context-specific yet globally informed. Implying a universal approach to sustainable transportation is insufficient given the varied challenges each region faces. In this context, transportation research covering multiple regions around the world were examined, offering insights into the region-specific challenges and innovation approaches, enabling the formulation of strategies that are both locally relevant and globally resonant.

Previous Vehicle Stock Model literature

Researchers have become more interested in the possibility of decarbonizing transportation in recent decades. Scenario modelling is a common practice that helps policymakers make decisions. For example, Chiodi et al. (2013) used the TIMES model to find the least-cost transportation option in Ireland. In addition, Grischkat et al. (2014) evaluated how introducing mobility services in the passenger transport sector might decrease GHG emissions in Germany.

In another example, Gallo (2011) examined the impact of implementing fuel surcharges while abolishing the vehicle ownership tax on fossil fuel usage and GHG emissions in Italy. Further, some literature highlighted that scenario studies imply that carbon CO2 emission reductions in the transportation sector could be accomplished without reducing mobility (Girod et al., 2012). The reality, on the other hand, indicates an upward trend in CO2 emissions. This emphasizes how

difficult it is to decouple economic development, transportation energy consumption, and severe environmental consequences.

Hill et al. (2019) refer to the 2040 ICEV ban date to demonstrate how the UK government's current carbon budgets would not be met under this scenario. Moreover, in their 2020 study, Craglia and Cullen determined that the rate of BEV adoption had the biggest influence on GHG emissions from private vehicles in the UK. Brand et al. (2020) moved one step further by simulating the ICEV ban date of 2030, indicating how an ICEV ban date earlier than 2040 would be beneficial. As 2030 approaches, it is becoming more important to consider the impacts of GHG emissions, especially in the case of missed ICEV ban dates. No studies have yet analysed the scenario with a higher EV uptake rate and corresponding to current governmental policies, which banned ICEVs by 2030 or 2040. This tentative scenario is close to reality in Norway, which instituted an ICEV ban in 2025.

In Indonesia, Atabani et al. (2012) researched fuel economy criteria for passenger automobiles. They noted that implementing fuel economy requirements would save 32 billion gallons of gasoline and result in a 1.46 million ton decrease in CO2 emissions. As per Kay et al. (2014), carbon emissions from the transportation sector must be reduced through price regulations, low-carbon technology, emission control for medium and heavy-duty vehicles, renewable fuels, and land use and transit policies. Moreover, according to Lucas and Pangbourne, in order to mitigate the consequences of climate change in Scotland, urgent carbon mitigation strategies for the transport sector are required. However, the government is missing informed links in the current scenario that would help make optimal decisions (Lucas & Pangbourne, 2014). Proost and Dender also identified and evaluated potential policy approaches to address transportation energy use and GHG emissions. These policy solutions can be classified as carbon or fuel taxes; credit exchange or trade; fuel economy standards; alternative technologies or fuels; modal shift; and land-use management to restrict sprawling (Proost & Van Dender, 2012). However, no studies have applied this concept to Qatar's transportation issue just yet.

Moreover, road infrastructure, technological attributes of vehicles, and total distance covered are factors that determine the quantity of non-exhaust emissions generated by the vehicle stock

(Harrison et al., 2021). Therefore, decreasing transportation demand results in a decrease of non-exhaust releases and vice versa. On the other hand, the potential low cost of BEVs contributes to the rebound effect that is driving up transportation demand. The long-term reductions in car operating costs made possible by BEVs could, however, cause a rise in transport demand (Craglia & Cullen, 2020).

He et al. (2021) conducted an emission analysis for the Asia-Pacific region from 1900-2050, considering the impacts on air quality and human health. They used the International Council on Clean Transportation (ICCT) Roadmap model and incorporated disruptive technologies such as vehicle automation and electrification in their dynamic scenarios for 2050. The authors had to make several assumptions due to the scarcity of specific regional datasets and profiles, making cross-country comparisons challenging. This study uses a bottom-up model, estimating road transportation emissions and upscaling to country-wide emissions. This approach integrates detailed factors such as vehicle ownership/activity data and specific emission and fuel consumption factors, which is crucial in capturing the potential impact of specific characteristics like urbanization, economic growth, or technological shifts. However, this approach requires a high degree of detailed information and modeling data, which can be difficult to gather or access. Results show that for the Asia-Pacific region, most nations will reach their peak emissions from road transport around 2030, except for India (around 2040) and Japan (early 2000s). Air quality would follow a similar trend but decrease more sharply over the coming decades due to increased environmental standards. The overarching scenario analysis shows that only with extensive changes, electrification, fuel economy, and possibly vehicle autonomy, the Asia-Pacific region will be able to reduce its overall emissions (He et al., 2021).

Wang et al. (2017) focused on China's transport sector using the Transportation Mode-Technology-Energy-CO2 (TMOTEC) model. They analysed multiple scenarios, mode characteristics, and technologies up to 2050, considering China's goal to achieve peak emissions by 2030. The model incorporates socio-economic factors, transport service demand, and different transport modes. Input characteristics for the scenarios include energy efficiency improvements, tax increases, and the promotion of electric vehicles. The model's ability to

simulate detailed scenarios makes it valuable for policymakers to evaluate the impact of various policies on energy consumption and emissions. The model analyzes a scope of detailed anticipated scenarios considering technological, policy, and energy consumption changes. It offers granularity in its analysis while still covering the 1900-2050 timeframe and integrating a wide array of bottom-up characteristics. However, this study does not directly adhere to models developed by US or EU institutes due to China's unique socio-economic and infrastructural landscape. The paper by Wang et al. (2017) shows that fleet size, freight volume, GHG emissions, and energy consumption will continue to rise beyond 2050. The road transport sector would remain dominant in both amount and impacts. The Comprehensive (CRP) model, which combines strong energy efficiency policies, electric vehicle implementation, and additional taxes on CO2 and fossil fuels, showed significant reduction potential. However, peak emissions would still occur past 2040 instead of 2030, as presented by the official Chinese standpoint.

Moreover, Krause et al. (2020) examined the EU's technical capability to reduce energy use and projected CO2 emissions in road transport by 2050. They used the DIONE model and insights from automotive industry specialists, researchers, and governmental bodies to assess various vehicular strategies, such as enhancing efficiency, streamlining transportation, and decreasing travel. The inclusion of external experts should result in lower uncertainties in the feasibility of the proposed scenarios. The DIONE model, created by the European Commission's Joint Research Centre (JRC), and the EMEP/EEA methodology, was originally designed for a pan-European context. The model specifically targets the localized perspective, while the EMEP/EEA emphasizes empirical data and broad coverage, more suited to the current Russian situation. The model has also been further elaborated with a cost-focused approach. The study reflects the anticipated 2050 situation if road transport electrification further develops, considering established policy direction and transportation network. Even in a conservative 'Mix' scenario, the fleet would have a 50% EV share compared to 20% ICEV. Freight sector electrification would lag at around 10%. Significant CO2 reductions of up to 70% can be expected by 2050 if the fleet is electrified and adapted, even in a 'pessimistic' scenario with unchanged efficiencies and no traffic smoothing or transport reduction. In an ideal scenario with high electrification, optimistic measures, and decarbonisation fuels, CO2 reductions could reach up to 90% compared to 1990 (tank-to-wheel

perspective). The energy production sector would need to keep pace in this sustainable transition (Krause et al., 2020).

Trofimenko et al. (2020) performed a similar case study for Russia using the IPCC methodology (Tiers 1–3) to certify several suggested scenarios, ranging from an inertial base case to more innovative and sustainable decarbonisation scenarios aimed at reaching the 1.5 degrees Celsius target. They incorporated socio-economic factors like demographic changes, economic implications, and fleet adaptations in their model to forecast emissions up to 2050 and calculate the degree of change over time, as well as the expected peak of emissions, as proposed by the Chinese government during the Paris Climate Conference. The paper focuses on reduced fossil fuel consumption under an innovative scenario. Gas-cylinder cars, electric, and hybrid vehicles would need to increase significantly. By 2050, under the 1.5-degree scenario, gasoline consumption would fall by 13.6 times, requiring a drastic shift in HDV and bus fleet electrification from nearly 0% in 2020 to 50-100% by 2050. The freight sector is expected to reduce GHG emissions by 39% in 2050 under the inertial scenario, solely through vehicle and efficiency improvements.

The studies rely on model-based approaches with varying degrees of data detail and emphasize the interplay of variables from technological shifts to policy dynamics. Scenario analysis is a shared methodological tool, envisioning dynamic futures based on local limitations and current state. A base case or reference scenario serves as a comparative benchmark, differing between authors due to current policies and technological capabilities. Technological Advancement Scenarios focus on emerging technologies, electric vehicle adoption, and fuel consumption rates, while Policy-driven scenarios incorporate changes like emission standards and green vehicle incentives, leaving room for interpretation and uncertainty.

In conclusion, from this literature covering the different regions, it is clear that the use of nationwide and aggregated data alone is not sufficient to reflect all local diversity that is present. Overarching models can fail to implement specific policy or socio-economic changes, yet with a more detailed dynamic model comes higher uncertainties as data sources have to be combined and may not be aligned. Nonetheless, the papers considered in this literature review provide a

exhaustive examination of future emission scenarios, covering multiple continents and possible implementations. Each paper, while rooted in its unique context, offers insights that are of paramount importance to the broader scientific community.

Several elements should be taken into account for further research in this field, namely the importance of historical context, the complexities of rapid urbanization, the synergy between technological innovations and policy, the need for region-specific solutions, and the value of interdisciplinary and comparative studies. Moreover, the dynamic between technological progress and policy measures stands out as a crucial factor shaping upcoming emission patterns. As discussions on sustainable transport progress, it becomes essential for subsequent studies to embrace a cross-disciplinary perspective.

2.3.2 Life cycle assessment of conventional and battery electric vehicles

This sub-section adopts a structured approach to explore LCA literature focusing on both ICEVs and BEVs. It commences by introducing the foundational LCA methodology. Following this introduction, it is divided into two distinct parts. The first part delves into a review of relevant LCA literature on these vehicle types in a general context from different regions such as the US, Switzerland, Poland, and more. The second part, however, narrows the focus to LCA studies conducted within the context of Qatar, providing insights into regional nuances.

In Qatar, gasoline is the main fuel source for light-duty vehicles and with diesel for the heavier fraction, increases in fossil fuel use are inevitable if no distributive actions are taken. This increase in fossil fuel use will affect factors such as urban air quality, energy security as well as climate change, thus ranging from local to the global level (Axon & Darton, 2021; Bui & Tseng, 2022; Perera & Nadeau, 2022; Rabbi et al., 2022). With natural gas as the main fossil fuel reserve, Qatar has focused predominantly on natural gas exploration and utilization in its power grid and services. The shift from ICEVs to BEVs will require large-scale developments and changes from manufacturers, government as well as infrastructure adaptations. This thesis will not cover the manufacturing/governmental obstacles of the transport sector, nor will it provide a plan for a country-wide infrastructure plan. Yet this research will explore the impacts that are attributed to

both scenarios as well as the future trends that can be expected from the technology learning effects.

For the comparative analysis between fossil-based ICEVs and electric (battery driven engine), some definitions and features must be addressed. Globally, ICEVs are focused on gasoline and diesel use with only small shares for alternative sources such as high-efficiency gasoline in F1, LNG or hydrogen. The latter energy sources are not widely available for the average consumer. With the exceptional position of Qatar in the natural gas industry, LNG could be seen as a possible scenario yet has several drawbacks which have restricted the wide use of this alternative combustion type. Yet, based on other work, on a consumer level, there is a high upfront cost, a slower-overall speed and special attention to the extremely low storage temperature (-162 degrees Celsius). On the emission level, LNG has the disadvantage of higher evaporative losses when idling, not only increasing risks in enclosed spaces as well as having a high impact on global warming as CH4 has a global warming potential (GWP) of 27-30 CO2-eq over 100 years (Boretti, 2019; Da Pan et al., 2020).

In the process of shifting the transport sector to battery-driven technologies, hybrid and plug-in hybrid options were introduced yet will not be discussed in this study due to the ineffectiveness of decarbonising the transport sector. It was shown that privately owned plug-in hybrid vehicles emit up to three times as much CO2 as officially reported. The professional electric use was only up to 15%, compared to the assumption of 70-85%. In their recommendation section, Plotz et al. (2022) state that PHEVs should lose their low-emission benefits in the EU due to their high real-world CO2 releases. Based on this and the lack of popularity in Qatar, the study excludes natural gas vehicles hybrid electric vehicles, as well as plug-in hybrid electric vehicles.

In order to determine the complete environmental impacts of a vehicle, it needs to be considered in the context of its entire lifespan. The LCA methodology is one of the widely recognized approach that can be chosen to quantify the environmental impacts of vehicles in multiple categories. This approach is helpful as it allows users to compare two different alternatives within a comprehensive environmental context. In general, there are a number of LCA studies that have been published in the public domain covering ICEVs and BEVs. The LCA tools and their

accompanying software enables rapid calculation and analysis of extensive data volumes. These have emerged from the efforts of diverse institutions in recent years, as a result of the high demand for life cycle forecasting and analysis of the impact of products and services. Their aim is to enhance economic viability and appeal to both market and the customers. The software can calculate and process a wide array of data sources including worksheets, Excel data with databases stored in clouds and available across institutions, environment professionals, and industrial field (Kiemel et al., 2022).

In conducting this literature review on LCA, a deliberate and strategic approach was taken in selecting studies to ensure a broad and inclusive representation of the field. This review includes a variety of research to cover different regions, diverse impact assessment methodologies, and a range of subject matters such as types of vehicles. The intention behind this diverse selection criterion is to provide a complete overview, acknowledging the complexity and multifaceted nature of LCA.

Studies originating from different regions are crucial in an LCA context. The inclusion of regional variations highlights environmental impacts and the different resource usage. Moreover, this review intentionally encompasses studies that employ different impact assessment tools and methods, such as ReCiPe, TRACI, and Multi-Regional Input-Output (MRIO) analysis. This methodological diversity allows for a more robust and nuanced understanding of LCA, where each method provides unique insights, particularly in quantifying and evaluating different environmental impacts from GHG emissions to resource depletion and ecological consequences. In addition, focusing on transportation, an area of growing importance and innovation in LCA, the review includes studies on various types of vehicles. This includes not only traditional gasoline-powered vehicles but also electric, hybrid, and alternative fuel vehicles, helping in understanding the full spectrum of environmental impacts associated with different transportation technologies.

The studies selected vary not only in their current assessment of environmental impact but also in their temporal scope. Some studies offer a snapshot of the environmental impact at a specific point in time, providing a detailed and immediate understanding of the LCA of vehicles and

technologies as they currently stand. In contrast, other research projects into the future, estimating the LCA for vehicles in upcoming years. This forward-looking analysis helps in understanding how technological advancements, changing energy grids, and evolving regulatory landscapes might influence the environmental impacts of future vehicles. Such projections can be used for strategic planning and for anticipating the environmental trajectory of transportation technologies.

Additionally, this review considers studies varying in scope, scale, and temporal frameworks. This approach ensures that the review captures a broad spectrum of perspectives, offering insights into how LCA can be applied and interpreted in different contexts. By examining studies that differ in their fundamental assumptions, methodological frameworks, and application areas, this literature review aims to present a holistic picture of LCA. This approach not only enriches the analysis but also reflects the evolving and interdisciplinary nature of the field.

To perform the following impact analysis, an extensive literature review was performed, often encountering confidential Life Cycle Inventories for which there is no specific information on the black-box processes (Ellingsen et al., 2014; Majeau-Bettez et al., 2011; Matheys et al., 2008; Van den Bossche et al., 2006). The approach of this report is to account for the complete vehicle life cycle, for which a comprehensive basis is given by research groups such as Bartolozzi et al. (2013), Samaras & Meisterling (2008), Faria et al., (2012), Nanaki & Koroneos (2013), Girardi et al. (2015), Canals Casals et al. (2016). For the regarded studies in the literature review, hybrid cars are often included or part of the scope. Due to information mostly on an aggregated basis or just covering specific phases and the inability of PHEV to decarbonise the transport industry, they will be excluded from this study.

In sum, the selection of studies for this literature review is guided by the principle of inclusivity and depth, aiming to foster an all-inclusive, multi-perspective understanding of LCA. This strategy enriches the analysis and reflects the dynamic, adaptable nature of LCA in addressing environmental and sustainability challenges.

Previous Life Cycle Assessment literature

Hawkins et al. have shown that an overall distance of 150,000 km for the lifetime of a BEV has the ability to CO2-eq emissions by 10% to 24% while taking into account the current European electricity mix (Hawkins et al., 2013). A considerable improvement in BEV lifetime emissions can be attained by lowering the effect of the automotive supply chain and promoting clean electricity, which has the potential to further reduce the GWP. Recent research has focused on the comparative use of the software across electric, hybrid, petrol, and alternative fuel vehicles (Marques et al., 2019). The main finding by Marques et al. was highlighting varying environmental impacts of each vehicle type throughout its lifetime, dependent on production, usage, and end-of-life phases. Hybrid and battery powered cars showed approximately 27% and 78% lower GHG effects compared to gasoline-powered automobiles respectively. Also, works of Shahi & Wang (2010) utilized a simulation-based approach using Pareto set points to enhance the selection process of BEVs and PHEVs batteries considering both economic and environmental advantages. It was discovered that Lithium-ion batteries had the lower emissions and operating costs, while NiMH batteries offered better fuel economy when compared to lead-acid batteries.

The recycling process is crucial for a thorough LCA. When compared to new products made from raw materials, recycling offers immediate advantages in the following areas: less energy is used, costs are lower when producing components from recycled products, environmental risks associated with disposal and imports are avoided, and the demand for scarce resources is decreased (Y. Chen et al., 2019). Nowadays, batteries are directly melted as part of the recycling process. Valuable materials like Co, Ni and Mn are retrieved and refined after transportation, find applications in making automobile bodies by producing stainless steel. Through the waste's thermal melting neutralization process, rare earth elements and lithium end up in the slag, utilized as aggregate for road construction. Other technologies such as leaching can be used to extract rare earth metals from batteries, but there is no current financial incentive for these techniques (Marques et al., 2019). The ongoing and further development of an effective and efficient recycling process and a viable plan for effective material reuse is still being discussed in relation to this issue (Hawkins et al., 2013). By reducing the need for raw material extraction and utilizing less energy compared to producing new components, this contributes to a decrease in CO2 emissions. Moreover, repurposing waste products into applications like roadbeds and

pavements further diminishes the carbon footprint associated with the extraction and processing of fresh materials.

In addition, it is crucial to mention that most studies have primarily concentrated on the passenger car market. Nevertheless, future LCA analyses examining the environmental impact of electric buses in urban transportation settings are equally essential. This is particularly significant considering the potential for urban transportation to become significant market for electric drive technology (and already is, to some extent) (Marques et al., 2019). The LCA approach for assessing the global environmental impact takes into account specific aspects of batteries (such as weight, type, size, capacity, specific energy, and cycle life) and operational conditions (including traffic congestion, driving behaviour, passenger capacity, and infrastructure profile), which play pivotal roles as influencing factors (Koroma et al., 2022).

For instance, a study with a well-to-tank boundary, evaluated the performance of ICEVs and BEVs while focusing specifically on electricity pathways to charge BEVs (Girardi et al., 2015). Numerous LCA papers use a pre-packaged database to assess the energy system that delivers electricity to BEVs. However, Girardi et al. attempted to improve the quality of data of electricity pathway by using rates from the national Italian electricity provider. The life cycle inventory (LCI) of electricity was calculated to adjust the readily pre-packaged datasets based on the official Italian data on the efficiency of power plants and emission factors. Given that more than 60% of electricity is produced in efficient combined cycle gas turbine power plants, the results from the paper show that BEVs perform better than ICEVs in all the environmental categories except for eutrophication and human toxicity (Girardi et al., 2015). A similar approach is used in this thesis where local electricity values are used rather than relying on pre-packaged databases for emission factors.

On the other hand, Garcia (2016) stated that LCA is frequently employed to evaluate and compare the environmental burdens of different vehicle powertrains; however, this method usually captures the burdens in a single point of time. This method lacks a future perspective concerning technological improvements, material processing, and developments in electricity generation (Nordelöf et al., 2014). To avoid this issue, Garcia (2016) claimed that the dynamic

LCA approach can provide the future impacts of a vehicle, thus improving the policy-making strategies. The results obtained in this study show that a fleet with BEVs will reduce overall Well-to-Wheel (WTW) GHG emissions in 2010, 2020, and 2030.

Furthermore, Argonne National Laboratory published a paper comparing the environmental impacts of alternative fuel technologies using the LCA approach. According to the paper, BEVs have the most potential for widespread application, and they pose the least environmental threat (Argonne National Laboratory, 2016). The paper examined the different fuel technologies and reported a study of GHG emissions, energy consumption, cost, and carbon abatement cost from cradle to grave in the United States. The study investigated the impact of ICEVs, HFCVs, PHEVs, HEVs, BEVs, and vehicles running on diesel. Even though the scope of the study evaluated midsize class of LDVs such as the Chevrolet Malibu, Dodge Dart, and Ford Fusion, the results should provide a general understanding of the lifecycle results for other LDVs (Argonne National Laboratory, 2016). The software used was GREET, which is a full life-cycle model supported by the Argonne National Laboratory (United States Department of Energy, 2020). The C2G results showed that currently ICEVs emits 457 g CO2-eq/mile, however, future vehicle efficiency improvements would help reduce those emissions to 352 g CO2/mile, and these emissions could be even reduced further in the future using low-carbon fuel to 142 g CO2-eq/mile under the right conditions. The study discovers that among the different technologies, BEVs have the potential for the most GHG reductions with 42 g CO2-eq/mile. This is especially true when BEVs use renewable sources of energy like solar and wind (Argonne National Laboratory, 2016).

Another study conducted by Bauer et al. (2015) also assessed the GHG emissions associated with different fuel technologies in their current form and future potential by 2030. While the study by Argonne National Laboratory only discussed GHG emissions, Bauer et al. explored more environmental impacts such as acidification, particulate matter formation, and toxicity (C. Bauer et al., 2015). The goal of the study was to compare different fuel technologies for a mid-sized vehicle operating in Switzerland. A “particular vehicle” means measurements of aerodynamic drag, weight, frontal area, and rolling resistance coefficient, whilst the driving cycle is defined as the speed versus time profile. The group uses the Worldwide harmonized Light vehicle Test

Procedure (WLTP) as a reference for the driving cycle, which can be further divided into the calculation of vehicle configuration and energy use (C. Bauer et al., 2015). Numerous vehicle technologies and fuel production pathways were chosen and assessed for the comparative LCA. The selection of vehicle technologies includes gasoline vehicles, diesel vehicles, HEV, HFCV, CNG, and BEV. It is important to mention that the BEV are assumed to be charged from European electricity mix and that the HFCV is consuming hydrogen from Natural Gas Steam Methane Reforming (NG SMR) Hydrogen Generation Plant. According to the study, the NG SMR is considered one of the most popular hydrogen generation method available today and is expected to stay this way in the future due to economic factors (C. Bauer et al., 2015).

The diesel hybrids, CNGs, and BEVs supplied with the European electricity mix all produced the lowest life cycle GHG emissions with around 210 g CO2-eq/km. This is largely because of the predictable decrease of the GHG intensity of the European electricity mixture from today's around 600 g CO2-eq/ kWh to less than 300 g CO2-eq/kWh. In this study, the most polluting fuel is gasoline which emits 300 g CO2-eq/km. Thus, the BEV will demonstrate the optimal performance in countering potential effects of climate change in 2030, decreasing emissions by almost half in comparison to the present levels. With HFCV, the total GHG emissions are just below gasoline vehicles with today's conditions and in 2030 (C. Bauer et al., 2015).

Based on their results, when it comes to environmental pollutants and human toxicity, BEVs are the predominant contributor due to the burdens associated with the European electricity mix as coal represents a large share of the feedstock and metal excavations which are used in battery and vehicle glider manufacturing. The same trend can be observed for acidification and PM formation from the use of coal as a primary fuel to create electricity. This means that if electricity was generated from a different source rather than from coal power plants, acidification and PM formation would sharply decrease. Bauer and others conclude by stating that the BEV technology is a much better overall option as it reduces GHG substantially compared to other options. In the best casebest-case scenario, BEVs can diminish the carbon footprint of existing and near-future passenger vehicles by up to 80% (C. Bauer et al., 2015).

In another example, Burchart-Korol et al. (2018) reported that BEV are anticipated to shape the trajectory of road transport evolution in both Poland and the Czech Republic due to the environmental benefits and enhanced comfort they offer. The authors use the LCA approach to provide a cradle to grave analysis with a special attention to fuel pathways (e.g., electricity pathways) and BEV charging. This paper uses a dynamic approach as the study analyses the present and future energy systems with a time scale from 2015 to 2050. The study also considered different scenarios where smart grids are used to supply electricity to BEVs using solely renewable energy. The findings indicated that both presently and, in the future, BEVs would exhibit lower GHG emissions and less fossil fuel depletion in Poland and the Czech Republic. However, simultaneously, BEVs were found to contribute more towards PM formation, human toxicity, eutrophication, and acidification than ICEVs. The outcomes of the study revealed that the environmental burden of present and future BEVs is higher in Poland than in the Czech Republic across all examined categories, primarily attributed to the type of electricity used for BEV charging. In both countries, the generation of electricity is the primary factor influencing the formation of PM in the case of BEVs. In terms of human toxicity, the most significant contributor for BEVs is associated with electricity, car, and battery production. Furthermore, the electricity utilized to charge BEVs was recognized as the primary driver for eutrophication and terrestrial acidification in both countries (Burchart-Korol et al., 2018).

The studies by Notter et al. (2010), Hawkins et al. (2012), Bauer et al. (2015), Tagliaferri et al. (2016), Lombardi et al. (2017), and Del Pero et al. (2018) serve as illustrative examples in the realm of this research. They present mfethodologies and findings that share similarities with the current research's approach and scope. These review and life cycle studies are not based on purely confidential or internal databases, making an informed calculation possible. Furthermore, these studies take into account the complete cycle of the ICEV/BEV, often missing from other literature. Even if the referenced studies are not performed for Qatar, they can give an overview of where the general impact can be situated for different geographical locations and their specific VKT.

Additionally, as pointed out by this thesis, the choice of lifetime VKT as well as the replacement of components is a crucial sensitivity parameter. As the VKT of the vehicle expands, battery operated vehicles have a lower relative impact per unit of distance and the advantages of clean electricity can pay off longer. This fact is shown by the review of 2018, shown in Figure 2.1.

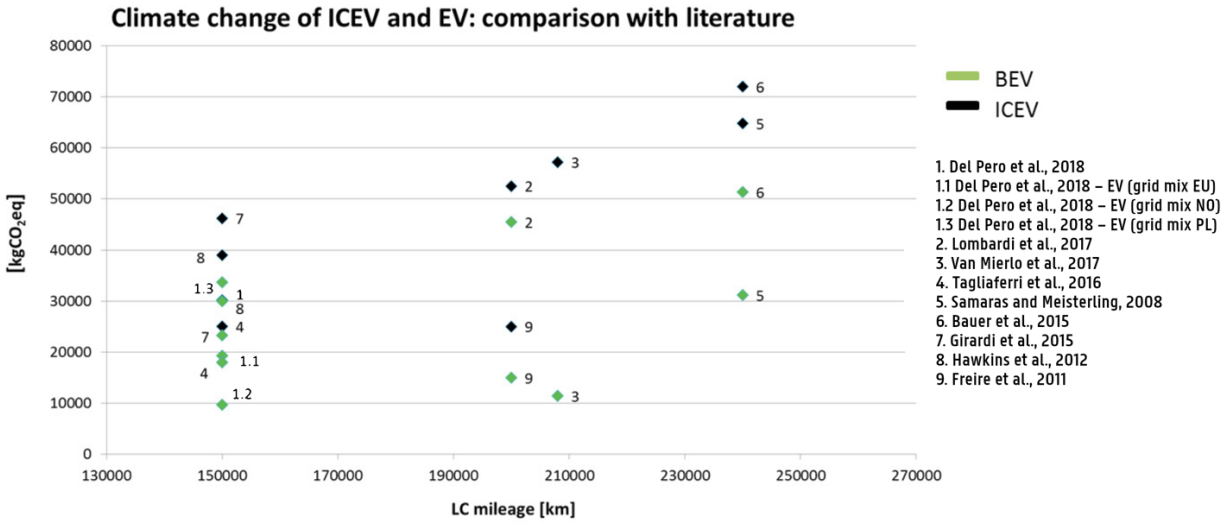

Figure 2.1: BEV (green) vs. ICEV (black) GWP tracked along different LCA studies (Del Pero et al., 2018).

Another study conducted by the Union of Concerned Scientists stated that the lifecycle CO2-eq emission from the manufacturing and operation of an EV is 51% lower compared to a mid-size gasoline car and 53% less for a full-size gasoline car (Nealer et al., 2015). This calculation was repeated for 2022 including the term 'truck' instead of a full-size car. This truck does not represent heavy-duty lorry trucks for the transport of goods. In this recalculation, mostly due to battery recycling options and substitution of bulk materials, the reduction from switching to a BEV car or truck is respectively 52 and 57%. The latter is explained by the lower energy efficiency, higher weight and lower aerodynamic properties of the pickup truck. Here, the same focus on the CO2-eq can be seen, leaving a void concerning impact indicators such as mineral resource use or human health.

Previous Life Cycle Assessment literature focusing on Qatar

Vehicle LCA in Qatar has been studied before. In one study, Al-Thawadi et al. centered on constructing comparative LCA models to assess emissions and energy related datasets of automobiles, buses, and metropolitan trains. The study applied gate-to-gate system boundaries which confined the analysis to specific operational stages. Specifically, the "gate-to-gate system boundary" refers to a limited LCA perspective that only considers the operational aspects of the vehicles, excluding factors like manufacturing and end-of-life processes. The author used the GaBi 6.0 model to compute ecological impacts for every functional unit of travelled passenger kilometers (Al-Thawadi et al., 2020).

The functional unit chosen by Al-Thawadi et al. (2020) for the study was 1000 passenger kilometers travelled (PKT). The results of the study indicated that during the operation phase, passenger vehicles produce more pollution than buses or rail across all impact categories. One note worth mentioning here is that the data used for these calculations were obtained from the TRACI impact assessment method database, which is a tool for the reduction and assessment of chemical and other environmental Impacts (Bare, 2011). The method was primarily developed for evaluating the environmental impacts of industrial processes in the United States (U.S. EPA, 2012). It does not fully account for the unique environmental and vehicle conditions specific to Qatar, such as its fuel emission factor, type and properties of vehicles used, and vehicle fuel economy.

In another study conducted by the same first author, Al-Thawadi and Al-Ghamdi (2019) performed a comparative LCA model of the environmental impacts of passenger vehicles and the metropolitan train system, excluding buses. This study used a similar gate-to-gate boundary approach and a functional unit of 1000 PKT. However, this study relies upon the ReCiPe impact assessment method which transforms a list of life cycle inventory outcomes into several indicators that show the relative intensity on an environmental impact group rather than the TRACI impact assessment method (Al-Thawadi & Al-Ghamdi, 2019; PRé Sustainability, 2016). The ReCiPe impact assessment method offers multiple perspectives like "hierarchist", "egalitarian", and "individualist" for impact assessment, whereas TRACI utilizes a straightforward approach focused on specific regional effects pertinent to the US (Ecoinvent, n.d.). One other difference is

that instead of using raw data from the TRACI inventory, this study exploits data obtained directly from the Qatar Rail Company to represent a more realistic conclusion.

In order to standardize the units for the project, the cabin size of the train was examined. According to Qatar Railways Company, the metropolitan train is designed to have a standard operational density of 4 persons/m2 while accommodating 416 passengers for each 3 car train. An average vehicle has an occupancy load of 3 passengers (Al-Thawadi & Al-Ghamdi, 2019). Thus, in order to standardize the environmental impacts of both alternatives, the study chose a functional unit of 1,000 PKT to standardize the environmental impacts of both alternatives. The environmental impacts of these transportation options were then calculated within a gate-to-gate system boundary perspective. Similar to the previous study, the boundary for private vehicles covers the unit processes related to vehicle fuel consumption while it is in operation. This means that the study did not use a C2G approach; it did not consider the manufacturing and end of life phases. Likewise, the system scope for the urban transportation system includes solely the operational aspects of the trains (or their use) and the non-traction elements (such as power and water consumption) specific to train stations.

The study's results reveal that passenger vehicles produces higher emissions on average when compared with public metro system across all impact groups. The impact of the train system is bifurcated into the traction system, accounting for 7% of total electricity usage, and the non-traction system (station operations), accounting for 93%. Notably, the water consumption impacts significantly contribute to the station operations, explaining the observed disparity in the findings of authors. The environmental impacts of each alternative, the passenger vehicles and the metro system were compiled and assessed to show the overall percentage contribution of each alternative. In terms of climate change impacts, passenger vehicles contribute 89% of overall emissions while the train system contributes the remaining 11%. The metro does not cause PM formation or water depletion; thus, passenger vehicles cause 100% of the impacts. Vehicles are also accountable for 99%, 93%, 76% of human toxicity, marine eutrophication, and terrestrial acidification respectively (Al-Thawadi & Al-Ghamdi, 2019).

A third study shows the macro-level environmental, social, and economic comparison between an ICEV, HEV, PHEV, and a BEV in Qatar. The authors employed a multi-regional input-output (MRIO)-based life cycle sustainability assessment (LCSA) to calculate nine macro-level indicators, evaluating the four alternatives accordingly (Onat et al., 2019). Unlike a typical LCA approach, the LCSA considers economic and social impacts in addition to environmental impact considerations. Social impact categories investigated in the study comprise total tax, compensation, employment, and human health impacts. Notably, ICEVs demonstrated superior benefits in terms of taxes, employment, and compensation, highlighting significant economic advantages associated with petroleum extraction and its supply chain activities, with the majority of benefits concentrated within Qatar's regional boundaries. Human health impacts varied among vehicle types with ICEVs primarily contributing to tailpipe emissions, while BEVs affected by electricity generation. Although the BEV penetration reduces human health impacts, it does not necessarily benefit social markers such as employment, tax, and compensation (Onat et al., 2019).

In terms of economic indicators, the study includes the GDP and operating surplus impacted by both ICEVs and BEVs. Results of the study indicated that fuel supply including petroleum extraction, its production and electricity generation in Qatar, was the principal contributor to GDP and operating surplus for all vehicle types. ICEVs were deemed more favorable for these macro-level indicators since they possess higher added value and operating surplus in the supply category of fuel with over 90% of economic benefits concentrated within Qatar's regional boundaries. This is in contrast to BEVs, where the main contribution to nation’s GDP is through electricity generation and supply chain related activities constituting approximately 48% and 49% of their annual consolidated GDP contribution. Meanwhile, fuel supply remained the dominant contributor to operating surplus for ICEVs representing at least 80% of vehicle's overall contribution. Ultimately, the study suggests that early adoption of alternatives to electric vehicles may not necessarily yield positive impacts on macro-economic markers (Onat et al., 2019).

Regarding environmental impacts, the study quantified upstream emissions linked to fuel supply within Qatar, tailpipe emissions, sectors within Qatar, and sectors outside Qatar. The literature specifically concentrates on the Sport Utility Vehicle (SUV) body style, analyzing two primary

stages: Well-to-Tank (WTT) and Tank-to-Wheel (TTW). WTT covers all upstream emissions related to fuel consumption, not only within Qatar but also in sectors beyond, whereas TTW refers to the direct tailpipe emissions of vehicles. The chosen functional unit for this study is 1 km (Onat et al., 2019).

The results demonstrate that tailpipe emissions are the biggest culprit in three categories: in terms of GWP, Particulate Matter Formation (PMF), and Photochemical Ozone Formation (POF). Additionally, study asserts that among all vehicle fuel technology options which are available, BEVs exhibits the least environmental impact. The table below summarizes the three different LCA literatures performed for vehicles in Qatar:

Table 2.1: Summary of LCA studies performed for road transport in Qatar in comparison to this study.

Literature	Powertrain	Type of LDV	Impact Assessment method	Database	Boundary
(Al-Thawadi et al., 2020)	ICEV	Not specified	TRACI	GaBi Database	Gate to gate
(Al-Thawadi & Al-Ghamdi, 2019)	ICEV	Not specified	ReCiPe	GaBi Database	Gate to gate
(Onat et al., 2019)	ICEV, HEV, PHEV, BEV	SUV	Multi-Region Input-Output	EXIOBASE 3.4	Gate to gate
This study	ICEV and BEV	LDVs, HDVs, and Buses	ReCiPe	Ecoinvent	Cradle to grave

2.3.3 Carbon calculator

This sub-section begins with a brief introduction to the carbon calculator and its purpose. It then provides an overview of previous applications of the Carbon Calculator (sometimes referred to in literature as the Global Calculator (GC)) model specifically. By reviewing the background and limitations of existing carbon calculator models, this sub-section lays the groundwork for the novel contribution to knowledge that will follow.

The Carbon Calculator to determine how different factors affect emissions leading up to 2050. The global population is steadily increasing, leading to heightened demands for energy and goods. In response, numerous research organizations and consortia have embarked on initiatives to define and measure the impacts from various sectors. Additionally, these entities are exploring methods to mitigate these impacts through specific behavioural changes and influencing established environmental impact metrics, such as the carbon footprint. One of the leading methods is the Carbon Calculator, initially directed at the national and EU level. The Carbon Calculator tool allows its users to envision multiple options that lead towards global GHG emission reduction, mainly in the sectors of energy systems, land and food demand, all up to 2050. This is done through a technique that integrates major contributors, such as the transport and manufacturing sector, supply and demand of electricity as well as the need for land in general, food, (bio-)energy and infrastructure (i.e. Buildings). It includes high-level variables, among others: climate change, differences in population, effects from urbanisation as well as GHG removal (GGR) techniques.

This technique goes beyond the low complexity of single-change models and users are able to generate custom emission reduction projections through changes in the interconnected, dynamic model. The model cover pollutants such as CO2, N2O and CH4 emissions as well as effects on land use distributions (Strapasson et al., 2014). This makes it a relevant tool for both the public and private domain with regard to assessing large-scale mitigation, land use and production management strategies. A relevant branch is thus amongst other policymakers, taking into account which policy changes will have the most impactful effect in the long term and which interconnected issues are present (Strapasson et al., 2014).

Strapasson et al. (2014) introduce the Land/Food/Bioenergy model of the calculator, a tool designed to apply mathematical methodologies for reconciling the growing demands for food crops, livestock, biofuels, and other bio-based products with the imperative of resource conservation. This model provides users the capability to simulate various land use change trajectories and the resultant GHG emissions, tailored to varying demands for land-dependent products and services projected up to 2050. The core of the adaptability of the Land/Food/Bioenergy 2050 model is based upon the weight levels (1-4, reflecting degrees of ambition) for the intermediate levers. These intermediate variables range from yields in energy and land use, consumption levels to waste flows and efficiencies. The Land/Food/Bioenergy model balances the necessary expansion characterised by the users' preferences by simulating several trajectories in line with the selected parameter weights ("Levels 1-4"). By interconnecting a variable such as "calories consumed per person", a whole array of effects is introduced in lower levels, e.g. the volume and sort of meats consumed, bioenergy yields, both crop and livestock yields (i.e. feed conversion ratios, share of feed systems connections, livestock densities and land use pasture systems), surplus land and efficiencies (forest & bioenergy) as well as waste and residue flows.

Previous applications of the Carbon/Global Calculator

Strapasson et al. (2014) introduce the primary conceptualisation of the underlying model as well as the extrapolations for the mentioned levers and sub-levers, such as livestock and crop yields, the evolution of calorie consumption around the globe as well as energy yields and surplus land covering. Interaction between energy needs, waste flows and livestock with land use is balanced in the Global Calculator by use of external sources such as the IPCC Bioenergy Potential (Strapasson et al., 2014).

Outside of the scope of the paper, no specific case studies were undertaken as it covers the methodology that was under construction in that timeframe. Uncertainties and complexities are inherent to this type of calculator tool, especially when associated with estimates on a global level and with input parameters that are limited in number, thereby simplifying the actual state. Nonetheless, the Global Calculator offers a methodology for exploring future projections of land

use change and its associated GHG impact. Decision-makers on a country level, as well as researchers interested in high-level future scenarios, are given access to a wide range of alternatives and perturbations with the prospect of updates as this project continues and new data sources become available.

Since the publication and concurrent launching of the Global Calculator tool, many countries have implemented parts or adapted the underlying strategies in their own national goals and research. One of those achievements is described in the paper by Alejandra Elizondo et al. (2017). The work presents an overview of a detailed assessment including energy strategy and climate change mitigation measures, specifically tailored for Mexico. The calculator tool in this case study was renamed the Mexico 2050 Calculator. Due to its relative simplicity and its transparency, the use of comparable calculators is a rising topic of interest. This Mexico-oriented paper serves as a relevant international case study of the methodology as Mexico is one of the larger economies in South America that has achieved a high level of resource diversification. Just like the original project, the Mexico 2050 calculator is built up as a comprehensive model. The tool integrates the primary sectors of Mexico's economy to produce a single impact in order to run an array of possible low-carbon 2050 future scenarios. Integration of energy and carbon dynamics is performed across interconnected sectors, while also encompassing a sensitivity analysis. In order to assess the current strategies of energy policy in Mexico, the author develops four unique low-carbon energy scenarios. At the time of publication (2017), Mexico had a high reliance on fossil fuels and was expected to double its energy consumption before 2050 in case a Business-as-usual approach would be followed. However, national plans such as the General Climate Change Law benchmark should change the direction Mexico goes, aiming to reduce emissions by 50% in 2050 in reference to 2000 levels. Just as for other nations, overarching plans are supported by lower-level initiatives, for Mexico this covers a carbon tax, sectorial initiatives and regulation as well as actions for cities, the transport and electricity sector as well as private citizens.

It should be noted that for the Mexico 2050 Calculator, not all interconnected issues for dietary changes, land use and carbon dynamics as well as bio-energy, which all significantly impact the final results, are implemented in the 1.5.0 version of the tool. In summary, the scenarios for the

2050 model of Mexico were set to reflect on the very ambitious side a fast Carbon Capture and Storage (CCS) deployment, a focus on zero-emission vehicles coupled with smart energy production chains and storage options. On the lower end, the other scenarios still display ambitious plans, but from a more technical feasibility standpoint, ranging from “Full Renewables” scenario, to the “Nuclear + Renewable” scenario, and lastly to the “Distributed Effort” scenario, where all sectors will contribute to higher yields, lower energy intensities and more savings overall.

The main results of Elizondo et al. (2017) work reveal that for Mexico, the industry and transport sector primarily drive the energy demand in 2050. Energy from fossil fuels is decreased in absolute terms yet continues to weigh on the total supply shares. Only by meaningfully incorporating nuclear energy into the supply mix can scenarios with a high demand for fossil fuels be shifted towards reduced reliance on these fuels. However, specifically for the 2050 electricity supply, Mexico can depend primarily on sources of clean energy. In that case, it would result in the majority share coming from renewables, with demand coming primarily from the industrial sector. Sectors such as industry and transport are at the higher end of this mitigation strategy, yet are not the frontrunners in the scenario. In effect, from these results, it is clear that a switch to greener energy sources, lower-impact transportation options and a smart allocation of funds are an important part of the 2050 trajectories. This also shows that policymakers can focus on those specific points, aiding the transformation by green initiatives while simultaneously reducing the emission options from the largest sectors. This can be tackled on both fronts by taxes, funding and certification protocols (Elizondo et al., 2017).

The tool could be extended towards business and policy decisions by constructing complementary models including local environmental constraints, public perception, and market trends. The tool could therefore be adjusted even further as a city-level calculator, as already done for major cities such as Beijing. In conclusion, the paper presents an assessment of Mexico’s possible low-carbon trajectories, giving insight into energy and climate change mitigation planning while highlighting the importance of integrated models in informing policy decisions on all levels.

Further, Strapasson et al. (2020) come back to reflect on the Global Calculator by assessing several ambitious scenarios against business-as-usual practices. This is done in order to check those possible trajectories against the proposed 2°C and 1.5°C global temperature change goals. This global warming limit is specified for the end of this century, making the Global Calculator tool is a valuable asset in the assessment of possible decision dynamics. To achieve this latter goal, the emission trajectory had to be further extrapolated from the 2050 endpoint to 2100, using the "emissions after 2050" lever.

Since the original launch of the tool and overall project, it has been implemented in nations on most continents, ranging from China, Australia, and South Korea to Switzerland, Nigeria, Ecuador, Brazil and Belgium. Not only has the tool been implemented for local or national planning, but it has also been a basis for many calculations in the context of the Nationally Determined Contribution (NDC).

The focus of the latter work of Strapasson et al. (2020) is to simulate the before-mentioned ambitious scenarios (2°C and 1.5°C) against on the BAU scenario which takes no mitigation ambitions into account. The other scenarios try to stay below a maximum temperature change of 1.5°C and 2°C by the year 2100, with a sensitivity analysis added at the end as was done similarly in the Mexico 2050 Calculator.

Wide-ranging simulations of energy, carbon, and land use dynamics consistently show the urgent need for combined and persistent mitigation efforts across various sectors if the goal of meeting climate targets is kept. Nonetheless, as a comparison, the Business as Usual or BAU Pathway reflects a 6°C trajectory for which no additional efforts are made to reduce GHG emissions beyond what is already happening today. Under this BAU option, energy flows are dominated by fossil fuels and GHG emissions continue to increase, therefore leading to a temperature rise approaching 6°C, as per IEA6DS (IEA). The GHG emission reduction scenarios for this literature are respectively the 2°C (2D) and 1.5°C (1.5D) Pathway. They show a future in which significant efforts are made to lower GHG emissions to reduce global warming with the 2D pathway aiming towards a substantial shift of renewable energy sources and increased energy efficiency. The 1.5D pathway is even more ambitious in this shift, yet it should be noted that more efforts

towards the 1.5D trajectory, need more substantial increases in mitigation changes (Strapasson et al., 2020).

The latter 1.5D scenario incorporates augmented efforts such as the implemented wind, solar, wave, and tidal energy (increased from 2% to 17% of the supply) in the 2°C model, to even higher levels, with only bioenergy making a significant jump. Both the manufacturing and buildings sectors will see a significant push downward in energy demand, almost halving by 2050 (Strapasson et al., 2020).

From the global GHG emission results and the sensitivity analysis, it becomes clear that for the BAU scenario, fuel combustion becomes an increasing share while land use doubles by 2050. In comparison to the D1.5 and D2 trajectories, where the latter land use decreases over time and fuel combustion emissions go from the majority to less than agriculture emissions. The sensitivity analysis reveals no single solution, instead, it emphasises the separate contributions. While it does underscore the fact that all sectors are essential in the mitigating process, it is highlighted that more sustainable diets, trying to increase livestock efficiency in a sustainable manner as well as the urgency for rapid enhancements in the utilization of fossil energy use are key.

In this study, a few discussion points are addressed by Strapasson et al. (2020) concerning external and not-included uncertainties. Technologies or implementations that are on the extreme end of the learning curve, such as fusion energy, the implementation of artificial meat as well as new carbon capture technologies are not included in the model at this point. The tool does not include feedback-loop effects such as climate vulnerabilities or the costs of climate adaptation by 2050. Biodiversity impacts as well as water equilibrium issues were also not directly included. Finally, some extra points should be considered, such as new innovations in robotics, AI and biotechnology which are changing the field increasingly fast. Such model parameters cannot be easily included due to their high degree of uncertainty and unknown impacts on GHG mitigation as well as land use.

In another publication, Cooper et al. (2016) examined seven international transportation initiatives that aim to cut back on road transport emissions. The evaluations of these initiatives

utilized the calculator to examine pollution reduction strategies within energy, land, and agriculture systems till 2050 along with consequential effects up to 2100. The article clearly highlighted that the calculator aids users in comprehending the comparative impact of actions in various industries on carbon reduction. The difficulties of comparing behaviours and presumptions across various models and studies are also addressed. Different initiatives were assessed based on both their overall and individual effects. Using standardized baselines and precise assumptions, the research illustrates how transportation initiatives impact global emissions. The analysis in the report promotes additional discussion of the programs it examines. For example, because the projected number of vehicles to be acquired and the required infrastructure are reduced when using rail or public transportation, there are significant cost savings. The targets for electric vehicles are likewise highly ambitious and will significantly reduce pollution. Compared to the sector's scale, the fuel efficiency initiatives for light-duty vehicles and airplanes have significant potential to reduce emissions by 0.67 percent and 0.10 percent, respectively (Cooper et al., 2016).

According to the study, modal shift is significant in emissions reduction among the projects, particularly considering the ambitious targets compared to more pragmatic assumptions made for technological initiatives. The calculators also indicates that high level of effort is required to bring about the necessary behavioural changes for achieving the desired level of public and non-motorized transportation under these initiatives. Despite this, switching to electric vehicles and trying to improve vehicle performance are seen as audacious but feasible measures ranging from level 3 to higher than level 4 in the calculator. Although the viability of any individual project may be in jeopardy, synergies between shifts in demand, method, and technique may affect the results. Each initiative's amount of effort depends on the level of effort put forth elsewhere. For instance, because fewer vehicles will be needed overall if mode-shifting is successful, achieving targets for automobile economies or fleet electrification will be simpler and more affordable (Cooper et al., 2016).

Concluding, the Global Calculator is a robust and versatile tool and indispensable in contemplating varying 2050 scenarios with a high degree of interconnect parameters. The tool

demonstrates the usefulness of joint and ongoing mitigation efforts over various sectors. Furthermore, it stresses the urgency in actions to meet climate targets and shows simultaneously that up-to-date data and modelling are of the utmost importance to adjust policies and mitigation efforts. With its variability, it is an ideal tool for high-level country studies as well as more specific cases such as city-level implementations. It could be imagined that, in case of new building opportunities or the expansion of large cities, this tool could be a critical part of shaping a sustainable future from the very start.

2.4 Research Gaps

While previous studies have employed various methods such as VSMs, LCA, and carbon calculators to examine the environmental impacts of road transport, there remain significant gaps in the context of Qatar's unique road transport landscape. Firstly, Qatar's specific circumstances are underrepresented in global VSM studies. Although research has shown that lowered road transport demand combined with electrified fleets can effectively reduce air pollutants and GHG emissions, no study has analysed the environmental outcomes of implementing ICEV bans in Qatar by 2030, 2035, and 2040. Moreover, the impact of air pollutants in Qatar's unique climatic and urban conditions is not sufficiently explored, and the inclusion of non-exhaust emissions from heavier BEVs in VSMs is lacking. In addition, the government has proposed targets to reduce GHG and air pollution emissions, however, a clear roadmap to accomplish those goals is yet to be explored. This project aims to fill this knowledge gap by evaluating the environmental impact of Kahramaa's policy to electrify 10% of the vehicle fleet. It will also determine which combination of vehicles in the national fleet will achieve the NDC goal.

Secondly, while LCA studies have compared the environmental footprints of ICEVs and BEVs, a profound focus on Qatar's evolving energy mix, predominantly based on natural gas, is essential. Existing LCA studies in Qatar often rely on non-specific datasets and gate-to-gate boundary systems, limiting their applicability. This study aims to leverage novel, Qatar-specific data and employ a C2G boundary system to provide a more comprehensive view of the vehicles' environmental footprint over a long-term perspective.

Lastly, despite the effectiveness of carbon calculators in quantifying decarbonization opportunities in other regions, Qatar lacks a tool tailored to its specific socio-economic and environmental parameters. Existing carbon calculators may not fully capture the complexities of Qatar's road transport system, necessitating the development of an integrated approach that holistically models the impacts of a wide range of decarbonization measures pertinent to Qatar's context. Addressing these research gaps is crucial for aligning Qatar's road transport sector with its national climate pledges. The findings will offer new knowledge about the potential evolution of road transport environmental policy in Qatar.

3 Scenario Analysis for Road Transport

3.1 Introduction

This chapter compares ICEVs and BEVs to examine how the road fleet could change with the introduction of road vehicle electrification. To assess potential reductions in GHG and air pollutant emissions, this chapter models a variety of road transport fleet scenarios to understand future impacts.

The VSM has been instrumental in shaping policies regarding BEV penetration rates, as it effectively models the adoption of alternative vehicle powertrains over a specific time period Brand et al., 2020; Chatterton et al., 2015; Craglia & Cullen, 2020; Mehlig et al., 2023). The review of the VSM was initially discussed in Chapter 2, and this chapter expands on it by modelling the future dynamics of the road transportation fleet, including LDVs, HDVs, buses, and motorbikes, using a newly developed VSM tailored for Qatar. This study distinguishes itself from previous simulations by incorporating air pollutant emissions, a factor often overlooked in earlier analyses. Electricity production emissions from charging BEVs, which were previously anticipated as a single CO2-eq emission factor, have been upgraded to include air pollutant emissions as well. This simulation is then used to create a variety of scenarios aimed at solving major policy problems around the introduction and operation of BEVs vehicles in Qatar.

Globally, several countries are attempting to reduce their carbon emissions and improve air quality by banning the sale of new ICEVs in the future. For example, Norway is committed to ban the sale of new ICEVs by 2025 (Ummelas, 2023). Other nations such as Canada, New Zealand, the Netherlands, etc. announced ICEV bans by 2030, while California and France will apply the ban in 2035 and 2040 respectively (Milman, 2021).

Similarly, Qatar has carried out steps to electrifying the road fleet. Transitioning from ICEVs to BEVs will contribute to further reduction of GHG emissions which may help meet the NDC commitments. For example, Qatar General Electricity and Water Corporation (Kahramaa), the sole transmission and distribution system owner, has set a goal to electrify 10% of the vehicle

fleet by 2030 (Qatar General Electricity & Water Corporation (KAHRAMAA), 2018). As the national grid operator, Kahramaa plays a crucial role in supporting the adoption of electric vehicles by ensuring the necessary infrastructure and electricity supply. Moving ahead, the country has established plans to adopt the Euro 5 emission standards for diesel vehicles as well as Euro 6 standards for gasoline vehicles which is considered an ambitious step to reduce harmful emissions from the transportation sector (Ministry of Municipality and Environment, 2021). These efforts demonstrate an intention to reduce transportation emissions in Qatar, however studies have not yet investigated the impact of these initiatives.

In Qatar, the shift to BEVs is primarily driven by the need to mitigate the environmental impact of traditional vehicles, particularly in terms of GHG emissions and air quality pollutants (M Ahmed et al., 2021). Studies have shown that the adoption of BEVs in Qatar could lead to reductions in Global Warming Potential, Particulate Matter Formation, and Photochemical Ozone Formation, along with being more cost-effective than traditional vehicles (Aboushaqrah et al., 2020). However, public perception and the willingness to transition to electric mobility remain significant challenges, necessitating robust government incentives and subsidies (Al-Buenain et al., 2021). The adoption of BEVs is further hindered by practical barriers such as long charging times, short driving ranges, and inadequate charging infrastructure (Khandakar et al., n.d.). Consequently, it is important for Qatar's policymakers to devise and implement targeted policies that specifically address these barriers, and accelerate the transition of BEVs in order to realize their potential.

In its NDC, Qatar communicated its intentions through the United Nations Framework Convention on Climate Change (UNFCCC). The country is committed to design a balanced approach where economic diversification, climate adaptation as well as mitigation are made a priority in future plans and actions. Qatar intends on enhancing its climate ambition by reducing its overall emissions targets in response to the guidance set forth in Article 4.4 of the Paris Agreement. Qatar aims to reduce its GHG emissions by 25% - relative to the business-as-usual scenario - by 2030 (Ministry of Municipality and Environment, 2021). This chapter will examine the most recent and crucial policy initiatives to diminish GHG emissions via using alternative

vehicle technologies while also keeping track of changes in air pollutant emissions.

The chapter focuses on modelling the future road transport fleet under a variety of scenarios in order to assess potential reductions in GHG and air pollutant emissions. The following step will be to explore the GHG and air pollution impacts of banning ICEVs by 2030, 2035, and 2040 respectively. Next, the study will investigate the GHG and air quality impacts of Kahramaa's goal of electrifying 10% of the fleet by 2030. Finally, this section will project the fleet configuration required to meet the NDC goals of reducing 25% of GHG emissions by 2030 relative to a business-as-usual scenario.

Once the results are obtained, a sensitivity analyses will be performed to evaluate the impact of the model's input parameters. Next, the outcomes of the analyses are utilized to explore the broader policy implications regarding the impact of introducing BEVs into the local Qatari road fleet.

3.2 Methods

In order to model the Qatari road transportation fleet from 2022 to 2050, the VSM is introduced. This segment discusses the model's framework, steps, and input parameters. According to the GHG protocol, road transportation can be split into three main emission scopes (The GHG Protocol, 2019):

- Scope 1: Emissions from fuel combustion
- Scope 2: Emissions from electricity consumption of the grid
- Scope 3: Transboundary emissions occurring outside the studied region

For this research scope 1 and 2 are examined. Given that the region of study is Qatar, scope 3 transmission and distribution losses are assumed to be included in scope 2 emissions as they are within the geographical boundary of the country. Moreover, the calculating approaches can be generally divided into top-down approach and the bottom-up approach. The top-down approach uses fuel consumption as a representative for travel activity and the result is then multiplied with the national emission factor, while the bottom-up approach requires more detailed inputs (vehicle population, activity data, type of vehicle, fuel, etc.). Several studies begin by using a top-down methodology and then transition more towards a thorough bottom-up approach which allows for a more practical emission mitigation judgment and strategy. The bottom-up approach would include determining vehicles bought within a specific region, the number of vehicles, average lifespan, and the emissions factor of different vehicle modes. For example, the IEA uses oil product sales to estimate the emissions from the transportation sector in Qatar. The GHG protocol states that the bottom-up approach presents more precise results and integrates better with city planning, thus, it will be used in this research (The GHG Protocol, 2019).

3.2.1 Structure of model

The earlier model employs a stock-flow group structure and a bottom-up approach, using an exogenous input scenario to project the road fleet from 2022 to 2050. This projection aims to determine the annual composition and characteristics of the road fleet. Starting with Qatar's

current road fleet in 2022, the model adds new vehicles annually through to 2050, while also accounting for vehicle removals based on an average scrappage rate.

This model covers all major road vehicle types in Qatar, including LDVs, HDVs, buses, and motorbikes; however, the bans are exclusive to LDVs as they constitute the overwhelming majority of vehicles in Qatar, thereby presenting a significant opportunity for CO2-eq emission reductions in the road transport sector. While HDV bans were not within the scope of this study, their inclusion could be an avenue for future research to provide a more comprehensive assessment of the potential emissions reductions across all vehicle types. Nevertheless, given the predominant reliance on ICEVs for both personal and commercial transport, transitioning to BEVs within this segment is pivotal for achieving Qatar's ambitious environmental targets and aligning with global efforts towards sustainable mobility.

It assigns fuel economy parameters based on the year of vehicle registration, acknowledging that vehicle technologies and features evolve annually. These prevailing technologies are primarily categorized by their powertrain types and fuel parameters.

The VSM applies a WTW CO2-eq system boundary, covering all emissions associated with the energy consumed by ICEVs and BEVs. This includes the fuels combusted in vehicles or in power stations and the upstream emissions from the fuel’s supply chain. For air pollutants NOx and PM2.5, only emissions from vehicles and power stations are considered to provide an indication for of how air quality may change within Qatar. This excludes air pollutant emissions from the upstream fuel supply chain, which may not have a material impact on Qatari air quality due to their location. The inclusion of these upstream air pollutant sources could be a useful addition in future research.

In this study, the model includes gasoline ICEVs and BEVs powered by electricity generated from natural gas. The model then calculates emissions by considering the distance travelled by each vehicle type. These emissions are aggregated yearly to produce a comprehensive profile of the entire fleet's emissions.

3.2.2 Starting fleet

The parameters for the initial fleet, which was used as an input for the model, were acquired from the traffic department at the Ministry of Interior. The historical records spanning from 2014 to 2018 of the vehicle population and the vehicle type composition were collected from the Transport and Communication Statistics published by the Traffic Department of the Ministry of Interior (Ministry of Interior, 2019). The future projections from 2022 to 2050 of vehicle population were estimated by using the coefficient of elasticity. The coefficient of elasticity uses variables such as GDP growth rate and population growth rate to produce overall vehicle population values. Generally, the increasing trend of vehicles in developed countries, such as Qatar, has followed a related pathway through an accelerated surge stage spanning 30-40 years. Then, vehicle population reaches a saturation stage where the trend stabilizes. During this saturation phase, vehicle ownership is mainly linked to various social and economic drivers such as population density, economic status, and more (Y. Wang et al., 2011). Over the past 20 years, passenger car ownership has experienced a significant increase in Qatar. The most apparent transformation in the Qatari vehicle fleet is the fast growth in the number of passenger vehicles resulting from private vehicles. This could be mainly linked to the relative cheap oil prices in the country as well as the high GDP per capita (Global Petrol Prices, 2022; The World Bank, 2020).

3.2.3 New vehicle sales

This stage is intended to allocate the technology share of new vehicle sales. For each vehicle type, the scenario describes the annual share of new vehicle sales per type of vehicle technology. Next, these shares are transformed into the penetration rate of new vehicles by monitoring the overall vehicle stock every year and introducing new vehicle sales in order to reach the targeted fleet number. The required number of new vehicles is then multiplied by the technology's proportion of new vehicle sales to get the annual need for each technology. This method produces the total number of new vehicles for each technology. For this phase, the inputs to the model are:

- Quantity of new vehicles sorted by technology
- The average vehicle lifespan

- The number of cars in the current fleet

3.2.4 Overall number of vehicles in the fleet

The purpose of this computation is to establish the current vehicle fleet's characteristics in light of new car sales. The new sales will have an influence on the average energy consumption, average vehicle lifetime, and the percentage of each technology in the vehicle fleet. The energy consumption is calculated by the type of vehicle based on the entire fleet parameters. To calculate the fleet wide average metrics, the required inputs are:

- Current car fleet attributes
- Lifespan of new vehicles
- Energy efficiency of new vehicles

3.2.5 Vehicles kilometers travelled

VKT is defined as the amount of travel for all vehicles in a specific geographical location within a certain period of time (Williams et al., 2016). VKT is used in both academic and commercial fields to help understand various travel trends over different locations and periods of time. While there are many tools used in the transportation sector, measuring VKT is a common one as it allows its user to identify proper policy decisions for matters such as infrastructure investments. It also plays a major role in identifying where resources are needed the most, and it is a vital measure to monitor and predict transportation scenarios (Texas A&M Transportation Institute, 2016).

VKT is an exogenous factor which was provided in the model via the input scenario. The VKT input is considered vehicle type-specific, varying between scenarios according to the specifics of each vehicle type. Road traffic VKT statistics were obtained from the National vehicle Inspection Company (FAHES) that inspects vehicles on an annual basis and provides odometer readings. The VKT was obtained from the official statistical record by FAHES. In addition, this research also presumed that the course of VKT from historical data would carry on in the near future. Thus, the

forecasted VKTs between 2022 and 2050 were determined using the coefficient of elasticity and historical data.

3.2.6 Vehicle parameters

In the model, the parameters that describe each vehicle are determined by its registration year. This establishes the average characteristics for the specified vehicle technology and type corresponding to that year. For this research, the parameters include the Euro standard, fuel consumption, GHG emissions, and air pollutant emissions, all consequent to the specific technology and year of registration.

Euro standards for exhaust and non-exhaust air pollutants

The Euro standard was not adopted in Qatar until 2002. In that year, the country announced that new cars sold will have to comply with the Euro 2 standard for both gasoline and diesel vehicles (Standardization Organization for G.C.C., 2003).This law was updated in 2019 when the national vehicle inspection company was instructed that all gasoline vehicles manufactured in 2018 and after should comply with the Euro 4 standard to pass the inspection. Diesel vehicles must comply with the Euro 5 standard from 2023 onwards. The model uses the mentioned timeline of Euro standard adoption for each type of vehicle.

According to the European Monitoring and Evaluation Programme (EMEP)/European Environment Agency (EEA) air pollutant emission inventory guidebook 2019, emissions from road transport are categorized into four distinct groups: emissions from fuel combustion in vehicle engines; emissions due to fuel evaporation within the fuel tank; emissions from tire and brake wear; and emissions from road surface abrasion. Notably, exhaust emissions are further divided into cold and hot emissions. Cold emissions occur during a vehicle's warming-up phase, while hot emissions occur during the driving phase (Ntziachristos & Samaras, 2019).

The most common method for emission estimation encompasses a combination of activity data and emissions factors (Ntziachristos & Samaras, 2019). Each of the three emission approximation approaches as described by the European Monitoring and Evaluation Programme - Tier 1, Tier 2,

and Tier 3 - demands a different set of parameters. Tier 1is based upon fuel consumed at a national level, while Tier 2 necessitates a more in-depth breakdown; by vehicle, fuel, engine type, distance travelled, and meteorological conditions. The meteorological conditions include factors such as minimum temperature, maximum temperature, and relative humidity. Tier 2 estimates are computed by combining both hot emissions (emissions produced when the engine has warmed up) and cold emissions (emissions produced during the warm-up of the vehicle) (Reiter et al., 2016). Further inputs, such as operational conditions, are required in Tier 3 (urban, rural, and highway driving patterns), trip characteristics (trip length and duration), and more advanced specifications. For air pollution emissions, this paper utilized the Tier 2 approach of the COPERT model, which is very commonly used in literature to compute emissions. The COPERT model requires local data such as fuel quality and meteorological conditions as inputs to produce results. Additional input information, such as the vehicle population composition and the VKT, are also needed. Meteorological data were acquired from the Qatari Civil Aviation Authority (Qatar Civil Aviation Authority, 2021).

By employing the EMEP/EEA emission inventory guidebook's tier 2 methodology which is programmed in the COPERT software, the air pollutant exhaust and non-exhaust emissions for NO_x, and $PM_{2.5}$, were calculated using the Euro standard applicable for each vehicle (European Environment Agency, 2021) . This method provides an emission factor for calculating the amount of kg of a specific emission per kilometer driven depending on the Euro standard, type of vehicle, and the technology as average values representing the vehicle fleet. These emission factors represent conventional activity conditions and speeds throughout the EU; they are designed to be robust at the international scale. Given the slow adoption of Euro standards in Qatar, this project assumes that Euro 4 is used for vehicle manufactured prior to 2030, and then, the adoption of Euro 6 standard starts. This assumption was made after the jump from Euro 2 to Euro 4 standard in 2018.

To reflect the ban model and the influence on emissions, the following table reflects the distribution between ICEV Euro standards in the fleet throughout the dynamic timeframe. As can be observed from this table, a high fraction (85%) of Euro 2 cars is present at the 2020 start of

the model, drastically reducing its share by the outflow of the model by 2030, for which less than 40% of the ICEV fleet would remain at this standard. From 2030 on, the Euro 4 standard goes from over 60% down to 11% in 2050 as by that time, all inflowing vehicles will adhere to the Euro 6 standard and only the remaining fleet would contribute to lower standards until the lifetime of those vehicles have been reached. This in its course is the leading cause of emissions that remain high even though ICEV vehicle sales are in any form of phase out as ICEV sale bans do not imply a sudden shift to only electric cars as soon as this ban goes into action. Additionally, this is further exacerbated by trucks, buses and other modes of transport, which can generally have longer lifetimes and slower turnover rates compared to the LDV fraction or passenger cars of the Qatar fleet.

Table 3.1: Breakdown of the share of LDVs categorized by Euro emission standards.

Year	Euro 2	Euro 4	Euro 6
2022	72.5%	27.5%	0.0%
2030	39.1%	60.9%	0.0%
2035	25.9%	40.3%	33.8%
2040	17.1%	26.6%	56.2%
2045	11.3%	17.6%	71.0%
2050	7.5%	11.7%	80.8%

The specific pollutants chosen for this study are NOx and PM2.5. the rational for choosing those two pollutants lies in their disproportionate impact compared to other pollutants. These two pollutants are prioritized due to their high prevalence in emissions from road vehicles and their significant health and environmental effect. NOx is a key precursor to ground-level ozone and a contributor to the GHG effect, while PM2.5 is known for its ability to deeply penetrate the respiratory system, leading to a range of serious health issues. By targeting these pollutants, the research aims to tackle the most critical aspects of air quality degradation and public health risks associated with vehicular emissions. This selective approach ensures that efforts are concentrated on mitigating the most harmful and abundant pollutants from road transport, this

maximizing the impact of pollution control and public health protection strategies (Li & Managi, 2021; McDuffie et al., 2021; Michiels et al., 2012; Winkler et al., 2018).

Fuel parameters

For ICEVs, this study investigates the fuel economy, followed by the fuel type and its improvement through history to compare the projections by the Global Fuel Economy Initiative and the IEA (Global Fuel Economy Initiative, 2021; IEA, 2021). To determine the fuel economy value representative of the current vehicle fleet in Qatar, a spreadsheet detailing all vehicles operational within the country was acquired from FAHES. This dataset was subsequently categorized according to vehicle types: sedans, sports vehicles, and SUVs. Following this classification, the "fuel economy" website, maintained by the official U.S. Department of Energy (Office of Energy Efficiency and Renewable Energy), was used to ascertain the fuel economies of the diverse array of vehicles (U.S. Department of Energy & EPA, n.d.). The fuel economy was initially determined for individual vehicle model within the Qatari fleet. Next, the average fuel economy for each vehicle type (sedans, sports vehicles, and SUVs) was calculated by weighting the individual fuel economies based on the number of available vehicles in each category. This approach ensured that the final fuel economy values were representative of the actual composition of the Qatari vehicle fleet.

For Qatar, this chapter takes into account the two primary transport fuels, namely gasoline petroleum and diesel for ICEVs. At the time of this study, there is no known commercial use of alternative fuels such as Liquefied Petroleum Gas (LPG) or biofuels in Qatar's transportation sector. Several factors influence economic and environmental costs of gasoline, including extraction location, market demand and government policies including certifications, standards as well as global carbon taxes. Global carbon prices are not enforced at this point, and thus are not a variable of this chapter. Final products vary depending on the wellbore and the processing unit, where they are refined and distributed to end customers in the country (Bouoiyour & Selmi, 2019). Diesel fuel in this thesis is solely for HDV and buses, but its supply chain is for the most part comparable to its petrol counterpart. Due to differences in technology, environmental standards and policies, emission factors vary widely for locations around the world. Coupling this

with the country-specific case for Qatar is a first step in providing support for policymakers and involved companies.

Generally, fuel economy has increased (Figure 3.1) with fuel consumption rates decreasing inversely. However, it is important to note that these figures are based on type-approval data from laboratory testing, which may not be representative of real-world driving conditions (ICCT, 2019). The ICCT has extensively studied this issue and found that the gap between type-approval and real-world fuel consumption has been widening over time (Baldino et al., 2017).

Looking at the regional level, vehicle fleets with relatively new and high-standard cars, HDV and buses only see a reduction rate between 0.9% and 1.5% (Figure 3.2). This rate is insufficient to reach the proposed targets of climate neutrality in 2050. Proposed targets range from 50% fuel economy reduction in 2030 to 50% in 2050 and CO2 neutral by 2050 and come from many institutions, from the Qatar National Plan to the UN, IEA, ICCP, Fuel institutes and many national or local consortia. This makes it hard to propose a single fuel or emission scenario for all vehicles. Additionally, it is often unclear if the targets are focused on ICEVs or if it includes a general reduction in emissions by the share of BEVs. In its last issue, the ICCT reported in 2022 that theoretical fuel economies and real-world values are deviating progressively more, and actual fuel consumption can be up to three times more (Plötz et al., 2022).

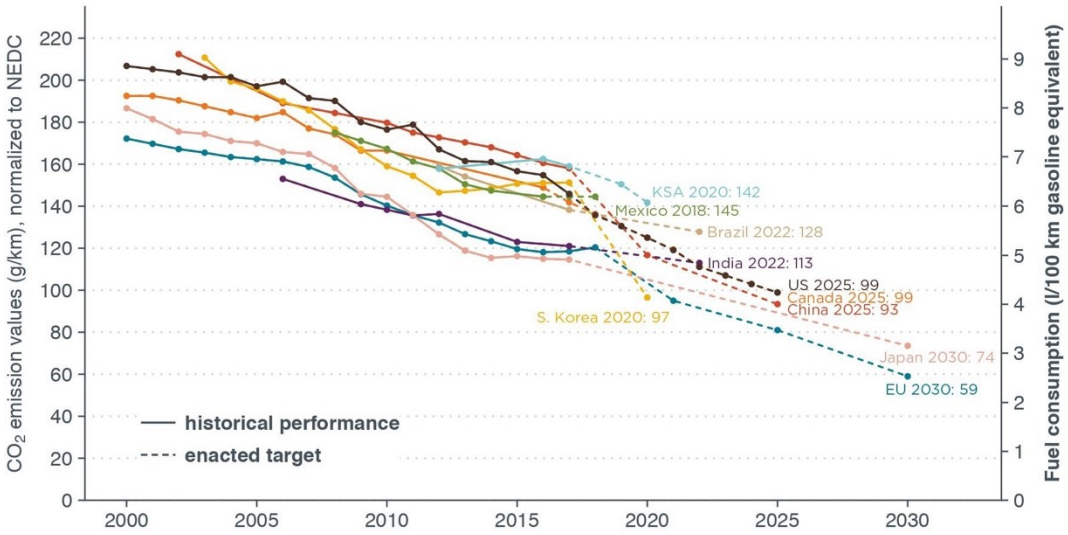

Figure 3.1: Passenger car CO2 emissions and fuel consumption, normalized to New EU Driving Cycle Method (NEDC) (ICCT, 2019).

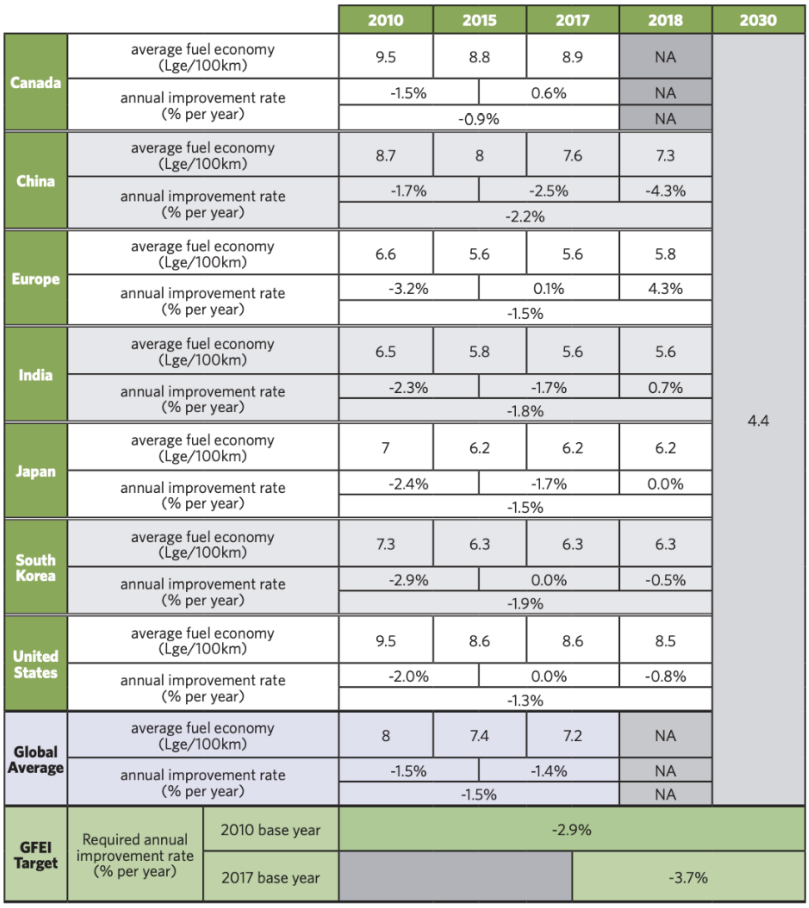

Figure 3.2: Improvements of average fuel economy in various regions and GFEI target for 2030 (Bandivadekar et al., 2020).

According to different studies, emissions from ICEVs in the real world have not improved over the last 10 years, and larger vehicles are even using more fuel (Craglia & Cullen, 2019; Dornoff et al., 2020). On the other hand, between 2020 and 2040, Cox et al. (2020) expects that the efficiency of ICEVs would increase. Together with the historical improvements, both the IEA and GFEI have made extrapolations on the expected fuel economy of LDV, trucks and buses. From the expected values and historical data, it is clear that deviations are seen in comparison to the reference scenario. The IEA introduces varying degrees of ambition in augmenting fuel efficiency in vehicle technologies. The first, referred to as the Stated Policies Scenario, takes into account the implications of pre-existing and declared legislative measures, such as mandates for zero-emission vehicles and the incremental phase-out of fossil fuel-driven engines. The second, known as the Announced Pledges Scenario, extrapolates from global governmental commitments to

climate change mitigation, as per the Paris Agreement and individual national pledges for net-zero emissions. This scenario serves as an investigative exercise to determine potential outcomes based on these global commitments. The third and most ambitious, the Net Zero by 2050 Scenario, aspires to a comprehensive transformation of the energy landscape by 2050, ensuring energy stability, accessibility, and economic viability in the process (Global Fuel Economy Initiative, 2021).

The hierarchy of ambition in these scenarios places the Net Zero by 2050 Scenario at the apex, representing the most aspirational set of objectives. The Announced Pledges Scenario occupies a median position, relying on the fulfillment of global climate commitments. Meanwhile, the Stated Policies Scenario, though less ambitious in comparison, retains an achievable level of ambition.

In terms of practicality and realistic achievability, the Stated Policies Scenario seems the most achievable amongst all three scenarios. It is grounded in extant legal frameworks and current policy directives. This lends it a level of immediacy and actionable clarity that may not be as apparent in the other two scenarios, which could be perceived as unrealistically ambitious and challenging to realize in full. For those reasons, this scenario will be used in this study for future fuel economy improvements.

For the fuel emission factor, both gasoline and diesel are expected to reach global environmental standards and therefore lower overall emissions (Ecoinvent, n.d.). As this study is not purely looking at theoretical improvements, the 2020 GFEI report was used to check for fuel economy improvements from manufacturing locations for Qatar vehicles (Bandivadekar et al., 2020). This is done as it is not feasible to represent all different brands, vehicles, and their specific expected improvements with effect on the overall Qatar fleet. Therefore, these location improvements were linked with the mentioned brands to make an average for Qatar thus more inclusive than just top-selling examples in the LDV range.

In the case of BEVs, the electricity source has to be identified as one of the key emissions during its use phase. One hundred per cent of electricity generated in Qatar comes from natural gas. It

is arguably the most challenging area to balance energy needs against environmental impacts from the continued use of fossil fuels. Comparing locally produced renewable energy, emissions per kWh are lower, yet Qatar has a negligible share of renewables. Based on the latest Kahramaa annual reports, Qatar has an electricity consumption of around 45 billion kWh (45,826 GWh in 2020) per year, the proposed solar plants are not expected to have high impacts. For the improvement rate in weight reduction, the same rate as for ICEV was assumed (1.5%) as global institutes have not presented an agreed-upon value for the BEV sector, and manufacturers are still in the early stages of their production lines. The fuel economy projections were chosen to be comparable to ICEV levels if no values were proposed by the manufacturer or any global institute such as the EPA or GFEI, even if this results in a possibly lower improvement rate.

Impact of air conditioning on vehicle fuel consumption

The VKT and emission factor alone are not enough to perform an accurate calculation for road GHG emissions. One additional factor that must be considered is the effect of Air Conditioning (A/C) on fuel economy. Under non-ideal weather conditions, A/C usage can reduce the fuel economy of an ICEV by up to 25%, and the percentages for HEVs, PHEVs, and BEVs can be higher (Office of Energy Efficiency and Renewable Energy, 2021). In other words, a vehicle operating an A/C uses more energy - and thus more fuel - to travel a specific distance than a vehicle not operating an A/C.

Qatar has one of the warmest climates in the Middle East, and people use A/C in their houses, offices, and vehicles year round. The table below represents the average monthly weather measured since 1962 by the Civil Aviation Authority (Qatar Civil Aviation Authority, 2021):

Table 3.2: Overview of the mean air temperature in Qatar.

Month	Mean Air Temperature (C)
January	17.7
February	18.6
March	21.9
April	26.6
May	32

June	34.7
July	35.5
August	35
September	33
October	29.7
November	24.8
December	19.8

Mean temperature as measured by the Civil Aviation Authority is an average that includes both day and night time temperature. It's reasonable to assume that drivers using their cars predominantly during the daytime hours - as most do - are experiencing temperatures above the mean and using significant A/C.

Two separate studies have investigated the impact of A/C on fuel consumption. The first study, conducted by Oak Ridge National Laboratory in collaboration with the Society of Automotive Engineers (SAE), evaluated the relative fuel consumption penalty associated with A/C use during idle and highway cruise conditions (Huff et al., 2013).

The results for the Corolla indicated that at 64.4 kilometers per hour (kph), the A/C system increases fuel consumption by over 22%, while at 129 kph, the increase is just 5%. In contrast, for the Ford Explorer at 64.4 kph, A/C usage leads to a 27% rise in fuel consumption, but at 121 kph, the increase is limited to 13% (Huff et al., 2013).

In the second study, several ICEVs, HEVs, a PHEV, and a BEV were tested for fuel and energy consumption under test cell conditions of 20°F, 72°F and 95°F. At 20°F, when the vehicle requires heating, the energy consumption increase ranges from 2% to 100% when compared to 72°F. This increase in energy consumption happens mainly during the cold start, when the powertrain losses are maximized. Once the powertrains reach operating temperatures, however, the energy consumption increases are diminished. At 95°F, when the vehicle requires cooling, the energy consumption increase ranges from 2% to 70%. These increases are due to the extra energy

required to run the A/C system to maintain a comfortable 72°F cabin temperature (Lohse-Busch et al., 2013).

The BEV experiences the largest increase in energy need at 20°F, but this is not a relevant concern because heating is generally not needed in Qatar. A BEV does experience an energy increase when cooling (27% and 21% for cold start and hot start respectively), however it is low compared to other vehicle types (Lohse-Busch et al., 2013). Nevertheless, an increase in energy consumption means an increase in fuel consumption and results in higher emissions. Thus, when calculating road emissions, it is important to factor in the impact of A/C usage during different seasons in Qatar to obtain accurate results.

3.2.7 Electricity generation

In this study, the electricity generation mix for Qatar from 2022 to 2050 is assumed to be 100% natural gas, without the inclusion of solar energy or natural gas with CCS. This assumption is based on several factors. Firstly, despite Qatar's significant solar energy potential, the current share of renewable energy in the country's electricity mix is low, and the infrastructure for large-scale solar power generation is not yet in place. Secondly, while CCS technology could potentially reduce the carbon footprint of natural gas-based electricity generation, it is still in the early stages of development globally, and has not been widely deployed locally in Qatar. Moreover, the additional costs and infrastructure requirements associated with CCS may hinder its implementation in the near future. Given these considerations, and the fact that natural gas is abundant and plays a dominant role in Qatar's energy sector, solar energy and natural gas with CCS are excluded from this study.

<u>Impact of vehicle electrification on the grid</u>

A study was conducted in Qatar to investigate the impact of large-scale adoption of BEVs on the country's electricity distribution network. Qatar has the highest consumption of electricity per capita in the world, and peak electricity consumption in the country has been growing by 5-6% in the last decade where the subsidized electricity prices are one of the reasons that have led to this high consumption. The study used stochastic simulations to evaluate different BEV

penetration scenarios based on sales data from Norway, the Netherlands, France, and China, as well as a hypothetical scenario where 10% of all vehicles in Qatar are BEVs. The results showed that the current electric grid can handle the first four scenarios, but in the case of the fifth scenario, where 10% of BEVs are charging simultaneously during peak summer hours (Safak Bayram, 2019). During my meeting with the utility distributor (Kahramaa), Mr. Thomas - the head of the conservation and energy efficiency department - told me that there will be an expansion to the grid capacity in 2022. This added capacity should prepare the grid to handle the worst case scenario outlined above (Kahramaa, 2021). Additionally, the amount of CO2 emissions produced during the generation of one kWh was obtained during this meeting.

Close to the end of 2022, Qatar opened its first solar farm with a generating capacity of 800 MW from photovoltaics (PV). This project is expected to provide more electricity to the grid rather than having to use more natural gas to produce electricity. The study also shows that charging those vehicles from 5 am to 11 am would lessen the peak demand presented by the BEVs. This way, BEV demand can be used to flatten the “duck curve” and reduce the undesired ramping up of natural gas generators in power plants. The work done in this paper shows that the introduction of BEVs in Qatar will not impact the electric grid (Safak Bayram, 2019). Moreover, Kahramaa has also conducted a similar study to measure the impact of BEV charging on the grid. He has assured me that based on his work, if 10% of all vehicles in Qatar were electric, the grid would not be affected. Some of the variables used in this study are mentioned below:

- Electricity demand for BEV: 17 kWh per 100 km
- Average driving distance: 24,000 km per vehicle
- Number of vehicles in the country: 1.5 million vehicles

Finally, all fuel emission factors, electricity emissions and vehicle efficiencies are shown in Table 3.3. The only valid method of lowering the internal direct carbon footprint of fuels is the addition of renewable bio-sources as carbon in a closed loop is not added to the overall footprint. The emission factor of the fuel reflects the overarching improvements to the highest state-of-the-art and therefore lowest emission profile. The fuel and energy consumption is expressed in L/km and

kWh/km in order to allow for easy model implementation and visualization. This way, final carbon footprints can be easily checked as kgCO2/km for both ICEV and BEV by multiplying the emission factor and vehicle efficiency.

Table 3.3: Full emission factors, Fuel efficiencies and energy consumptions for LDV, HDV and buses, 2022-2050.

	2022		2030		2040		2050	
ICEV	Fuel Emission fact. ($kgCO_2/l$)	Vehicle fuel efficiency (km/l)	Fuel Emission fact. ($kgCO_2/l$)	Vehicle fuel efficiency (km/l)	Fuel Emission fact. ($kgCO_2/l$)	Vehicle fuel efficiency (km/l)	Fuel Emission fact. ($kgCO_2/l$)	Vehicle fuel efficiency (km/l)
Sedan	2.855	12.14	2.827	13.69	2.697	16.36	2.539	23.43
SUV	2.855	6.67	2.828	7.52	2.697	8.01	2.539	10.56
Sports vehicle	2.855	10.91	2.828	12.30	2.697	10.30	2.539	16.29
HDV	3.138	2.76	3.099	3.12	3.035	4.92	2.972	5.56
Bus	3.138	2.34	3.099	2.86	3.035	4.65	2.972	4.88
	2022		2030		2040		2050	
BEV	Electricity emission (kg CO2/kWh)	Vehicle fuel efficiency (km/kWh)	Electricity emission (kg CO2/kWh)	Vehicle fuel efficiency (km/kWh)	Electricity emission (kg CO2/kWh)	Vehicle fuel efficiency (km/kWh)	Electricity emission (kg CO2/kWh)	Vehicle fuel efficiency (km/kWh)
Sedan	0.539	6.25	0.478	7.04	0.478	8.20	0.478	9.52
SUV	0.539	5.00	0.478	5.65	0.478	6.58	0.478	7.63
Sports vehicle	0.539	4.55	0.478	5.13	0.478	5.95	0.478	8.74
HDV	0.525	5.00E-01	0.462	5.64E-01	0.462	6.56E-01	0.462	7.63E-01
Bus	0.517	5.71E-01	0.455	6.45E-01	0.455	7.50E-01	0.455	8.73E-01

3.2.8 Ban scenarios

As mentioned, this part will discuss the scenarios of banning ICEV in Qatar by 2030, 2035, and 2040. For each banning date, 5 pathways are developed based on the UK CCC scenarios and then adjusted accordingly for Qatar (Committee on Climate Change, 2020). The vehicle electrification pathways developed for the UK provide a reasonable foundation to inform modeling and analysis

for Qatar, despite differences between the two countries. Firstly, the foundational aspects of vehicle electrification and pathways to decarbonization exhibit a degree of universality, making them applicable to Qatar. Elements such as the declining costs of batteries, the evolving needs for charging infrastructure, and the patterns of consumer adoption are influenced by global market trends and technological advancements. These dynamics are not unique to the UK; they are part of a global shift in the automotive industry towards electrification. Moreover, Qatar's electricity grid mix is reliant on natural gas, which is somewhat similar to the UK's current grid mix. This similarity in the energy landscape suggests that the adoption of BEVs in Qatar may follow a similar trajectory to that projected by the CCC for the UK. Lastly, due to the lack of Qatar-specific BEV adoption scenarios or equivalent projections, the use of the UK CCC scenarios provides a reasonable starting point for assessing the potential impact of BEV uptake in Qatar. While the specific adoption rates may differ due to local factors, the overall trends and patterns can serve as a valuable reference for policy planning and analysis in the Qatari context.

The small geographic size of Qatar enhances the feasibility and appeal of BEVs in the country. In smaller countries, issues such as range anxiety and the development of comprehensive charging infrastructure can be more easily and efficiently addressed. Even though the current share of BEVs in Qatar is almost non-existent, this logistical advantage, coupled with the global shift towards BEVs, makes the transition, once it starts, more manageable and appealing for consumers in Qatar. In addition, the modularity and adaptability of the UK's pathways are key. They are not rigid frameworks but are designed to have a degree of flexibility that can help in other studies. This flexibility allows Qatar to adapt the overarching narrative of the UK's pathways to its own unique context, ensuring that the specific quantitative and qualitative aspects of the transition are tailored to Qatar's specific needs and goals. The 5 pathways are as follows:

- Balanced Pathway: considers developments occur to drive improvements in a balanced manner.
- Widespread Engagement: considers higher levels of behavioral and societal shifts. As a result, individuals and businesses are ready to create more modifications to their lifestyles/operations.

- Tailwinds: considers significant improvements in behavioral and societal actions as efforts go further than the balanced pathway.
- Headwinds: considers that changes only in behavioral societal actions occur in a lesser than anticipated scale.
- Business as usual (BAU): considers the current local trend of no electrification.

Each of the 5 pathways mentioned will be analyzed for each of the three banning scenarios. The graphs below provide a detailed breakdown of the percentage of BEV sales for each pathway in the years 2030, 2035, and 2040:

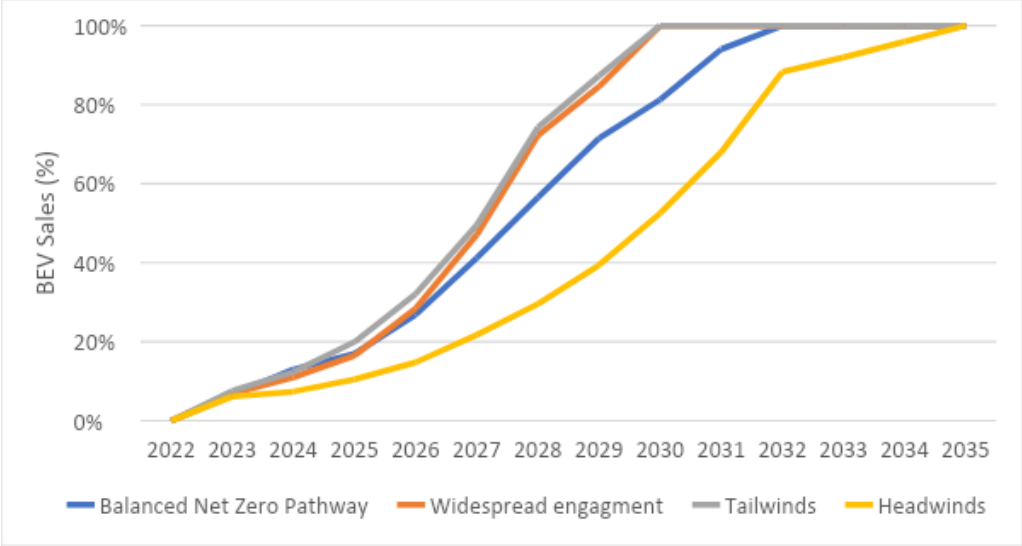

Figure 3.3: Share of BEV sales in order to achieve the ICEV ban goal by 2030.

Both the tailwinds and the widespread engagement pathways result in 100% BEV sales by the 2030 goal, but the tailwinds pathway increases more rapidly in the years leading up to 2030. The balanced net zero pathway starts off as the fastest approach to sales with 13.00% in 2024, but this is followed by a comparatively slower growth rate curve: by the end of 2030, only 81.2% BEV sales would be achieved. Following this pathway would require two additional years to achieve 100% sales. The least favorable pathway for achieving BEV sales by 2030 is headwinds, which is predicted to achieve only slightly more than 50% of BEV sales. By following this pathway, 100% sales would be achievable in 2035, five years later than the other pathways discussed. The lower sales of the headwinds approach indicates the importance of societal actions and demonstrates

their direct correlation with the transition to Battery Electric vehicles. The biggest increase in sales in the headwinds pathway is between 2031-2032, when sales would jump by 20.31%. Though balance of development and improvement is a good approach for transitioning to battery electric vehicles, it lacks the inclusiveness of behavioral and societal parameters, leading to decline in the growth rate of BEV sales.

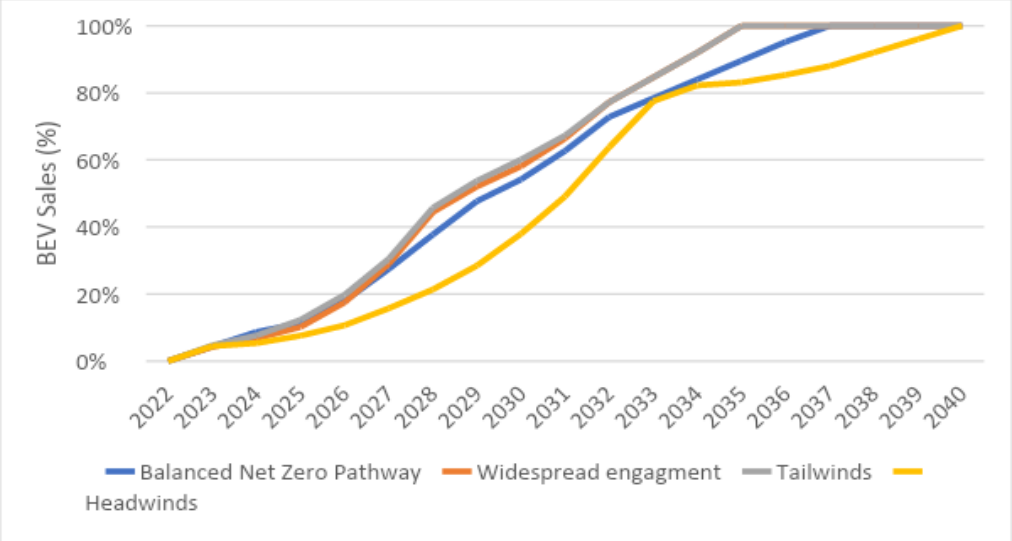

Figure 3.4: Share of BEV sales in order to achieve the ICEV ban goal by 2035.

Considering the 2035 goal, the widespread engagement and tailwinds pathways show strikingly similar results in the share of BEV sales in order to achieve the ICEV ban goal, especially after 2031. Up until 2031, the tailwinds pathway has the higher electrification rates of these two pathways. Headwinds is the least favorable pathway for transition to BEV as it would only achieve 83.11% sales by 2035. In the first year, however, the headwinds pathway barely leads the sales rate from balanced net zero pathway and widespread engagement, coming second only after tailwinds. The worst sales increase of 0.89% between two consecutive years would occur between 2023-2024 and 2034-2035. Balanced net zero pathway would result in 89.60% BEV sales by 2035, which is still a higher rate than headwinds because it optimizes BEV improvement and development. It would achieve 100% sales two years after the 2035 goal. This pathway would do its best sales in 2024, with 1.05% higher sales than the tailwinds pathway. After the initial two

years, the tailwinds pathway would be the best way to achieve maximum BEV sales. No other pathway would beat its sales percentage after 2024.

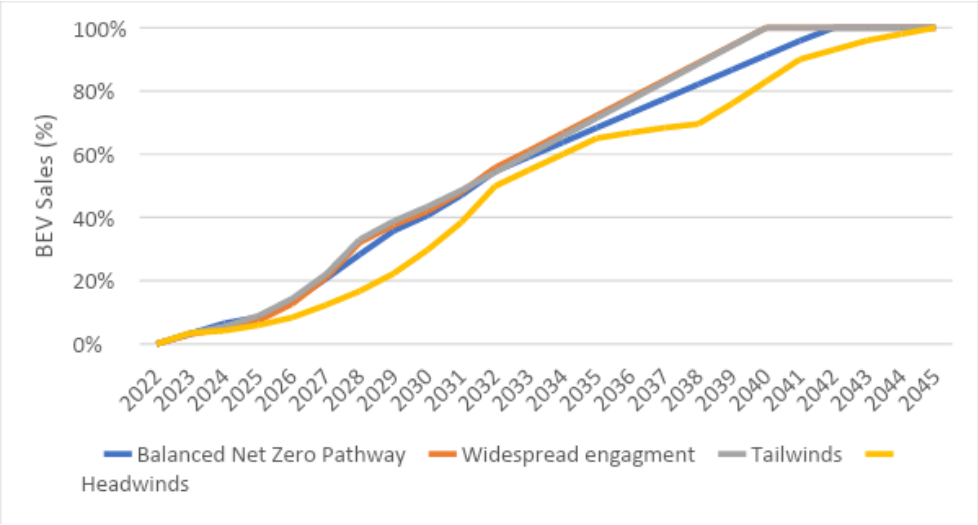

Figure 3.5: Share of BEV sales in order to achieve the ICEV ban goal by 2040.

Complete technology transitions such as the change from ICEV to BEV would require long term planning and involvement of both private and government sectors. However, Qatar's total dependence on carbon-based fuels makes this transition very difficult. In the years leading up to 2040, widespread engagement turns out to be an only slightly better approach than tailwinds, but both pathways will lead to 100% goal attainment of replacement of ICEV with BEV by the target year 2040. The turning point for these two pathways would be in 2032. Up until then, the tailwinds pathway would have higher BEV sale rates, and from 2032 to 2039, widespread engagement would perform better than tailwinds. Balanced net zero pathway would reach 91.29% of BEV sales by 2040 and 100% sales in 2042. This pathway would lead all other pathways in 2024, with 6.50% BEV sales compared to the next highest, tailwinds, with 5.50% BEV sales that year. The best sales increase for the balanced net zero pathway would be between 2027-2028, with a 7.7% increase. All four pathways would reach a 100% BEV goal achievement by 2045, five years after the stated goal. This may indicate the burden on humans and economic loss if the transition to electric vehicles is rushed. Considering the previous scenarios, the 2040 goal is the

only scenario where widespread engagement performs better than the tailwinds pathway for achieving 100% BEV sales.

3.2.9 Kahramaa electrification target

As mentioned earlier, Kahramaa has set a goal to transform 10% of Qatar's LDV vehicle fleet to electric vehicles by 2030. In this research, 4 pathways are created (linear, exponential 1, exponential 2, and s-curve) leading to the year 2030 in which Kahramaa has achieved their national goal. In this section, the project includes two different electrification scenarios. The first scenario presents a future where only sedan vehicles are electrified (SUVs and sports vehicles are still considered ICEVs) as they have reached a higher market maturity rate at the time of this study than SUVs and sports vehicles. The second scenario assumes that the same rate of electrification applies to all LDVs (sedans, SUVs, and sports vehicles).

3.3 Results

The section presents the results of modeling the future road transport fleet under a variety of policies in order to assess potential reductions in GHG and air pollutant emissions. This section will quantify the present GHG and air pollution emissions from road transport in Qatar. The next step is to explore the GHG and air pollution impacts of banning ICEVs by 2030, 2035, and 2040 respectively. Next, this section will investigate the GHG and air quality impacts of Kahramaa's goal of electrifying 10% of the fleet by 2030. Finally, it will project the pathway required to meet the NDC goal of reducing 25% of GHG emissions by 2030 relative to a BAU scenario.

3.3.1 Ban scenario results

Based upon the model characteristics described in the previous chapters, the results will be structured along the 2030, 2035 and 2040 ICEV ban implementations separately. From these ICEV ban alternatives, a comparative analysis can be performed on the overall implications as well as the pathway-specific intricacies. From the calculated results, CO2-eq emissions both on a yearly basis as well as the cumulative emissions for the 4 scenarios and the business as usual (BAU) can be derived. The focus of the results will center around the CO2-eq emissions, NOx and PM2.5 pollutants in order to be in line with available literature.

In regards to the yearly CO2-eq emissions, except for the BAU scenario, all other scenarios show a similar pattern in reducing CO2-eq emissions (Figure 3.6). It can be observed that the slope of the BAU scenario (averaged over the 2020-2050 timeframe) exceeds the reduction potential of the alternative scenarios. More specifically, over this 2020-2050 timeframe, the BAU scenario adds an average of 248 kt CO2-eq yr^{-1} to the modelled emissions. If the focus is put on 2022 up to 2042, a slightly higher slope or increase of the BAU can be observed, coming to an average of 258 kt CO2-eq yr^{-1} emitted more. In comparison, for the alternative scenarios, the results show the desired reversal of this trend with a reduction of the calculated CO2-eq emissions of, on average, 200 kt CO2-eq yr^{-1} (2022-2050) with little variance between pathways.

Moreover, as can be seen from the yearly CO2-eq emissions profile, there is a short timeframe (2026-2030) in which the start of vehicle turnover is quite large and for which emissions are stable. When the rate of decrease is calculated from that moment on, emissions from the ICEV ban would result in an average reduction of 320 kt CO2-eq yr^{-1} in the period 2030-2042. Nonetheless, with a similar rate of reduction and thus a similar endpoint, it is clear that all ICEV ban pathways in this scenario come to a CO2-eq emission in 2050 which is 23% lower than the initial starting point of 2022. The final calculated emissions of these pathways come to 7.42 Mt CO2-eq yr^{-1}. At the same time, the BAU scenario would result in a 61% increase in 2050 compared to 2022, coming to 17.81 Mt CO2-eq yr^{-1}.

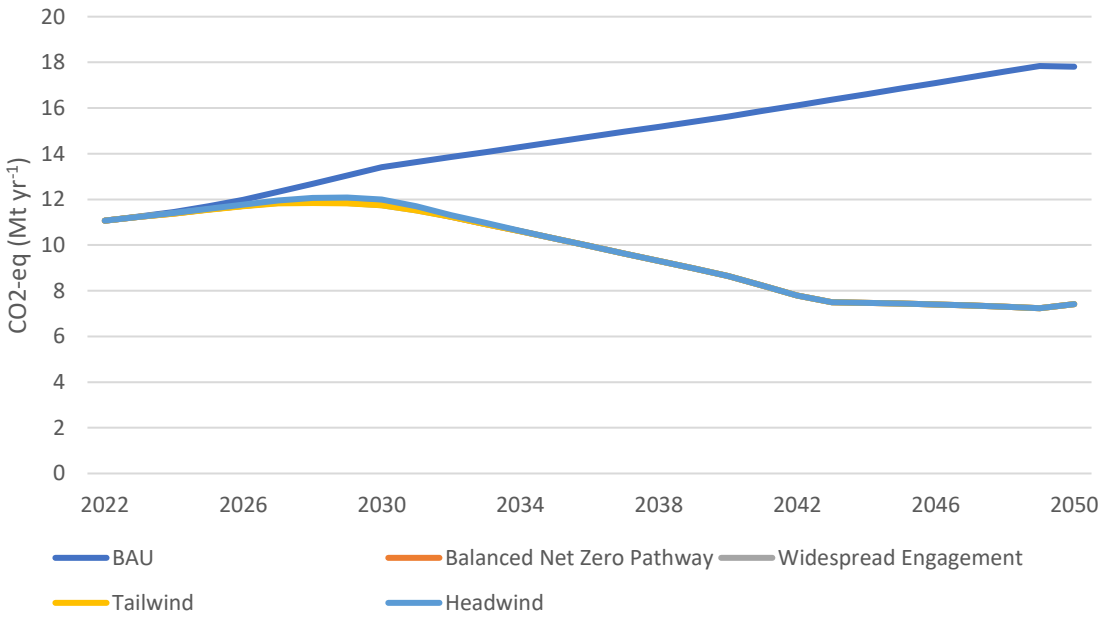

Figure 3.6: Annual CO2-eq emissions corresponding to the alternative scenarios (2030 ICEV ban scenario).

In the same regard, due to the closeness of the CO2 reduction potential of the different alternative pathways, the cumulative CO2 emissions show the same pattern. The 2030 ICEV ban scenario shows the way these policies can curb emissions on a yearly basis as well as reduce the overall cumulative emissions from Qatar. As the emissions from the different pathways (Figure 3.6) have not reached a complete zero-carbon level, cumulative emissions cannot level off by 2050 (Figure 3.7). Nonetheless, introducing the mentioned ICEV ban policies, independent from the pathway, has some visible effects and shows the potential to reduce the cumulative

emissions of Qatar. By 2050, the 2030 ICEV ban would lead to a 34% reduced cumulative emission compared to the BAU scenario. Specifically, this would result in a cumulative CO2-eq emission of 424 Mt yr^{-1} in 2050 in the case of the BAU compared to only 280 Mt CO2-eq yr^{-1} if the ICEV ban were implemented, with negligible differences between the four examined pathways. As described before, this ICEV ban does not result in a complete levelling off of the emissions but proves to be a significant part of the overall solution.

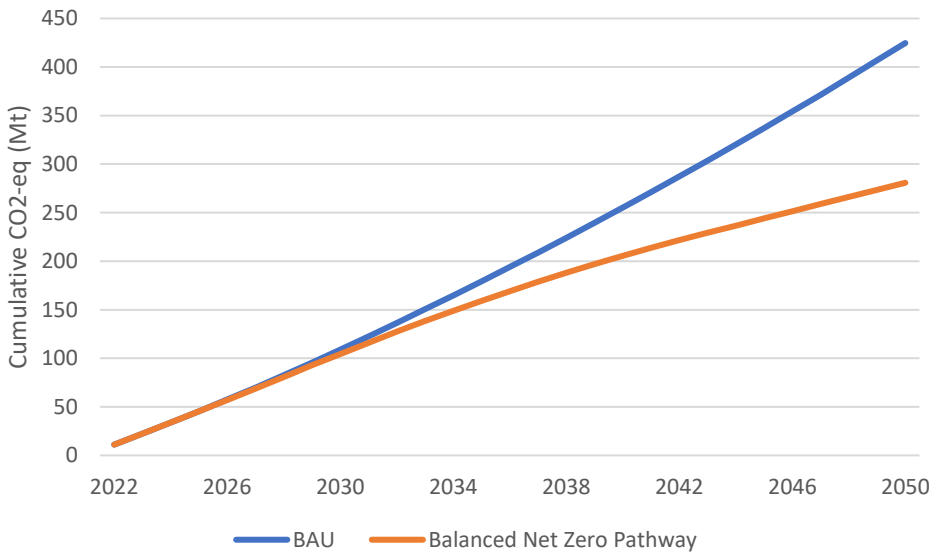

Figure 3.7: Cumulative CO2-eq emissions corresponding to the BAU and Balanced Net Zero pathway (2030 ICEV ban scenario). The other pathways exhibit almost similar trends to the Balanced Net Zero pathway, and thus, have been omitted for clarity.

The ICEV ban is seen to have a potential advantage in the case of NOx and PM2.5 emissions, therefore both the yearly and cumulative emissions were modelled for the 2030 ICEV ban scenario and applicable pathways. While the effects on these pollutants are not as pronounced as those observed for the latter CO2-eq case, they nonetheless contribute to the needed understanding of the environmental impacts and large-scale implications of the BEV transition. Similar to the CO2-eq results, the different pathways show a parallel trajectory, thus the results of the calculations can be discussed generally as the comparison of the BAU pathway in relation to the ICEV ban case.

The analysis of the yearly NOx emissions revealed the strongest improvement trend from the pollutants considered. The ICEV ban scenarios would gradually decrease emissions which would result in 2050 emissions that are 30% lower for all pathways compared to the 2050 BAU emissions. This gradual reduction of the NOx pollutants results in a cumulative emission that is around 20% lower for the ICEV ban pathways in 2050 as would be the case for the 2050 BAU emissions. If the same ICEV ban pathways are calculated for the PM2.5 pollutants, the emissions will be reduced by 12% in 2050 compared to the 2050 BAU pathway. Meanwhile, the cumulative emissions for the ICEV ban pathways are reduced by 9% in relation to the 2050 BAU cumulative results.

A separate calculation was conducted focusing solely on the emissions from newly sold LDVs, allowing for a more targeted analysis of the impact of the ban on this specific segment. Just as for the previous descriptions, the model characteristics remain equal and the reliance on fossil fuels thus of course further impacts these pollutants in the same way. For the emissions over the years up to 2050, the CO2-eq and NOx charts show a comparable trend, as can be seen in Figures 3.8 and 3.9. From these calculations, it is obvious that the ICEV ban makes a significant impact on CO2-eq and NOx emissions, with again Widespread engagement and Tailwind pathways as the first scenarios to reduce the emissions, followed by the Balanced Net Zero Pathway and eventually the Headwind pathway. The time differences between the Tailwind and Headwind scenarios are similarly 5 years with the Balanced pathway in between.

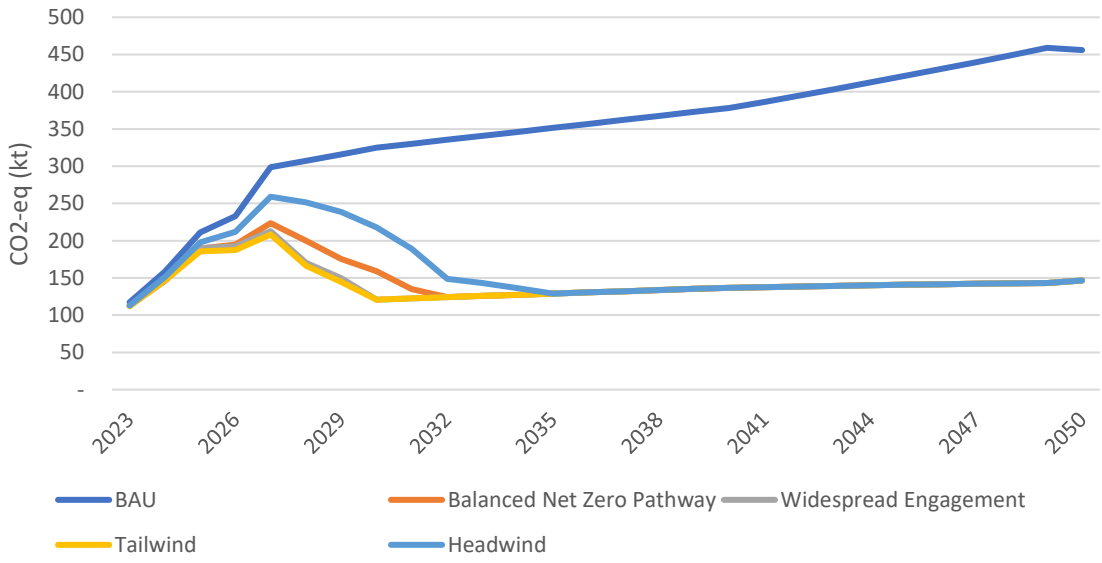

Figure 3.8: Annual CO2-eq emissions, new LDV sales only using 2023 as a starting point, corresponding to the BAU and alternative scenarios.

Compared to the BAU pathway, the ICEV ban results in a CO2-eq emission which is almost 68% lower in 2050 while the NOx emissions would be impacted even more, as the 2050 levels would be reduced by just over 73%. The PM2.5 levels on a year-to-year basis up to 2050 would still improve (Figure 3.10), yet the final reduction in 2050 would only be 15% with little to no difference between the different pathways compared to the 2050 BAU. For the cumulative emissions of the mentioned pollutants, the main improvements are seen for NOx, CO2-eq and on a small scale also for PM2.5. Concerning the BAU model results, NOx, CO2-eq and PM2.5 emissions are reduced with respectively 61%, 56% and 15% in 2050 compared to the BAU emissions for 2050.

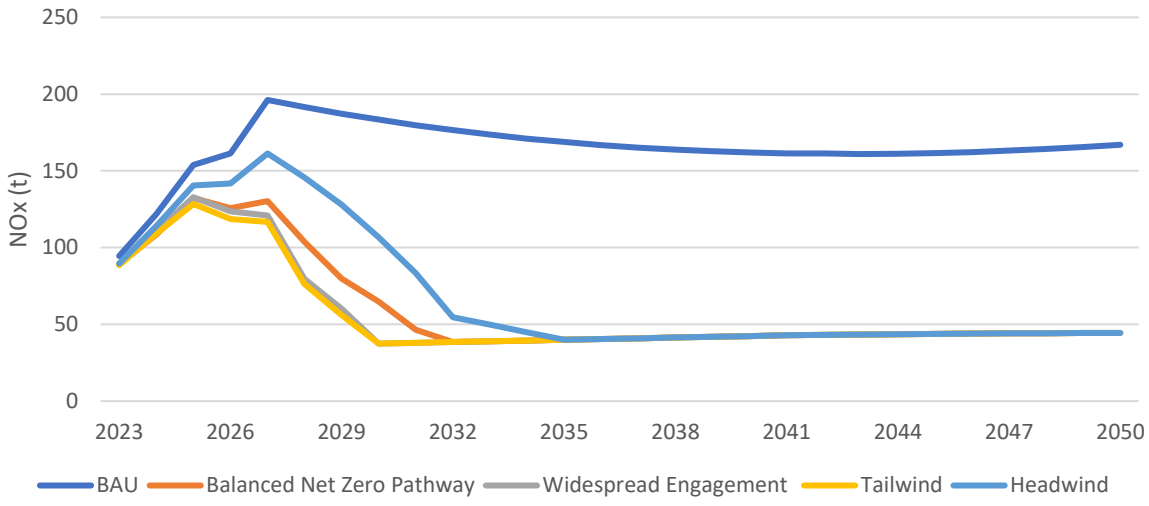

Figure 3.9: Annual NOx emissions, new LDV sales only using 2023 as a starting point, corresponding to the BAU and alternative scenarios.

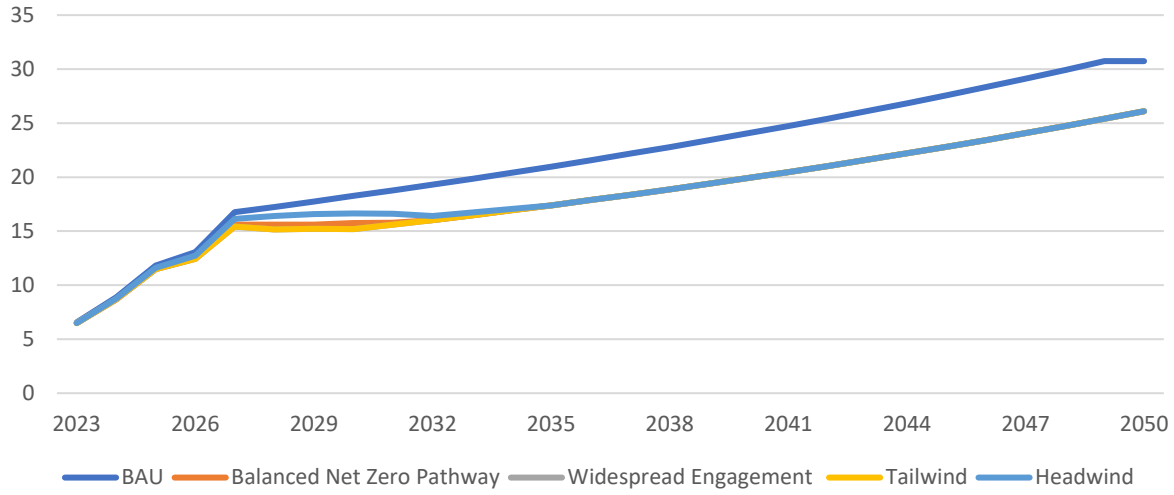

Figure 3.10: Annual PM2.5 emissions, New LDV sales only using 2023 as a starting point, corresponding to the BAU and alternative scenarios.

From the results of the 2030 ICEV ban, likewise, the model was adapted to reflect the ICEV bans for the years 2035 and 2040. With the starting point and the final composition of the model remaining equal, the differences between the ICEV ban scenarios are mainly the adoption rate and the speed at which the system around it changes. Returning to the complete fleet, this leads to the final 2050 emissions coming to 7.42 Mt CO2-eq yr^{-1}. Similarly, the final 2050 values of NOx

and PM2.5 emissions are equal to the results from the 2030 ICEV ban section, namely 9.42 and 1.17 kt yr^{-1} of NOx and PM2.5 emissions. Therefore, the results of the 2030, 2035 and 2040 ICEV bans should be focused on the slopes of the year-to-year emissions, as they represent the amount of change in that timeframe, and the impact the timing itself of the ICEV ban has on the cumulative results.

For this comparison, Figures 3.11 and 3.12 show the main differences of the calculated CO2-eq emissions on a year-to-year basis to interpret the slopes of the ICEV ban timings as well as the cumulative CO2-eq emissions. These figures are the main visualization of the comparison of the BAU and Balanced Net Zero pathway in case of the 2030, 2035 and 2040 ICEV ban implementation.

From the calculations, it can be concluded that respectively for the 2030, 2035 and 2040 ICEV ban, the slope and thus change in emissions is the most significant in the periods 2030-2043, 2032-2045 and 2035-2048. The slopes for the Balanced Net Zero pathways reduce the emissions by 334, 385, and 478 kt CO2-eq yr^{-1} for the 2030, 2035 and 2040 ICEV ban implementations. The final 2050 emissions still result in the previously reported 7.42 Mt CO2-eq yr^{-1}.

Nonetheless, the difference between ICEV ban implementation years shows the needed and sudden implementation of BEVs to achieve the final Balanced Net Zero goal. As laid out before, the moment of this ICEV ban implementation will result in a sudden turnover of ICEVs, yet also influences the overall impact of the cumulative emissions of the pollutants of focus. Later implementation of ICEVs can leave time for a smooth BEV adoption curve, yet reduces the overall potential to mitigate cumulative CO2-eq, NOx and PM2.5 emissions.

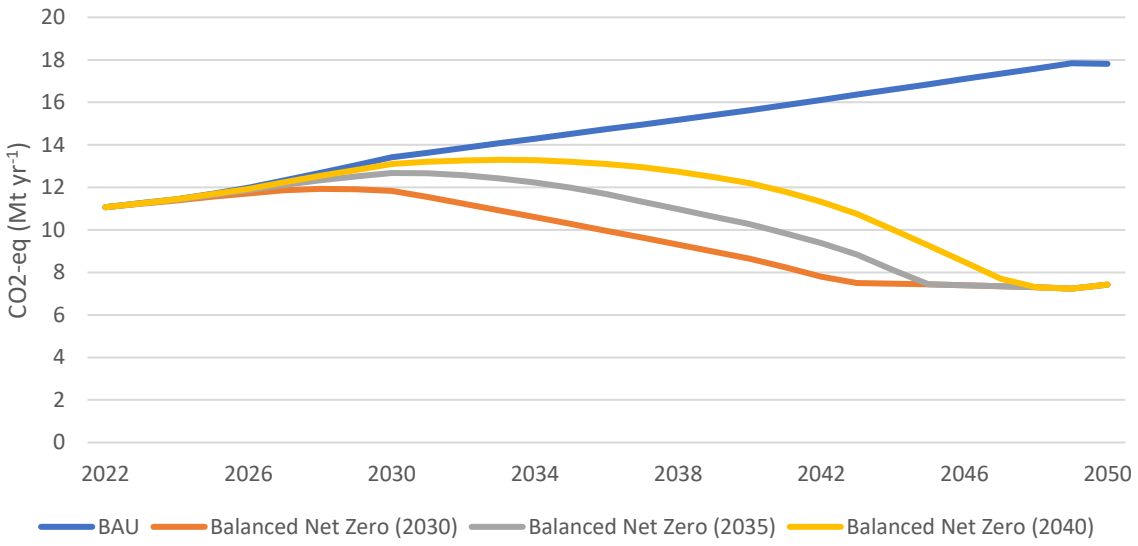

Figure 3.11: Annual CO2-eq emissions, comparison of the BAU and Balanced Net Zero - ICEV ban scenarios.

The cumulative CO2-eq emissions are shown in Figure 3.12, which demonstrates that an early 2030 ICEV ban would reduce the cumulative CO2-eq emissions by 34% in 2050 compared to the BAU scenario. In case the ICEV ban would be introduced in 2035, the potential would be reduced to 28% and only 23% lower compared to the BAU in 2050 if the ban is only enforced by 2040. Specifically, the final cumulative CO2-eq emissions for the 2030, 2035 and 2040 ban scenarios are 280, 304 and 329 Mt of CO2-eq while the BAU comes to a cumulative CO2-eq emission of 425 Mt in 2050.

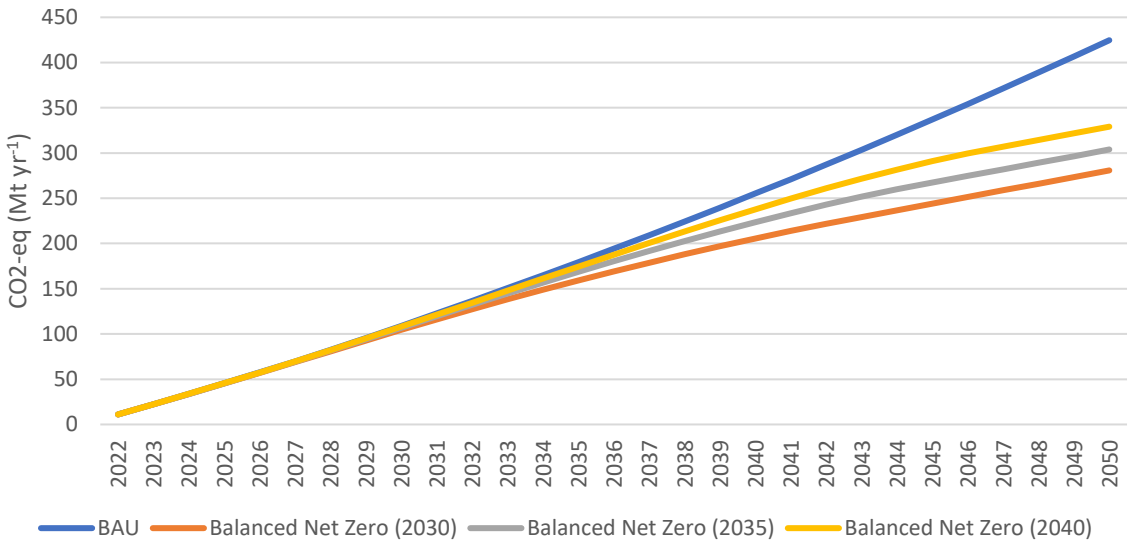

Figure 3.12: Cumulative CO2-eq emissions, comparison of the BAU and Balanced Net Zero - ICEV ban scenarios.

Exemplary of the small difference for new LDV sales only, the cumulative CO2-eq emissions are shown in Figure 3.13. There, it is visible that the ICEV bans still result in significant reductions, but later implementations hinder the final potential. Compared to the BAU scenario, the 2030, 2035 and 2040 ban respectively would reduce the cumulative CO2 emissions in 2050 by 56%, 52% and 47%.

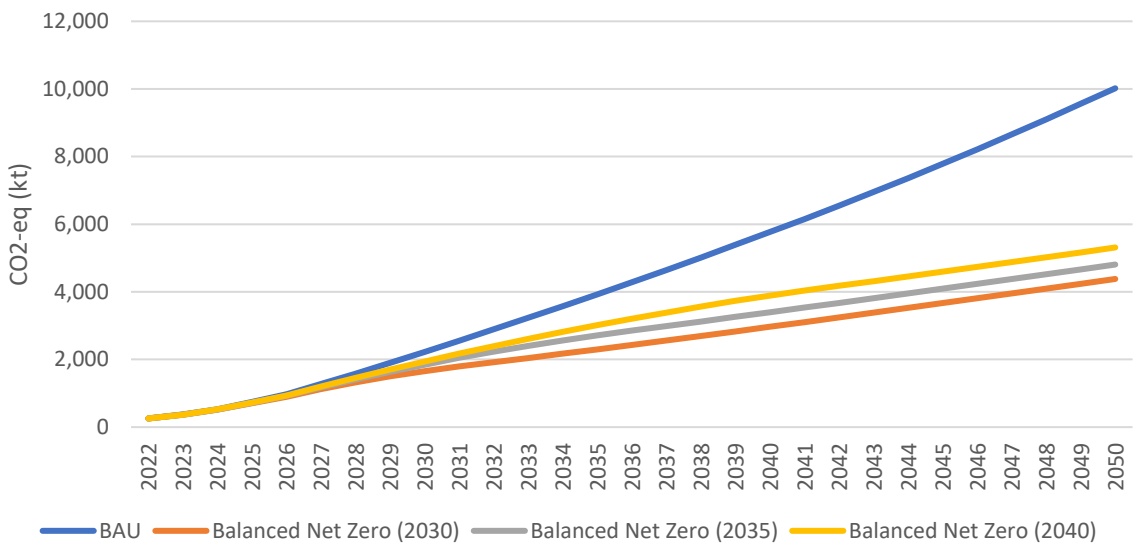

Figure 3.13: Cumulative CO2-eq emissions, comparison of the BAU and Balanced Net Zero - ICEV ban scenarios – new LDV sales only.

3.3.2 Kahramaa electrification target results

The results for this section show that the total CO2-eq emissions will be 13.4 Mt yr^{-1} in 2030 if no electrification occurs to the fleet. If Kahramaa's goal of electrifying 10% of vehicles only applies to sedans (not SUVs or Sport Vehicles), CO2-eq emissions will be reduced to 12.6 Mt yr^{-1} in 2030, which is 0.8 Mt less of CO2-eq emission than the no electrification (BAU) scenario. In the linear pathway, there is a constant increase in CO2-eq emissions reduction beginning from 2022. For example, there would be an increase of 168 kt CO2-eq yr^{-1} emissions reduction between 2022-2023, 203 kt yr^{-1} increase between 2023-2024, and an increase of 169 kt CO2-eq yr^{-1} from 2024-2025.

A similar steady CO2-eq emissions reduction growth trend would be observed in the exponential 1 pathway. For example, there would be 197 kt yr^{-1} increase of CO2-eq between 2022-2023, a 220 kt CO2-eq yr^{-1} increase between 2023-2024, an increase of 178 kt CO2-eq yr^{-1} between 2024-2025, 231 kt yr^{-1} increase between 2025-2026, and an increase in emissions reduction of 289 kt CO2-eq yr^{-1} from 2026-2027. From there, the rate of change becomes almost constant and the following changes would be observed for the next three years: 289 , 288 and 288 kt CO2-eq yr^{-1}

emissions. Another similar trend of constant increases in carbon reduction would be observed with the exponential 2 pathway: 143 kt CO2-eq yr^{-1} between 2022–2023, 228 kt CO2-eq yr^{-1} between 2023-2024, and a dip to 191 kt CO2-eq yr^{-1} emission reduction between 2024-2025.

The s-curve pathway would have the biggest fluctuations in the rate of change in CO2-eq emissions from 2022 until 2030, when 10% electrification of sedans would be accomplished. From 2022-2023, the s-curve pathway follows the biggest increase in rate of change with a 201 kt CO2-eq yr^{-1} increase. Between 2024-2025, the biggest dip in change of CO2-eq concentration is also found on the s-curve pathway with 143 kt CO2-eq yr^{-1} emission. After that year, the rate of change of CO2-eq yr^{-1} emissions is always on the positive side. The biggest change for CO2-eq emissions is also in the S curve pathway: 351 kt yr^{-1} between 2029-2030. The overall progress of the s-curve pathway is highly variable, with the lowest of all the pathways in 2025 and highest in 2030. Exponential 2 follows a similar but reversed trend with big change in 2024, decrease in 2025, growth until 2027, and decreased growth rate again until 2030. If Kahramaa's goal of electrifying 10% of the fleet is achieved, 1.62 Mt CO2-eq yr^{-1} emissions will be avoided by the year 2030 on average.

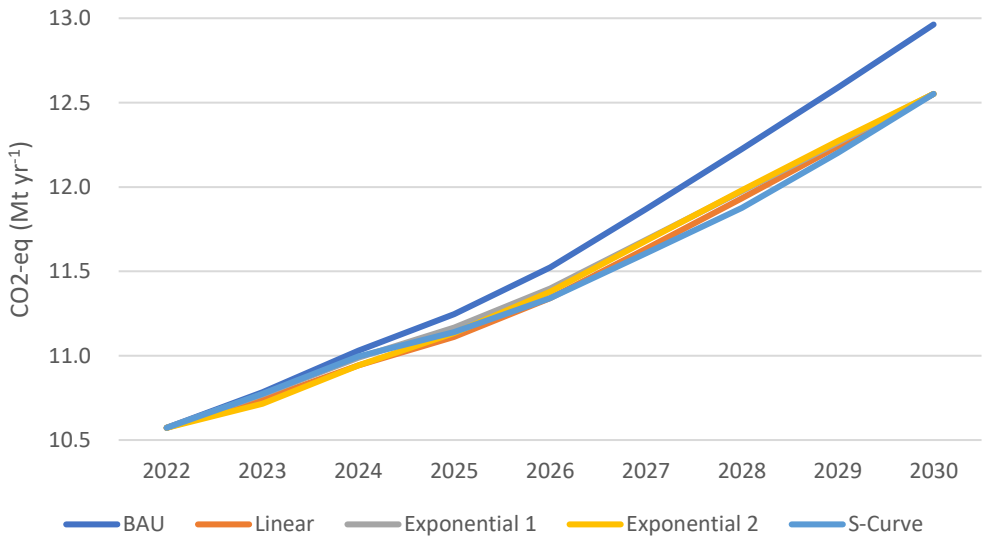

Figure 3.14: Annual CO2-eq emissions from electrifying 10% of sedans by 2030.

On the other hand, with 10% electrification of all vehicle types by Kahramaa, including SUVs and sports vehicles, CO2-eq emissions will be reduced to 12.4 Mt yr^{-1}, which is 564 kt less of CO2-eq yr^{-1} emissions than without electrification. The 10% electrification of all vehicles, including sports vehicles and SUVs, cut down the CO2-eq emissions by an additional 153 kt yr^{-1} more than the reduction from sedans alone. From this, it is observed that sedans are the biggest GHG emitter out of the three vehicle groups as electrifying 10% of sedans alone cut down the CO2-eq emissions by 411 kt yr^{-1}, which is almost 2.7 times the emissions reduction achieved by both sports and SUVs.

In this scenario of distributed electrification, the linear pathway is moderate with its rate of change of CO2-eq falling between the exponential 2 and s-curve pathways. The growth rate curve follows the trend of increasing-decreasing-increasing, with the biggest dip in change in CO2-eq emissions between 2024-2025, followed by the highest change in growth rate of 290 kt CO2-eq yr^{-1} between 2029-2030. At the end of 2030, the linear pathway change of CO2-eq would be only behind the s-curve change. The trends of exponential 1 pathway follow almost the same pattern, except after 2026, the change in trend would be decreasing instead of increasing. The exponential 2 pathway would again have a highly variable growth rate, with the least emissions of CO2-eq in 2023. Then, emissions would be highest among the four pathways in the exponential 2 pathway, with 220 kt CO2-eq yr^{-1} increase between 2023-2024. The rate of change of CO2-eq emissions would again be highest in the exponential 2 pathway from 2025 to 2027, with 233 and 286 kt yr^{-1}, respectively. The rate of change of CO2-eq emissions would be lowest in this pathway from 2027 to 2030, with the least change of 245 kt yr^{-1} between 2029-2030. This indicates a decline in rate of change of emissions of CO2-eq in the exponential 2 pathway, whereas all other three pathways follow an increasing trend in the last three years. Therefore, the exponential 2 pathway is a better contender for achieving reduced CO2-eq emissions within the given timeline.

The rate of change of CO2-eq emissions would be highest in the s-curve in 2023, with 197 kt CO2-eq yr^{-1} emissions. The highest decline in the change in CO2-eq emissions would be in the s-curve in between 2024-2025 with only 117 kt CO2-eq yr^{-1} emissions. However, the trend follows a sharp increase in emissions after that, leading to higher emissions than other pathways. Consequently,

the s-curve pathway would not be recommended because its emissions are lowest only in the first three years, after which it follows a sharp inclined peak of CO2-eq emissions. On average the accumulative amount of avoided CO2-eq emissions if Kahramaa's target is achieved is 2.22 Mt.

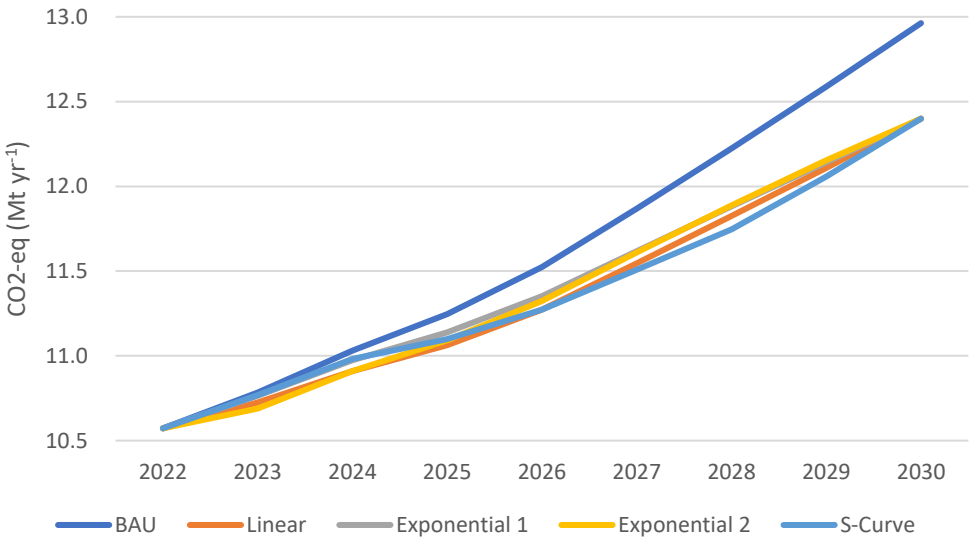

Figure 3.15: Annual CO2-eq emissions from electrifying 10% of the fleet by 2030.

3.3.3 Reducing road emissions by 25%

Qatar's NDC goals target a 25% reduction in GHG emissions by 2030, relative to a BAU scenario that projects emissions at 13.4 Mt CO2-eq yr^{-1}. This target stipulates a reduction to Mt CO2-eq yr^{-1} to align with the NDC objectives, demonstrating an unprecedented commitment to tackling the global climate crisis and securing a sustainable future.

However, projections indicate that even with the implementation of a 2030 ICEV ban, Qatar's efforts will fall short of this ambitious target. In the scenario considering a Balanced Net Zero pathway for 2030, emissions are anticipated to reach 11.8 Mt CO2-eq yr^{-1}, marking approximately a 12% decrease in emissions from the BAU scenario, rather than the aimed 25%. This discrepancy demonstrates the challenges faced by Qatar in meeting its NDC goals within the stipulated timeframe and highlights the need for enhanced strategies and measures to accelerate the reduction of GHG emissions in the road transport sector in order to achieve the desired reductions.

This section undertakes the task of finding the configuration of vehicles necessary in Qatar by the year 2030 to achieve the stated emissions reduction target. The analysis will include an exploration of the number of BEVs required to replace conventional vehicles to affect the desired reduction in emissions.

As Qatar aims to reduce its GHG emissions by 25% by 2030, the fleet composition prescribed in Figure 3.17 could be used to meet this goal. The proposed changes to Qatar's vehicle fleet include the introduction of a high number of BEVs: 1,978 BEV buses, 13,934 ICEV HDVs, 90,393 ICEV SUVs, 70,259 ICEV sports vehicles, and the largest increase, 148,347 ICEV sedans. Clearly, sedans would play a major role in the GHG and air pollution in 2030 because they would be the most common vehicles on the road by that time. Even in 2022, if we combine all other vehicles in Qatar, the number of total transport entities, including BEV buses, BEV SUV, BEV sports vehicles, BEV sedans, ICEV buses, ICEV HDV, ICEV SUVs and ICEV sports vehicles, is 802,147. ICEV sedans make up 84.65% of these total vehicles. The total number of vehicles in 2030 without ICEV sedans would be 977,385; with ICEV sedans, the total vehicle count would rise to 827,402. The

percentage of ICEV sedan to total vehicles (84.65%) remains the same. The three transport vehicle types containing the most potential to reach the 25% less emissions goal would be the BEV private transport, i.e. BEV SUV, BEV sports vehicles and BEV sedans, meaning there is a lot of opportunity for this market to grow.

With the number of BEV buses remaining the same, Qatar needs to increase the BEV in SUV, Sports vehicles, and sedans by 116,096, 90,235 and 190,526, respectively. While BEV needs to be introduced in the market, the ICEV, including ICEV buses and HDV, can remain the same. Already there are 849 more buses running on electric batteries than on internal combustion engines, so not much change is required in this sector. Also, if we compare the number of buses in 2022 and 2030, the ICEV buses decreased by 1,327 in 2030. On the other hand, there were only 262 BEV buses in 2022 but 2,240 BEV buses in 2030, representing a huge increase of 854.9%.

The major change required for achieving the 25% reduction target is a decrease in the number of ICEV private vehicles and an increase in BEV private vehicles. ICEV SUVs, ICEV sports vehicles and ICEV sedans need to decrease by 203,531, 158,194 and 334,016, respectively. This indicates a decrease of 40.36% among all three categories of private vehicles. To achieve this, it needs to be incorporated into societal and behavioral changes and modifications in business and operations. Clearly, the biggest indicator is the decline of ICEV sedans, sports vehicles, and SUVs along with enhancement in BEV sedans, sports vehicles, and SUVs. The increase in the number of BEV SUVs, sports vehicles and sedans would be 116,096, 90,235 and 190,526, respectively. The numbers are huge but necessary for achieving the desired target of emission reductions. This would be a challenging task as there would be no initial market of BEV vehicles in this category, but also it would create new opportunities for companies to invest. ICEV buses and HDV would not play much of a role in emission reduction, so they can continue with the same number of vehicles.

The major changes required in the increasing order of their importance would be: ICEV sedans, ICEV SUVs, BEV sedans, ICEV sports vehicles, BEV SUV, and BEV sports vehicles. The higher the number of a particular type of vehicle on the road, the more they can influence the emissions of both GHGs and air pollution. Given this, policymakers can take into account the number of vehicles of particular type when making policies for emission reductions. To conclude, ICEV

sedans would play a major role in emission reduction on road transport in Qatar and should be seriously considered by policymakers.

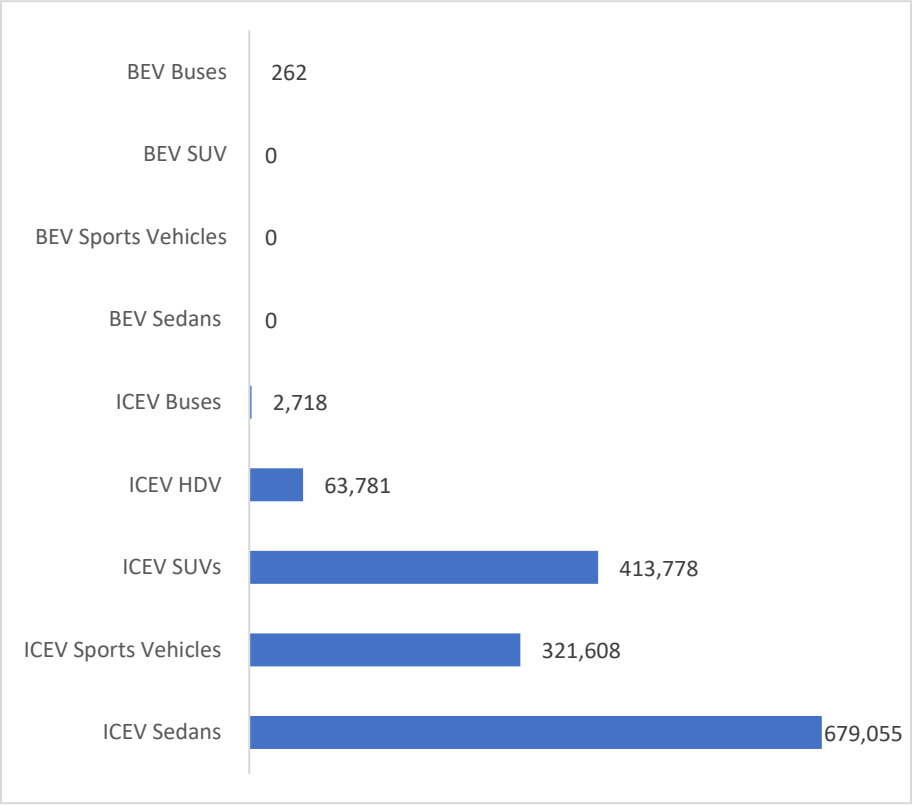

Figure 3.16: Vehicle fleet composition in 2022.

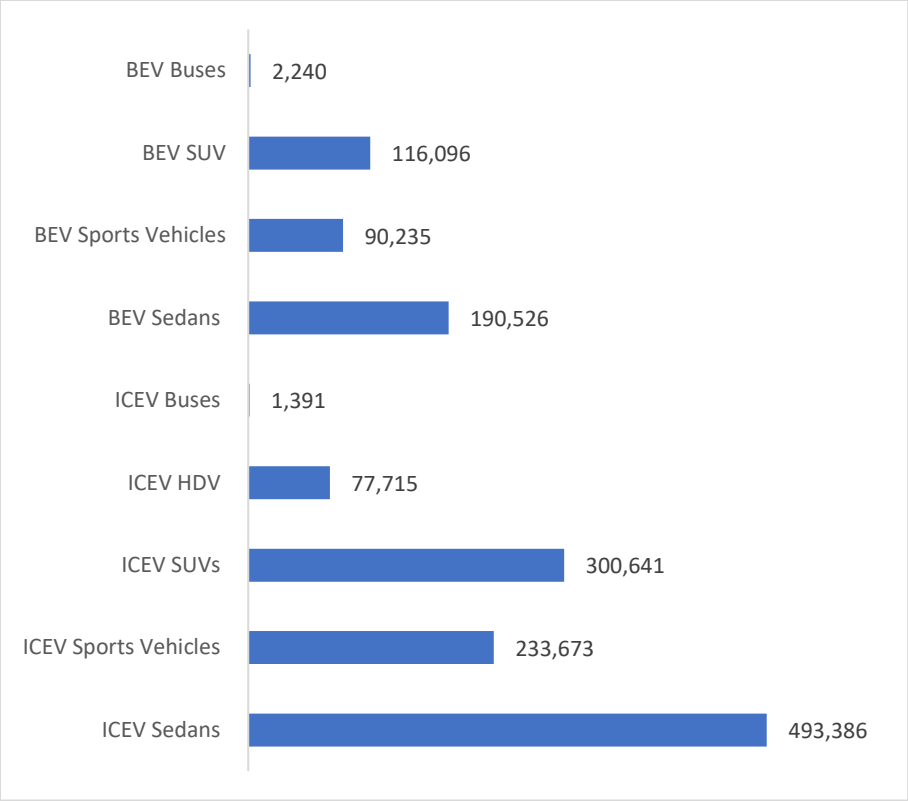

Figure 3.17: Vehicle fleet composition in 2030 required to reach the 25% CO2-eq reduction goal.

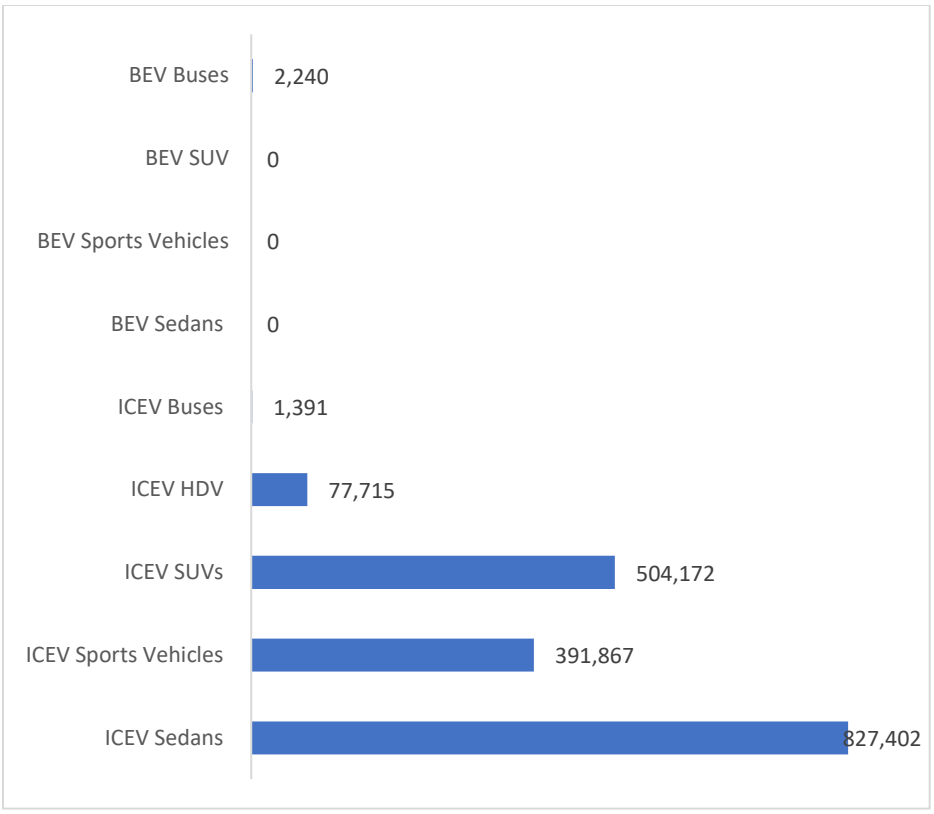

Figure 3.18: Vehicle fleet composition in 2030 in a no electrification scenario.

3.4 Sensitivity study

3.4.1 Introduction

Sensitivity analysis stands as an important tool in policy analysis and environmental planning, providing insights into how variations in inputs can influence results that in turn can affect policy decisions. This section introduces the concept and importance of sensitivity analysis, with a focus on its application to evaluating the implications of Qatar's road transport policies on GHG emissions. The One-at-a-Time (OAT) approach, recognized for its simplicity and efficacy, is highlighted as the chosen method for this analysis. Unlike multivariate techniques that alter several inputs simultaneously, the OAT approach varies one input at a time while keeping others constant, thereby isolating the effects of individual inputs on the outcome (Kim, 2016). This method is particularly suited to the context of Qatar's transition to electrified mobility, where it helps understand how specific policy decisions—such as the overall distance travelled, fuel economy of vehicles, and other factors—can impact environmental outcomes.

The primary objective of conducting a sensitivity analysis within the framework of Qatar's transition to electrified mobility is to systematically evaluate how variations in key inputs influence the outcomes related to GHG emissions. This analysis aims to identify which aspect holds the most sway over emissions reductions, thereby guiding strategic decisions and resource allocation. Through these objectives, the sensitivity analysis contributes to the refinement of policy measures, ensuring they are both effective in reducing emissions and flexible enough to adapt to evolving circumstances.

3.4.2 Method

The OAT sensitivity analysis varies one input at a time, using historical data, technology projections, and emissions models to quantitatively assess how changes in key factors like vehicle distance, fuel economy, and transportation policies impact GHG emissions from the transportation sector. The sensitivity analysis for Qatar's transition to electrified mobility investigates the impact of four key inputs – number of vehicles, distance travelled, vehicle fuel economy, and electricity emission factor - on CO2-eq emissions, varying each independently to assess their individual effects on the road transport sector's environmental outcomes. In this analysis, the changes in the inputs are assumed to occur from 2022 onwards.

Number of vehicles

The vehicle number directly influences emissions by altering the total number of vehicles on the road. An increase in vehicle numbers, without a corresponding rise in BEV adoption, could potentially negate the emissions benefits gained from electrification. Conversely, a decrease, or a shift towards electric vehicles, can significantly reduce overall emissions.

The OAT sensitivity analysis, which involved varying the number of vehicles by introducing a lower and upper bound (±10%), informs about the impact of vehicle numbers on CO2-eq emissions. The lower bound scenario, where the number of vehicles is reduced by 10%, demonstrates the potential for emissions reductions. This decrease in vehicle numbers could be achieved through various policy measures, such as promoting public transportation, encouraging carpooling, or implementing urban planning strategies that reduce the need for personal vehicle ownership. On the other hand, the upper bound scenario, where the number of vehicles is increased by 10%, highlights the potential risks associated with unchecked growth in vehicle ownership. If the number of vehicles on the road continues to rise, the emissions would naturally increase as well. This shows the importance of implementing policies that not only promote the adoption of BEVs but also manage the overall growth of the vehicle fleet.

Distance travelled

Change in distance travelled reflects the mobility patterns within Qatar and is a crucial factor in determining emissions. The OAT sensitivity analysis, which involved introducing lower and upper bounds for the distance travelled per vehicle, showing how variations in mobility patterns can impact CO2-eq emissions in Qatar.

For the lower bound, the analysis utilized data from the Odyssee-Mure project, which showed a decrease in distance travelled by car between 2000 and 2019 in most European countries, with an average reduction of around 1,700 km/year at the EU level. By taking the average VKT per vehicle of several European countries (Austria, Germany, the Netherlands, France, Greece, EU, and Spain) and comparing it to the VKT used for Qatar in this study, a percentage decrease was obtained and applied to the OAT analysis (Odyssee-Mure, 2023). This lower bound scenario demonstrates the potential for emissions reductions through decreased mobility.

On the other hand, the upper bound scenario was based on data from U.S. states where Americans drive the most, specifically Wyoming, Mississippi, New Mexico, Missouri, and Georgia (Meyer, 2024). By taking the average VKT per vehicle of these states and comparing it to the VKT used for Qatar, a percentage increase was obtained and applied to the OAT analysis. This upper bound scenario highlights the potential risks associated with increased mobility and higher VKT per vehicle.

Fuel economy

Vehicle fuel economy is pivotal because improvements in this area for vehicles can lead to reductions in CO2-eq emissions. A paper by Wi & Park (2013) analyzes the uncertainty in evaluating vehicle fuel economy using the FTP-75 test procedure. The study employed vehicle simulations conducted using the AVL CRUISE software to model the engine, transmission, drivetrain, and other components. The models were validated against vehicle test data. Different driving profiles were created to examine the impact on fuel economy. These profiles included driving at the highest and lowest allowable speeds per the test tolerance, driving with maximum and minimum allowable acceleration/deceleration, and driving with periodic speed variation from the target speed.

The results showed that driving at the highest allowed speed improved fuel economy by 2.7% while driving at the lowest speed reduced it by 3.0% compared to the base case. Maximum acceleration reduced fuel economy by 6.8% while minimum acceleration improved it by 5.0%, indicating that acceleration has a bigger impact than speed. Periodic speed changes of higher amplitude and frequency significantly reduced fuel economy, by over 8% in the worst case (Wi & Park, 2013). For this sensitivity analysis, the highest improvement (5%) and deteriorating rate (8%) are selected in order to show the impacts of fuel economy on the results.

Adopting these values ensures that the study considers the most significant sources of uncertainty in fuel economy evaluation. By using these highest and lowest values, the study will be able to capture the full range of potential fuel economy variations that can occur within the permissible limits of the FTP-75 test procedure. This approach is conservative and provides a robust assessment of the potential impact of driving patterns on fuel economy. Furthermore, using these values aligns with the paper's suggestion to consider additional rules to regulate these uncertainties, as they demonstrate the need to address the substantial influence of driving patterns on fuel economy results.

Electricity emission factor

The electricity emission factor is a critical input especially for BEVs. This factor measures the amount of CO2-eq emissions produced per unit of electricity consumed. A lower emissions factor signifies that the electricity used to charge BEVs generates fewer emissions, making BEVs an increasingly cleaner option compared to ICEVs. For the lower bound of the electricity emission factor in the OAT sensitivity analysis, this study considers the potential impact of the Alkharsaah solar project on Qatar's electricity mix. The Alkharsaah project is expected to generate 10% of Qatar's electricity, and by incorporating this project into the electricity grid, Qatar aims to reduce its reliance on carbon-intensive energy sources, primarily natural gas (TotalEnergies, 2022). Choosing the 10% figure based on the Alkharsaah project's planned capacity provides a more careful foundation for the sensitivity analysis, as it avoids relying on arbitrary assumptions and aligns with the available data on Qatar's solar energy development. This shift would effectively improve the electricity mix by reducing the proportion of fossil fuel-based generation. As a result,

the overall emission factor of Qatar's electricity supply would decrease, as solar energy has a significantly lower carbon footprint compared to natural gas.

For the purpose of this sensitivity analysis, this study calculated that the Alkharsaah solar project will improve the electricity mix by 9.6%. This value is used as the lower bound for the OAT analysis, representing a scenario where the successful implementation of the Alkharsaah project leads to a tangible reduction in the electricity emission factor.

For the upper bound, a 20% increase from the current electricity emission factor of 0.539 kg/kWh is selected, setting it at approximately 0.647 kg/kWh. This adjustment accounts for potential shifts towards more carbon-intensive energy sources or scenarios where current efforts to reduce emissions plateau or face setbacks. Natural gas remains central to electricity generation in many regions including Qatar. This reliance is often reinforced by economic growth, which escalates energy demand, particularly in expanding industrial sectors. As economies expand, the urgency to meet this demand occasionally outstrips the pace at which renewable energy sources are integrated into the national grids.

Another reason for a potential increase in the emission factor is the variability in the efficiency of natural gas power plants. Older, less efficient plants may be called upon to meet rising energy demands, leading to higher emissions per unit of electricity generated. Additionally, changes in natural gas quality, such as the use of gas with higher carbon content or lower methane content, could result in increased emissions. Furthermore, the emission factor could be affected by the operating conditions of the natural gas power plants. For instance, plants operating at part-load or during start-up and shut-down phases may have higher emission rates compared to optimal baseload operation. Lastly, any leakages or fugitive emissions along the natural gas supply chain, from extraction to transportation and storage, could contribute to an overall increase in the emission factor.

Considering these potential factors, a 20% increase in the electricity emission factor represents a reasonable upper bound for the sensitivity analysis, accounting for the possible variations in natural gas quality, power plant efficiency, operating conditions, and supply chain emissions that

could impact the overall emissions intensity of the electricity generated from natural gas. This approach ensures that the analysis remains grounded in plausible future states, showing how different emission factors could impact outcomes, thus aiding the planning and decision-making processes.

By analyzing these inputs through the OAT sensitivity analysis approach, it is possible to set the most influential factors in reducing transportation emissions within Qatar. This analysis not only aids in identifying the leverage points within the transport sector for emissions reduction but also informs the prioritization of policy interventions to achieve Qatar's ambitious environmental targets.

3.4.3 Sensitivity study results

The findings from the OAT sensitivity analysis provide a look into how fluctuations in key input assumptions can affect CO2-eq emissions. The analysis conducted for the number of vehicles within the context of the 2030 ICEV ban under the Balanced Net Zero Pathway has yielded results that closely correlate the number of vehicles with CO2-eq emissions. For the number of vehicles, the analysis indicates a lower bound percentage decrease of approximately 10%, reducing the emissions to 9.96 Mt CO2-eq yr^{-1}. The upper bound analysis reveals a percentage increase of roughly 10.06%, raising emissions to 12.18 Mt CO2-eq yr^{-1}. Specifically, a decrease in the number of vehicles by 10% results in equivalent reduction in CO2-eq emissions, likewise for the increase. This one-to-one ratio indicates a direct and proportional relationship between the number of vehicles on the road and the resultant emissions.

This outcome is indicative of the impact that vehicle quantity has on overall emissions. It suggests that policies directly influencing the number of vehicles in circulation, whether through restrictions or incentives for reduction, can have a directly proportional effect on emission levels. The findings reinforce the role that vehicle population control measures, such as incentives for carpooling, public transportation usage, and limitations on vehicle registrations, could play in achieving Qatar's emissions reduction targets.

The analysis which examined the impact of changes in distance travelled on CO2-eq emissions yielded the largest range of results. For the lower bound, the study utilized data from Odyssee-Mure resulted in a 53.82% decrease in emissions, reducing the total to 5.11 Mt CO2-eq yr^{-1}. Conversely, the upper bound scenario resulted in a 22.35% increase in emissions, raising the total to 13.54 Mt CO2-eq yr^{-1}. These results underscore the significant influence of distance travelled on CO2-eq emissions and emphasize the importance of implementing policies that encourage sustainable mobility choices and reduce overall VKT to achieve emissions reductions.

For fuel economy, the results of the sensitivity analysis suggest that improvements in fuel economy can lead to significant reductions in CO2-eq emissions, although the impact is less pronounced compared to the number of vehicles or the distance travelled. Fuel Economy

changes result in a lower bound decrease of 3.85%, reducing emissions to 10.64 Mt CO2-eq yr^{-1}, whereas the upper bound entails an increase of 7.17%, with emissions climbing to 11.86 Mt CO2-eq yr^{-1}. On the other hand, in 2022, the electricity emission factor remained constant at 11.07 Mt CO2-eq yr^{-1}, showing no change from the original result. The lack of variation in the electricity emission factor can be attributed to the fact that, at this point in time, no electric vehicles are being deployed in Qatar, as the ban on ICEVs has not yet taken effect. Consequently, the share of electricity in the transportation sector's energy mix remains unchanged, and the emission factor associated with electricity production does not influence the overall CO2-eq emissions from transportation.

The results for the years 2030, 2040, and 2050 demonstrate the evolving impact of the four key inputs on CO2-eq emissions under the Balanced Net Zero Pathway for the 2030 ICEV ban. In 2030, distance travelled continues to exhibit the most significant influence, with a 53.79% decrease for the lower bound and a 22.40% increase for the upper bound. The number of vehicles and fuel economy show moderate changes, while the electricity emission factor has a relatively small impact. By 2040, the electricity emission factor's influence grows, with a 4.73% decrease for the lower bound and an 8.81% increase for the upper bound, reflecting the increasing importance of the electricity mix as the vehicle fleet becomes more electrified. Distance travelled remains the most influential input, while the number of vehicles and fuel economy show slightly smaller changes compared to 2030. In 2050, the electricity emission factor becomes even more significant, with a 6.34% decrease for the lower bound and an 11.18% increase for the upper bound. Distance travelled still has the largest impact, while the number of vehicles and fuel economy show further reduced changes. These results highlight the shifting dynamics of CO2-eq emissions over time, with the electricity emission factor becoming increasingly crucial as the transportation sector transitions towards electrification. Policymakers must adapt their strategies accordingly, focusing on reducing VKT, improving vehicle efficiency, and decarbonizing the electricity grid to achieve long-term emissions reduction goals.

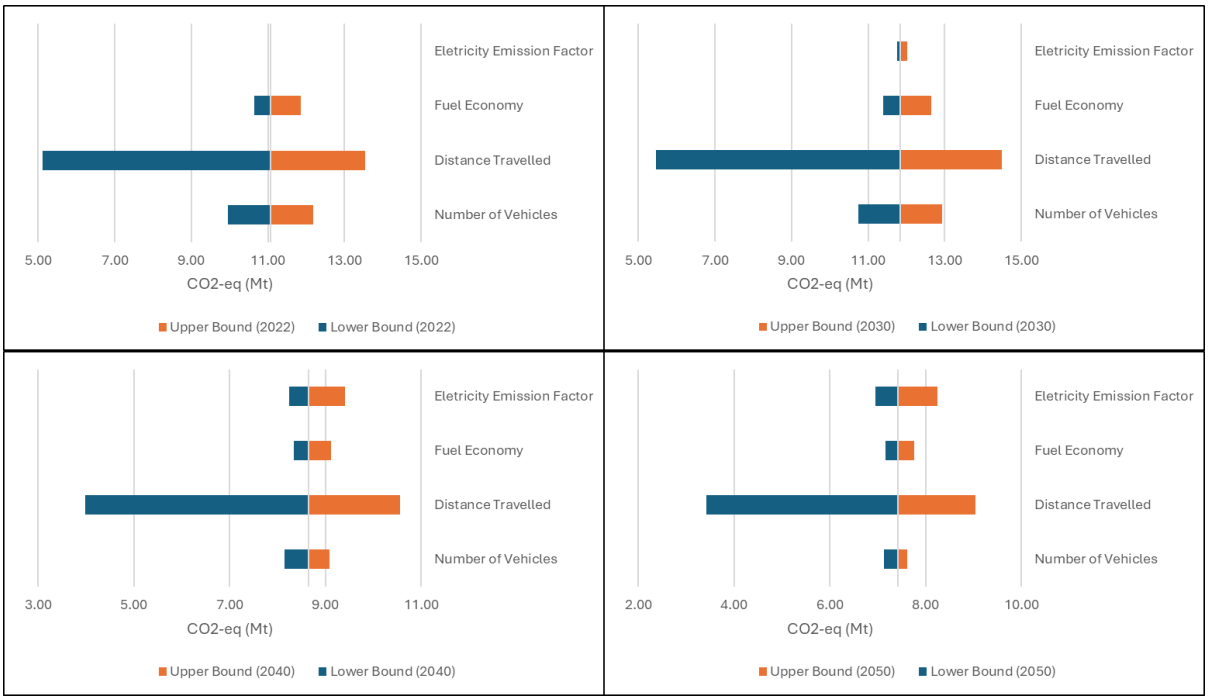

Figure 3.19: Clockwise from top left: OAT sensitivity analysis results for the Balanced Net Zero Pathway 2030 ICEV ban in 2022; OAT sensitivity analysis results for the Balanced Net Zero Pathway 2030 ICEV ban in 2030; OAT sensitivity analysis results for the Balanced Net Zero Pathway 2030 ICEV ban in 2050; OAT sensitivity analysis results for the Balanced Net Zero Pathway 2030 ICEV ban in 2040.

The analysis of the Balanced Net Zero Pathway, particularly concerning the proposed 2035 ban on ICEVs, shows the differential impact of the four used factors on CO2-eq emissions across the time horizons of 2030 and 2040. The 2022 and 2050 years are not included in this analysis, as the results for 2022 are the same across the 2030, 2035, and 2040 ban scenarios since the impact of the ban has not occurred yet, and the results for 2050 are the same since all vehicles are electrified at this point.

In 2030 and similar to previous results, distance travelled has the most substantial influence, with a lower bound of 5.85 Mt CO2-eq yr^{-1} (53.86%) and an upper bound of 15.51 Mt CO2-eq yr^{-1} (22.36%). The number of vehicles follows, with a lower bound of 11.50 Mt CO2-eq yr^{-1} (9.28%) and an upper bound of 13.85 Mt CO2-eq yr^{-1} (9.26%). Fuel economy shows a lower bound of 12.19 Mt CO2-eq yr^{-1} (3.84%) and an upper bound of 13.56 Mt CO2-eq yr^{-1} (6.99%). While the electricity emission factor has the least impact, with a lower bound of 12.59 Mt CO2-eq yr^{-1} (0.68%) and an upper bound of 12.86 Mt CO2-eq yr^{-1} (1.45%). In 2040, distance travelled remains the most influential input, with a lower bound of 4.73 Mt CO2-eq yr^{-1} (53.91%) and an upper

bound of 12.53 Mt CO2-eq yr^{-1} (22.08%). The number of vehicles and fuel economy have similar impacts, with lower bounds of 9.64 Mt CO2-eq yr^{-1} (6.12%) and 9.92 Mt CO2-eq yr^{-1} (3.38%), respectively, and upper bounds of 10.90 Mt CO2-eq yr^{-1} (6.17%) for both inputs. The electricity emission factor's influence increases compared to 2030, with a lower bound of 9.89 Mt CO2-eq yr^{-1} (3.68%) and an upper bound of 11.06 Mt CO2-eq yr^{-1} (7.73%).

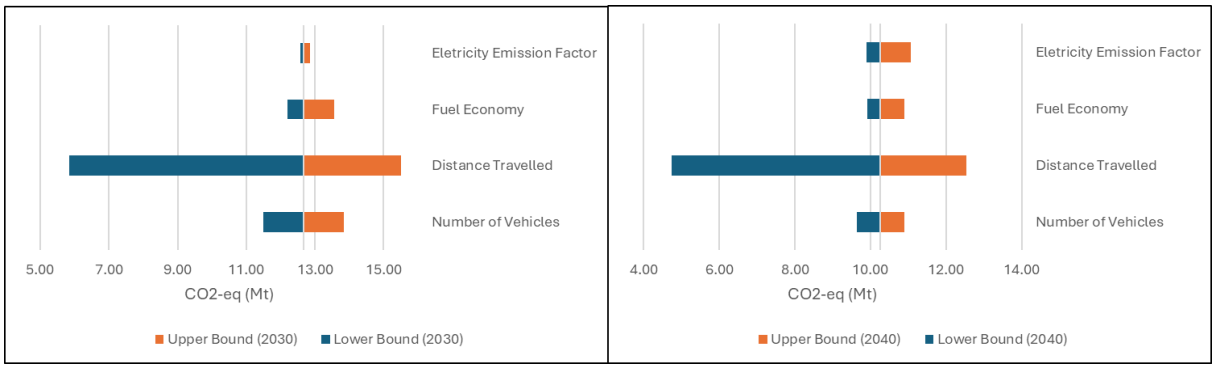

Figure 3.20: Left panel, OAT sensitivity analysis results for the Balanced Net Zero Pathway 2035 ICEV ban in 2030. Right panel, OAT sensitivity analysis results for the Balanced Net Zero Pathway 2035 ICEV ban in 2040.

Building upon previous analyses, the study omits the years 2022 and 2050, focusing instead on the years of 2030 and 2040 within the framework of the Balanced Net Zero Pathway, particularly in the 2040 ban on ICEVs. In the year 2030, it is revealed that the distance travelled exerts the highest influence on CO2-eq emissions, presenting a variance between a lower estimate of 6.05 Mt CO2-eq yr^{-1}, accounting for 53.81% of emissions, and an upper estimate of 16.02 Mt CO2-eq yr^{-1}, representing 22.34% of the total. Following this, the total number of vehicles contributes to emissions with a lower estimate of 11.88 Mt CO2-eq yr^{-1} (9.25%) and an upper estimate of 14.31 Mt CO2-eq yr^{-1} (9.29%). Fuel efficiency emerges as the next impactful factor, with emissions ranging from a lower estimate of 12.59 Mt CO2-eq yr^{-1} (3.86%) to an upper estimate of 14.02 Mt CO2-eq yr^{-1} (7.07%). The influence of the electricity emission factor is found to be the least, with a lower boundary of 13.00 Mt CO2-eq yr^{-1} (0.72%) and an upper boundary of 13.28 Mt CO2-eq yr^{-1} (1.41%).

Progressing to 2040, the hierarchy of influencing factors largely remains the same. Distance travelled maintains its position as the predominant factor, with its impact between a lower

boundary of 5.62 Mt CO2-eq yr^{-1} (53.89%) and an upper boundary of 14.89 Mt CO2-eq yr^{-1} (22.19%). The vehicle number in circulation continues to affect emissions, demonstrated through a lower estimate of 11.37 Mt CO2-eq yr^{-1} (6.73%) and an upper estimate of 13.02 Mt CO2-eq yr^{-1} (6.80%). Fuel efficiency's contribution to emissions is between a lower estimate of 11.75 Mt CO2-eq yr^{-1} (3.64%) and an upper estimate of 13.00 Mt CO2-eq yr^{-1} (6.62%). Notably, the impact of the electricity emission factor witnesses a relative increase from 2030, with its influence ranging from a lower estimate of 11.81 Mt CO2-eq yr^{-1} (3.14%) to an upper estimate of 12.98 Mt CO2-eq yr^{-1} (6.46%).

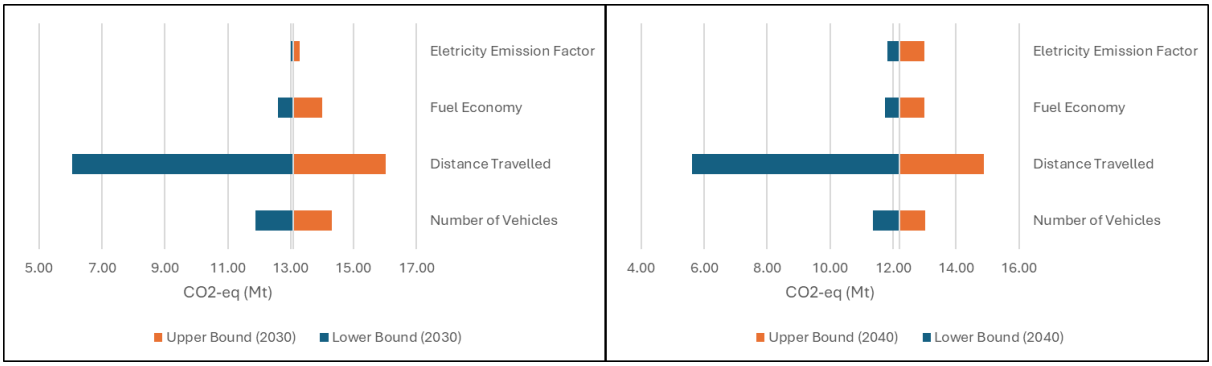

Figure 3.21: Left panel, OAT sensitivity analysis results for the Balanced Net Zero Pathway 2040 ICEV ban in 2030. Right panel, OAT sensitivity analysis results for the Balanced Net Zero Pathway 2040 ICEV ban in 2040.

For the cumulative emissions, the decision to focus on the 2040 ICEV ban scenario as a representation stem from an assessment of Qatar's current trajectory, where the prospects for achieving ICEV bans by 2030 or 2035 appear to be challenging. Analysis under the Balanced Net Zero Pathway, predicated on the 2040 ICEV ban, reveals that the parameter of distance travelled vastly impacts emissions, presenting a spectrum of change: a significant reduction of 53.88%, equivalent to 152 Mt CO2-eq, to an increase of 22.21%, corresponding to 402 Mt CO2-eq. The number of vehicles in operation emerges as the next critical factor, showing a potential decrease in emissions by 7.70% (304 Mt CO2-eq) or an increase of 7.70% (354 Mt CO2-eq). Fuel efficiency is another considerable factor, with its impact ranging from a decrease of 3.68% (317 Mt CO2-eq) to an increase of 6.71% (351 Mt CO2-eq) in emissions. Among the inputs considered, the electricity emission factor is identified to have the minimal impact, with emissions potentially decreasing by 0.95% (326 Mt CO2-eq) or increasing by 4.56% (344 Mt CO2-eq).

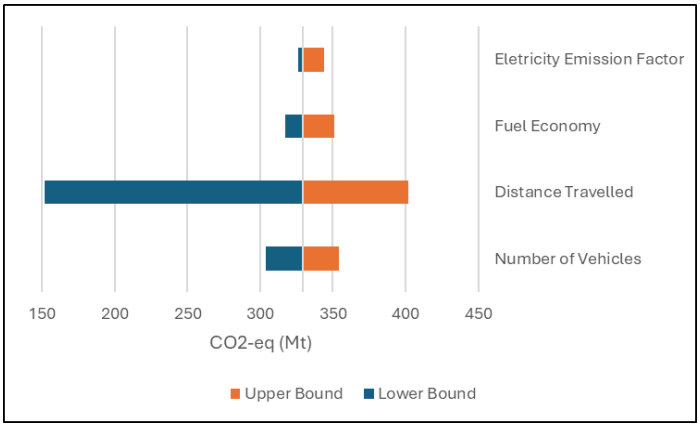

Figure 3.22: OAT sensitivity analysis results for the cumulative Balanced Net Zero Pathway 2040 ICEV ban.

3.5 Discussion

The analysis conducted in previous sections has examined the projected impact of the proposed ban on ICEVs on CO2-eq, NOx, and PM2.5 emissions in Qatar. Set against the backdrop of the nation's ambitious environmental targets, the study particularly focuses on the role of electrified mobility as a strategic approach to meeting these objectives. The findings lay out a detailed comparison of anticipated emission reductions under different policy scenarios, considering ban strategies for the years 2030, 2035, and 2040.

The results indicate a potential for emissions reduction, particularly when the ICEV ban is initiated by 2030. The earlier the ban is implemented, the more significant the decline in emissions, which highlights the benefits of swift policy action. A BEV fleet in Qatar has considerable advantages over an ICEV fleet in reducing CO2-eq emissions from 2022 to 2050. However, the benefits to air quality of a BEV fleet are less drastic, although a steady decrease in vehicle NOx emissions is expected to occur as BEV adoption increases, leading to a growing difference between ICEV and BEV fleet emissions. An earlier implementation in 2030 results in a 34% reduction in cumulative CO2-eq emissions by 2050 compared to the BAU scenario, while a 2035 ban leads to a 28% reduction, and a 2040 ban results in a 23% reduction. This highlights the importance of early action in maximizing the environmental benefits of the ICEV ban and underscores the need for policymakers to carefully consider the trade-offs between allowing more time for a smoother transition and achieving more significant emission reductions.

The comparative analysis has the advantage of screening for differences based on the introduction year of the ICEV ban. This can be particularly useful in the context of a nation-wide evaluation of either the cumulative GHG emissions, the needed speed of policy implementation or a more detailed comparison of BEV integration effects. The latter is crucial for energy producers and policymakers to scale up efforts and make sure no overshoot events can occur on peak demand occasions. Even if peak demands can be met without additional capacity or energy inputs, the degree and speed of BEV adoption are still important in the overall grid stability and supply chain. Specific obstacles could pose a hazard to the overall sustainable transition goal and the overall Qatar 2030 Vision.

For this first ICEV ban scenario, even with current penetration rates hovering at the lower end of the spectrum, in the 2030 ICEV ban, the difference between the Tailwinds/Widespread engagement scenario and the Headwinds scenario is only 5 years. The Balanced Net Zero Pathway is located in-between concerning the effectiveness of BEV sales and reaches a 100% rate by 2032 as can be seen in the methodology chapter of this work.

The ICEV ban also positively impacts NOx and PM2.5 emissions, although to a lesser extent than CO2-eq emissions. The reduction in these pollutants contributes to improved air quality and public health, further emphasizing the importance of the ICEV ban as part of a comprehensive sustainability strategy. When considering the effects of the ICEV ban on new LDV sales separately, the reductions in CO2-eq and NOx emissions are even more pronounced, reaching 68% and 73%, respectively, by 2050 compared to the BAU scenario. This suggests that targeting new vehicle sales can be an effective approach to accelerating the adoption of BEVs and reducing emissions in the transportation sector.

As Qatar is heavily reliant on fossil fuels and the ICEV ban is not inherently linked to a complete switch to renewables, the NOx results should be regarded from that perspective. This again proves the need for a transition strategy that not only puts focus on the vehicle type but the energy production as well in the case of centralized electricity from natural gas. Nonetheless, the consistent reduction of the parameters of focus does show that a general benefit is expected from the described ICEV ban.

It is possible that the pace at which BEVs are adopted will have only a minor impact on PM2.5. Investigations are now being conducted on technological ways to reduce non-exhaust PM2.5 emissions. The possible reduction methods being considered include wheel alignment, material choice, compliance with type and brake wear Euro standards, and post-release wear particulate capture (Harrison et al., 2021; Particle Measurement Programme, 2016; The Tyre Collective, 2024). The problem is that these technologies have yet to be tested in the real world. The uncertainty of non-exhaust emission factors makes it difficult to assess how much reduction in overall road transport PM2.5 emissions will be accomplished. The effectiveness of new technological methods to reduce non-exhaust related emissions can be enhanced by increasing

the precision and reducing the uncertainty of these emission parameters. This indicates that non-technical approaches, such as reducing VKT, are viable strategies for mitigating non-exhaust related PM2.5 emissions.

While the ICEV ban shows high potential for reducing emissions, it is essential to recognize that it is not a standalone solution. A comprehensive approach to decarbonization in Qatar should also address the reliance on fossil fuels in electricity production, as the benefits of BEVs are inherently linked to the cleanliness of the energy source used to power them. The results of this analysis can help inform policymakers and stakeholders in Qatar as they work towards achieving the Qatar National Vision 2030 and its sustainability goals. The ICEV ban, particularly when implemented earlier, can serve as a component of a broader strategy to reduce emissions, and improve air quality.

The analysis of Kahramaa's goal to transform 10% of Qatar's LDV vehicle fleet to electric vehicles by 2030 shows the potential reduction of CO2-eq emissions under different electrification scenarios and pathways. In the first scenario, where only sedan vehicles are electrified, the CO2-eq emissions are reduced by 411 kt CO2-eq yr^{-1} in 2030 compared to the no electrification (BAU) scenario. This reduction emphasizes the impact of targeting a specific vehicle type, such as sedans, which have a higher market maturity rate for electrification. The linear pathway in this scenario shows a constant increase in CO2-eq emissions reduction, indicating a steady progress towards the electrification goal. The exponential pathways (1 and 2) also demonstrate similar trends, with varying rates of change in emissions reduction over the years. The s-curve pathway exhibits the biggest fluctuations in the rate of change, with the highest increase in emissions reduction between 2029-2030.

The second scenario, which assumes a 10% electrification rate applied to all LDVs (sedans, SUVs, and sports vehicles), results in greater reduction of CO2-eq emissions, amounting to 564 kt yr^{-1} less than the BAU scenario in 2030. This additional reduction of 153 kt yr^{-1} compared to the sedan-only electrification scenario shows the impact of an approach target all-vehicle electrification. The different pathways in the second scenario exhibit varying trends in the rate of change of CO2-eq emissions. The linear pathway shows a moderate rate of change, with the

highest increase between 2029-2030. The exponential 1 pathway follows a similar pattern, with a decreasing trend after 2026. The exponential 2 pathway has a highly variable growth rate, with the highest emissions reduction between 2025-2027 but the lowest rate of change from 2027-2030. This suggests that the exponential 2 pathway may be more effective in achieving reduced CO2-eq emissions within the given timeline. The s-curve pathway, despite having the highest rate of change in 2023, experiences a sharp decline between 2024-2025 and then follows a steep increase in emissions, making it less favorable compared to the other pathways. The cumulative impact of achieving Kahramaa's electrification target is notable, with an average of 2.22 Mt of avoided CO2-eq emissions by 2030. This demonstrates the long-term benefits of vehicle electrification and its potential to contribute to Qatar's overall sustainability goals.

As mentioned earlier, Qatar's NDC goals aim to reduce GHG emissions by 25% by 2030, relative to a BAU scenario that projects emissions at 13.4 Mt CO2-eq yr^{-1}. To align with these objectives, Qatar needs to decrease its emissions to 10.06 Mt CO2-eq yr^{-1} in 2030, showcasing its strong commitment to addressing the global climate crisis and ensuring a sustainable future. However, the projections suggest that even with the implementation of a 2030 ICEV ban and following the Balanced Net Zero pathway, Qatar's emissions are expected to reach 11.8 Mt CO2-eq yr^{-1}, representing only a 12% decrease from the BAU scenario.

To achieve the 25% emissions reduction target through vehicle electrification, Qatar must alter its vehicle fleet composition by 2030. The most straightforward change involves the introduction of a substantial number of BEVs across various vehicle categories. The analysis suggests that Qatar needs to incorporate 1,978 BEV buses, 13,934 ICEV HDVs, 90,393 ICEV SUVs, 70,259 ICEV sports vehicles, and a staggering 148,347 ICEV sedans into its fleet. Sedans, in particular, would play a role in CO2-eq and air pollution levels in 2030, as they are expected to be the most prevalent vehicles on the road.

Achieving this transformation requires the incorporation of societal and behavioral changes, as well as modifications in business operations. The most significant indicators of success will be the decline in ICEV sedans, sports vehicles, and SUVs, along with the enhancement of their BEV counterparts. Although this transition presents challenges due to the lack of an initial market for

BEV vehicles in these categories, it also creates new opportunities for companies to invest in and support the shift towards cleaner transportation. By implementing the necessary changes in vehicle fleet composition and promoting the adoption of BEVs, Qatar can work towards achieving its NDC goals and contribute to the global effort to mitigate climate change.

The dynamics of transportation demand play a crucial role in this scenario. An increase in demand, if not managed effectively, could offset the gains made through electrification and efficiency improvements, showing the importance of holistic policies that address both supply and demand aspects of transportation. In essence, the reduction of CO2-eq emissions in the road transport sector requires a concerted effort that integrates technological advances with strategic policy frameworks and behavioral changes, aiming for a sustainable balance between mobility needs and environmental imperatives.

This discussion section is dedicated to interpreting these results, understanding their wider environmental implications, and evaluating the efficacy of proposed policy measures in the quest to reduce emissions. It seeks to draw meaningful connections between the empirical evidence and strategic policy considerations, shedding light on the path forward for Qatar's sustainable transportation initiatives and compliance with global emission reduction commitments.

3.5.1 Sensitivity study discussion

In all the scenarios analyzed using the OAT sensitivity approach, distance travelled consistently emerges as the most impactful factor in determining the CO2-eq emissions from Qatar's transportation sector. This prominence is attributed to the breadth of the lower and upper bound ranges. This is followed by the vehicle number, which demonstrates the second-largest impact on the overall emissions trajectory. Fuel economy ranks third in terms of its influence on emissions, while the electricity emission factor exhibits the least impact among the four inputs considered.

Additionally, the sensitivity analysis endeavours to provide a basis for adaptive management strategies that can respond to future changes in technology, market conditions, and environmental constraints. This involves scenario analysis, robust decision-making, and adaptive

management. By exploring a range of plausible future scenarios, the sensitivity analysis can help identify the key uncertainties and risks that may affect the outcomes of Qatar's road transport policies, allowing decision-makers to develop contingency plans and adapt their strategies accordingly. The results gained from the sensitivity analysis can support the development of robust policies that perform well across a wide range of possible future conditions, rather than being optimized for a single, most likely scenario. By monitoring the performance of road transport policies over time and comparing actual outcomes with the results of the sensitivity analysis, decision-makers can identify emerging trends, adjust their strategies, and refine their policies to ensure continued progress towards GHG emissions reduction goals.

This sensitivity to travel distance indicates the potential effectiveness of policies that encourage reduced vehicle usage, such as promoting remote work, implementing flexible work schedules, or developing more compact city designs that minimize the need for long commutes. It also points to the potential environmental benefits of enhancing public transportation systems to reduce the total distance travelled by personal vehicles. The variation in emissions with changes in distance travelled also emphasizes the importance of considering urban planning and transportation policies together. Integrating these can effectively reduce the average distance travelled per vehicle, thus directly impacting emission levels. If Qatar were to experience an increase in VKT per vehicle, due to factors such as urban sprawl, lack of public transportation options, or cultural preferences for private vehicle ownership, it could lead to an increase in GHG emissions, even if the adoption of electric vehicles is accelerated.

The sensitivity analysis results emphasize the importance of considering mobility patterns and VKT per vehicle when developing transportation policies aimed at reducing GHG emissions. While promoting the adoption of BEVs is important, it is equally important to implement measures that encourage sustainable mobility choices and reduce the overall distance travelled by private vehicles. This could include investing in efficient and attractive public transportation systems, promoting compact urban development, and creating safe and convenient infrastructure for cycling and walking.

The sensitivity analysis also shows the importance of considering the vehicle fleet size in environmental policy planning. The straightforward relationship between the number of vehicles and emissions provides a clear leverage point for policymakers: a 10% shift in vehicle numbers translates into an almost identical percentage change in emissions.

For the electricity emission factor, its relative influence increases over time suggesting a growing importance of the electricity sector's decarbonization in later years. This shift aligns with the expected increase in BEV penetration and emphasizes the critical interplay between vehicle electrification and the power generation mix. The inclusion of the Alkharsaa solar project in Qatar's electricity mix is a significant step towards reducing the country's carbon footprint and mitigating the environmental impact of its energy sector. By displacing a portion of natural gas-based electricity generation, the project contributes to lowering GHG emissions and supports Qatar's efforts to transition towards a more sustainable energy future.

Moreover, the successful implementation of the Alkharsaa project could pave the way for further expansion of renewable energy in Qatar. As the country gains experience and confidence in solar power generation, it may invest in additional projects, gradually increasing the share of renewables in its electricity mix. This growth in renewable energy capacity would further reduce the electricity emission factor over time, contributing to more substantial emissions reductions in the long run.

The OAT sensitivity analysis, by considering a 9.6% improvement in the electricity mix as the lower bound, displaying the potential impact of renewable energy projects like Alkharsaa on Qatar's electricity emission factor. The results of the analysis can inform policymakers and stakeholders about the importance of investing in and supporting the development of renewable energy infrastructure to achieve significant emissions reductions in the electricity sector.

3.6 Conclusions

Research on the impact of different electrification scenarios on CO2-eq and air pollutant emissions in Qatar's road transport fleet was conducted using a VSM and OAT sensitivity analysis. The study compared the emissions between a BEV fleet and an ICEV fleet under various ICEV ban scenarios from 2020 to 2050. The results showed that the inclusion and market share of BEVs would lead to reductions in TTW CO2-eq emissions compared to a fleet of ICEVs. However, to achieve net-zero emissions in the road transport industry, Qatar's electricity grid should be decarbonized in conjunction with the adoption of BEVs.

The impact of BEV fleets on future PM2.5 emissions remains uncertain due to the uncertainties surrounding non-exhaust emission factors. Until the late 2040s, air pollutant emissions from electricity production will be insignificant compared to those from vehicle activities. PM2.5 emissions from electricity production are expected to remain low relative to non-exhaust emissions from 2020 to 2050. However, NOx emissions from power plants currently outweigh vehicle emissions, and this trend is expected to continue.

Achieving the 2030 ban on ICEVs would have a considerable effect on CO2-eq emissions, but a smaller impact on air quality. The total CO2-eq emissions until 2050 will depend on the rate of BEV uptake, while pollutant emissions were less affected by the uptake rate. Increased BEV adoption resulted in a slightly quicker reduction in NOx emissions. Lowering transport demand will have a higher impact on improving air quality, particularly in reducing PM2.5 emissions, as vehicle electrification has a limited effect on these particulates.

The comparative analysis of different ICEV ban scenarios (2030, 2035, and 2040) demonstrated that early action is crucial in maximizing the environmental benefits of the policy. For example, the 2030 ICEV ban scenario is projected to result in a 34% reduction in cumulative CO2-eq emissions by 2050 compared to the BAU scenario. The study also analyzed Kahramaa's goal to transform 10% of Qatar's LDV fleet to electric vehicles by 2030, showing the potential for emissions reductions under different electrification scenarios and pathways. Targeting specific

vehicle types, such as sedans, can be an effective strategy for reducing emissions, while a comprehensive approach targeting all vehicle types can lead to even greater reductions.

However, Qatar's heavy reliance on fossil fuels for electricity generation means that the environmental benefits of BEVs will be limited until the energy sector transitions to cleaner sources. The study highlights the need for a comprehensive approach to decarbonization, addressing both the transportation and energy sectors. If necessary socioeconomic modifications are not made, the introduction of a BEV fleet will have a larger effect on CO2-eq emissions than it will have on air quality. This analysis serves as a foundation for informed decision-making, ensuring that Qatar meets its environmental objectives and contributes to the global effort against climate change.

The analysis and findings presented in this chapter have contributed to achieving the research aim of evaluating Qatar's road transport policies and strategies for GHG emission reduction. By examining the impact of different ICEV ban scenarios, the impact of Kahramaa electrification goal, and the fleet configuration needed to reduce transport GHG emissions by 25%, this chapter informs about the effectiveness these various policies. Moreover, the recommendations derived from this analysis, such as the need for a comprehensive approach to decarbonization and the importance of early action in implementing ICEV bans, directly support the ultimate objective of providing strategic insights and recommendations for achieving Qatar's national targets of reducing GHG emissions from road transport by 2030 and facilitating a sustainable transition to a low-carbon transport system by 2050.

In addressing the main research question of this study, the findings from this chapter demonstrate that Qatar's current road transport policies, particularly the proposed ICEV bans and electrification goals, have the potential to reduce CO2-eq emissions. However, these policies alone may not be sufficient to meet the national target for 2030. The analysis shows that while a 2030 ICEV ban could lead to reductions in CO2-eq emissions, achieving the 25% reduction target would require more aggressive measures, including a specific fleet configuration of BEVs and ICEVs across various vehicle categories. To sustain and enhance these reductions through 2050, the study suggests a multi-faceted approach that includes early implementation of ICEV bans,

accelerated BEV adoption, integration with renewable energy sources, and demand management strategies. This holistic strategy is important for Qatar to fulfill its environmental commitments and transition to a low-carbon transport system.

4 Life Cycle Assessment

4.1 Introduction

BEVs are currently presented as one of the serious alternatives to ICEVs, attempting to reduce the use of fossil fuels, impacts on air quality, and GHG emissions. In recent years, studies have shown that the electric passenger cars represent the ability to reduce transportation-related GHG emissions and urban air pollution (Ellingsen et al., 2014). Specifically, in terms of the quality of urban air, this is confirmed by a current study which estimates that 500,000 people die each year from pollutants in the European Union, where air pollution is primarily caused by was from transport, mainly in the cities (Manzetti & Mariasiu, 2015). Concerning GHG reductions, BEVs are expected to be more energy efficient in general and, in the relevant countries, to help the development of sustainable energy sources in the national production mix. Following regulations to minimize traffic pollution and restrict GHG emissions, BEVs are being incorporated into more and more cities in Europe and the USA (Manzetti & Mariasiu, 2015).

To support policymakers, producers as well as the general public, in the transition process, this study investigates the environmental impact of the use of GHG emissions as well as more specific environmental issues associated with ICEVs and BEVs through a comparative LCA study. An LCA is a method for assessing the environmental impacts of a product or system throughout its entire life cycle, from raw material extraction, manufacturing, use, end-of-life disposal or recycling (European Commission-JRC-IES, 2010). This chapter will focus on an LCA study, which will account for impacts ranging from global warming, resource depletion to human toxicity for vehicles in Qatar.

4.2 Methodology, process description, and data input

The environmental impact of ICEVs and BEVs are associated with the fourth pillar of the QNV 2030. Representing a complete assessment of the environmental burdens, the full fuel and vehicle cycle, as described by the C2G system boundary, will be utilised. To characterize the long-term carbon footprint, the global warming potential over a time horizon of 100 years was chosen

along the global ReCiPe methodology, with special consideration for sector-specific impact classes. For Qatar, most in-use cars run on gasoline, therefore the introduction of BEVs would result in high a reliance on electricity generated from natural gas. All information on vehicle types, ranging from personal LDVs to HDVs diesel vehicles, will be presented in the following chapters. To cover the current situation as well as an impression of future impacts, a dynamic model was constructed for the timeframe 2022-2050, with intermediate results for 2030 and 2040.

As the outcome of life cycle impact assessments are perceived as pointers of the probable impact, the correct interpretation should be in comparison to an alternative, as done for this thesis. Instead, separately describing results as objective values of environmental impacts should be avoided. This study follows the guidelines created for LCSA, along ISO standards 14040/44. As put forward by these standards, the overarching framework consists of 4 steps:

- Goal and scope definition
- Life cycle inventory (LCI)
- Life cycle impact analysis (LCIA)
- Final interpretation

The goal and scope were defined in the introduction of the study, this section is focussed on the framework consisting of the basis for the life cycle inventory and data analysis. For this data and inventory, a quality guideline was put in place in the introduction as well as the supporting literature chapters as reference. The quality of all inventory data and uncertainties was addressed in its respective chapter. Moreover, system boundaries are set as the complete life cycle of the vehicle. For background processes which cannot be studied in the scope of this study, the use of Ecoinvent databases and the SimaPro software will ensure that relevant data is included and reliable.

All processes or components are considered in the current state-of-the-art for the basic static scenario. The main reduction potential concern fuel economy, technology advances such as battery improvements and weight reduction. The implementation and its effect on the results

will be assessed in its respective chapter. For the extrapolation of the dynamic model, all adaptations will be discussed.

Changes in fuel economy will result in lower fuel requirements per kilometre driven over the studied timeframe 2022-2050. Lower vehicle impacts and lowering indirect impacts from the fuel source will be included. For BEV, as for vehicle and fuel improvements in general, the reduction in impacts will result from improvements in energy production, comparable to lowering fuel impacts, the lower energy needs over time, lower vehicle weight and separately the novel or more efficient technologies on the vehicle level, which compares to battery efficiencies and different chemistries. Additional cases can be discussed in the context of sensitivities or as part of the discussion at the end of the chapter. Futuristic adaptations such as autonomous driving or behavioral changes are not discussed as uncertainty in this field is very high.

4.2.1 Goal and scope definition

To support policymakers, producers as well as the general public in the QNV2030 transition process, this study investigates the overall environmental impacts associated with ICEV and BEV operating in Qatar. By entering the electric vehicle industry as a country with a developing economy, Qatar seeks to reduce its carbon impact. With this goal, Kahramaa launched the National Program for Energy Conservation and Efficient Use, announced in 2018 as the official start of the "Electric Car Charging Stations Project – Phase 1" and the "Green Car Initiative" (Qatar General Electricity & Water Corporation (KAHRAMAA), 2018). It is aimed to set up 400 charging stations in Qatar by 2022, inspiring the use of EVs and setting in action the way to transform 4% of Qatar's vehicle fleet into BEVs by 2022 and 10% by 2030 (C. Kumar, 2019). Qatar's Ministry of Transport has set an electrification goal of the public bus transport fleet of 25% by 2022 which was achieved (Ministry of Transport, 2022).

4.2.2 Functional unit

The functional unit is a measurement to represent the outcomes of the environmental impact assessment. This FU should allow a basis for easy comparison between goods or services while providing repeatability of the study. In case of the full life cycle of vehicles with different propulsion systems or functions, defining the functional unit is not always straightforward. As different functional units convey different results, it is important to communicate clearly and adapt where necessary. In the case of light or personal vehicles, a functional unit of driving 150,000 km is often proposed as a standardised lifetime, with for HDV a proposed transported weight over its lifetime. This study will, independent from the proposed lifetime, scale the components to the gathered data specific to Qatar.

As this study will consider different vehicle types, the functional unit should be calibrated over or rescaled to a uniform value of 'passenger kilometres travelled' as this is in line with 'kilometre-tonnes transported' for HDV. This is done by using the average load of the vehicle for its travelled distance instead of starting from its empty weight, possibly under-accounting for the mass it will transport over time. This functional unit can be further linked to the emissions per km or per

lifetime of the vehicle, both ICEV and BEV. The choice of having a single 'kilometres travelled' over all scenarios is preferred over the tons*km functional unit, as this would give the false impression that the only important factor is a linear correlation between weight and fuel consumption or emissions. Generally, the unit tons*km is commonly used in the transportation sector, particularly HDVs, to measure the transport service provided, with an emphasis on the service part. This unit takes into account both the distance travelled (kilometres) as well as the carried load (tons), providing an accurate modelling measure and the possibility to implement specific characteristics for specific loads or distances. For instance, two vehicles travelling with different loads will not necessarily have an equal environmental impact. Advanced modelling can further specify and implement direct emissions based on the mentioned characteristics while still leaving the opportunity to calculate back to a single kilometre travelled in case a specific weight and distance travelled is known. The calculation will therefore be a ratio as a single unit, representative of a single car, not as the environmental impact for the whole fleet. Calculation on the latter level would add an additional multilayer variable, falling outside of the scope. The final result value can therefore be notated as kg CO2-eq per km travelled.

In most scientific articles, it is assumed that the battery will last as long as the vehicle lifetime (150,000 km). Yet this is still a developing reference point in literature and no fixed guidelines are available. Therefore, if specific vehicles or databases show a discrepancy on this part, both the lifetime, end-of-life and relevant maintenance operations will be addressed and included. This would be implemented by scaling resources or component use, either as a linear or discrete addition. Replacing the battery of an electric vehicle would therefore result in either a fraction above 1 (linear) or 2 batteries. All final assumptions or model characteristics will be included in the respective chapters.

Generally, as battery technology further adapts and reaches higher maturity in the market, the overall quality of materials becomes more standardised and variance in current vehicles is reduced. Variance in literature and its effect on the comparative model will be discussed in the appropriate chapters.

4.2.3 System boundaries

For life cycle sustainability assessments, large discrepancies can be observed by including or excluding specific parts of the production chain, supporting processes or end-of-life scenarios. To reduce the amount of possible variance, Product Environmental Footprint Category Rules (PEFCR) were created, for which predetermined system boundaries or data sources are put forward, going further than the ISO standards. For ICEVs and BEVs, it was reviewed that no complete PEFCR are available. Nonetheless, the guidelines were analyzed in order to maximise comparability, replication and to further improve the quality of this analysis.

With the full C2G assessment, ranging from 2022-2050, the comparison of environmental impacts caused by ICEVs and BEVs will have to be scaled to a uniform end product. The methodology of this approach will be discussed in the following chapters. By use of a C2G approach, as opposed to a cradle-to-gate, is based on the shift of impacts in different product stages. The C2G concept is therefore more inclusive than measurements such as WTW, WTT, and TTW, as these are only accounting for parts of the life cycle while not integrating the end-of-life phase.

4.2.4 Methodology and selection of the Life Cycle Impact Assessment

The evaluation is performed on the C2G level to ensure the complete life cycle of the studied system. This study is designed along the ISO 14040:2006 and 14044:2006 norms. With the goal of this chapter looking to calculate the impact of a single unit as an ICEV or BEV car, the final results can be unified. In order to facilitate transparency, appropriate LCA protocols were followed as good practice. These ISO guidelines range from a checklist of inputs or materials that have to be taken into account to a dataset with given variables to the careful description of system boundaries and overarching LCA practices.

To reduce the degree of uncertainty while optimizing data quality, there is a need to define suitable data sources, foreground and background data as well as its temporospatial characteristics. Foreground data was collected from existing studies, literature reviews or obtained from publicly available statistics and sources to reduce variability and uncertainties.

Data gaps were closed by interpolation or assumptions based on the literature review. Background data was based on the literature review as well as Ecoinvent or governmental databases. To frame these methodologies, it is crucial to make the differentiation between the scopes of the impact assessment (European Commission-JRC-IES, 2010; The GHG Protocol, 2019):

- Direct emissions from identifiable and controllable sources
- Indirect emissions from identifiable and controllable sources
- Emissions from sources not identifiable or controllable yet related to the examined issue

Only a full C2G evaluation will explore all three scopes, therefore other studies can still report correct but deviating impact results if no attention is put on the official scope and goal. Direct emissions are calculated by the fossil fuel combustion leaving the exhaust. Emissions or environmental impacts related to the exploration of this fossil fuel, nor getting it to its location is included in this direct-emission scope. Indirect emissions determine the amount of GHG caused by the latter process or emissions associated with auxiliary processes and electricity generation. Finally, scope 3 deals with emissions produced by upstream and downstream processes, including emissions resulting from auxiliary and manufacturing processes, not directly linked with the core model (U.S. EPA, 2021). The specifics of the mentioned scopes will be further addressed in the static and dynamic models for this work.

As will be refined in the literature section, the manufacturing and operation chain of ICEV and BEV are broadly seen as very similar. Its foundation consists of a manufacturing step with the collection of raw materials (referred to as mining & refining) which moves into the design of its separate parts (e.g., operational parts such as brakes, metal sheets or power-transfer parts such as batteries, motor blocks, and controller chips). The assembly of these parts is followed by transporting the final product to its distribution location. From this point on, emissions shift from an indirect scope to direct inputs as the operator is in control of the vehicle (ICEV or BEV). Further in the background are the processes which made the resource extraction or assembly line possible, which have a similar system framework, therefore cut-off levels and scope definition is a helpful tool in differentiating the criticality of background processes without creating data gaps.

According to the European Commission (European Commission, 2020), vehicles are divided into 4 main categories, ranging from passenger transport to agricultural and forestry tractors. This does not match with for example the GREET model, which focuses on the LDV fraction, uncoupling it in sedans, SUVs and Pickup trucks (Table 4.1). This misalignment creates data gaps or makes differentiation in data inventories hard to extrapolate as data is regularly aggregated as averages. For the GREET model, this misalignment goes further as pickup trucks are not clearly defined in EU legislation, meaning that a portion of SUVs or truck vehicles could still be counted in the N-category. This makes modelling of complete vehicle fleets more complex and comparison hard if data is not available on the subcomponent level.

Table 4.1: Misalignment vehicle classifications (European Commission, 2020).

EU Commission classification	GREET model
Category M: vehicle used to transport passengers	Sedans SUV Pick-up Truck
Category N: vehicles used to transport goods	/
Category L: 2- and 3-wheel vehicles and quadricycles	/
Category T: agricultural and forestry tractors and their trailers	/

Vehicles that belong in the M categories are classified as LDVs, with a maximum gross weight rating <= 10,000 pounds (4,536 kg) such as cars, vans, and SUVs. For Qatar, this category represents 94.6% of registered vehicles in the country (Ministry of Interior, 2019). This type of vehicle will be one of the focus points of this study, aside from sports vehicles, SUVs and trucks. In the GREET methodology, each vehicle type will be modelled separately as they have their own emission profile. This is especially useful for the calculation of complete vehicle fleet averages or if the total emission profile for a country should be calculated in a dynamic study. According to the report by the Interior Ministry, the substantial proportion of sports vehicles in Qatar's transportation fleet renders the GREET model unsuitable for accurately representing the country's entire vehicle fleet. Therefore, including this vehicle class in an adapted model would result in a more correct representation of the country-wide emission profile. The main driver of

the adapted model is that sports vehicles have an overall higher demand and lower engine fuel economy (Mccartt & Hu, 2017). This impact on direct emissions could be extrapolated, yet if indirect emissions are considered, both construction and supply chains will differ, further putting the emphasis on extending the model to include this type of transportation.

To summarize, for LDV, the distinction is made as they have distinct emission profiles, features and weights as well as contrasting power characteristics and drivetrain designs which influence the fuel economy (Mccartt & Hu, 2017). The more extreme example is the large share of sports vehicles in Qatar which, with heavier and more powerful engines proved to have a lower fuel efficiency, therefore influencing the overall impacts of the vehicle. The choice of HDV and bus types was done on publicly available information, literature and current databases. Both HDV and buses have a large share of older European brands such as Mercedes yet are replaced by both European and international brands. Therefore, the choice was made to focus on well-established databases (Ecoinvent) and the availability of large brands in the region, namely Volvo (manufacturing Turkey), M.A.N. and Mercedes (manufacturing Germany) and Tata group/Mercedes (production Middle east). This results in a global mix of production locations which can be reflected in SimaPro.

The environmental impacts were quantified by use of the ReCiPe methodology as implemented in SimaPro (last available version of software and databases). As a methodology, the ReCiPe method is a widely used and therefore unofficially recommended tool to provide a basis for repeatability and standardization of Life Cycle Sustainability Assessments. Other methodologies are described where relevant, regarding differences in approach and recalculation efforts for comparability of results. For this work, a special focus was put on five critical impact categories to guide the inventory data and literature review, but all midpoint and endpoint categories will be illustrated.

In general, the ReCiPe 2016 harmonized life cycle impact assessment method is a widely recognized methodology for conducting LCA studies. It provides a complete and robust framework for assessing the environmental impacts of products and processes at both the midpoint and endpoint level while providing a standardized approach to LCA studies. This ensures

consistency and comparability across different products and processes. The overall methodology includes a set of impact categories, indicators, and characterization factors that are widely accepted by the scientific community, allowing for a more transparent and rigorous assessment of the environmental and enabling stakeholders to make more informed decisions.

The ReCiPe 2016 impact categories cover a wide range, ranging from climate change, human toxicity, freshwater eutrophication to land use among others. This too provides a more thorough and holistic assessment of the impacts, allowing for a better understanding of the overall sustainability of the system being analyzed.

Finally, the ReCiPe methodology allows for assessment at both midpoint and endpoint levels. Midpoint indicators provide a more detailed analysis of the environmental impacts of a specific process or material, while endpoint indicators provide a more holistic assessment of the overall impact on human health, ecosystem quality, and resource availability. This allows for a more nuanced and complete analysis of the environmental impacts of products and processes. Even though the ReCiPe methodology was developed initially in 2008, it is regularly updated to reflect the latest scientific knowledge and understanding. This makes it one of the most recent and updated assessment methods available to LCA practitioners, ensuring the methodology remains relevant and accurate, further enabling stakeholders to make informed decisions based on the latest scientific evidence. Therefore, this methodology is widely recognized and accepted by regulatory bodies, governments and industry associations while thus also able to inform policy decisions and business strategies.

To represent the changes for the dynamic ICEV-BEV model in Qatar, the main impacts were assumed to be in line with the overarching literature on transportation, mining of raw materials and vehicle use. The focus will therefore be on indicators such as global warming, particulate matter, human toxicity, acidification and resource depletion. These impacts cover a broad range, coupling the environmental and health issues to the 4 pillars of the Qatar 2030 goals. As indicators go beyond pure environmental impacts, the term LCA is used synonymously with LCSA, pointing to the wider implications. Nonetheless, all impact categories will be given in the final tables of the Appendix.

Even though the ReCiPe impact method is considered to be a robust and thorough approach, some criticisms and limitations remain, particularly with respect to the impact categories of land use and water consumption. For land use, impacts from land use change, such as the conversion of natural habitats to agricultural or urban use are not fully accounted for, leading to an underestimation with an unknown degree of uncertainty. This issue is particularly key in regions where land use change is a significant issue. Similarly, the water consumption impact category has been criticized for not fully capturing the environmental impacts associated with water use, particularly in regions where water scarcity is a significant issue. Furthermore, as it does not differentiate specifically between different types of water sources, e.g. freshwater versus saltwater, extra uncertainty is added. Thus, as both inventories and calculation methodology for land use and water footprint are unsuitable for this study, results for these categories are not focused upon.

Yet, all impact categories will be included in the Appendix of the thesis to promote transparency of the overall environmental assessment. In both cases (land and water-FP), large discrepancies can be seen in the collection and interpretation of data. This view is not widespread over the complete LCSA community but was concluded for this research after due diligence by academic sustainability assessment experts, published frequently in the International Journal of Life Cycle Assessment. Finally, impacts from single events, spills or indirect implications are not clearly incorporated, leaving unfair comparisons, most likely with a favorable bias toward fossil fuels.

Methodologies generally range from sector-specific to overarching global standards. The impact categories are listed in Table 4.2. Impacts are calculated as implemented in SimaPro including all current inventories. To promote transparency and allow translation to different methodologies, the scope and calculation setup will be discussed in the following chapters in accordance with the availability and gathering of foreground data.

Table 4.2: Environmental footprint impact categories (European Commission-JRC-IES, 2010).

Impact category	Unit
Acidification	molc H+ eq.
Climate change	kg CO2 eq.

Ecotoxicity, freshwater	CTUe
Eutrophication	kg P eq.
Eutrophication, terrestrial	molc N eq.
Human toxicity	CTUh
Ionising radiation, human health	kBq U235 eq.
Land use	kg C deficit
Ozone depletion	kg CFC-11 eq.
Particulate matter	kg PM2.5 eq.
Photochemical ozone formation	kg NMVOC eq.
Resource depletion mineral, fossil and renewable	kg Sb eq.
Resource depletion, water	m3 water eq.

Acidification

High-temperature fuel combustion emits NOx, sulphur dioxide (SO2), and ammonia (NH3), which form acids in the atmosphere and, upon deposition, impair plant health and reduce biodiversity and productivity (European Commission-JRC-IES, 2010).

Global warming (climate change - GHG)

Global warming, largely attributed to human activity, is increasing air and ocean temperatures and sea levels. Its effects on weather patterns, ecosystems, food production, human health, and infrastructure are well-documented, though some elements like feedback loops related to melting ice are less understood. The balance of the climate system is affected by changes in atmospheric concentrations of GHGs and aerosols, in its way influenced by the type of land cover and solar radiation. Different GHGs (e.g. CO2 or methane) will have different results, primarily based on radiative forcing characteristics and the substances' lifetime. Therefore, CO2 is the reference unit for evaluating mixed emission profiles (European Commission-JRC-IES, 2010).

In this study, to ensure consistency in modeling climate change impacts, all GHG emissions are converted to CO2-eq values using the 100-year GWP factors published by the Intergovernmental Panel on Climate Change (IPCC). The latest version of the method for calculating climate change impacts considers CO2 uptake from air and biogenic CO2 emissions, which becomes critical for

bio-based materials. Yet, to allow fair comparison, biogenic and non-biogenic CO2 are considered to have the same environmental impact (European Commission-JRC-IES, 2010; IPCC, 2006).

Human toxicity

Chemicals emitted in water, soils or into the air will come into contact with humans through various pathways. The amount, concentration and lifetime of the chemical will be crucial for the characterisation of contact pathways. If chemicals are harmful, effects range from cancer or non-cancer-related diseases. For this research, the transportation sector is addressed as it emits pollutants leading to human toxicity such as PM, nitric oxide (NO), and nitrogen dioxide (NO2) (Department for Environment Food & Rural Affairs, 2020; European Commission-JRC-IES, 2010).

Particulate matter

The impact assessment model considers the division between primary and secondary particulate matter. While primary PM is emitted directly, secondary PM originates from chemical reactions, forming by non-methane volatile organic compounds and precursors such as NOx, NH3 and SOx. This links the issue of particulate matter and acidification, especially in locations with high traffic, high density of combustion processes or enclosed spaces, e.g. cities and traffic centres. The method adapts to the variation in population density and the heights of emission points. The PM2.5 fraction of particles with a diameter less than 2.5 μm is used as the reference for impact calculations as no models are proposed to cover the nanoparticle scale and further research is still ongoing (European Commission-JRC-IES, 2010).

Resource depletion

As minerals must be mined, fossil fuels extracted for burning or conversion, also fresh water sources are depleted at a higher rate than they can be replenished. This depletion rate in comparison to its possible replenishment rate gave rise to the resource scarcity indicator. For non-renewable resources such as fossil fuels and minerals, the impact assessment method considers extraction with reserves of a fixed resource. Characterization factors are quantified for metals, fossil fuels and, in the case of reserves, mineral compounds. The impact assessment

method for water depletion distinguishes between six levels of water scarcity, accounting for regional severity and availability (European Commission-JRC-IES, 2010).

Midpoints and endpoints

Easier understood, LCA environmental impacts are generally communicated on the midpoint level. Midpoints are defined as the connecting points in the causal chain that link the environmental impacts to its life cycle inventory analysis. Before endpoints are derived, midpoint characterization factors or indicators are used to reflect the relative significance of the underlying impact pathways. Examples of commonly used midpoint characterizations include global warming potential, photochemical ozone formation (smog), and particulate matter formation. However, some methodologies have also aggregated these factors into endpoint characterizations, resulting in endpoint categories such as damage to human health, ecosystems, and resource availability within ReCiPe (European Commission-JRC-IES, 2010).

In ReCiPe2016, "Damage to ecosystem quality" is defined as the cumulative impact of species loss occurring locally over time and space. However, global species extinction risk can also be regarded as a potential indicator of ecosystem quality alongside local species loss. To incorporate global species decline in life cycle impact assessment for water and land use, methodologies have already been proposed by Chaudhary et al. (2015) and Verones et al. (2020). Nevertheless, additional research is necessary to extend this approach to other impact categories.

4.2.5 Vehicle Lifetime and kilometers travelled

With regard to the functional unit, an unofficial standardization effort has been in progress since the broader use of LCA studies (Reap et al., 2008). Part of this approach is the rescaling of the emission profile of vehicles to a single unit using similar system boundaries. Such approaches are regularly guided by the LCA practitioners and the available information from producers. In case products are not on the market for an extended time, real lifetime averages are not available and functional units are related to the expected design characteristics.

The functional unit could encompass a single kilometer travelled as well as a single person travelling over 1 kilometer. For the transport of goods, a ton of goods being moved over a single kilometer is a reasonable candidate. The choice of having a single 'kilometer travelled' over all scenarios is preferred over the tonnes*km functional unit, as this gives an overall false impression that there is a linear correlation between weight and fuel consumption or emissions outside of the model. This can easily be visualized by an empty truck returning after drop-off. If not modelled correctly, this return is expected to emit no GHG or have no impact. Therefore, data is often scaled from an average freight load factor, as seen in the Ecoinvent database, which this study incorporates by the SimaPro software.

This aggregation or assumption is often neglected in environmental studies as it is not intuitive to implement with data difficult to collect. The benefit of this methodology is the straightforward implementation and transparency. For this study, electricity and fuel mixes will be a local mix and are thus specific for Qatar, vehicles and components are based on literature and adapted as such, as not every single component will be assembled or produced in Qatar. The implementation of the lower-impact BEV (EU-based) will be adopted.

Table 4.3 presents the total VKT reported for different regions by the respective authors. To take into account standardization efforts, calculations will be mindful of the functional lifetime of 150,000 km as often followed (Del Pero et al., 2018; Girardi et al., 2015; Hawkins et al., 2013; Tagliaferri et al., 2016) yet will be rescaled for the specific case as proposed in this research. Components that would not last the complete life cycle or need additional maintenance will be

adapted or scaled (Ecoinvent). The impact of scaling and additional maintenance can be studied further in the sensitivity analysis. Using a single kilometer travelled as the FU allows for the scaling of different vehicle lifetimes, making it suitable for analysing future scenarios or adaptations. For Qatar, by analysis of the National Vehicle Inspection (FAHES) and the transportation and vehicle fleet, it could be concluded that the annual VKT is 26,330 km for passenger vehicles. This VKT is situated between the VKT for buses (18,645km, 1 km/litre of diesel) and transport or freight trucks (49,720km, 3 km/l diesel) as reported by Al-Thani (2020). According to the information provider IHS Markit, the average age of an operational LDV went from 11.8 to 12.1 years in 2021 (IHS Markit, 2022). As the vehicle kilometres travelled method has a focus on representing the use phase of the vehicle, this aspect is incorporated in LCA. Based on public information from the EPA (US), UN and EU, the range for HDV and buses were established as a lifetime mileage of 1.9 and 1.5 million km. This will be part of the sensitivity analysis as large differences could be seen, ranging from 20,000 km up to 320,000 km travelled yearly, depending on the type of bus and its location (Al-Thani et al., 2020).

Table 4.3: Vehicle lifetime with expected total distance travelled.

Literature	Region	Distance Travelled	Unit
Bicer & Dincer (2018)	US	239,000	km
Nanaki & Koroneos (2013)	Greece	250,000	km
C. Bauer et al. (2015)	EU	240,000	km
Nealer et al. (2015)	US	286,400	km
Ellingsen et al. (2016)	EU	180,000	km
Mayyas et al. (2017)	US	320,000	km
Messagie et al. (2014)	EU	200,000	km
Ou et al. (2013)	China	240,000	km
Sharma et al. (2013)	Australia	150,000	km

4.2.6 Model framework and assumptions

Of all the main influential factors proposed by global institutes or manufacturers (Figure 4.1), this study modelled the implementation of fuel and electricity consumption, its indirect (coming from processes and products to deliver the needed inputs of the system) impacts and improvements. These variables as well as vehicle compositions are derived from literature, often pointing back to the fleet registered in the European Union and the UK, the use of the GREET model and SimaPro datasets. This study added to this literature from specific manufacturer data and technical sheets (including Suzuki, Tata, Tesla, Hyundai, n.d.) due to its geographical relevance. No direct production data were obtained from vehicle or truck manufacturers, yet could be indirectly accessed through Ecoinvent datasets and SimaPro application. Average values for fuel and electricity consumption were assessed, yet further adapted on available literature to reflect the Qatar dynamic scenario.

This work uses specific data which has not been found in literature or comparable studies for Qatar. The fuel consumption of the in-use vehicles was derived from the Qatari MoI, with the HIS Markint lifetime and FAHES mileage. Diesel personal LDV cars are excluded as this is an irrelevant fraction of the Qatar fleet. Nonetheless, diesel-operated HDV are the focus of the HDV fraction in this work. Biofuels are not included in this study as Qatar has limited resources in this capacity, and overall implementation of biofuels will be insufficient to cover all gasoline or fuel needs while keeping topics such as food security feasible for Qatar. Furthermore, with more regions implementing ICEV bans, these investments would thus not pay off in the longer term. As PHEVs are likewise only a partial solution to the decarbonization issue while simultaneously requiring both gasoline as well as electric car infrastructure, this study leaves this option out of scope.

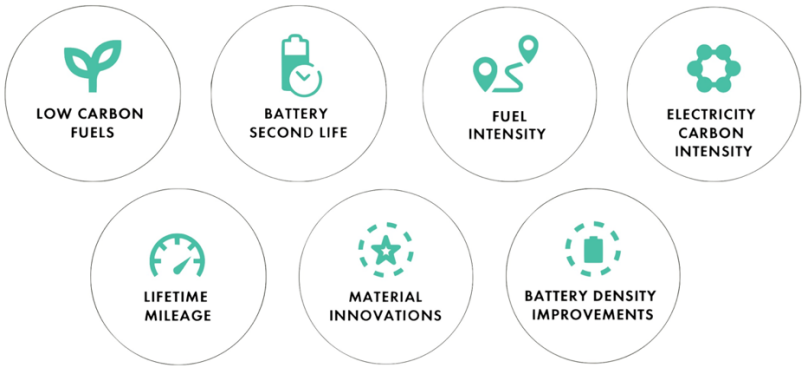

Figure 4.1: Main improvements implemented for ICEV and BEV (Fuels Institute, 2022).

4.2.7 Vehicle cycle and system parameters

In the vehicle cycle, the overall footprint covers the C2G system boundaries. Mining & refining, vehicle production, maintenance, and recycling/end-of-life are considered. Impacts and emissions associated with background processes are included. Expert-specific databases (Ecoinvent) are used in combination with SimaPro. As life cycle inventory data is not available for one specific country or process, aggregation is often done on the country, region or continent level. Qatar is part of the following used locations and regions, both according to the UN and Ecoinvent databases:

- Qatar (QA)
- Middle East, Ecoinvent (RME)
- Rest-of-world (RoW)
- GLO (Global)

The following regions are closely linked and proxy processes can be used after expert review:

- Saudi Arabia (SA)
- United Arab Emirates (AE)

The latter regions were in hindsight not used for the static or dynamic models, yet could be used to further elaborate the sensitivity analysis or recalculate the results to reflect its impact from different electricity or fuel locations. Independent of the vehicle type, the production will largely

be originating from Asian and European brands and production locations. For HDV and buses, production often takes place in locations closer to the importing country, driven by labour and transportation costs. The LDV share was determined on public sources such as the HIS Markit and Qatar Market Research. This was coupled with the Ecoinvent database inventory, where not only underlying products and processes can be adapted, but also components were adapted to the Qatar case study. The weight distribution of LDV subtypes (sedan, SUV and sports car) was kept stable over the timeframe 2022-2050. As the ICEV manufacturing is a stable and established industry, the improvements were only assumed for BEV, both in vehicle as battery mass.

For BEV, the battery cycle includes the production of the packs, including raw material extraction and processing, cell production and assembly including transport. All models are constructed as laid out by ISO standards 14040/44. Second-life use for a battery pack after the lifetime of the vehicle is not considered in the end-of-life treatment because of the low maturity of this sector. Generally, the low maturity of the in the battery market leads to higher uncertainties. Battery recycling can significantly reduce emissions and overall associated impacts and thus will be included in the context of material recycling without reuse. Recycling of other vehicle components is considered as this sector is well established and components such as steel or copper are highly recyclable. Maintenance operations and in-service replacement of consumables such as tires, exhaust/after-treatment, coolant, oil, urea, and others are included in database and operation literature (Ecoinvent product and process documentation). As reported in the manufacturer literature, BEVs require fewer auxiliary consumables as mentioned before due to the lower complexity of the drivetrain system. In the case of multiple sources or proxy values, data will be ranked and weighted by the degree of certainty, its characteristics and its degree of detail.

The modelled BEV incorporates the well-known Lithium manganese oxide (LiMn2O4) battery type, also known as LMO, Li-ion batteries, and have emerged as an excellent choice for electric vehicles, as they combine their unique properties and specific requirements of BEVs. This encompasses a high power output, as LiMn2O4 batteries are known for high power capacity, a critical requirement that allows for quick acceleration. On the other hand, their thermal stability

makes this type safe for use in BEVs, as they often operate in a wide range of temperatures and can generate significant heat during operation. Additionally, their cost-effectiveness is due to the raw material availability which is relatively abundant and thus cheaper compared to those used in new and research-limited lithium-ion batteries. Lastly, LiMn2O4 batteries have a relatively long cycle life, which means they can be charged and discharged many times without significant degradation. This is crucial for BEVs, which require batteries that can last for many years of regular use, without the risk of degradation (W. Chen et al., 2019; X. Chen et al., 2012; S. Rangarajan et al., 2022).

However, it's worth noting that LiMn2O4 batteries also have some limitations. For instance, they have a lower energy density compared to the newest lithium-ion battery chemistries that are being developed, which means they can store less energy for a given size or weight. They also have a relatively high self-discharge rate, which means they can lose a significant amount of stored energy over time when not in use. Future research has the potential to further improve their performance and mitigate their limitations, making them even more attractive for use in BEVs (S. Rangarajan et al., 2022).

Covering a complete LCA, inventories include processes considering water, energy, and material use in the vehicle's lifetime (Bras et al., 2012). Even though an ICEV or a BEV (without fluids, batteries and, tires) is produced from various materials, materials such as iron, aluminium, steel, copper, and plastic comprise more than 90% of the vehicle's weight while with additional electronics, the largest material shares are stable (Dhingra et al., 1999). Therefore, the obtained emissions from the production phase of the ICEVs are shown in Table 4.4 as a reference to be checked against the results (The Institute of Life Cycle Assessment Japan, 2015). The conclusion will refer back to these emission profiles, as production, use phase and recycling are highly country and region-specific. Often related to local guidelines and environmental laws. The study will expand on general assumptions and try to compile a specific emission for each type of vehicle, relating as close as possible to the Qatar situation.

For the production of BEVs, the emissions are procured from literature and the Ecoinvent database yet adapted for the Qatar case study (Hawkins et al., 2013). Even though ICEV-BEV

studies have been performed, the case study of Qatar is underrepresented and dynamic models are often neglected. This study focuses on this aspect, combining global trends, national goals of climate neutrality and producer-specific data for Qatar.

Table 4.4: CO2-eq emissions of key components during the production phase for ICEVs and BEVs.

Part	Vehicle Type	Emissions (kg CO_2 eq)	Reference
Chassis	ICEV	4219	ILCAJ
Engine and Transmission	ICEV	1274	ILCAJ
Battery	BEV	6337	Hawkins et al.
Electric Motor	BEV	1070	Hawkins et al.
Inverter	BEV	641	Hawkins et al.

Though power transmission and generation are different between ICEV and BEV, it is clear that the overall production processes of both vehicles share a lot of manufacturing steps. This way, manufacturing can be retrofitted and impacts from production units can be estimated. Yet, as shown by Figure 4.2, the mass of a BEV light-duty passenger car is around 20% heavier than its internal combustion alternative. This extra weight and associated impact will prolong the time needed to cross the payback time on the impact level but can reduce over time as the BEV market matures. It is assumed the battery weight will improve at a similar pace as the electricity impact, which is a conservative rate of 1.5%. This research will perform this exercise for LDV, HDV and buses, for the timeframe 2022-2050 with intermediate results for 2030 and 2040. The results will therefore cover all the steps to give a concise overview of the differences and impacts.

Assembly	Mass [kg]	
	ICEV	BEV
BiW	292.7	303.6
Closures	176.5	170.0
Suspension/chassis	252.7	252.5
Interiors	173.9	177.1
Drivetrain	222.5	459.8
Electronics	56.7	53.0
Total vehicle	**1175.0**	**1415.7**

Figure 4.2: ICEV and BEV mass assembly LCI (Del Pero et al., 2018).

4.2.8 Fuel parameters

This section was introduced and discussed in the previous chapter where fuel parameters for ICEVs and BEVs were established. This was accomplished by analyzing fuel economies values from the U.S. Department of Energy, examining historical improvements in fuel types, and referencing predictions from organizations such as the IEA.

This study also emphasizes the significance of both direct and indirect emission sources, with indirect emissions often referred to as "well-to-wheel" emissions. To clarify, when burned, diesel and gasoline release inherent direct carbon footprints of 2.655 kgCO2/l and 2.363 kgCO2/l respectively. Emission factors depend heavily on practices like venting and oil production standards. To reiterate, in Qatar, gasoline petroleum is used for LDVs, while diesel fuel is used for both HDVs and buses. Recent trends have shown an improvement in fuel economy, although reduction rates of vehicle fleets hover around 0.9 to 1.5%. These rates may fall short of the ambitious 2050 climate neutrality targets set by various global institutions. There are discrepancies between theoretical and real-world fuel economies, with actual consumption sometimes tripling. For BEVs, electricity source is a key emissions contributor during usage. In Qatar, this electricity comes entirely from natural gas. Renewables have a minor share, and current solar plants might not significantly impact this status quo.

Moreover, emission estimation typically relies on activity data and emission factors. The European Monitoring and Evaluation Programme proposes three approaches for estimation, ranging from Tier 1's basic information requirements to Tier 3's complex inputs like driving

patterns. For this study, the Tier 2 approach of the COPERT model was employed, which integrates factors like fuel quality, vehicle population data, and meteorological conditions sourced from the Qatari Civil Aviation Authority (2021 study).

With fuel economy becoming better over the years yet with the exclusion of biofuels in the gasoline mix for Qatar, the direct emission factor should be assumed to be stable for all dynamic scenarios (2022-2050). This study will provide the basis for dynamic models following global trends and improving processes. This encompasses reducing impacts from fossil extraction and higher environmental norms as put forward by the QNP, having an influence on the indirect carbon footprint.

The different electricity impacts for LDV, HDV and buses are due to differences in voltage and power infrastructures available at the site of the vehicle. As electricity is produced at high voltage, with every downscaling process, small losses occur. HDVs and buses will be charged with higher voltage electricity compared to LDVs as companies have access to more complex infrastructure, thus lowering the impact per kWh (Ecoinvent, n.d.).

Bus emission profiles were tested under real conditions as theoretical values can differ strongly, as reported by the IPCC. Two producers' part in this test were Bozankaya Sileo and Solaris, for which a real energy consumption between 1.65 and 1.84 kWh per kilometre was reported (Ebus yearly test, Germany). As only a few companies provide this type of BEV, this energy consumption profile can be assumed for the general market maturity. The change over the years is modelled similarly to the BEV LDV and global improvement for Asia/EU (1.5%). In case large variances were encountered, the range is given.

4.3 Results and discussion

4.3.1 ICEV comparison

In the following sections, this study delves deeper into the comparative analysis between ICEVs and BEVs. This comparison will be broken down into several sub-sections, each focusing on a specific aspect of the vehicles' environmental impact. This results and discussion section will describe the mentioned critical metrics and offers insights into the vehicles' contribution to, among others, climate change, a pressing global concern.

Following this, it is possible to analyze on a more detailed level the impacts due to factors such as the energy consumption of both vehicle types. The analysis will consider the various stages of the vehicles' lifecycle, from production to operation and eventual disposal. Subsequent sections will delve into other environmental impact categories, and the introduction of a detailed comparison between ICEVs and BEVs, highlighting the strengths and weaknesses of each vehicle type in the mentioned areas.

The findings from these sections will provide a detailed understanding of the environmental impacts and resulting implications of using or transitioning from ICEVs to BEVs. Such in-depth analysis can serve as a valuable resource for stakeholders in the automotive and energy sectors, informing decision-making processes and guiding future research directions.

ICEV sedan

Before the direct comparison of internal combustion and battery electric vehicles, the separate vehicles and results should be assessed. This is being done in order to locate internal hotspots, the improvement options and the main takeaways for each vehicle and timeframe. With the LDV fraction made up of sedans, sports vehicles and SUVs, all subcategories were calculated for the timeframes 2022-2030-2040-2050. Using the values of fuel characteristic in the previous chapter (Table 3.3), the model includes Qatar-specific emission profiles for both the fuel type, its direct and indirect impacts as well as relevant vehicle characteristics.

Table 4.5 represents the midpoint ReCiPe indicators of focus, selected as global warming, particulate matter, acidification, human health and resource scarcity (mineral and fossil). The complete table of results is given in the appendix of the thesis. The Endpoint ReCiPe indicators, as described earlier, provide an aggregated value for damage to Ecosystems, Human health and Resources. These results will be concentrated at the end of the vehicle type comparison.

For the results of the ICEV sedan, even with the reported reduction in emissions from fuel and efficiency improvements, the sedan cannot reach its target of climate neutrality by 2050. The final fuel economy is set by the GFEI and IEA as described in the framework of the model, yet relies upon a steady improvement over its course. Aside from the carbon footprint, the main improvements are in fine particulate matter, acidification, and fossil resource depletion. The latter is mainly due to a large improvement in motor efficiency. For the ICEV sedan in 2022, 72% of its carbon footprint is due to its use phase, similar to ICEV/BEV literature as production of the vehicle is relatively uncomplicated compared to battery and electric motor production. For this vehicle, the motor is only around 3% of the overall carbon footprint and 2.3% of the fossil resource scarcity. The indirect emissions related to gasoline use are responsible for over 15% of the overall GWP. The fossil resource scarcity is here naturally dominated by gasoline exploration with 83%. In 2050, as lowering fuel needs don't completely fall to zero, the use-phase still is responsible for 68% of the carbon footprint with 56% of the resource scarcity due to gasoline exploration. In order to decrease the mineral resource scarcity as well as the toxicity parameters, other aspects of the ICEV would have to be tackled.

Table 4.5: Impact assessment ICEV sedan 2022-2050, impacts per km travelled.

Impact category	Unit	ICEV LDV sedan 2022	ICEV LDV sedan 2030	ICEV LDV sedan 2040	ICEV LDV sedan 2050
Global warming	kg CO2 eq	2.34E-01	2.11E-01	1.87E-01	1.63E-01
Fine particulate matter	kg PM2.5	2.27E-04	2.09E-04	1.64E-04	1.29E-04
Terrestrial acidification	kg SO2 eq	5.49E-04	4.97E-04	3.62E-04	2.58E-04
Human carcinogenic toxicity	kg 1,4-DCB	1.22E-02	1.20E-02	1.16E-02	1.12E-02
Human non-carcinogenic	kg 1,4-DCB	1.47E-01	1.44E-01	1.38E-01	1.33E-01
Mineral resource scarcity	kg Cu eq	7.89E-04	7.80E-04	7.48E-04	7.24E-04
Fossil resource scarcity	kg oil eq	8.76E-02	7.90E-02	5.70E-02	3.50E-02

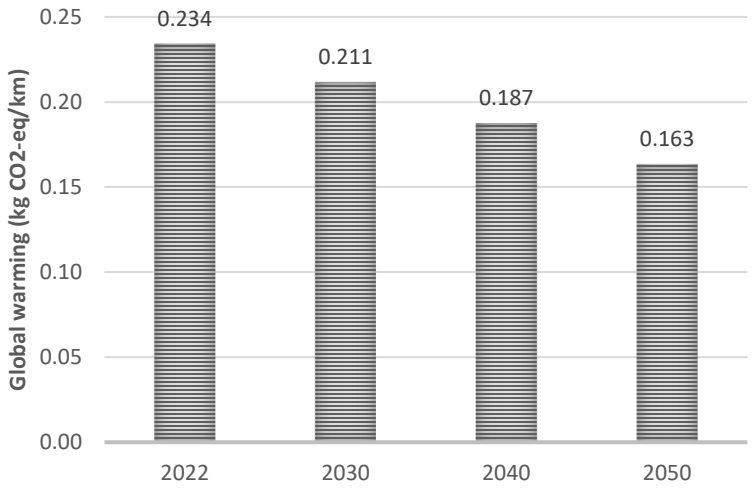

Figure 4.3: Global warming indicator, ICEV sedan 2022-2050, kgCO2-eq/km.

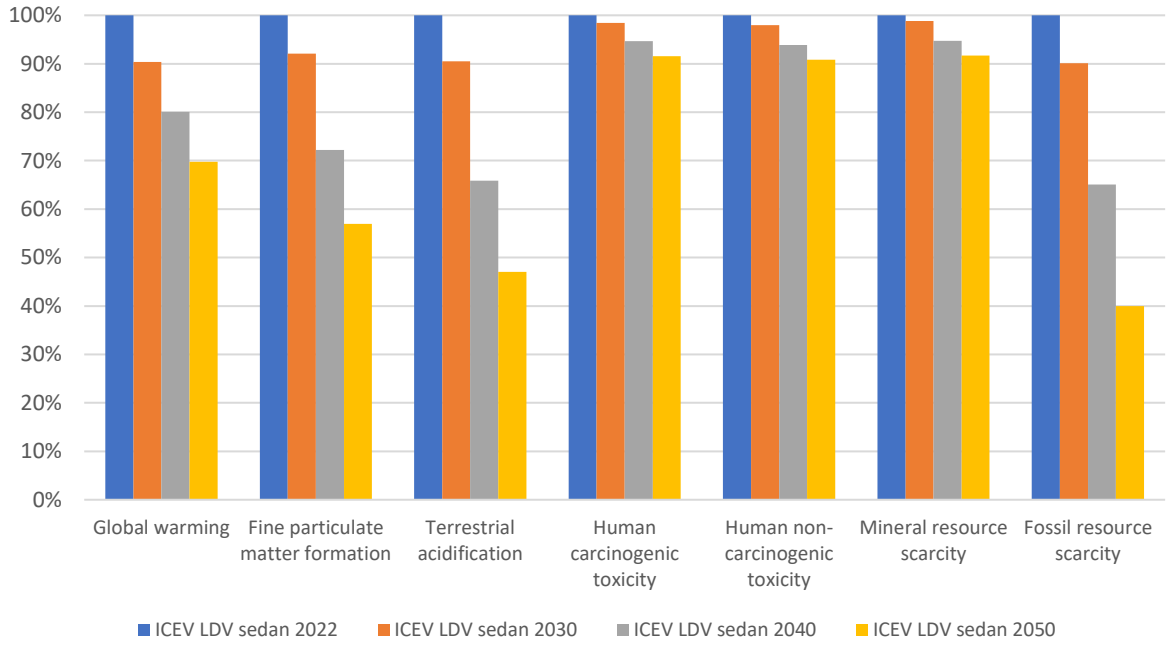

Figure 4.4: Focus indicators for ICEV LDV sedan 2022-2050, per km, ReCiPe Midpoint (%; relative to max impact).

ICEV sports vehicle and SUV

The calculation was repeated for the SUV and sports vehicle, as Qatar has a high fleet share compared to other countries. As could be seen for the sedan, the carbon footprint is reduced

with improvements in fuel economy. Yet, the use-phase is still dominant in the carbon footprint and fossil resource scarcity in the case of fuel exploration. Both for the SUV and sports vehicle, the final GWP is still higher than a small LDV sedan. For this yearly mileage of 26,330 km/y for over 12 years, every SUV counts almost always as 1.5 sedans if scaled back per kilometre driven. Just as for the SUV, with a trend of going larger, fuel economy shortly reverses in the future.

Table 4.6: Impact assessment ICEV sports vehicle 2022-2050, per functional unit.

Impact category	Unit	ICEV LDV sport 2022	ICEV LDV sport 2030	ICEV LDV sport 2040	ICEV LDV sport 2050
Global warming	kg CO2 eq	2.65E-01	2.40E-01	2.62E-01	1.92E-01
Fine particulate matter formation	kg PM2.5 eq	2.63E-04	2.43E-04	2.35E-04	1.68E-04
Terrestrial acidification	kg SO2 eq	6.29E-04	5.71E-04	5.47E-04	3.46E-04
Human carcinogenic toxicity	kg 1,4-DCB	1.47E-02	1.44E-02	1.44E-02	1.37E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.72E-01	1.69E-01	1.67E-01	1.59E-01
Mineral resource scarcity	kg Cu eq	9.21E-04	9.11E-04	9.04E-04	8.57E-04
Fossil resource scarcity	kg oil eq	9.92E-02	8.96E-02	9.97E-02	5.70E-02

Table 4.7: Impact assessment ICEV SUV 2022-2050, per functional unit.

Impact category	Unit	ICEV LDV SUV 2022	ICEV LDV SUV 2030	ICEV LDV SUV 2040	ICEV LDV SUV 2050
Global warming	kg CO2 eq	4.08E-01	3.67E-01	3.31E-01	2.93E-01
Fine particulate matter formation	kg PM2.5 eq	3.72E-04	3.39E-04	2.91E-04	2.05E-04
Terrestrial acidification	kg SO2 eq	9.19E-04	8.24E-04	6.81E-04	4.25E-04
Human carcinogenic toxicity	kg 1,4-DCB	1.84E-02	1.81E-02	1.76E-02	1.67E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	2.17E-01	2.11E-01	2.05E-01	3.05E-01
Mineral resource scarcity	kg Cu eq	1.16E-03	1.14E-03	1.10E-03	1.05E-03
Fossil resource scarcity	kg oil eq	1.54E-01	1.39E-01	1.27E-01	7.21E-02

ICEV LDV comparison

The full environmental assessment indicator table for all indicators will be given in the appendix, both for all LDV types and all timeframes. A significant reduction in the overall impact could only be seen in the fossil resource scarcity, the particulate matter and acidification. The GWP for all timeframes and vehicle types is shown in Figure 4.5, stating clearly that none of the LDV types can achieve decarbonization or reach overall low-carbon targets without additional implementations. It has to be noted that, due to the inconsistency of the GFEI and IEA projections, together with the increase of SUV and sports vehicle sizes, even though efficiencies increase and standards become better, a small uptick in impacts can be noticed between the 2030 and 2040 scenario. This is not a dealbreaker for the overall interpretation of this dynamic scenario, as this has been the case for sedan vehicles before and for the fleet level overall impact. This has been established by many authors and governments since the 1990's, but a more recent terminology for this is the rebound effect, stating that through improvements and easier access, the overall impact still increases. For this work, the vehicle weight overrides the improvements of the standards, shortly worsening the impact before it decreases to its set goal by the GFEI and IEA.

In case of advanced fuel efficiencies and lower direct fuel emissions, the sourcing of the fuel would become important. The production of the vehicle represents between 27 and 19% of the carbon footprint in 2050 (sedan and SUV resp.), coming from 9-11% in 2022. With lowering impacts from direct emissions, otherwise negligible processes become more important. This is also applicable for maintenance of the car and indirect impacts due to road wear and related emissions.

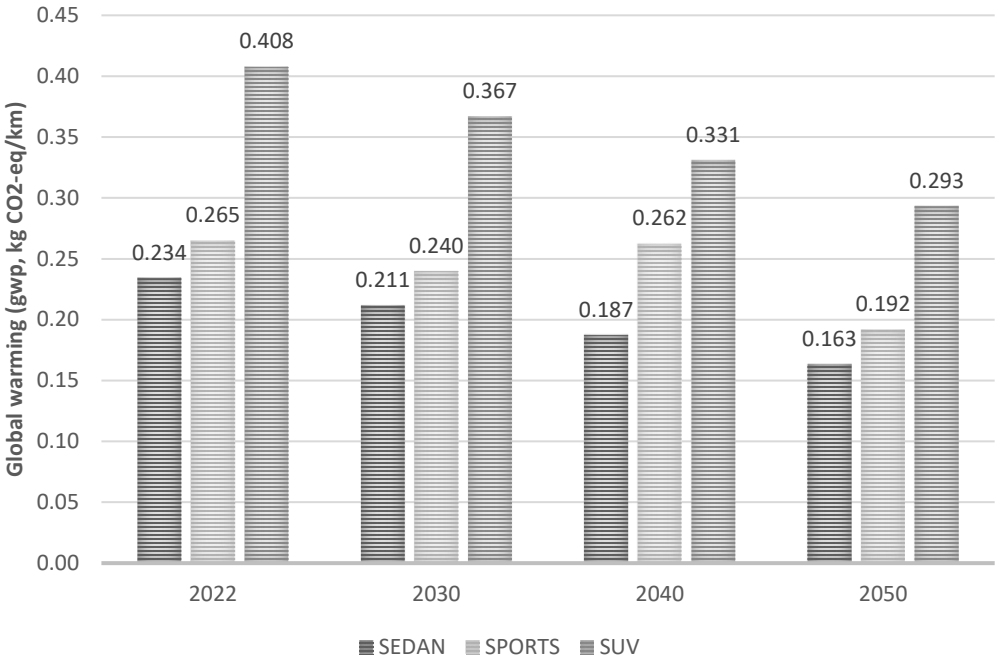

Figure 4.5: GWP for all LDV types, 2022-2050, kgCO2-eq/km.

The final comparison of the ICEV LDV is shown in Figure 4.6 and Figure 4.7, making clear that even with advanced implementations of fuel efficiency and lowering impacts for the use phase, SUV and sports vehicles still have a higher carbon footprint compared to the sedan scenario. This trend can be seen as well for human toxicity and mineral resource scarcity, as the latter two vehicles have an overall higher material and technology demand. Not only for the midpoint categories, yet also shown in the endpoint categories, sport and SUV vehicles perform over the complete 2022-2050 period worse than the current sedan.

It should be noted that the GWP of the ICEV sports vehicle is projected to increase from 2030 to 2040, contrary to the general expectation of decreasing emissions. This is also reflected in the fossil resource scarcity, as this impact is closely linked with the fuel use and thus carbon footprint for this ICEV model. Generally, it is expected that over time, due to technological advancements and improved efficiencies, emissions and impacts continue to go down, which is not true for this 2030-2040 model result. This counterintuitive trend can be attributed to several factors related to the specific characteristics, fuel use and fuel impacts used by the sports vehicles. As this is fundamentally based upon the projections from global institutes, the choice was made to keep

this small uptake in 2040 as the final downtrend in emissions converges. This can be understood as multiple factors will influence the total fuel needs, for which during a given year the balance is upwards while over time, other characteristics can reduce the overall impact by further improving on other ends.

One of the primary reasons outside of the model characteristics is often the increase in the weight of these vehicles. Sports vehicles, known for their high performance, often incorporate heavier engines and larger models over time to enhance their power and speed capabilities. This increase in weight leads to higher energy consumption, even if the energy efficiency of the vehicle improves. Another factor here is the trend towards larger and more luxurious sports vehicles, thus requiring more energy to operate, which can lead to an increase in emissions, even if the emissions per unit of vehicle weight or distance travelled decreases. This phenomenon is not unique only to the sports vehicle sector as it has been observed in other sectors, where improvements in efficiency are offset by increases in size or weight, leading to an overall increase in emissions, which can be true on fleet-level as well. It should also be noted that as fuel economy values were deduced from international sources, the detailed reasoning behind the increase in fuel economy of 2040 compared to 2030 is beyond the scope of this study. This highlights the importance of considering all aspects and sources of a vehicle's design and operation when assessing its environmental impact.

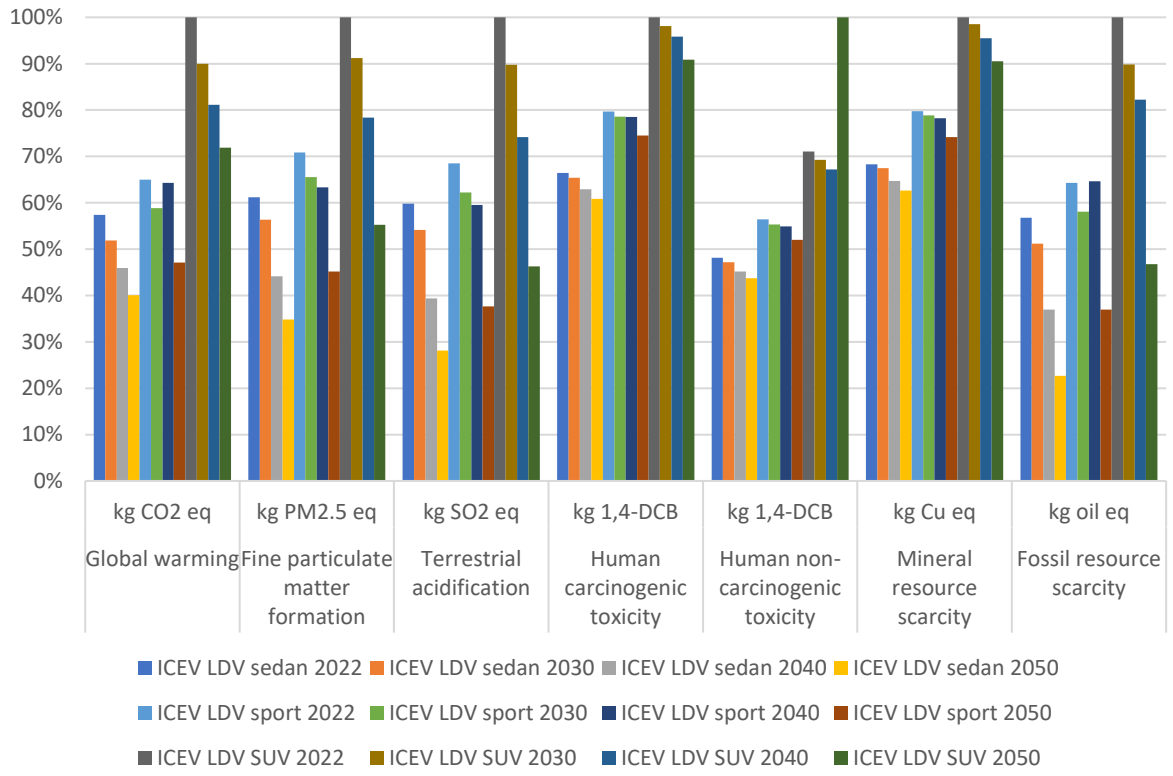

Figure 4.6: Focus indicators for all LDV ICEV 2022-2050, per functional unit, ReCiPe Midpoint (%; relative to max impact).

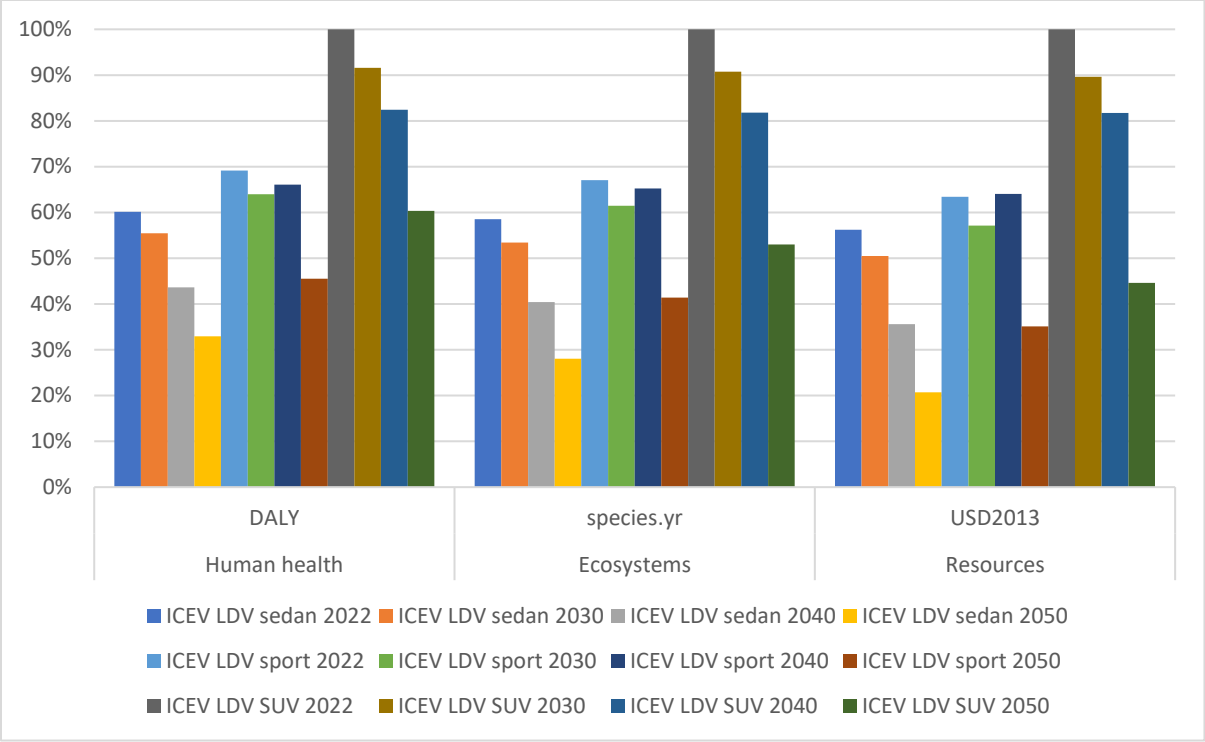

Figure 4.7: Endpoint indicators for all LDV ICEV 2022-2050, per functional unit, ReCiPe (%; relative to max impact).

ICEV HDV and bus

Compared to the ICEV LDV fraction, the HDV and buses do not run on petrol or gasoline but diesel fuel. The use of diesel has both advantages and disadvantages. Diesel has, with its denser oil fraction a higher energy density and thus better thermal efficiency. For a complete overview of the differences between gasoline, diesel and biobased alternatives, the framework section of this chapter covers this aspect.

On the other hand, the indirect emission profile is worse for diesel compared to gasoline, yet overall, vehicles tend to have longer lifetimes and better fuel economies. This trade-off played out in the ICEV market and will be assessed later for the ICEV/BEV comparison. In case of the carbon footprint for the average scenario, meaning no excessive transport loads or capacity buses, the footprint is similar for the 2022-2050 dynamic models. As a theoretical extreme, if an HDV would carry its maximal load over its complete lifetime and assume a linear relation between fuel economy and carrying load, the impact would thus be almost 4-fold (Figure 4.8). Even with

these improvements, as they still rely on fossil resources, which will not be sufficient for a low-carbon future, yet impacts are reduced.

For the carbon footprint of the ICEV HDV and bus scenario, it can be seen that, most likely due to higher incentives and already implemented environmental standards, the HDV improves faster, yet the bus scenario does end up with a lower impact. Yet, as already mentioned, an ICEV will transport larger units of mass over its lifetime and therefore also have a lower impact if this scenario would be scaled by using a basket of goods approach. In that case, instead of a single km travelled, one could repeat the calculation to reflect a unit of goods or service and reflect on the impact for that unit. An example of this would be the price of the transported goods versus the price of a bus trip, both in relation to the cost of operation. This example shows the further importance of carefully defining the functional unit and indirect effects.

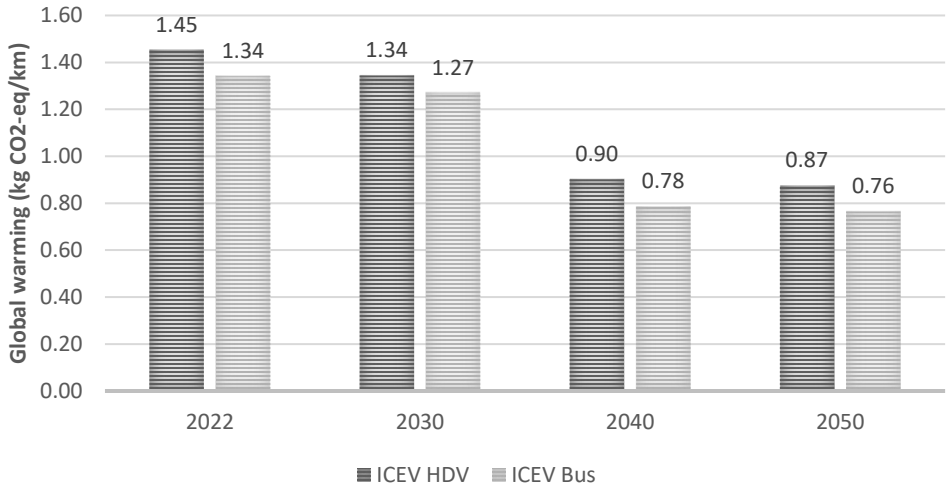

Figure 4.8: GWP for HDV and bus, 2022-2050, kgCO2-eq/km.

The Midpoint ReCiPe results for the ICEV bus vs HDV scenario are shown in Figure 4.9 and Figure 4.10. Here, it can be deduced that fine particulate matter and acidification are mostly reduced in the HDV scenario in the early stages of 2022-2050. This is mainly due to the transformation of the HDV fleet from Euro 4 up to higher standards. Earlier iterations of the EURO norms had exponential improvements in this area, therefore the higher the standard from EURO5 upwards,

the lower the expected return in environmental improvements. Even as the HDV transport higher average loads (16-32 tons), the change to higher EURO norms results in similar acidification and particulate matter formation compared to the bus transport. The possible explanation here is the focus on goods transport from both manufacturers and governments, therefore pushing higher standards more quickly in this sector. Yet, for the carbon footprint, human toxicity and resource scarcity (both fossil and mineral), the bus transport scores significantly better than the HDV. The full tables are given in Table 4.8 and Table 4.9. The focus was put on the impact from the maximal load over its lifetime, increasing the impact by almost 4-fold yet not influencing the overall improvements and trends.

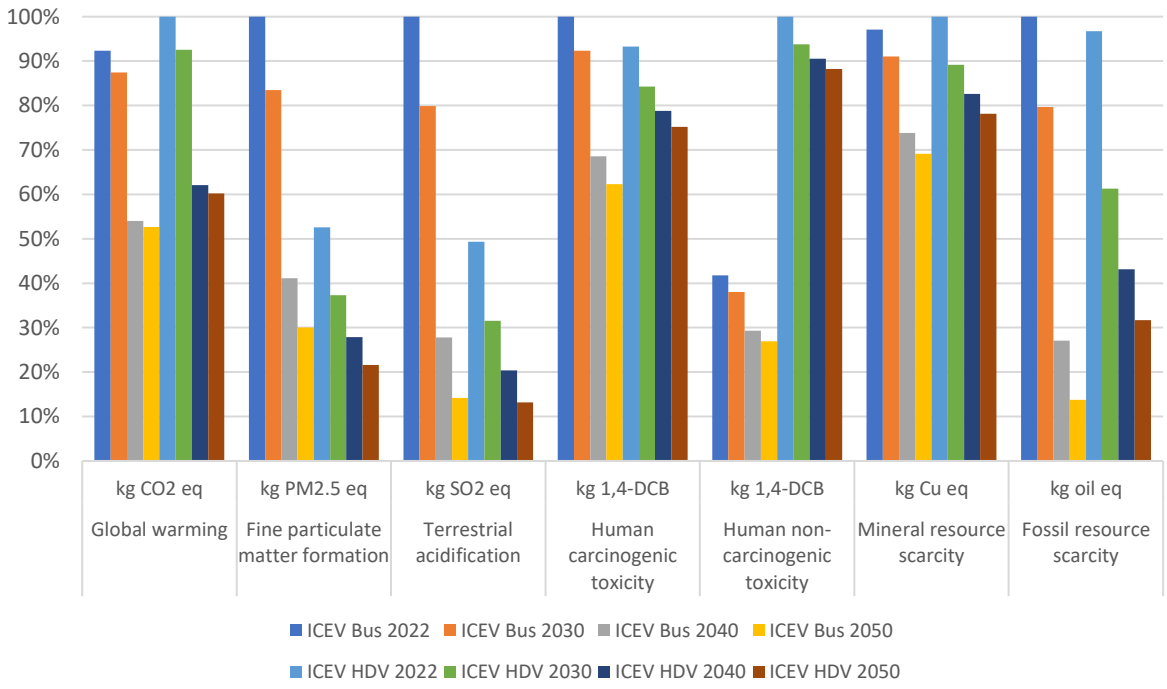

Figure 4.9: ICEV bus HDV comparison on ReCiPe midpoint level, per functional unit, 2022-2050.

Table 4.8: Impact assessment ICEV HDV 2022-2050, per functional unit.

Impact category	Unit	ICEV HDV 2022	ICEV HDV 2030	ICEV HDV 2040	ICEV HDV 2050
Global warming	kg CO2 eq	1.45E+00	1.34E-00	9.02E-01	8.75E-01
Fine particulate matter formation	kg PM2.5 eq	1.32E-03	9.36E-04	6.99E-04	5.42E-04
Terrestrial acidification	kg SO2 eq	3.21E-03	2.05E-03	1.33E-03	8.57E-04

Human carcinogenic toxicity	kg 1,4-DCB	2.44E-02	2.20E-02	2.06E-02	1.97E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	4.54E-01	4.26E-01	4.11E-01	4.01E-01
Mineral resource scarcity	kg Cu eq	1.17E-03	1.05E-03	9.70E-04	9.18E-04
Fossil resource scarcity	kg oil eq	4.35E-01	2.75E-01	1.94E-01	1.42E-01

Table 4.9: Impact assessment ICEV bus 2022-2050, per functional unit.

Impact category	Unit	ICEV bus 2022	ICEV bus 2030	ICEV bus 2040	ICEV bus 2050
Global warming	kg CO2 eq	1.34E+00	1.27E+00	7.85E-01	7.64E-01
Fine particulate matter formation	kg PM2.5 eq	2.51E-03	2.10E-03	1.03E-03	7.54E-04
Terrestrial acidification	kg SO2 eq	6.51E-03	5.20E-03	1.81E-03	9.23E-04
Human carcinogenic toxicity	kg 1,4-DCB	2.62E-02	2.42E-02	1.79E-02	1.63E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.90E-01	1.73E-01	1.33E-01	1.22E-01
Mineral resource scarcity	kg Cu eq	1.14E-03	1.07E-03	8.67E-04	8.12E-04
Fossil resource scarcity	kg oil eq	4.49E-01	3.58E-01	1.22E-01	6.17E-02

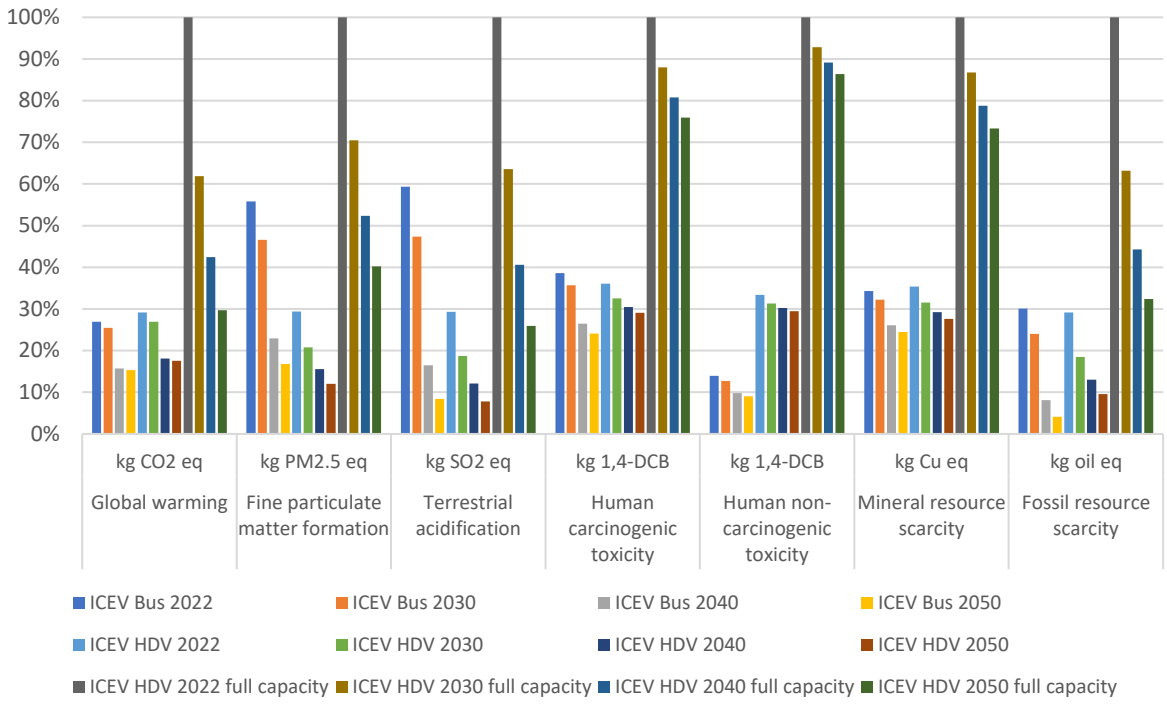

Figure 4.10: ICEV HDV average load, full capacity and ICEV bus, per functional unit, ReCiPe Midpoint indicators.

Even though the impact per kilometre travelled by ICEV sedan is up to 10 times lower compared to the bus scenario, a correct comparison should be drawn. The bus is modelled as having a maximal capacity of around 50 people, therefore, if a conservative occupancy of 32 people on the bus is assumed, the ReCiPe results can be seen in Figure 4.11. Even with all advances and highly improved fuel economy, all indicators show an advantage for the bus system if one would calculate it back to a single person travelling. As said, the degree of improvements is derived from global institutions, unknown to be met by 2050. All uncertainties, Monte Carlo simulations and sensitivities will be addressed in their respective chapter.

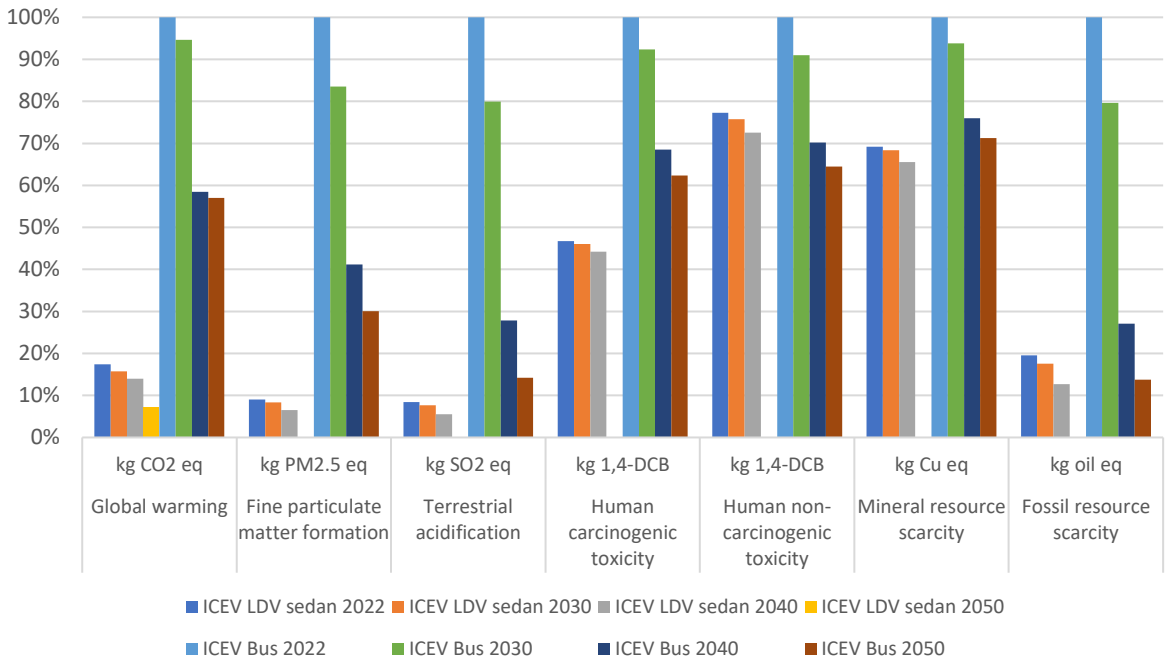

Figure 4.11: ICEV sedan vs bus, 2022-2050, per functional unit, ReCiPe Midpoint indicators.

4.3.2 BEV comparison

Just as was done for the ICEV category, all BEV scenarios were calculated for the timeframe 2022-2050. In the first part, the LDV will be discussed, linking afterwards the HDV and bus model before the comparison is made with the ICEV category and the sensitivity analysis is done. It should be noted that the ICEV were modelled as an optimistic GFEI/IEA scenario, and it is unclear if all future projections will be feasible after the long advance in technology and increase in fuel economy. Yet, this comparison makes it ideal to compare the internal combustion future with the switch to BEV.

To further reflect this case, the BEV scenario is calculated excluding carbon capture. This scenario will thus look at the ICEV best-case and BEV business-as-usual with only marginal improvements. If this scenario shows a significant improvement, all carbon capture implementations can be seen as lowering the national carbon footprint of Qatar or the overall impact of the transport sector.

<u>BEV sedan</u>

The environmental indicators of focus in this study show that for this base case of BEV LDV sedans, without battery improvements or large leaps in efficiency, the main reduction in impact is seen for fossil resource scarcity and the global warming indicator Figure 4.13. This is due to the electricity use, located centrally as it is produced by natural gas and no renewable energy is part of the grid mix in Qatar. The influence on the carbon footprint itself is shown separately in Figure 4.12. Further improvement options for the BEV will be discussed in the sensitivity and the uncertainty analysis.

Table 4.10; Impact assessment BEV sedan 2022-2050, per functional unit.

Impact category	Unit	BEV LDV sedan 2022	BEV LDV sedan 2030	BEV LDV sedan 2040	BEV LDV sedan 2050
Global warming	kg CO2 eq	1.91E-01	1.73E-01	1.62E-01	1.54E-01
Fine particulate matter	kg PM2.5 eq	3.13E-04	3.08E-04	3.05E-04	3.03E-04
Terrestrial acidification	kg SO2 eq	7.35E-04	7.23E-04	7.15E-04	7.08E-04
Human carcinogenic toxicity	kg 1,4-DCB	3.06E-02	3.03E-02	2.99E-02	2.97E-02
Human non-carcinogenic	kg 1,4-DCB	8.40E-01	8.30E-01	8.20E-01	8.14E-01

Mineral resource scarcity	kg Cu eq	3.56E-03	3.52E-03	3.49E-03	3.46E-03
Fossil resource scarcity	kg oil eq	6.66E-02	5.87E-02	5.45E-02	5.10E-02

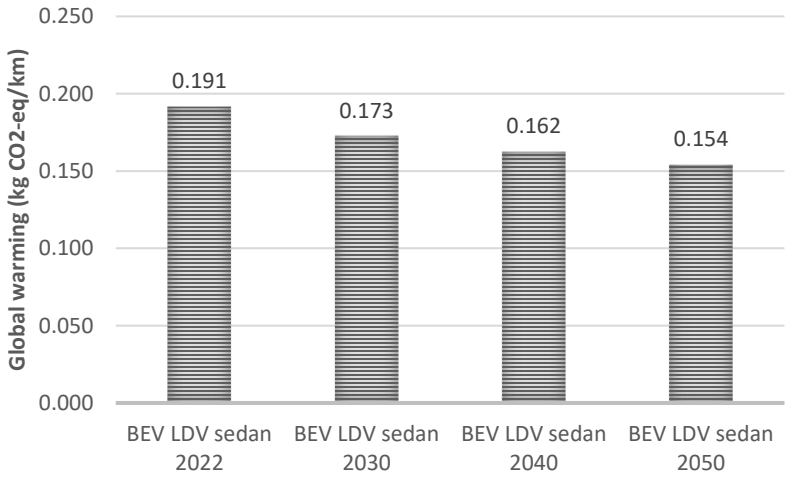

Figure 4.12: GWP for BEV LDV sedan, 2022-2050, kgCO2-eq/km.

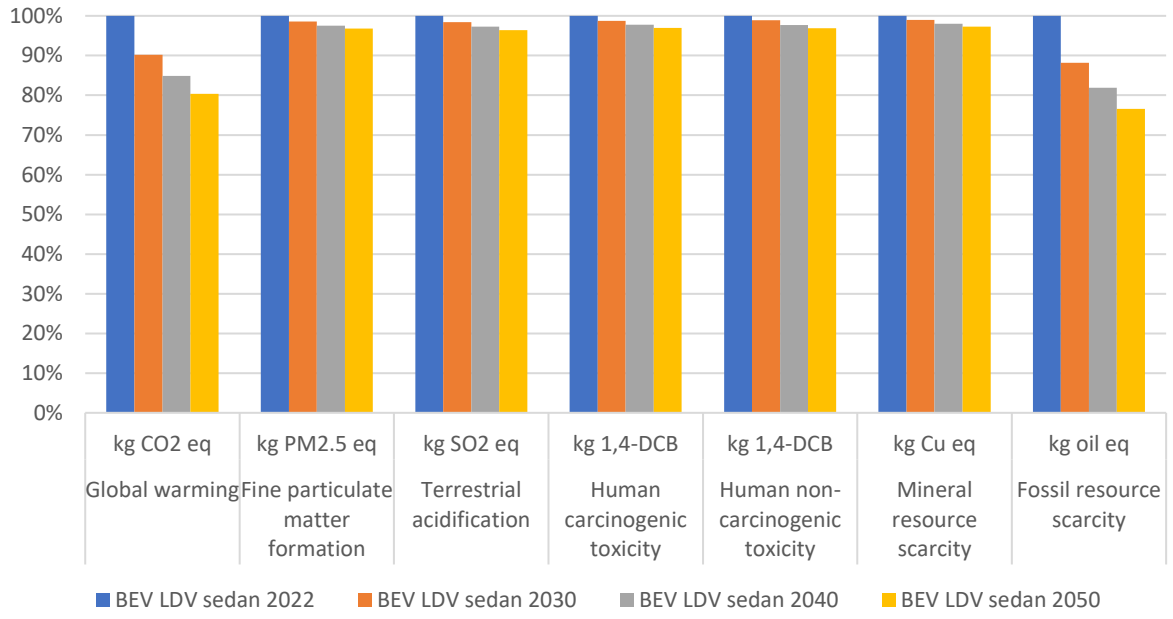

Figure 4.13: Focus indicators for BEV LDV sedan 2022-2050, per functional unit, ReCiPe (%; relative to max impact).

BEV sports vehicle and SUV

The same calculation was repeated for the SUV and sports vehicle, again showing that environmental indicators of focus, without the mentioned improvements, mainly are reduced for

fossil resource scarcity and the global warming indicator Figure 4.15. This is due to the electricity use, located centrally as it is produced by natural gas and no renewable energy is part of the grid mix in Qatar. For the BEV section, the same amount of lifetime kilometres is implemented as for the ICEV. In comparison to the ICEV alternative, the difference between the sedan, sports and SUV options is relatively small. A contributing factor here is the locally produced electricity and similarity of vehicle and battery production. The carbon footprint which is often communicated separately, is given in Figure 4.14, also showing the similarities over the given timeframe.

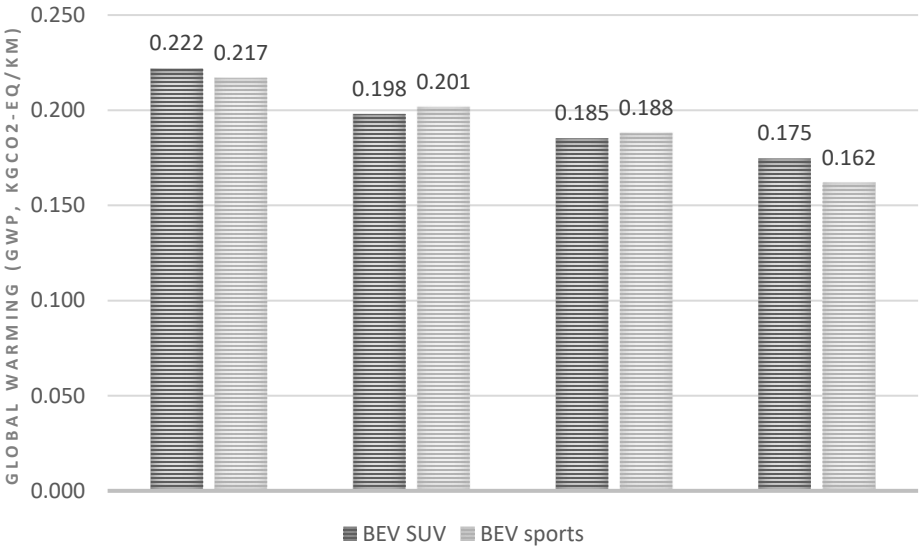

Figure 4.14: GWP for BEV LDV sedan, 2022-2050, kgCO2-eq/km.

Table 4.11: Impact assessment BEV sports vehicle 2022-2050, per functional unit.

Impact category	Unit	BEV LDV Sport 2022	BEV LDV Sport 2030	BEV LDV Sport 2040	BEV LDV Sport 2050
Global warming	kg CO2 eq	2.17E-01	2.01E-01	1.88E-01	1.62E-01
Fine particulate matter formation	kg PM2.5 eq	3.25E-04	3.20E-04	3.17E-04	3.10E-04
Terrestrial acidification	kg SO2 eq	7.66E-04	7.55E-04	7.45E-04	7.29E-04
Human carcinogenic toxicity	kg 1,4-DCB	3.20E-02	3.16E-02	3.12E-02	3.07E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	8.89E-01	8.78E-01	8.67E-01	8.54E-01
Mineral resource scarcity	kg Cu eq	3.74E-03	3.70E-03	3.66E-03	3.61E-03

Fossil resource scarcity	kg oil eq	7.68E-02	7.04E-02	6.48E-02	5.39E-02

Table 4.12: Impact assessment BEV SUV 2022-2050, per functional unit.

Impact category	Unit	BEV LDV SUV 2022	BEV LDV SUV 2030	BEV LDV SUV 2040	BEV LDV SUV 2050
Global warming	kg CO2 eq	2.22E-01	1.98E-01	1.85E-01	1.75E-01
Fine particulate matter formation	kg PM2.5 eq	3.35E-04	3.29E-04	3.25E-04	3.22E-04
Terrestrial acidification	kg SO2 eq	7.94E-04	7.79E-04	7.68E-04	7.60E-04
Human carcinogenic toxicity	kg 1,4-DCB	3.35E-02	3.29E-02	3.25E-02	3.22E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	9.49E-01	9.36E-01	9.24E-01	9.14E-01
Mineral resource scarcity	kg Cu eq	3.95E-03	3.90E-03	3.85E-03	3.82E-03
Fossil resource scarcity	kg oil eq	7.83E-02	6.84E-02	6.31E-02	5.87E-02

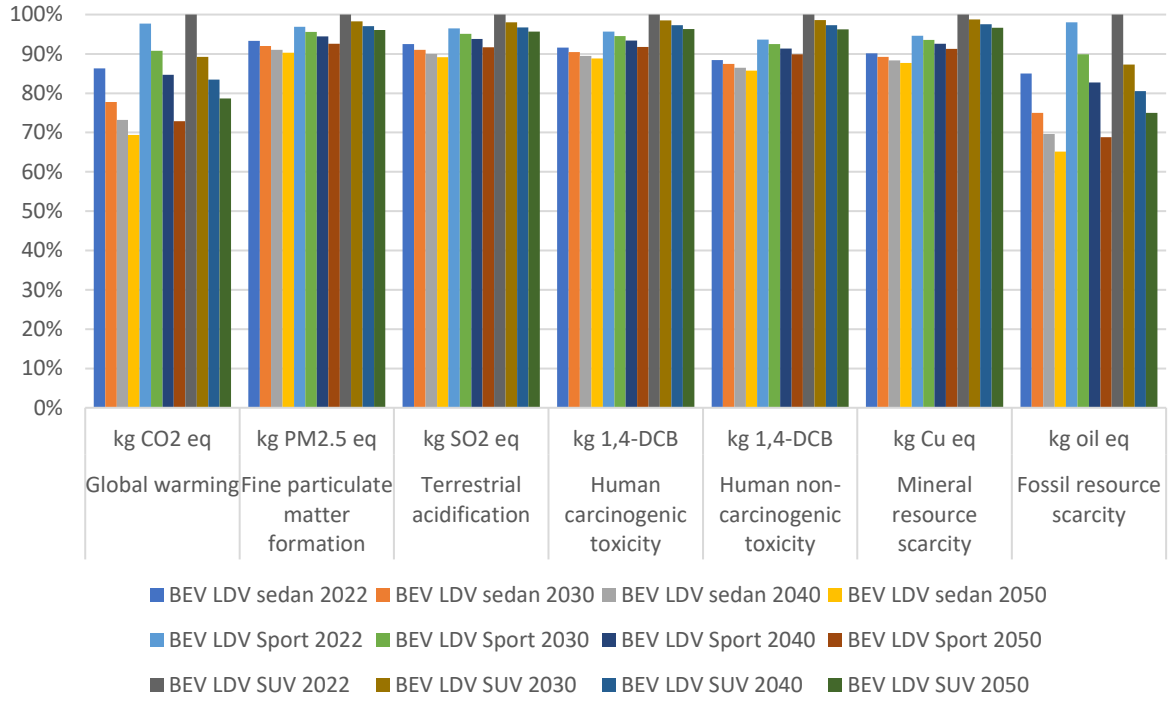

Figure 4.15: Focus indicators for BEV LDV 2022-2050, per functional unit, ReCiPe (%; relative to max impact).

Concerning the similarities in vehicle production and central electricity generation, it should be noted that discrepancies can be observed between literature and available databases regarding the impact of the electric vehicle itself. It is a general conclusion that the electric vehicle production, before the use-phase is started, has the largest impact, vastly outweighing the impact of an ICEV.

The section below addresses this notion by calculation of 3 electric vehicle options. The available alternatives range from 2 European-type manufacturing options, a very light electric vehicle option, a general sedan option, and a sedan option with production globally. The global electric vehicle thus reflects a higher share of transport and possibly lower environmental standards, both in emissions as in energy production. As Qatar has a high GPD, high purchasing power and a high living standard with import relations all around the globe, the BEV type with higher standards can be implemented. The type of vehicle does not reflect that every component is produced and assembled in Europe, it reflects a standard of production and environmental diligence compared to higher impact products which can be imported as well from locations such as Southeast Asia. From a modelling standpoint, this is not an issue, as market products can be adapted for different transport distances and locations. Still, it is interesting that production location and indirect effects are causing large discrepancies. For the global market vehicle, 18% of the carbon footprint and 36% of the mineral resource scarcity is due to battery production. The additional reason the middle option was chosen can be seen in Figure 4.17. Here, there is a higher degree of detail for the overall product, with a clear understanding of the underlying parts. Furthermore, the share of battery production and its impact is in line with widespread literature. The battery in this case is responsible for 32% of the carbon footprint and 50% of the mineral resource scarcity impacts.

Table 4.13: Impact assessment BEV vehicle types, per functional unit.

Impact category	Unit	BEV, LiMn2O4 battery type	BEV, LiMn2O4 battery type, very light model	BEV, with LiMn2O4 battery {GLO market}
Global warming	kg CO2 eq	5.87E+03	2.53E+03	1.03E+04
Fine particulate matter formation	kg PM2.5 eq	1.25E+01	5.17E+00	2.48E+01

Terrestrial acidification	kg SO2 eq	3.29E+01	1.34E+01	5.48E+01
Human carcinogenic toxicity	kg 1,4-DCB	1.83E+03	8.33E+02	3.50E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	5.22E+04	1.99E+04	7.60E+04
Mineral resource scarcity	kg Cu eq	2.71E+02	1.14E+02	3.74E+02
Fossil resource scarcity	kg oil eq	1.89E+03	8.17E+02	2.61E+03

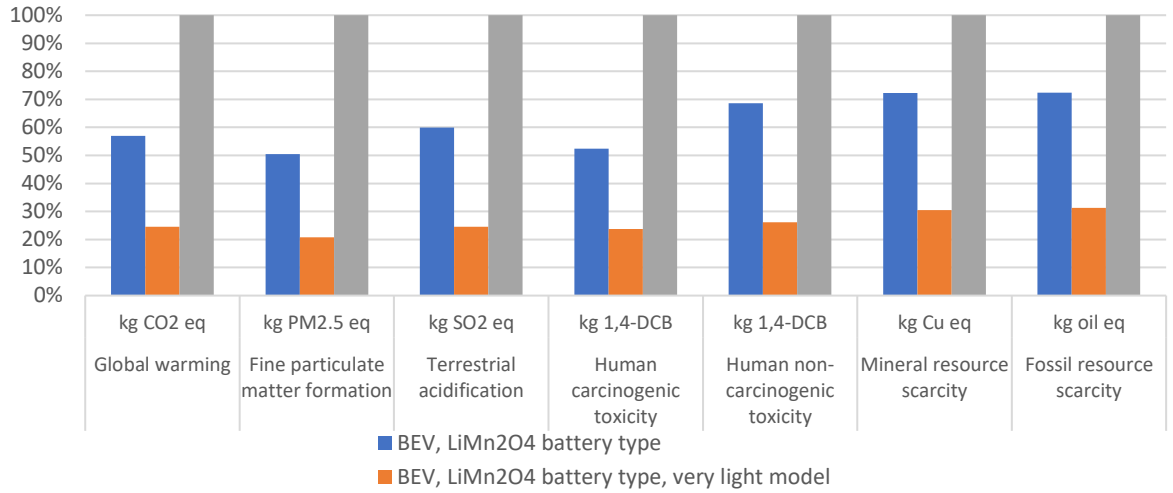

Figure 4.16: Focus impact indicators for BEV sedan types, per functional unit, ReCiPe (%; relative to max impact).

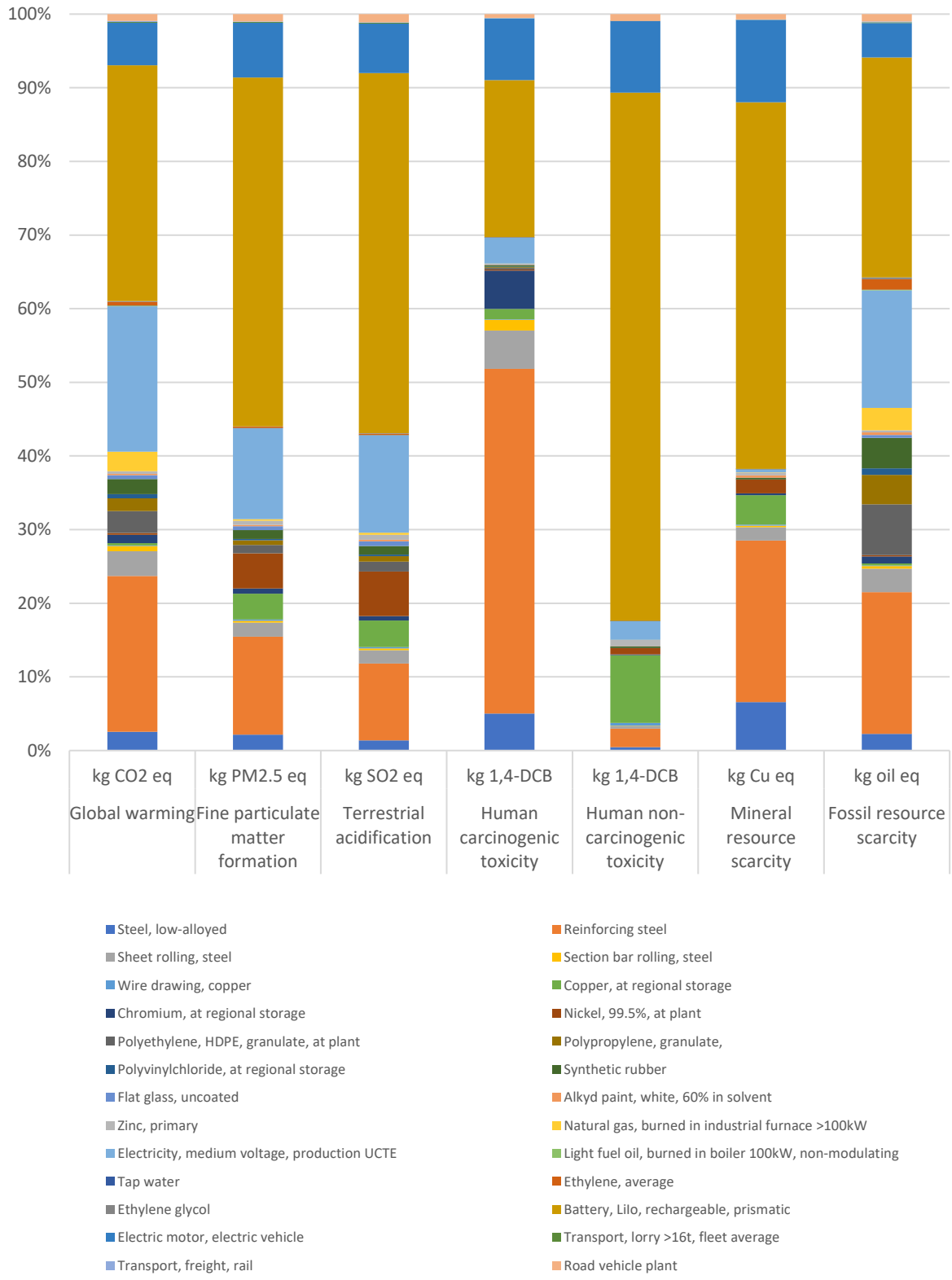

Figure 4.17: Focus impact categories (ReCiPe) for LDV BEV components, per unit.

BEV HDV and bus

As described in the framework, with a focus on the ICEV-BEV comparison, the goal is to keep most variables and design options constant to assess the influence of the specific BEV characteristics. For the BEV HDV and bus, this is mainly the improvement in battery weight, the lower energy consumption and as part of the sensitivity analysis, the alternative battery chemistry options. Both the BEV bus and HDV were modelled as close to their ICEV counterpart, switching out the drivetrain and adding the needed battery pack. In the case of the HDV, the 2022 battery pack weighs 6,543kg, lowering to 4,285kg in 2050. The BEV bus is assumed to have a similar degree of improvement, yet has a smaller battery pack as it is closer to charging locations and is less reliant on long distances away from infrastructure.

The ReCiPe results and the carbon footprint are shown separately in Figure 4.18 and Figure 4.19 as well as in Table 4.14 and Table 4.15. The full ReCiPe results are again added to the Appendix of this thesis. Similar to the ICEV HDV and Bus scenario, the impact per driven distance is not too distinct, yet of course, the transported goods and service are different. In the case of the Bus scenario of 2022, 94% of the lifetime emissions will be due to electricity use. This is mainly as this type of vehicle has a very long lifetime compared to its BEV LDV counterparts and the vehicle itself, the battery and production become less relevant for the overall impacts. With such a share going to electricity production, lowering the energy consumption, and lowering the impact of the electricity itself is key.

Looking at the HDV in 2022, the same shares are applicable, with only 2.1 and 0.3% of the carbon footprint due to the production of the battery pack and electric motor. If both the bus and HDV are modelled for the 2050 scenario, this only changes very slightly to almost 4% of the carbon footprint coming from battery and electric motor production. The disposal of batteries in 2050 reaches only 0.3% of the carbon footprint and 0.7% of the mineral resource scarcity.

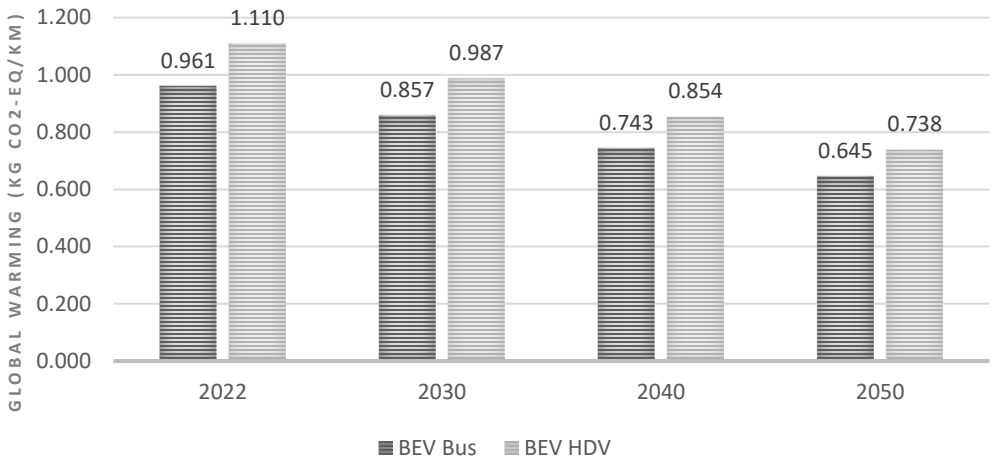

Figure 4.18: GWP for BEV HDV and Bus, 2022-2050, kgCO2-eq/km.

Table 4.14: Impact assessment BEV HDV 2022-2050, kgCO2-eq/km.

Impact category	Unit	BEV HDV 2022	BEV HDV 2030	BEV HDV 2040	BEV HDV 2050
Global warming	kg CO2 eq	1.11E+00	9.87E-01	8.54E-01	7.38E-01
Fine particulate matter formation	kg PM2.5 eq	3.09E-04	2.78E-04	2.44E-04	2.15E-04
Terrestrial acidification	kg SO2 eq	8.01E-04	7.19E-04	6.29E-04	5.52E-04
Human carcinogenic toxicity	kg 1,4-DCB	2.16E-02	2.01E-02	1.84E-02	1.70E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	5.74E-01	5.28E-01	4.78E-01	4.35E-01
Mineral resource scarcity	kg Cu eq	2.08E-03	1.90E-03	1.69E-03	1.52E-03
Fossil resource scarcity	kg oil eq	4.52E-01	4.01E-01	3.45E-01	2.97E-01

Table 4.15: Impact assessment BEV bus 2022-2050, per functional unit.

Impact category	Unit	BEV Bus 2022	BEV Bus 2030	BEV Bus 2040	BEV Bus 2050
Global warming	kg CO2 eq	9.61E-01	8.57E-01	7.43E-01	6.45E-01
Fine particulate matter formation	kg PM2.5 eq	2.70E-04	2.49E-04	2.26E-04	2.06E-04
Terrestrial acidification	kg SO2 eq	5.89E-04	5.35E-04	4.77E-04	4.26E-04
Human carcinogenic toxicity	kg 1,4-DCB	2.25E-02	2.15E-02	2.05E-02	1.96E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	3.27E-01	3.04E-01	2.79E-01	2.58E-01

Mineral resource scarcity	kg Cu eq	1.63E-03	1.53E-03	1.42E-03	1.33E-03
Fossil resource scarcity	kg oil eq	3.94E-01	3.50E-01	3.02E-01	2.60E-01

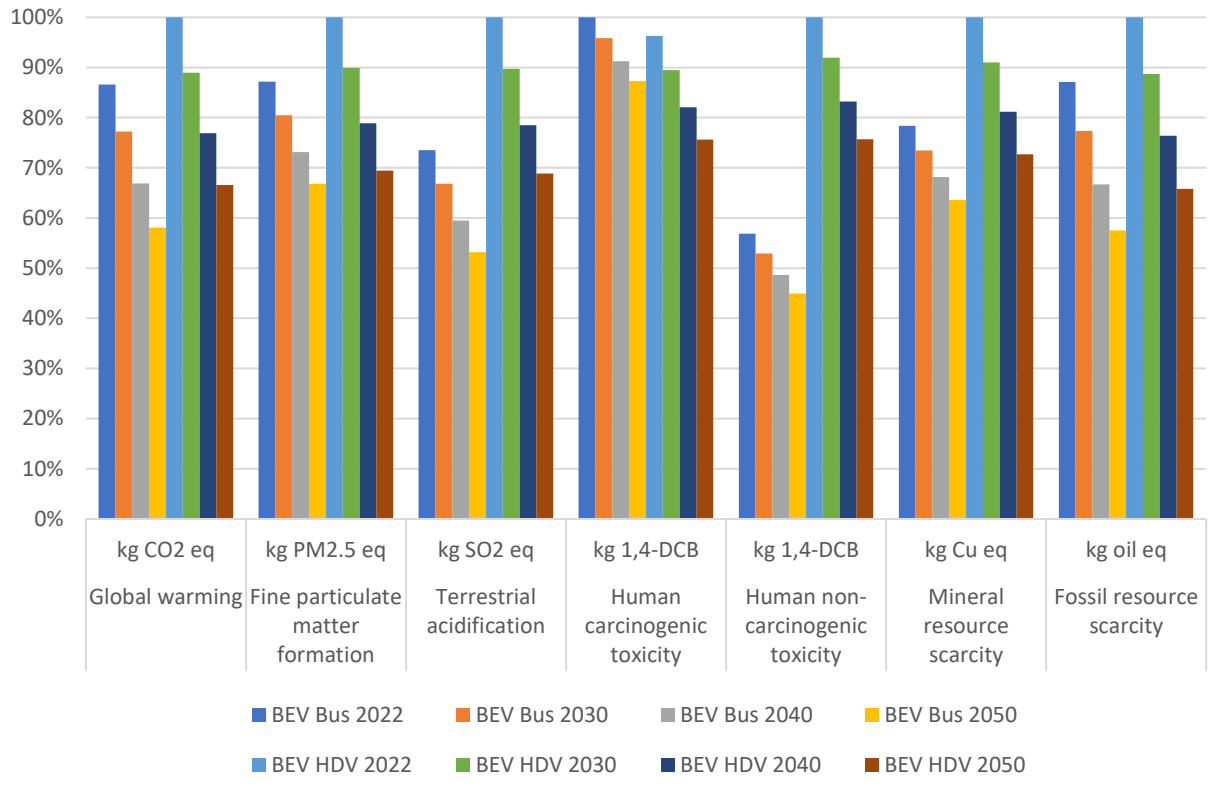

Figure 4.19: Focus impact categories for BEV HDV and bus, per functional unit, ReCiPe (%; relative to max impact).

4.3.3 ICEV-BEV analysis

With the analysis of the ICEV and BEV section separately, as well as having a rough idea on the main contributors for these vehicles, the next section of the results will be dedicated to the comparison between the ICEV and BEV alternatives. As described in the framework, most variables and design options should be kept constant to assess the influence of the specific characteristics.

ICEV-BEV LDV

Coupling back on the difference in hotspots of the different vehicles, the ICEV SUV and BEV SUV, both for 2040 are given in Figure 4.20 and Figure 4.21 as an example. From this, it is clear that the direct tailpipe emissions from petrol use are still dominant for the ICEV while the BEV is mostly impacted by the car production, its battery, and repairs/changes over time. If the ICEV and BEV alternatives are put against each other, for every km travelled over its lifetime, the overview becomes hard if assessed at the same time. Therefore, the sedan, sports vehicle and SUV will be compared one by one. The focus will be on the differences between the vehicles, for the exact values, the respective chapter from the ICEV and BEV analysis can be analyzed, as well as the Appendix with the full result tables.

As could be observed in other literature sources, the main improvement of BEV comes from the lowering of the carbon footprint. As it uses a central and optimized source, even with current and new technologies, over its lifetime, the BEV would have a lower overall carbon footprint. On the other hand, as the BEV battery, compared to the burning of fossil fuels has a larger impact on the mining of mineral resources and related impacts, the ICEV has some upsides. Moreover, due to the higher weight and thus lower fuel economy, in the case of the sports vehicle and SUV, even with current electricity production, the BEV would remain the better option in reducing the carbon footprint and fossil resource scarcity. Yet, as for the sedan, mineral resources remain very high for the BEV scenario. The detailed charts are shown in Figure 4.22, Figure 4.23 and Figure 4.24.

Specifically, Figure 4.24 provides the comparison of the focus impact categories for ICEV and BEV SUVs, using the ReCiPe method. The primary impact categories considered here include global warming (carbon footprint), fine particulate matter formation, mineral resource scarcity, and fossil resource scarcity. The global warming potential, also referred to as the carbon footprint, is a significant concern, and for this category, BEV SUVs demonstrate a significant advantage, starting off with almost half the carbon footprint of their ICEV counterparts. This difference is primarily due to the absence of direct tailpipe emissions in BEVs.

Mineral resource scarcity is another critical factor, particularly given the increasing demand for rare earth metals in battery production. In this category, ICEVs currently have an advantage due to their lesser reliance on these scarce resources. However, ongoing research and development in battery technology aim to reduce this dependence, potentially shifting this balance in the future.

On the other hand, when considering fossil resource scarcity, BEVs are clearly the more sustainable option. As they do not rely on fossil fuels for operation, their impact in this category is significantly lower. Again, only in the scenario of the most optimistic 2050 reductions in ICEV fuel needs, the two technologies could become comparable.

In conclusion, Figure 4.24 illustrates the complex interplay of environmental impacts associated with ICEVs and BEVs. While BEVs show clear advantages in terms of global warming potential and fossil resource scarcity, they currently face challenges related to mineral resource scarcity. This underscores the importance of continued research and innovation in vehicle technology, fuel efficiency, and battery design to ensure a sustainable transition to low-emission vehicles.

ICEV-BEV HDV and Buses

Coupling the ICEV and BEV scenarios for the HDV and Buses, the overall message changes slightly. In all considered temporal milestones—2022, 2030, 2040, and 2050—the carbon footprint remains consistently lower for electric HDVs and buses as compared to their conventional counterparts. With diesel as a known contributor to particulate matter, the BEV fraction does show very significant improvement in comparison to the ICEV HDV and bus scenarios. Just as was

seen for the LDV, the very large battery packs imply that the mineral resource scarcity is better for the ICEV than for the BEV alternatives. The detailed charts are shown in Figure 4.25 and Figure 4.26. It should be noted that the ICEV projection beyond 2030 is in a best-case scenario, and it is very unclear that this would be met.

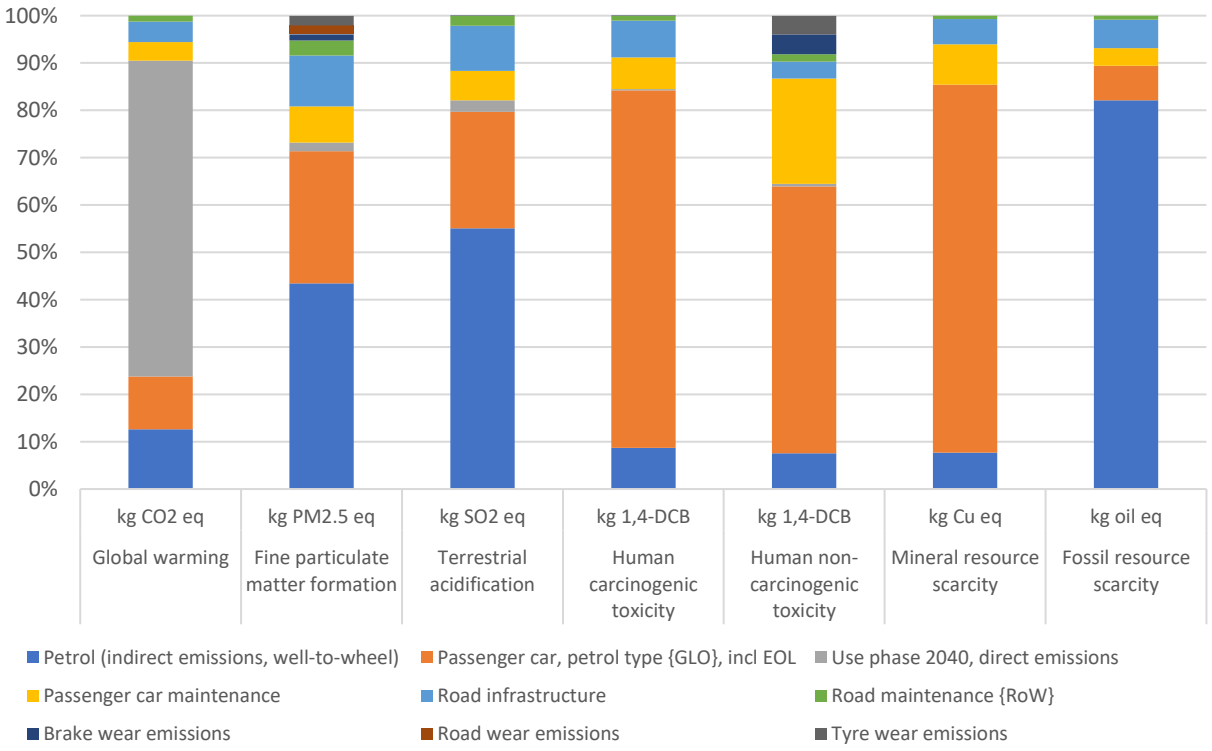

Figure 4.20: ICEV SUV 2040, Midpoint ReCiPe, contributing hotspots, per functional unit.

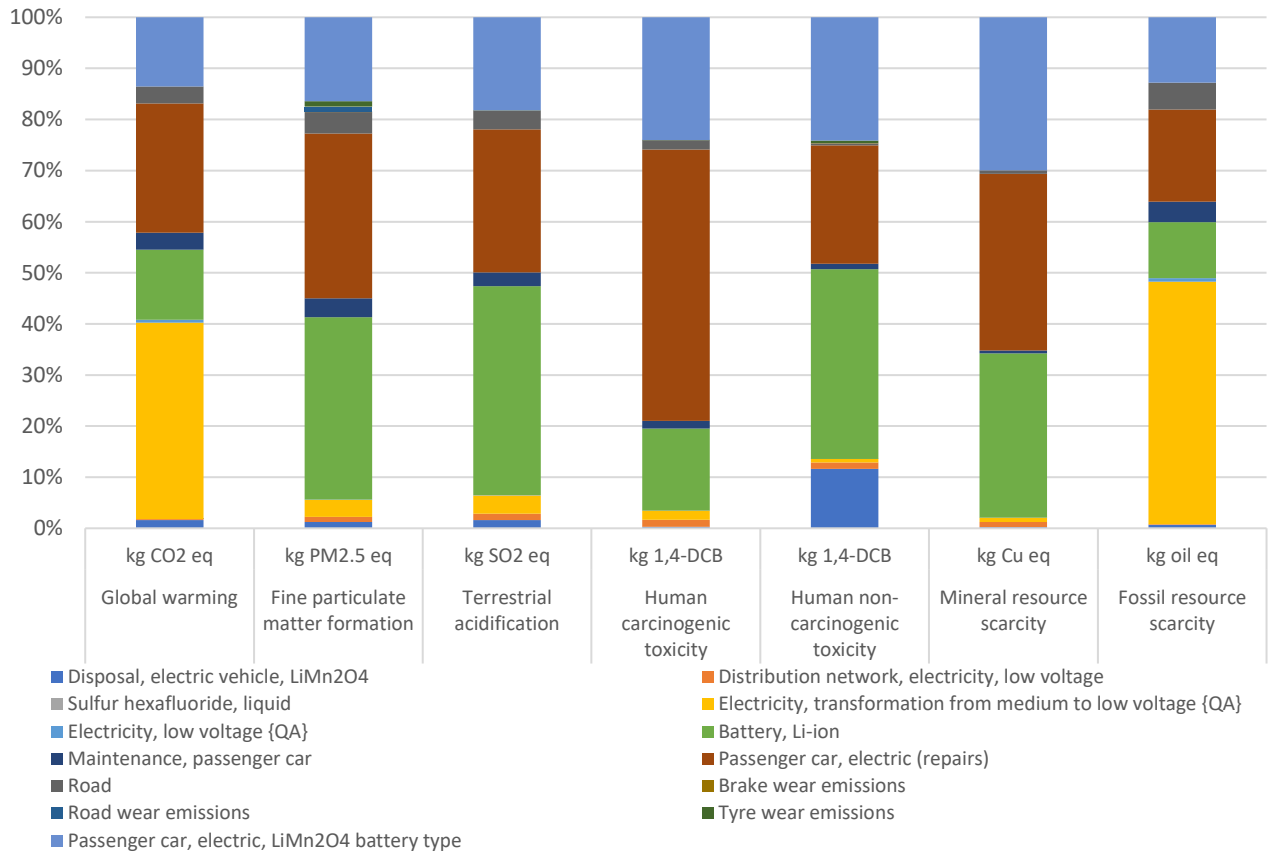

Figure 4.21: BEV SUV 2040, Midpoint ReCiPe, contributing hotspots, per functional unit.

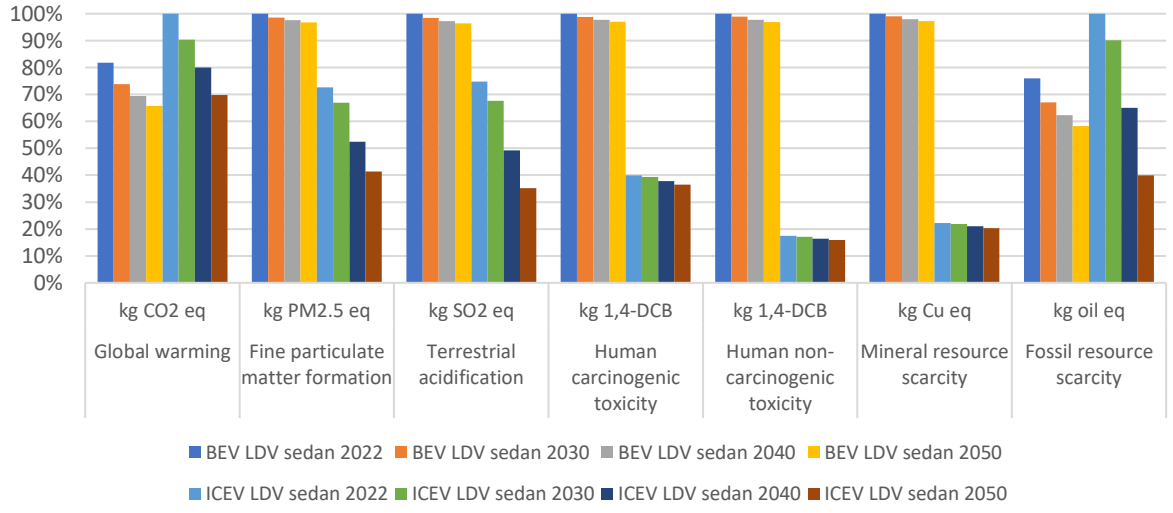

Figure 4.22: Focus impact categories for ICEV-BEV sedan, per functional unit, ReCiPe (%; relative to max impact).

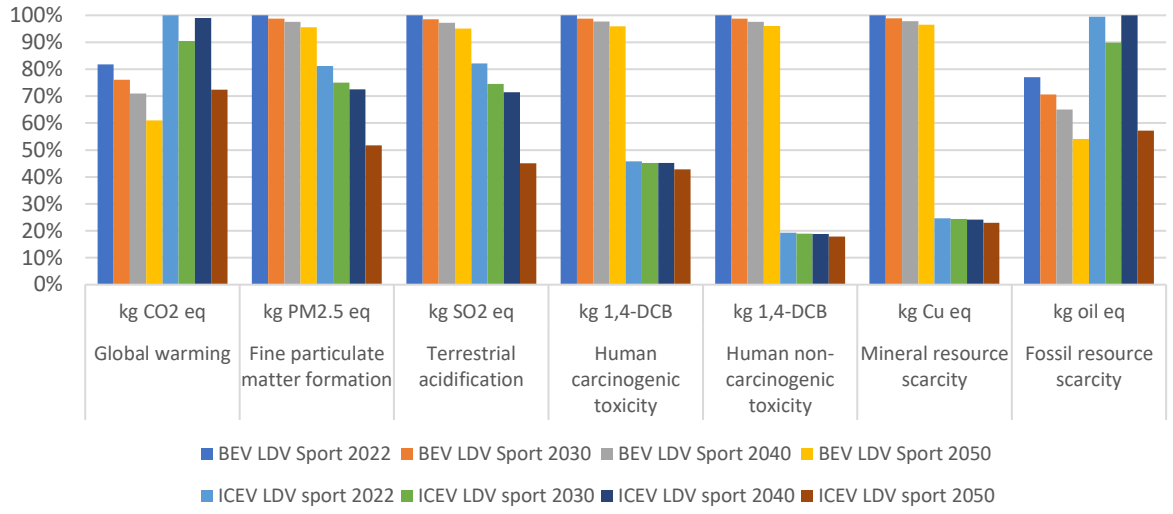

Figure 4.23: Focus impact categories for ICEV-BEV sports vehicle, per functional unit, ReCiPe (%; relative to max impact).

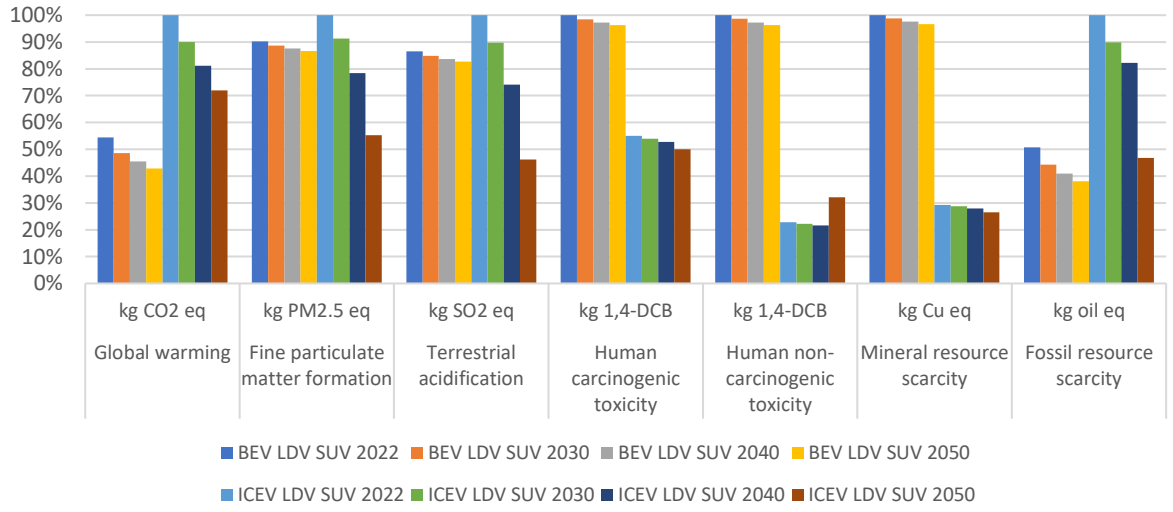

Figure 4.24: Focus impact categories for ICEV-BEV SUV, per functional unit, ReCiPe (%; relative to max impact).

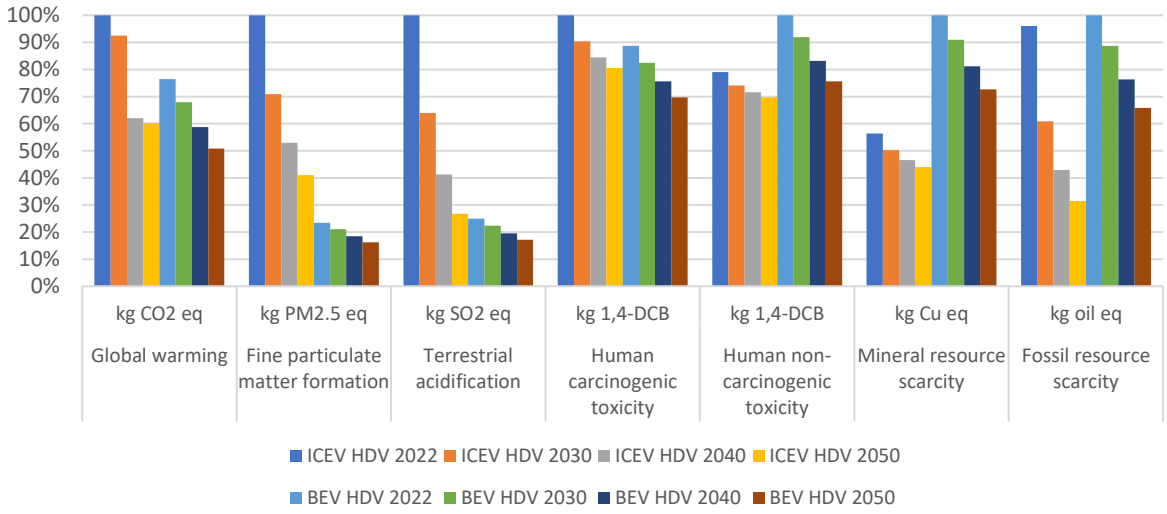

Figure 4.25: Focus impact categories for ICEV-BEV HDV, per functional unit, ReCiPe (%; relative to max impact).

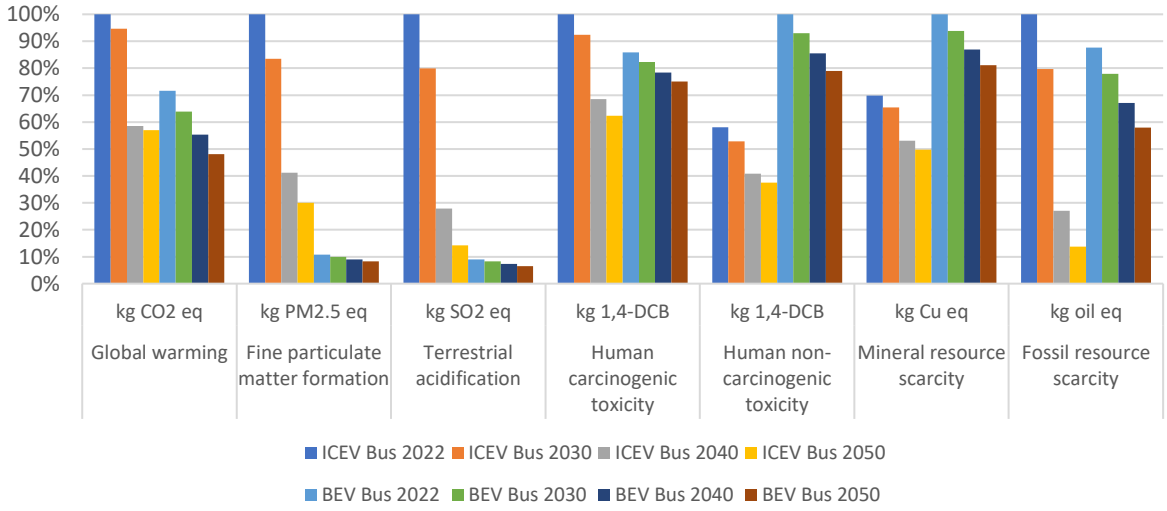

Figure 4.26: Focus impact categories for ICEV-BEV Bus, per functional unit, ReCiPe (%; relative to max impact).

4.4 Break-even analysis

Aside from the changes over time for the BEV and ICEV separately, details from break-even and sensitivity analysis can show additional facts for this comparison study from distinct perspectives. Possible tipping points as well as assumption validations can be checked at this point. As Qatar has global import relations and a high living standard, more expensive but therefore higher standard and lower impact vehicles, mainly imported from European plants can be a valid assumption. This does influence the break-even analysis on many fronts. Moving forward, production locations and environmental standards will become increasingly important as battery improvements continue and with lowering weights, BEV manufacturing could come on par with ICEV models. Therefore, this assessment is done for both vehicle options. Aside from this aspect, the influence of the exceptional and best-case projection of the GFEI is assessed with their implications over the vehicle lifetime.

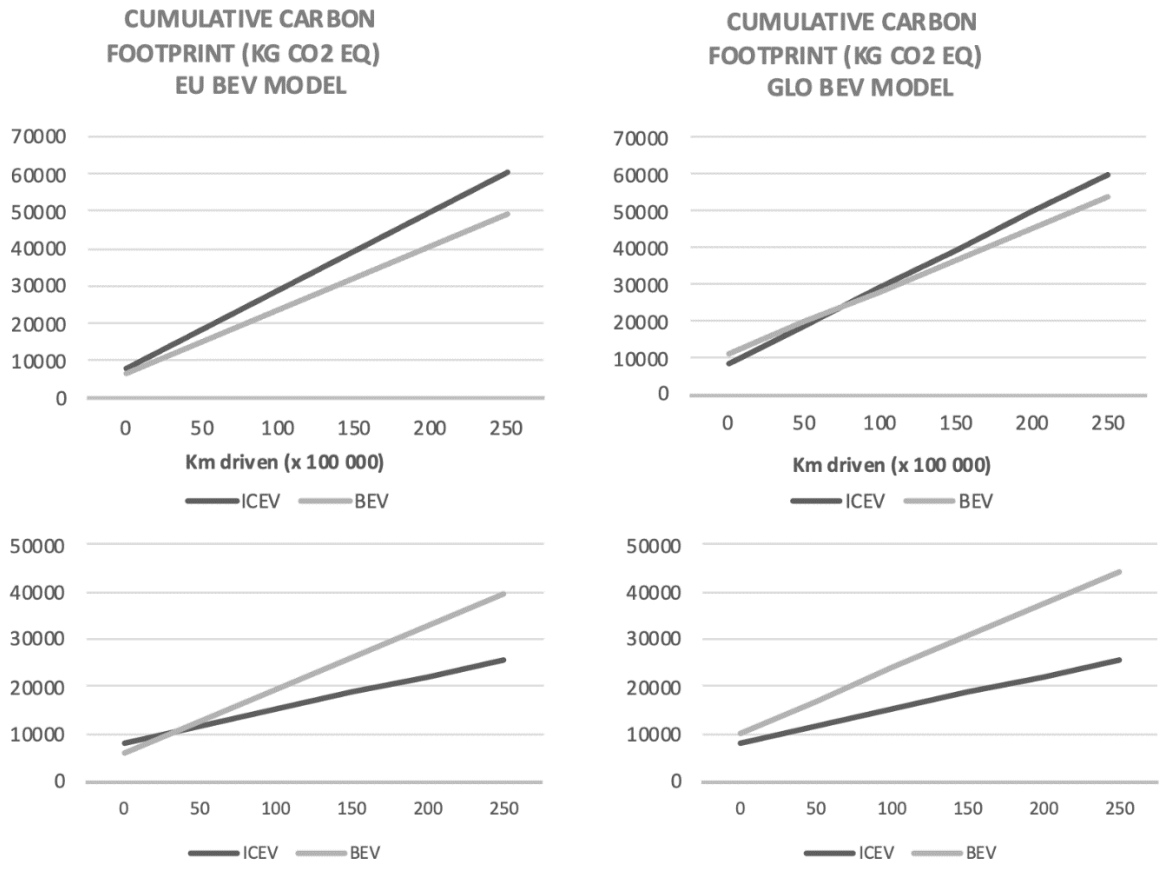

Figure 4.27: GWP ICEV - BEV break-even point 2022 (top) and 2050 GFEI targets met (bottom), difference in break-even point by vehicle model selection.

Figure 4.27 illustrates that choosing the lower-impact EU BEV results in an immediate advantage for the electric alternative, contrary to the heavy burden often attributed to electric vehicles in numerous articles. On the right side of the figure, the break-even analysis for electric vehicles produced using the global mix is presented, indicating a generally higher impact. Nevertheless, these vehicles still become a more favorable option than ICEVs after approximately 80,000 km as of 2022.

In this chapter, the fuel economy projections provided by the GFEI for ICEVs by 2050 are not incorporated. The decision to exclude these figures is rooted in the perceived exceptional optimism of the GFEI's projections. However, it's worth noting that if this same exercise is repeated for 2050 using the GFEI's very optimistic fuel economy values, the roles are reversed and the ICEV becomes the better option for reducing the carbon footprint as seem in figure 4.27.

The conclusion from this is EU/Global production is an important sensitivity of the research literature, as it makes clear that countries that have the ability to implement or attract lower emission vehicle options and can reduce their impact from the early stage instead of only relying on low-emission fuels. Furthermore, as many companies are still in the development phase and further discoveries are not outside of expectations, both the weight and impact could decline over time and should be reassessed in future research.

This break-even is not taking into account any carbon capture or storage technologies which could be centrally implemented at the natural gas plant. The fact this ICEV fuel economy would be reached is addressed in an upcoming section. Yet, the overall cumulative carbon footprint is clearly lower compared to the 2022 scenario.

In conclusion, from the 2020-2050 EU/Global break-even it can be derived that, in line with other literature, it is expected that the BEV has an initially higher impact but has a lower impact over time (shown in top left, 2022 GLO). On the other hand, if the very optimistic fuel economy projections by the GFEI in 2050 are achieved, this would mean that the ICEV ends up with a lower overall emission, which is improbable as no data has shown prototypes of such fuel economies.

4.5 Sensitivity analysis

Aside from the ICEV and BEV results and the comparison between the counterparts of this research, there are still options open that could influence the overall interpretation or later runs of this study. In the previous chapter, it was stated that the GFEI had forecasted the ICEV fuel economy improvements and had produced very optimistic numbers. If these projections are not met, the advantage of the BEV compared to the ICEV will be greater over time. This is especially true if the break-even analysis is repeated. To illustrate the simple example of ICEV not reaching the proposed GFEI targets (but still reaching 2030 levels), while BEV just continue on the feasible path without any additional capture, it can be seen in Figure 4.28 (right) that the BEV remains the better option in 2050. The better option BEV in 2050 starts with a lower impact and there would be no crossing line. Nonetheless, the electric vehicle and transportation sector is not yet a completely mature market, so extra improvements can be expected, ranging from lower energy needs to the application of different battery types or central carbon capture to lower the emissions of electricity.

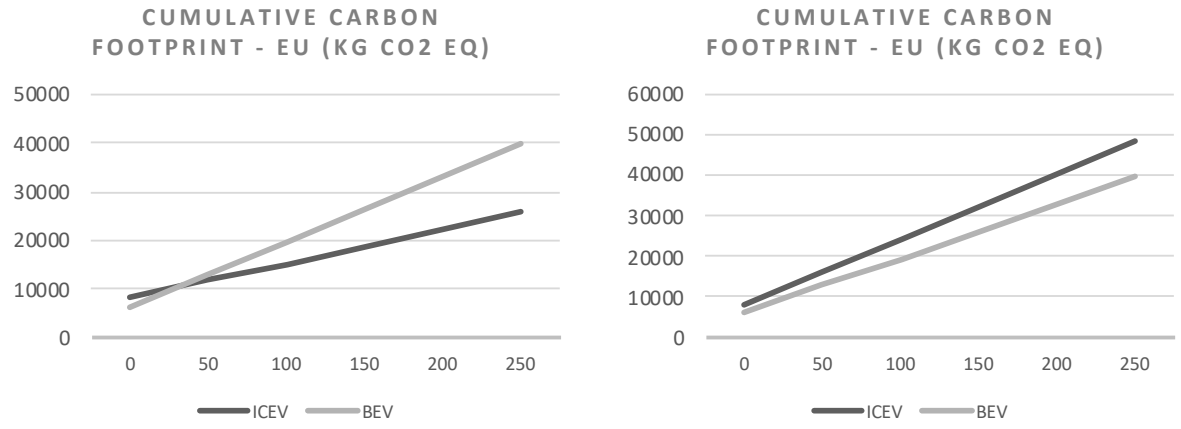

Figure 4.28: Break-even - sensitivity analysis, 2050 ICEV scenario with GFEI 2050 level targets met (left) with 2050 ICEV scenario with GFEI 2030 level targets met (right).

The difference in setting targets and the possibility of not reaching these are shown in this regard in order to give an impression of the possible changes further research could bring. On another

note, for the BEV fraction, currently, the main battery compositions implemented in electric vehicles are the NMC, NCA and prismatic lithium types, respectively described in the literature chapter. The significant difference between those types in use is the cycle lifetime and its energy density, influencing the impact from resources, mining and production. With more than 4,000 cycles, prismatic lithium is more stable yet has a lower energy density of around 170Wh/kg compared to NMC811 with ca. 275Wh/kg but only 2,000 cycles. The difference between the 111 and 811 NMC is largely the number of ions to the amount of oxygen present in the chemical structure.

Figure 4.29 shows the impact a unit of mass has for all the focus midpoint indicators. Yet, as noted before, the energy density of the battery material is not equal, as is the lifetime. Figure 4.30 reflects therefore the impact the type of chemistry has as it is scaled to the number of cycles it would endure. From this, the most advantageous material would be the stable 4,000 cycle iron phosphate lithium battery as often used in HDV and buses. The only downside of this material is the lower charging speeds and the higher weight for a similar battery pack. In the case of small sedans, a simple battery of around 125 kg could in that case quickly go over 200 kg with longer charging times.

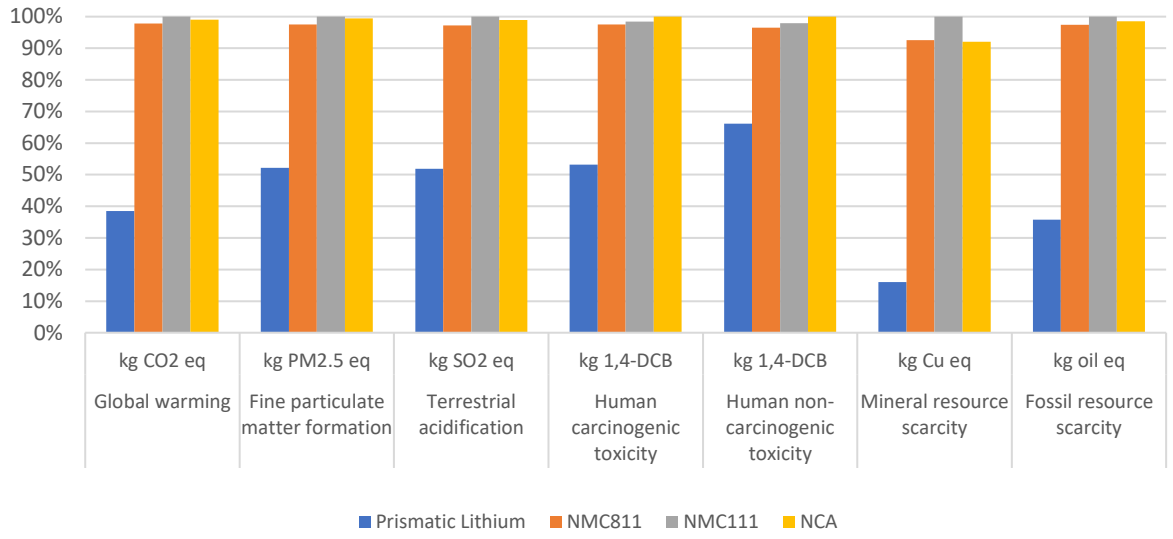

Figure 4.29: Battery chemistries, ReCiPe midpoint method, per kg of material.

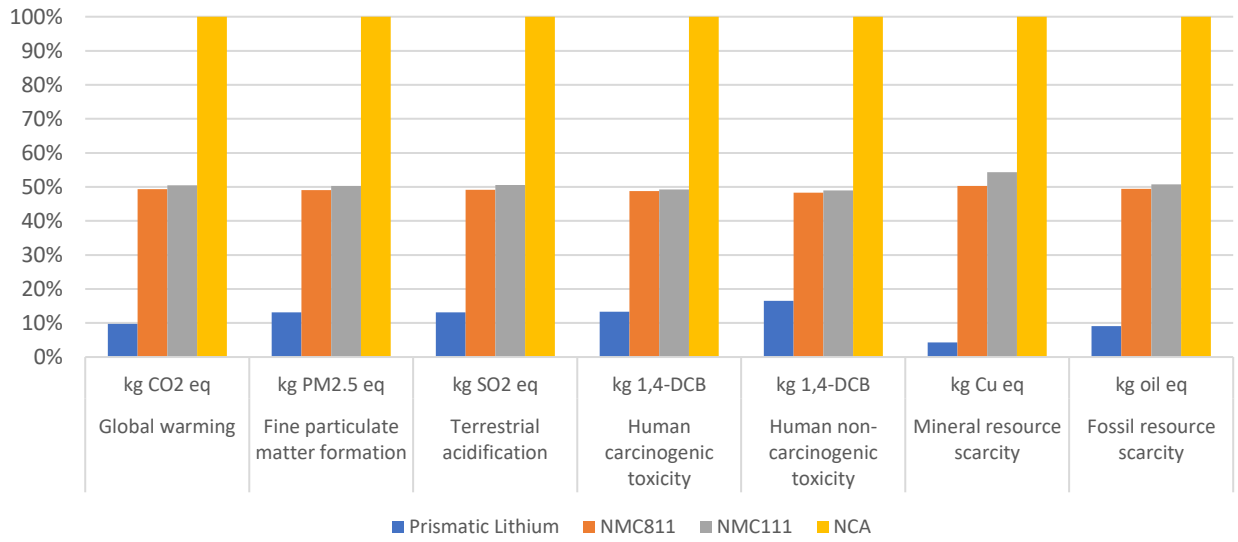

Figure 4.30: Battery chemistries, ReCiPe method, scaled to the theoretical cycles of the material, per functional unit.

4.5.1 Uncertainty analysis

In the last section of this chapter, the uncertainty analysis is performed. This is done in 2 parts, namely the individual uncertainties for all the midpoint indicators and afterwards the uncertainty on the comparison. The latter analysis gives an indication of the degree scenario A has a lower impact compared to scenario B. The examples that will be used are in line with the ones used for the description of the results, ranging from ICEV-BEV LDV sedan in 2022 and 2050 to the HDV in 2030. The following charts are the output from the SimaPro software, which cannot be modified. The full tables are given with all confidence intervals and characteristics needed for further evaluation.

ICEV sedan 2022

The uncertainty of the ICEV and BEV sedan case in 2022 are given in Table 4.16 as well as the visual representations (Figure 4.31 Figure 4.32), both using the SimaPro Monte Carlo tool using 10,000 runs. The visual representation of the uncertainty of the impact categories is a direct export of the SimaPro software and is thus not interactive. As discussed earlier, the water consumption impact class is still underrepresented in the collection of databases, further expanding the uncertainty. Because of this fact, this impact category was left out of the focus of this study.

Table 4.16: uncertainty analysis ICEV sedan 2022, per functional unit.

Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Fine particulate matter formation	kg PM2.5 eq	2.28E-04	2.27E-04	4.98E-06	2.19E+00	2.19E-04	2.39E-04	4.98E-08
Fossil resource scarcity	kg oil eq	8.76E-02	8.76E-02	7.09E-04	8.09E-01	8.63E-02	8.91E-02	7.09E-06
Freshwater ecotoxicity	kg 1,4-DCB	1.14E-02	1.11E-02	2.08E-03	1.83E+01	8.30E-03	1.60E-02	2.08E-05
Freshwater eutrophication	kg P eq	6.93E-05	6.78E-05	7.31E-06	1.05E+01	5.98E-05	8.74E-05	7.31E-08
Global warming	kg CO2 eq	2.34E-01	2.34E-01	1.79E-03	7.64E-01	2.31E-01	2.38E-01	1.79E-05

Human carcinogenic toxicity	kg 1,4-DCB	1.23E-02	1.16E-02	3.69E-03	3.01E+01	7.38E-03	2.07E-02	3.69E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1.47E-01	1.37E-01	4.90E-02	3.34E+01	1.07E-01	2.48E-01	4.90E-04
Ionizing radiation	kBq Co-60 eq	4.67E-03	3.61E-03	3.64E-03	7.79E+01	2.45E-03	1.40E-02	3.64E-05
Land use	m2a crop eq	8.29E-03	8.27E-03	4.20E-04	5.07E+00	7.50E-03	9.16E-03	4.20E-06
Marine ecotoxicity	kg 1,4-DCB	1.50E-02	1.47E-02	2.66E-03	1.77E+01	1.12E-02	2.09E-02	2.66E-05
Marine eutrophication	kg N eq	2.58E-06	2.57E-06	1.31E-07	5.09E+00	2.34E-06	2.85E-06	1.31E-09
Mineral resource scarcity	kg Cu eq	7.90E-04	7.82E-04	7.44E-05	9.42E+00	6.66E-04	9.58E-04	7.44E-07
Ozone formation, Human health	kg NOx eq	3.53E-04	3.52E-04	1.08E-05	3.06E+00	3.35E-04	3.76E-04	1.08E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.83E-04	3.82E-04	1.13E-05	2.95E+00	3.64E-04	4.07E-04	1.13E-07
Stratospheric ozone depletion	kg CFC11 eq	1.54E-07	1.54E-07	3.09E-09	2.00E+00	1.49E-07	1.61E-07	3.09E-11
Terrestrial acidification	kg SO2 eq	5.50E-04	5.49E-04	8.17E-06	1.49E+00	5.35E-04	5.67E-04	8.17E-08
Terrestrial ecotoxicity	kg 1,4-DCB	1.28E+00	1.26E+00	7.88E-02	6.17E+00	1.17E+00	1.47E+00	7.88E-04

In the uncertainty data analysis, visualised by the given graphs, it was deduced that most impact categories had favorable scores, indicating that the evaluated products or processes had lower deviations in the impacts of those categories. However, water consumption and ionizing radiation were identified as areas of concern, as described, which is in line with literature. Despite these uncertainties, the study's focus categories had the lowest uncertainty, providing good confidence in the main conclusions drawn from the analysis. This means that while there is still some uncertainty regarding the study's findings, the results of the focus categories can be relied

upon to provide accurate information on the environmental impact of the products or processes being evaluated. To further assess the uncertainties associated with the study's findings, additional analyses will be conducted for the other scenarios, as well as a comparative uncertainty analysis which will be performed. By doing so, the study will be able to provide a more comprehensive understanding of the environmental impacts of the evaluated products or processes, allowing for more informed decision-making.

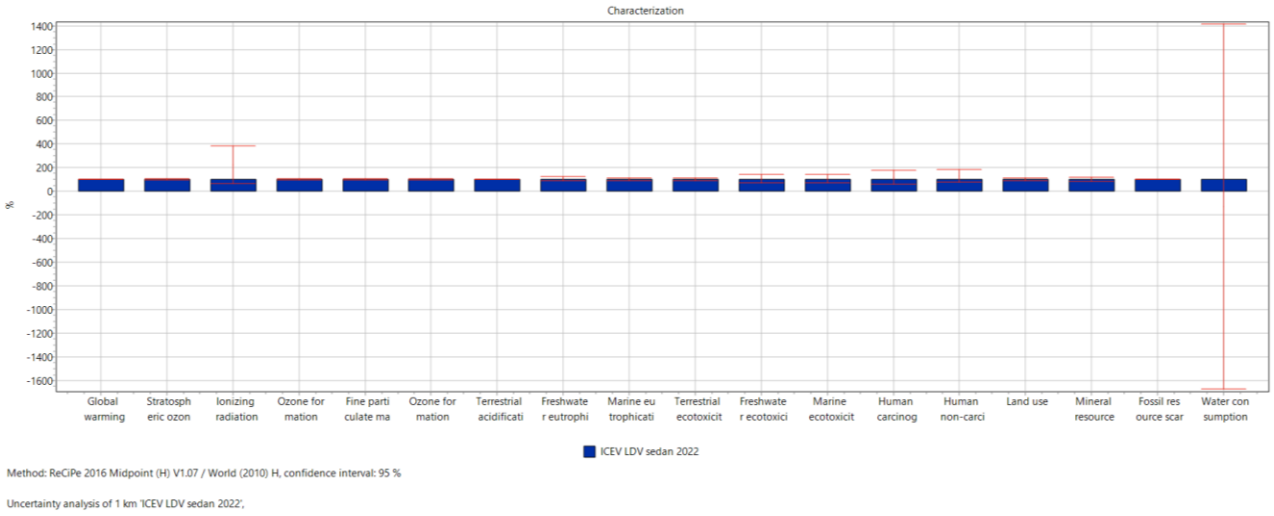

Figure 4.31: Overall uncertainty of impact categories, ICEV sedan 2022, per functional unit.

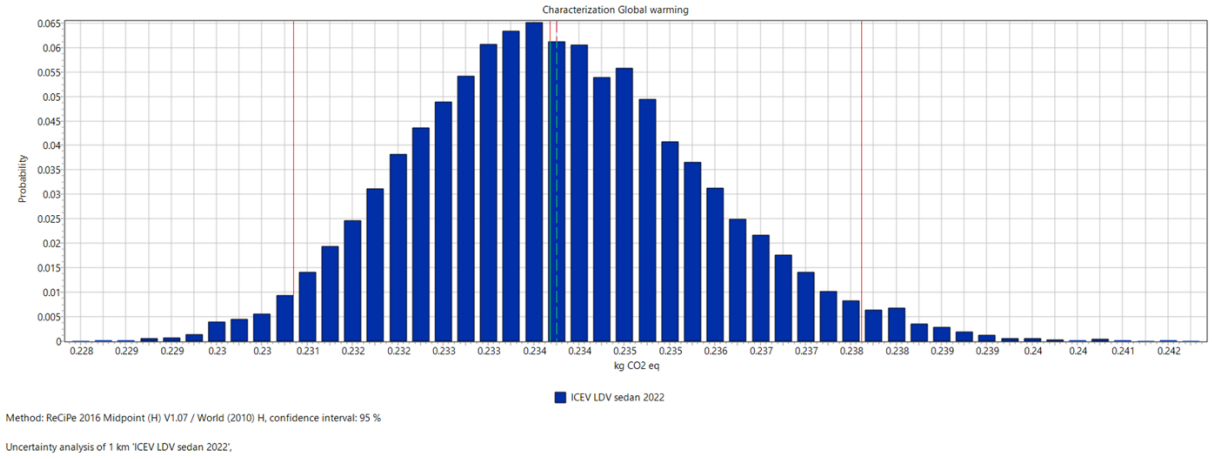

Figure 4.32: GWP indicator uncertainty, ICEV sedan 2022, per functional unit.

BEV sedan 2022

The same uncertainty analysis was repeated for the BEV sedan, given in Table 4.17 as well as the simplified visual representation (Figure 4.33), using the SimaPro Monte Carlo tool using 10,000 runs. The visual representation shows larger variances overall, yet with smaller extremes compared to the ICEV scenario. Similar to the ICEV, the water consumption impact class is still underrepresented in the collection of databases but is less present in the model. Therefore, the main variances are seen in the ionizing radiation, often linked to electricity production.

Table 4.17: uncertainty analysis BEV sedan 2022, per functional unit.

Impact category	Unit	Mean	Median	SD	CV	2,50%	97,50%	SEM
Fine particulate matter formation	kg PM2.5 eq	2,77E-04	2,75E-04	1,80E-05	6,50E+00	2,48E-04	3,19E-04	5,70E-07
Fossil resource scarcity	kg oil eq	6,47E-02	6,41E-02	6,90E-03	1,07E+01	5,25E-02	8,07E-02	2,18E-04
Freshwater ecotoxicity	kg 1,4-DCB	4,47E-02	4,50E-02	1,24E-02	2,78E+01	2,06E-02	6,97E-02	3,93E-04
Freshwater eutrophication	kg P eq	1,26E-04	1,24E-04	3,16E-05	2,50E+01	8,68E-05	1,79E-04	9,99E-07
Global warming	kg CO2 eq	1,83E-01	1,82E-01	1,40E-02	7,63E+00	1,57E-01	2,14E-01	4,41E-04
Human carcinogenic toxicity	kg 1,4-DCB	2,86E-02	2,74E-02	7,45E-03	2,60E+01	1,87E-02	4,73E-02	2,36E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	6,78E-01	6,35E-01	4,71E-01	6,95E+01	3,76E-01	1,12E+00	1,49E-02
Ionizing radiation	kBq Co-60 eq	1,13E-02	7,82E-03	1,18E-02	1,04E+02	2,05E-03	4,25E-02	3,74E-04
Land use	m2a crop eq	6,68E-03	6,34E-03	1,91E-03	2,87E+01	4,01E-03	1,18E-02	6,05E-05
Marine ecotoxicity	kg 1,4-DCB	5,76E-02	5,79E-02	1,55E-02	2,69E+01	2,77E-02	8,93E-02	4,90E-04
Marine eutrophication	kg N eq	1,07E-05	1,06E-05	1,01E-06	9,46E+00	9,01E-06	1,30E-05	3,20E-08
Mineral resource scarcity	kg Cu eq	3,21E-03	3,20E-03	2,19E-04	6,82E+00	2,82E-03	3,68E-03	6,92E-06
Ozone formation, Human health	kg NOx eq	4,44E-04	4,31E-04	7,05E-05	1,59E+01	3,41E-04	6,27E-04	2,23E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	5,13E-04	4,92E-04	9,99E-05	1,95E+01	3,78E-04	7,65E-04	3,16E-06
Stratospheric ozone depletion	kg CFC11 eq	7,64E-08	7,52E-08	1,07E-08	1,40E+01	5,91E-08	9,94E-08	3,39E-10
Terrestrial acidification	kg SO2 eq	6,38E-04	6,33E-04	4,19E-05	6,57E+00	5,68E-04	7,35E-04	1,32E-06
Terrestrial ecotoxicity	kg 1,4-DCB	2,74E+00	2,50E+00	9,72E-01	3,55E+01	1,60E+00	5,34E+00	3,08E-02
Water consumption	m3	1,40E-01	1,42E-01	4,21E-02	3,00E+01	4,30E-02	2,15E-01	1,33E-03

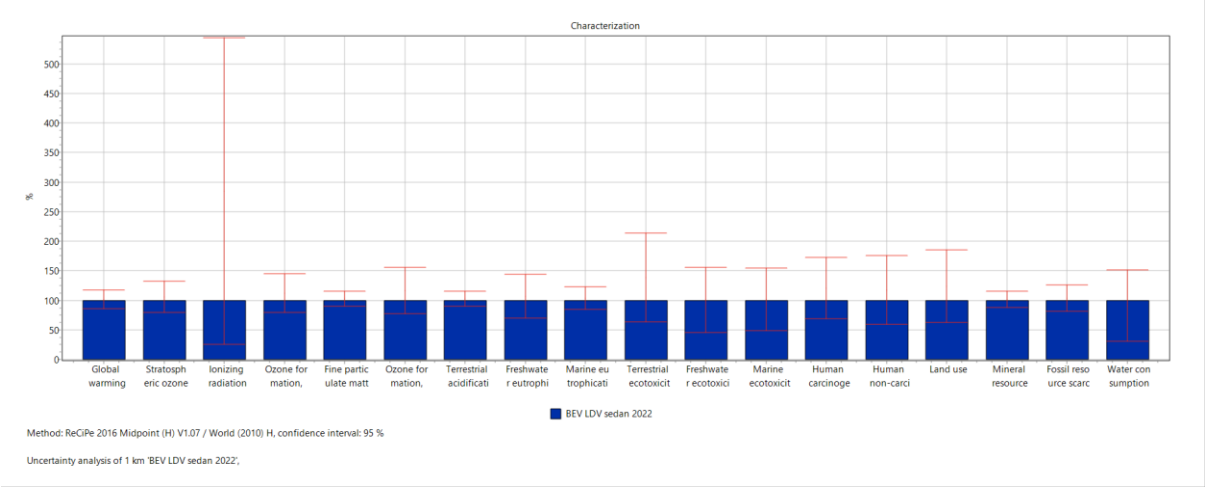

Figure 4.33: Overall uncertainty of impact categories, BEV sedan 2022, per functional unit.

ICEV vs BEV uncertainty analysis

This section will go into detail concerning the uncertainty that a given scenario A has a lower impact compared to scenario B for the specific impact category of focus. For the following uncertainty tables and figures, the percentage reflects the Monte Carlo cases for which the impact of scenario A is lower than the impacts of scenario B and vice versa. A -100% result (blue) shows that in almost all possible cases, scenario A is preferred and has lower overall impacts, while a +100% shows the opposite case. The examples that will be used are in line with the ones used for the description of the results, ranging from ICEV-BEV LDV sedan in 2022 and 2050 to the HDV in 2030. Again, all cases were calculated by use of the SimaPro Monte Carlo software, using a fixed 10,000 runs setup. As this setup uses a certain number of random permutations of the model, multiple runs of this analysis can give slightly different results, yet the overall message is conclusive.

The message this uncertainty analysis provides is that in case small changes are made in the underlying processes, such as the weight of the vehicle, the fuel economy and the emissions overall, the overarching answer still holds up. As impact indicators can differ between both

scenarios, such as a lower carbon footprint of the BEV yet a higher mineral resource impact, this should be assessed for all categories.

Figure 4.34 shows that for the ICEV BEV sedan 2022 comparison, the BEV will always be the better option in regard to the ICEV in reducing the impacts of the carbon footprint and fossil resource scarcity. On the other hand, the ICEV will, due to no need for the battery pack, almost always score better in mineral resource scarcity and acidification. For the absolute impacts, a separate chapter of the results has to be reviewed as this uncertainty analysis reflects the occurrence of lower/higher impacts, not the absolute value of the impact category.

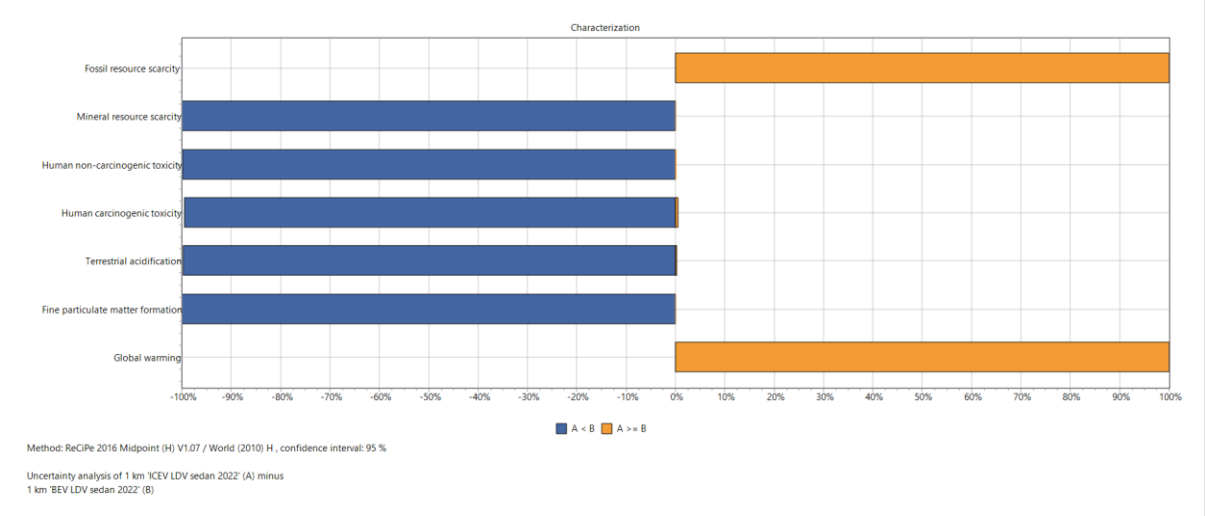

Figure 4.34: Uncertainty analysis of ICEV sedan (A) impact lower than BEV sedan (B) impact, 2022.

Table 4.18: Uncertainty analysis of ICEV sedan (A) impact lower than BEV sedan (B) impact, 2022.

Impact category	A >= B	Mean	Median	SD	CV	2,50%	97,50%	SEM
Fine particulate matter formation	100	8.53E-05	8.40E-05	1.34E-05	1.57E+01	6.31E-05	1.16E-04	1.34E-07
Fossil resource scarcity	0.04	-2.10E-02	-2.15E-02	2.72E-03	-1.30E+01	-2.50E-02	-1.45E-02	2.72E-05
Global warming	0.02	-4.25E-02	-4.32E-02	5.91E-03	-1.39E+01	-5.18E-02	-2.88E-02	5.91E-05
Human carcinogenic toxicity	99.7	1.84E-02	1.87E-02	4.95E-03	2.70E+01	8.85E-03	2.62E-02	4.95E-05
Human non-carcinogenic toxicity	99.96	6.94E-01	6.45E-01	2.13E-01	3.07E+01	4.87E-01	1.18E+00	2.13E-03
Mineral resource scarcity	100	2.77E-03	2.77E-03	1.20E-04	4.32E+00	2.53E-03	3.01E-03	1.20E-06

Terrestrial acidification	100	1.85E-04	1.82E-04	2.78E-05	1.50E+01	1.41E-04	2.48E-04	2.78E-07

As previously discussed in the break-even and sensitivity analysis, if extreme 2050 ICEV targets set by the GFEI would be reached with the standard improvement for the BEV scenario, the ICEV would be the preferred option. This is also reflected in this uncertainty analysis (Figure 4.35), as fuel economy is extreme.

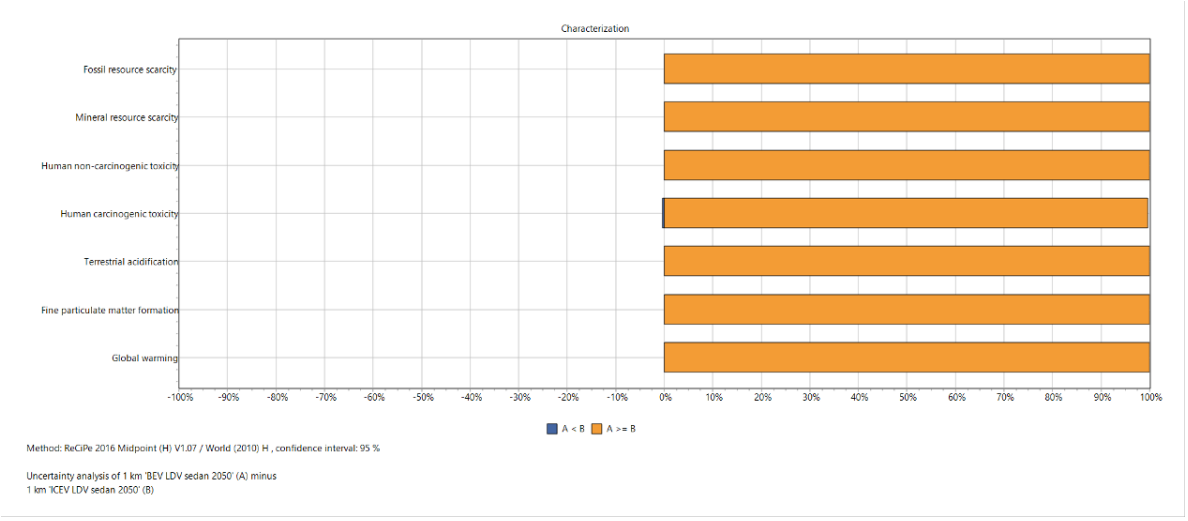

Figure 4.35: Uncertainty analysis of ICEV sedan (B) impact lower than BEV sedan (A) impact, 2050 – ICEV adapted to 2050 GFEI fuel economy targets.

Table 4.19: Uncertainty analysis of ICEV sedan (B) impact lower than BEV sedan (A) impact, 2050 – ICEV adapted to 2050 GFEI fuel economy targets.

Impact category	A >= B	Mean	Median	SD	CV	2,50%	97,50%	SEM
Fine particulate matter formation	100	1.73E-04	1.72E-04	1.31E-05	7.55E+00	1.52E-04	2.03E-04	1.31E-07
Fossil resource scarcity	100	1.60E-02	1.56E-02	2.65E-03	1.66E+01	1.20E-02	2.24E-02	2.65E-05
Global warming	100	5.82E-02	5.75E-02	5.80E-03	9.95E+00	4.91E-02	7.16E-02	5.80E-05
Human carcinogenic toxicity	99.67	1.85E-02	1.88E-02	5.18E-03	2.81E+01	9.02E-03	2.59E-02	5.18E-05
Human non-carcinogenic toxicity	99.97	6.83E-01	6.35E-01	2.55E-01	3.74E+01	4.90E-01	1.15E+00	2.55E-03
Mineral resource scarcity	100	2.74E-03	2.74E-03	1.15E-04	4.21E+00	2.51E-03	2.96E-03	1.15E-06
Terrestrial acidification	100	4.50E-04	4.47E-04	2.67E-05	5.94E+00	4.07E-04	5.10E-04	2.67E-07

In line with the respective results and sensitivity analysis chapter, for the ICEV-BEV HDV scenario, the results are not completely in one direction. The ICEV would be the preferred option for most of the fossil and mineral resource impacts, but in case of fine particulate matter and acidification, the BEV scenario is preferred. Here it is important to note that the single value from the LCA, showing that the carbon footprint of the ICEV would be lower in 2030 compared to the BEV, mainly driven by the very optimistic fuel economy, is not giving a full 100% favour to the ICEV scenario. Still, in a small but important fraction of the cases, the BEV would still be the better option, even with very optimistic ICEV fuel economy projections.

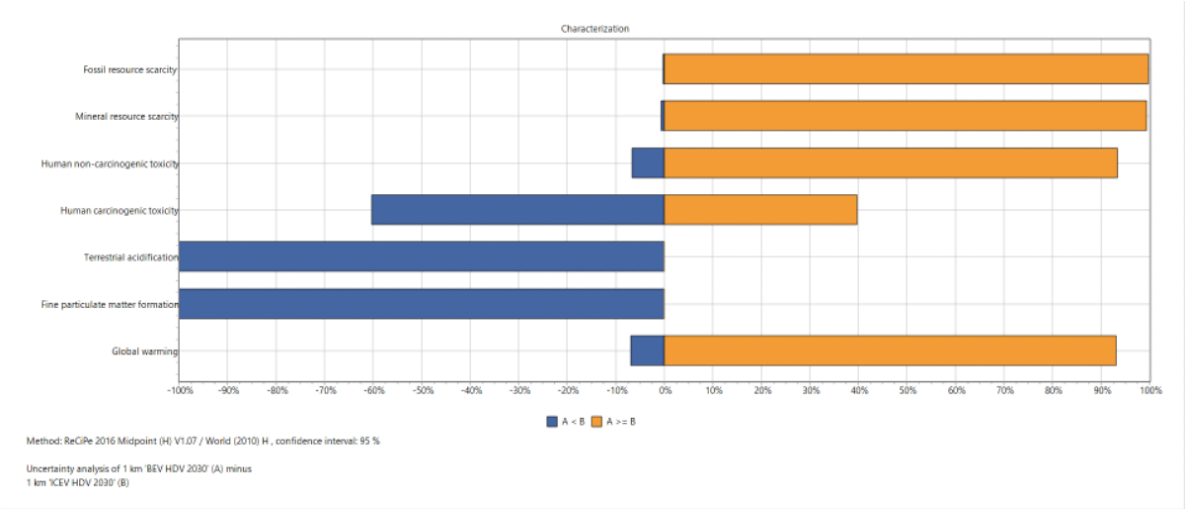

Figure 4.36: Uncertainty analysis of ICE HDV (B) impact lower than battery electric HDV (A) impact, 2030 – ICE HDV adapted to GFEI fuel economy targets.

Table 4.20: Uncertainty analysis of ICE HDV (B) impact lower than battery electric HDV (A) impact, 2030 – ICE HDV adapted to GFEI fuel economy targets.

Impact category	A >= B	Mean	Median	SD	CV	2,50%	97,50%	SEM
Fine particulate matter formation	0	-6.59E-04	-6.38E-04	1.11E-04	-1.68E+01	-9.34E-04	-5.09E-04	1.11E-06
Fossil resource scarcity	99.72	1.25E-01	1.31E-01	2.56E-02	2.04E+01	6.12E-02	1.58E-01	2.56E-04
Global warming	93.09	8.46E-02	9.28E-02	5.36E-02	6.33E+01	-4.58E-02	1.64E-01	5.36E-04
Human carcinogenic toxicity	39.78	-1.98E-03	-1.11E-03	5.06E-03	-2.55E+02	-1.41E-02	5.15E-03	5.06E-05

Human non-carcinogenic toxicity	93.33	1.02E-01	1.00E-01	7.18E-02	7.05E+01	-4.17E-02	2.52E-01	7.18E-04
Mineral resource scarcity	99.34	8.47E-04	8.88E-04	2.34E-04	2.76E+01	2.91E-04	1.18E-03	2.34E-06
Terrestrial acidification	0	-1.34E-03	-1.30E-03	2.28E-04	-1.70E+01	-1.91E-03	-1.03E-03	2.28E-06

For the bus scenarios, starting in 2022, the advantage is mostly for the ICEV, with the BEV scoring favorably only for fine particulate matter and acidification. Yet, in 2050, if very optimistic fuel standards set by the GFEI are used, it would have to be expected that the ICEV bus would be better in again most impact categories except for the mineral resource scarcity and the toxicity impact category.

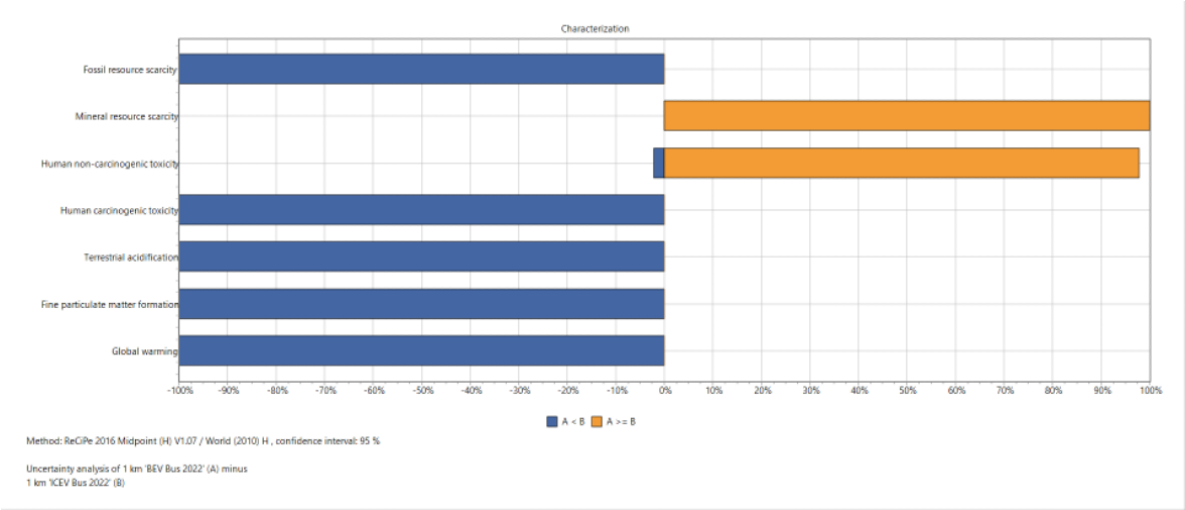

Figure 4.37: Uncertainty analysis of ICE bus (B) impact lower than battery electric bus (A) impact, 2022.

Table 4.21: Uncertainty analysis of ICE bus (B) impact lower than battery electric bus (A) impact, 2022.

Impact category	A >= B	Mean	Median	SD	CV	2,50%	97,50%	SEM
Fine particulate matter formation	0	-5.49E-04	-4.85E-04	2.69E-04	-4.90E+01	-1.23E-03	-2.32E-04	2.69E-06
Fossil resource scarcity	100	1.98E-01	1.98E-01	NAN	NAN	1.98E-01	1.98E-01	NAN
Global warming	100	4.21E-01	4.20E-01	6.97E-03	1.66E+00	4.11E-01	4.38E-01	6.97E-05
Human carcinogenic toxicity	100	3.32E-03	3.32E-03	1.25E-05	3.76E-01	3.31E-03	3.35E-03	1.25E-07
Human non-carcinogenic toxicity	98.23	1.36E-01	1.35E-01	6.05E-02	4.46E+01	1.77E-02	2.56E-01	6.05E-04

Mineral resource scarcity	100	5.13E-04	5.13E-04	1.19E-10	2.33E-05	5.13E-04	5.13E-04	1.19E-12
Terrestrial acidification	0	-4.97E-04	-4.97E-04	5.86E-11	-1.18E-05	-4.97E-04	-4.97E-04	5.86E-13

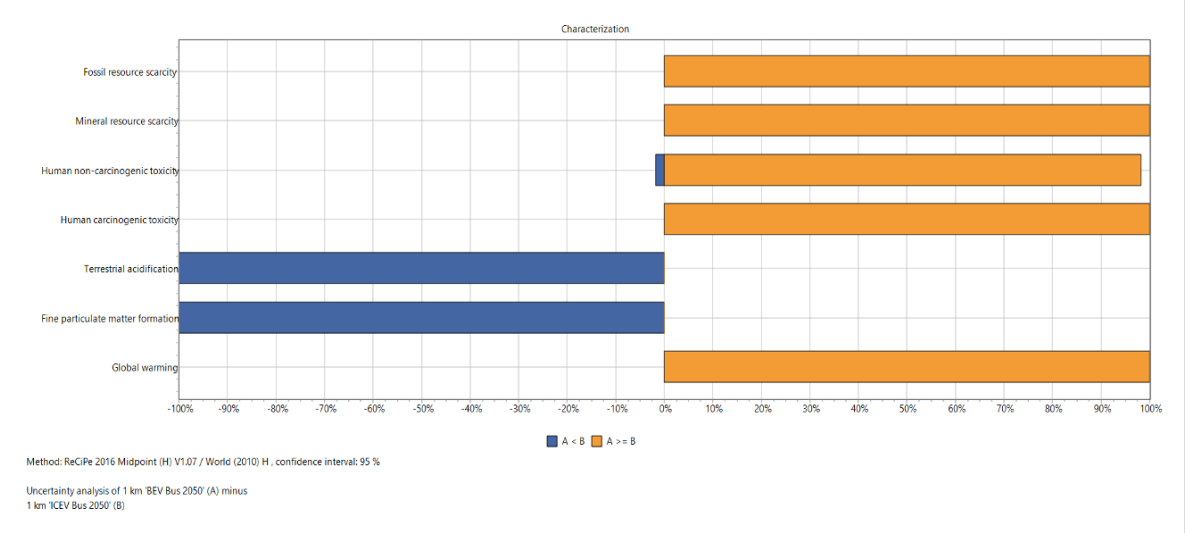

Figure 4.38: Uncertainty analysis of ICE bus (B) impact lower than battery electric bus (A) impact, 2050 – ICE bus adapted to 2050 GFEI fuel economy targets.

Table 4.22: Uncertainty analysis of ICE bus (B) impact lower than battery electric bus (A) impact, 2050 – ICE bus adapted to 2050 GFEI fuel economy targets.

Impact category	A >= B	Mean	Median	SD	CV	2,50%	97,50%	SEM
Fine particulate matter formation	0	-2.25E-03	-2.20E-03	3.94E-04	-1.75E+01	-3.16E-03	-1.61E-03	3.94E-06
Fossil resource scarcity	0	-5.53E-02	-5.53E-02	NAN	NAN	-5.53E-02	-5.53E-02	NAN
Global warming	0	-3.80E-01	-3.79E-01	3.88E-02	-1.02E+01	-4.58E-01	-3.06E-01	3.88E-04
Human carcinogenic toxicity	0	-3.69E-03	-3.59E-03	9.29E-04	-2.52E+01	-5.79E-03	-2.14E-03	9.29E-06
Human non-carcinogenic toxicity	97.84	1.36E-01	1.36E-01	6.29E-02	4.64E+01	9.96E-03	2.57E-01	6.29E-04
Mineral resource scarcity	100	4.93E-04	4.93E-04	8.11E-11	1.65E-05	4.93E-04	4.93E-04	8.11E-13
Terrestrial acidification	0	-5.93E-03	-5.85E-03	9.44E-04	-1.59E+01	-8.02E-03	-4.33E-03	9.44E-06

As a final point of this uncertainty analysis, two important facts, aside from the ICEV-BEV comparison should be addressed, namely the choice of standards, environmental diligence, production location and the choice of vehicle in its respective class. Firstly, in the LDV fraction, it was clear that, if reasonable fuel economies would be implemented, the BEV would be a wise option. Yet, in comparison to the LDV share itself, it is clear that the choice of a smaller sedan was generally a better option than an SUV or sports option. This uncertainty was assessed and is visualised in Figure 4.39. There, it is visible that the chance of a sports vehicle being a better option is close to zero. This also puts the latter result of the not-100% uncertainties into perspective.

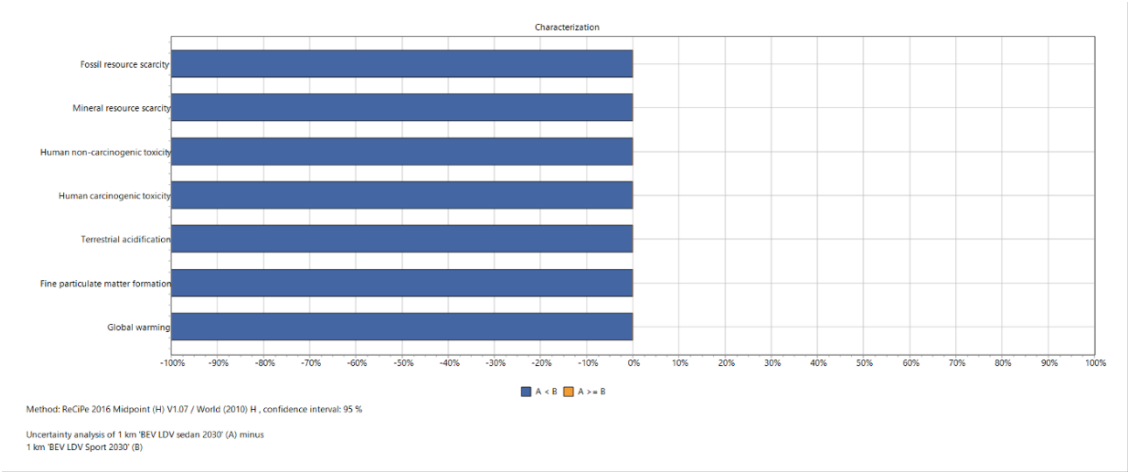

Figure 4.39: Uncertainty analysis of BEV sedan (A) impact lower than BEV sports (B) impact, 2030.

Table 4.23: Uncertainty analysis of BEV sedan (A) impact lower than BEV sports (B) impact, 2030.

Impact category	A >= B	Mean	Median	SD	CV	2,50%	97,50%	SEM
Fine particulate matter formation	0	-1.21E-05	-1.21E-05	9.45E-07	-7.79E+00	-1.41E-05	-1.06E-05	9.45E-09
Fossil resource scarcity	0	-1.17E-02	-1.17E-02	9.22E-05	-7.89E-01	-1.19E-02	-1.15E-02	9.22E-07
Global warming	0	-2.88E-02	-2.88E-02	3.05E-04	-1.06E+00	-2.95E-02	-2.83E-02	3.05E-06
Human carcinogenic toxicity	0	-1.36E-03	-1.25E-03	7.46E-04	-5.47E+01	-2.40E-03	-8.65E-04	7.46E-06
Human non-carcinogenic toxicity	0	-4.79E-02	-3.83E-02	5.21E-02	-1.09E+02	-1.33E-01	-1.78E-02	5.21E-04
Mineral resource scarcity	0	-1.71E-04	-1.70E-04	1.52E-05	-8.90E+00	-2.04E-04	-1.44E-04	1.52E-07
Terrestrial acidification	0	-3.22E-05	-3.20E-05	2.77E-06	-8.59E+00	-3.79E-05	-2.79E-05	2.77E-08

Furthermore, the production location was assessed and shown to be highly impactful for the global scenario. This is visualised by Figure 4.40, showing that only for the human toxicity impact category, there a small 2% of the cases, for which the non-global market mix vehicle would be a better option. By this analysis, it is clear that not only the ICEV or BEV vehicle type is important, the production location, its regulations and downstream implications can negate the complete story and should therefore be inspected carefully.

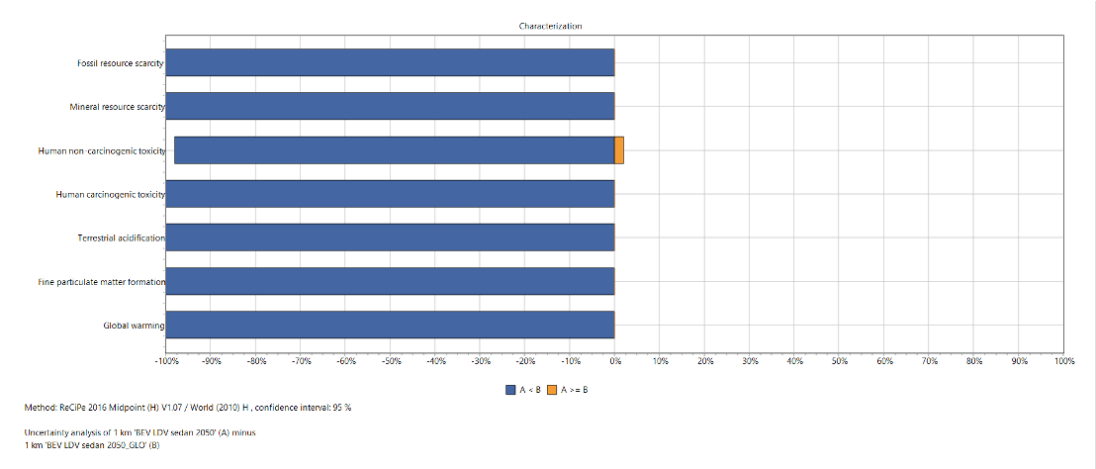

Figure 4.40: Uncertainty analysis of BEV sedan (A) impact lower than BEV sedan global model (B) impact, 2050.

Table 4.24: Uncertainty analysis of BEV sedan (A) impact lower than BEV sedan global model (B) impact, 2050.

Impact category	A >= B	Mean	Median	SD	CV	2,50%	97,50%	SEM
Fine particulate matter formation	0	-3.58E-05	-3.60E-05	2.64E-06	-7.37E+00	-4.07E-05	-2.94E-05	2.64E-07
Fossil resource scarcity	0	-2.08E-03	-2.16E-03	3.93E-04	-1.88E+01	-2.75E-03	-1.06E-03	3.93E-05
Global warming	0	-1.29E-02	-1.30E-02	1.22E-03	-9.49E+00	-1.53E-02	-9.93E-03	1.22E-04
Human carcinogenic toxicity	0	-4.93E-03	-5.17E-03	1.29E-03	-2.62E+01	-6.84E-03	-1.19E-03	1.29E-04
Human non-carcinogenic toxicity	2	-7.53E-02	-8.18E-02	3.01E-02	-4.00E+01	-1.04E-01	2.04E-04	3.01E-03
Mineral resource scarcity	0	-3.04E-04	-3.00E-04	6.05E-05	-1.99E+01	-4.46E-04	-1.48E-04	6.05E-06
Terrestrial acidification	0	-6.38E-05	-6.39E-05	7.04E-06	-1.10E+01	-7.69E-05	-4.57E-05	7.04E-07

4.6 Conclusions

This study presents an exhaustive comparison between ICEVs and BEVs in Qatar from 2022 to 2050. The analysis is conducted using the globally acknowledged ReCiPe Midpoint method, which provides a detailed assessment of various impact categories. The results indicate a trend of decreasing environmental impact for both ICEVs and BEVs over the years, with BEVs generally having a lower impact in most categories. However, the data also reveals some uncertainties and unclear future scenarios, which are worth discussing both from an analytical point of view as well from their overall implications and trends.

As the shift towards BEVs accelerates, their potential to reduce GHG emissions becomes increasingly evident when compared to ICEVs. For instance, by 2050, BEV sedans are projected to emit 1.54E-01 kg CO2-eq/km, which is lower than the 1.63E-01 kg CO2-eq/km for ICEV sedans. The difference is more pronounced in SUVs, where BEVs are expected to emit 1.75E-01 kg CO2-eq/km by 2050, nearly half of the 2.93E-01 kg CO2-eq/km emitted by ICEV SUVs. This suggests that BEVs will play a crucial role in helping Qatar meet its GHG reduction targets. However, in regions like Qatar, where electricity is mainly generated from natural gas, this could potentially offset some of the environmental benefits of BEVs. Renewable energy sources remain the preferred option for reducing the emissions associated with charging BEVs, but even with fossil fuel-generated electricity, BEVs show lower impacts compared to coal-powered electricity grids.

One of the main areas of uncertainty is the impact of vehicle production and disposal. Many countries do not provide detailed information on these aspects, which could significantly affect the overall environmental impact of both ICEVs and BEVs. Future studies could focus on these areas to provide a more comprehensive comparison. For instance, human carcinogenic toxicity for BEV sedans, while projected to decrease slightly, remains higher than for ICEV sedans, with BEVs expected to emit 2.97E-02 kg 1,4-DCB/km in 2050, compared to 1.12E-02 kg 1,4-DCB/km for ICEVs. Similar trends are observed for human non-carcinogenic toxicity, where BEVs are projected to emit 8.14E-01 kg 1,4-DCB/km by 2050, higher than ICEVs.

Further detailed information or real-life data on the potential impact of technological advancements on the environmental performance of both types of vehicles could increase the certainty of the proposed fuel, energy, and vehicle characteristics. For instance, improvements in battery technology could reduce the environmental impact of BEVs, especially in terms of resource use. By 2050, BEV sedans are projected to consume 3.46E-03 kg Cu-eq/km, significantly higher than ICEV sedans (7.24E-04 kg Cu-eq/km). Similarly, advancements in engine efficiency and alternative fuels could improve the performance of ICEVs.

Exemplary of this fact is the environmental impact of battery production for BEVs, a significant area of concern in the sector. The extraction and processing of lithium, cobalt, and other materials used in batteries can lead to substantial GHG emissions as well as other environmental impacts. For instance, lithium extraction often involves significant water use, which can be problematic in water-scarce regions. Cobalt mining, on the other hand, has been linked to serious social and environmental issues in countries like the Democratic Republic of Congo. Future research could further explore alternative battery technologies or recycling methods that could mitigate these impacts, building upon the basis of this thesis.

The transition to BEVs could also have health benefits. Studies have linked air pollution from fossil energy sources and vehicle emissions to a range of health issues, including respiratory diseases, cardiovascular diseases, and premature death. By reducing tailpipe emissions, BEVs could potentially lead to improvements in air quality and public health, or a change to pinpointed locations where such emissions are concentrated and easier to mitigate.

The comparative LCA of ICEVs and BEVs presented in this chapter contributes to achieving the research aim of the thesis. By providing a detailed assessment of the environmental impacts of these vehicle types across various categories, this chapter explains the potential benefits and challenges of transitioning from ICEVs to BEVs in Qatar. The analysis results, including impact assessments and exploration of alternative battery technologies, offer guidance to help Qatar achieve its national targets of reducing GHG emissions from road transport by 2030 and transitioning to a sustainable low-carbon transport system by 2050.

5 Carbon Calculator

5.1 Introduction

Road vehicles are one of the most significant causes of GHG emissions and air pollution on a local, regional, and worldwide scale (Jain & Khare, 2009). An imbalance between the rising number of automobiles and the capacity of road networks has developed due to the rising of per capita income, mobility, city expansion, education facilities, and the spread of job hubs (Ahmad et al., 2013). Significant traffic congestion and restricted vehicle speed give rise to severe air and noise pollution concerns (Lebel et al., 2007; Sen et al., 2010; Tiwari, 2002). Based on a study conducted by the World Energy Council, emerging cities in developing nations would have increased commuting distance per person per day compared to OECD countries, potentially leading to an even more remarkable rise in air pollution in the future (Jain et al., 2016). For example, rising automobile emissions in Doha - the capital of Qatar – is one of the reason that made it one of the most polluted cities in the world (Scott, 2014).

In Qatar, energy used for transport has increased in the past couple of decades due to the high growth in vehicle purchases triggered by the high GDP per capita in the country. This, along with cheap oil prices, made transport one of the largest carbon-emitting sectors in Qatar. The primary energy feedstock used in cars in Qatar is gasoline, as 92.9% of all vehicles run on it according to the Traffic Department at the MoI (Ministry of Interior, 2019). Compared to diesel, which is extensively used in many European and Asian nations, gasoline is a cleaner form of energy; nevertheless, the environmental benefits are mitigated by the overall increase in vehicle ownership and usage, leading to higher cumulative emissions (UK Energy Research Centre, 2019).’

The gradual elimination of new gasoline and diesel vehicle sales by a specified date has been proposed as one of several "disruptive" policies over the past five years, aimed at accelerating the shift towards a low-carbon transportation system. Numerous countries and localities have committed to phasing out traditional vehicles between 2025 and 2040 (WorldAtlas, 2018), and automakers have also set independent targets (Gupta, 2019). The Decarbonising Transport

strategy proposed by the UK Department for Transport aims to acknowledge that the longest passenger and freight journeys will continue by road, especially in rural areas. Thus, decarbonizing motor transport is critical, arguably more important than elsewhere. A November policy halted new petrol and diesel car and van sales from 2030, mandating all new cars and vans be zero-emission by 2035. A consultation proposes ending sales of non-zero emission HDVs by 2040, with lighter HDV bans by 2035. There is also a commitment to start consultations on ending non-zero emission vehicle sales for all vehicles by 2040, charting a course to all-zero emission vehicles. Within a year, consultations will also consider advancing the phase-out date to 2035, or earlier for new non-zero emission two- and three-wheelers. The government itself aims for a 25% ultra-low emission car fleet by December 2022, striving for a 100% zero-emission fleet by 2027 . Furthermore, a study by Sprei, (2018) suggests that the combination of universal electrification, shared transportation, and automation holds significant disruptive potential.

However, some concerns have been raised regarding this approach. Firstly, the definition of a ULEV is vague, which might still allow the sale of HEVs after 2040. Secondly, the 2040 target is considered less ambitious compared to global standards, with many advocating for an earlier implementation, possibly a decade sooner (Climate Change Committee, 2018). Thirdly, there is widespread skepticism about the effectiveness of the proposed policies. Concerns include the need for improvements in battery charging infrastructure, the continuation of incentives for specific ULEV purchases, and the consideration of establishing a car tax (G. Bauer et al., 2021). Fourth, according to scientific data, the goals established for vehicle efficiency and fuel decarbonization fall well short of what is needed to fulfil carbon targets. Despite the most optimistic carbon intensity projections based on the latest test cycle results and the newly agreed CO2 reductions in new vehicles and vans by 2030 (37.5 percent and 31 percent over 2021 levels for cars and vans, respectively), the mix of automobiles sold in the next two decades will lock in fossil fuels for an extended period of time (Morgan, 2019).

Consequently, there is a scarcity of research evaluating the different objectives and phaseouts of the main trade-offs in reducing GHG emissions, improving air quality, and improving public health at various scales. There are also significant public acceptance concerns; how people purchase

vehicles and how cars must be marketed to support emissions reduction are essential considerations. Because technical substitution alone may be insufficient to meet ambitious targets for carbon and local air pollution reduction, “avoiding” travel and “shifting” behaviour to the most environmentally friendly form of transportation will have to play a much more significant role (Creutzig et al., 2018).

This chapter seeks to address the central research question: "How would different measures and technologies influence the decarbonization of the road transport sector in Qatar by 2050?" This analysis is crucial not only in assessing the potential effectiveness of these measures in achieving the 2050 decarbonization goals but also serves as a link to the insights from the literature review. The existing literature explores theoretical and empirical aspects of decarbonization strategies in the transport sector, offering a broad spectrum of perspectives and findings. This chapter extends this discourse by applying these insights specifically to Qatar, employing the carbon calculator to quantify and compare the impacts of various initiatives. It bridges the gap between broader theoretical frameworks and empirical studies in the literature and the practical, policy-oriented analysis at the heart of this thesis.

In order to answer this question, the chapter employs a strategic approach that centers on the development and application of the carbon calculator. This model enables users to quantitatively evaluate the impacts of different policy levers on the carbon emissions of Qatar's road transport sector. The chapter will begin by laying out the methodology, which is rooted in the avoid-shift-improve framework. This will be followed by explaining the logic behind the calculations performed by the model. The scope of road transport under consideration in the study is then outlined. This forms the basis for further discussion on the nature of various levers and their respective Ambition Levels that are incorporated into the model. Lastly, a list and descriptions of the different levers used are presented. Each of these components is designed to provide a clear roadmap towards understanding the potential paths Qatar can take to achieve GHG reductions in road transport by 2050.

5.2 Methodology

The aim of this chapter is to show the potential GHG emission scenarios in Qatar's transportation sector through 2050 in a systematic and transparent way. This research defines and explains the numerous levers that can impact GHG emissions from LDV, HDV and buses. Within each lever, there is a range of possibilities with varying levels of ambition ranging from low to high. Overall, the levers may be classified as follows (GIZ, 2015):

- Avoid/reduce: These levers include altering behaviour, enhancing logistics, and adjusting urban design in order to minimize transportation demand.

- Shift: These levers include strengthening public infrastructure, modifying behaviour, and making public transportation more appealing in order to shift usage to more efficient modes such as public transportation.

- Improve: These levers are aimed at making vehicles emit less GHG and increase their efficiency.

The project incorporates the most significant and well-known decarbonizing options, such as vehicle electrification, energy efficiency developments, societal changes, and other relevant solutions. Further, technologies with unknown impacts such as automation or that are not immediately related to decarbonization are excluded from the model. However, it is important to note that this work is incapable of quantifying all potential consequences in all cases. Therefore, each level will be given 4 different levels of ambition. The transport module considers a variety of factors, including energy use and overall GHG emissions, which are calculated in the project.

5.2.1 Calculations

To calculate the overall GHG emissions and the energy consumption from the transport sector, the transport module uses a bottom-up method. This computation relies on historical data and forecasts until 2050 (The various Ambition Levels are explained in upcoming sections). The calculation methodology uses a number of steps to estimate total GHG emissions sequentially as seen in Figure 5.1:

- Average activity per person per mode [passenger-kilometer (pkm)/person]
- Total average transport activity per mode [pkm or ton-kilometer (tkm)]
- Vehicle transport distance per mode [vehicle-kilometer (vkm) or tkm]
- Technology share for each mode [%]
- Vehicle transport distance per mode per technology [vkm or km]
- Energy intensity per mode per technology [MJ/vkm or MJ/pkm]
- Emission factor per mode per technology [kgCO2eq/MJ]
- Total GHG emissions [kgCO2eq]

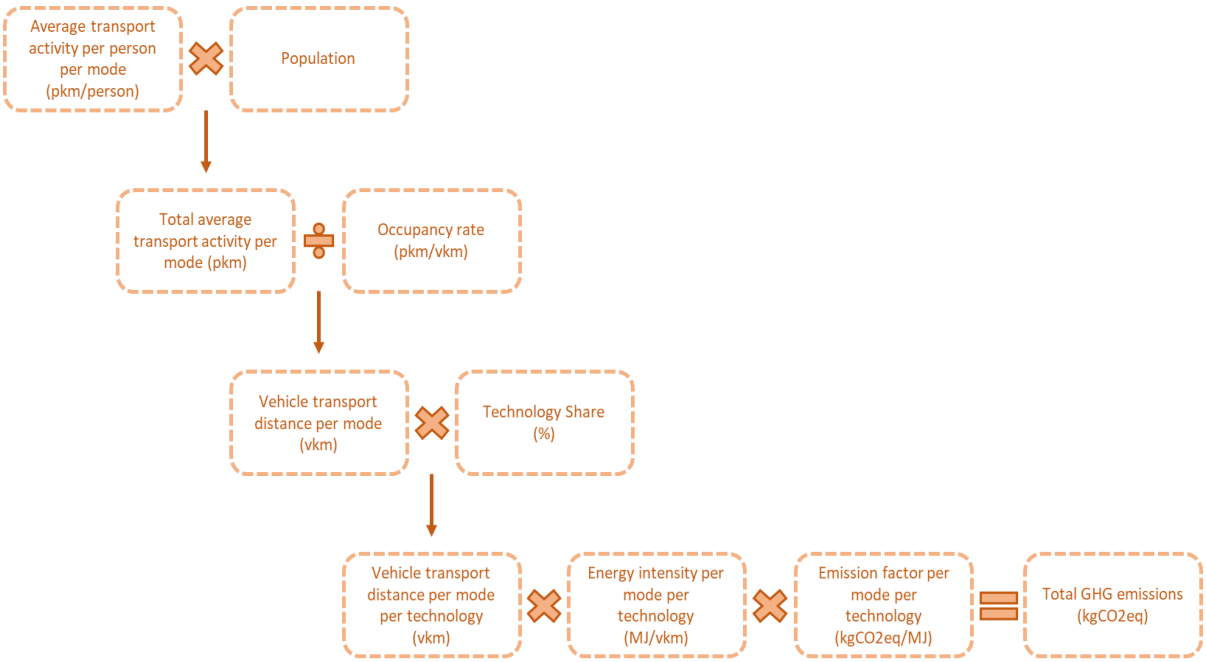

Figure 5.1: Calculation logic framework for road vehicles, illustrating the methodology used to estimate total GHG emissions in CO2-eq.

5.2.2 Scope of road transport

The road transport modules' scope is defined in Table 5.1 as follows:

- The different modes
- The different technologies
- The types of fuels

Table 5.1: Scope of vehicle modes, technologies, and fuel types used in the study. The table outlines the categories of vehicles, including conventional and alternative fuel technologies, as well as the types of fuels analyzed.

Modes	**Light duty vehicles**	**Sedan** **Sport Utility Vehicles** **Sports Vehicle**
	Heavy Duty Vehicles	
	Buses	
	Metro	
Technologies	**Light duty vehicles**	**Internal Combustion Engine Vehicles** **Battery Electric Vehicles**
	Heavy Duty Vehicles	**Internal Combustion Engine Vehicles**
	Buses	**Internal Combustion Engine Vehicles** **Battery Electric Vehicles**
	Metro	**Electric Metro**
Types of fuels	**Diesel**	**Internal Combustion Engine Vehicles**
	Gasoline	**Internal Combustion Engine Vehicles**
	Electricity	**Battery Electric Vehicles**

5.3 Lever's descriptions and Ambition Levels

The forthcoming section delves into the details that drive the carbon calculator model. The primary focus is a detailed list and analysis of levers, based on the Avoid/Reduce-Shift-Improve method. The discussion then extends to explore the multitude of factors influencing the application of the Avoid/Reduce-Shift-Improve method, aiming to provide insights into how external variables can impact the efficacy or limitations of these strategic levers. Following this, attention is directed towards the Ambition Levels, providing a list that offers a comparative analysis of the reasoning of each lever's implementation.

The next part of the section engages in a holistic discourse on the lever itself. Delving into each lever's nuances, starting with a descriptive overview, followed by its current status, and then, the discussion unfolds further with a review of literature-based forecasts, thus depicting potential scenarios for 2050. Feedback from stakeholders is also incorporated to render a real-world perspective on each lever's application and effectiveness. The segment concludes with tailored Ambition Levels suggested for this study, derived from the examination carried out throughout the section.

5.3.1 List and description of levers

In order to estimate the energy consumption and GHG emissions of the transport sector, the Avoid-Shift-Improve strategy proposed by the ICCT is used. The Avoid/reduce-Shift-Improve method uses a bottom-up approach to demonstrates the primary variables that impact transport energy consumption and GHG emissions (Façanha et al., 2012):

- Avoid travel demand and minimize the use of cars required by doing the following:
    - Lower transportation activity
    - Increase the occupancy rate of a vehicle and its load factor
- Shift to a less carbon intensive mode of transport and utilize public transport options

- Improve transport efficiency by manufacturing new vehicles with better fuel economy and switching to more efficient fuels and technologies

Each of the above-mentioned variables of impact is influenced by a slew of other factors. Details are given in the table below:

Table 5.2: Classifications of the Avoid/reduce-Shift-Improve approach.

Avoid/Reduce		
No.	Factor of influence	Examples of external drivers
1	Transport demand	1. Social drivers include demographical factors such as the number as well as the age structure of the population, sociocultural trends such as the widespread remote work, general behavior as well as the awareness, and so on. 2. Technological drivers include the advancement of faster, more comfortable modes of travel, as well as the development of autonomous cars. 3. Economic drivers include fuel prices, GDP per capita, the degree to which the economy/industry is globalized (for freight), and others. 4. Political drivers include urban planning, etc.
2	Occupancy rate	1. Social drivers include social trends (e.g. carpooling and automobile sharing), as well as changes in behavior. 2. Economic drivers include fuel prices (which might result in an increase in the operational expenses of freight hauls, for example), GDP per capita, and so on. 3. Political drivers include subsidies and other ancillary measures that promote freight logistics effectiveness.
Shift		
No.	Factor of influence	Examples of external drivers
3	Modal shift	1. Social drivers include demography - a major influence on social change (age structure of the population, etc.). 2. Economical drivers include cost of fuel and cost of public transport usage. 3. Political drivers include public infrastructure availability and public transportation efficiency.
Improve		
No.	Factor of influence	Examples of external drivers
4	Evolution of efficiency	1. Technological drivers include the number of available and accessible clean vehicles, etc. 2. Economical drivers include additional support to R&D.

		3. Political drivers include subsidies and other ancillary measures incentivizing the use of energy-efficient automobiles.
5	Changes in technology and energy vectors	1. Technological drivers include the readiness of emerging technological options and the accessibility of alternative fuels. 2. Economic drivers include the price associated with new/alternative technologies and fuels, etc. 3. Political drivers include the establishment of suitable infrastructure, etc.

5.3.2 List of levers

The levers for LDV transport are outlined in Table 5.3:

Table 5.3: Levers for LDV transport, including the units used.

Lever	Brief description
Transport demand (vkm)	The demand for transportation is given in vehicle-kilometers per capita per year.
Modal share (%/mode)	The modal share indicates how passengers travel: by vehicle, bus, or other modes of transport.
Occupancy (person/vehicle)	Occupancy refers to the number of passengers per vehicle.
Vehicle efficiency (litre/km)	This vehicle efficiency illustrates the improvement in energy consumption of a vehicle.
Technology development (% of new vehicles/technology)	This lever quantified the extent to which low-emission technology has been adopted.
Fuel type (%/fuel type)	The fuel type lever details the type of fuel such as gasoline, diesel, electricity, etc. Note that this lever also applies to the fuel used for HDVs and buses.

The levers for HDV transport are outlined in Table 5.4:

Table 5.4: Levers for HDV transport, including the units used.

Lever	Brief description
Transport demand (tkm)	The transport demand is the distance travelled by HDVs measured in tkm.
Vehicle efficiency (litre/km)	This vehicle efficiency illustrates the improvement in energy consumption of a vehicle.
Technology development	This lever described the extent to which low-emission technology has been adopted.

(% of new vehicles/technology)	

The levers for bus transport are outlined in Table 5.5:

Table 5.5: Levers for bus transport, including the units used.

Lever	Brief description
Transport demand (vkm)	The demand for transportation is given in vehicle-kilometers per capita per year.
Occupancy (person/vehicle)	Occupancy refers to the number of passengers per vehicle.
Vehicle efficiency (litre/km)	This vehicle efficiency illustrates the improvement in energy consumption of a vehicle.
Technology development (% of new vehicles/technology)	This lever quantified the extent to which low-emission technology has been adopted.

5.3.3 Ambition Levels definition

The table below covers the four Ambition Levels for this study:

Table 5.6: Description of Ambition Levels for GHG emission reduction scenarios.

Lever	Description
Ambition Level 1	This level includes forecasts that are consistent with a business-as-usual scenario.
Ambition Level 2	This is a more ambitious scenario than business as usual, yet it falls short of utilizing all of the available options.
Ambition Level 3	According to current technological advancements and the best practices seen in specific geographic locations, this level is regarded as highly ambitious yet attainable.
Ambition Level 4	In order to achieve this level of transformational change, a wide range of additional efforts are required, including significant shifts in societal functions, rapid adoption of impactful initiatives on broad scales, major technological advances, and breakthroughs, etc.

5.4 Levers justification and structure

Source selection for the carbon calculator project was highly systemized, employing stringent quality standards. These included but were not limited to, the most recent data, the degree to which the article is related to the research problem, and the nature of its source (which may be the author or publication). Peer-reviewed articles, industry reports, and reputable academic research were relied upon to ensure current, authentic, and reliable information. Filtering sources that need to articulate a 2050 outlook for each area studied. The methodically collected data would have been most appropriate, relevant, and broad enough to justify assumptions to base projections on into the carbon calculator, with adjustments to suit scenario-specifics for Qatar. This process guarantees a transparent basis with a robust research methodology on which the ambition paths in the calculator can be built.

Most importantly, there are few studies or data on future projections specific to Qatar; therefore, the application of global sources is utilized for the project. Considering this dearth of area-specific statistics, global figures are the following option to come up with educated estimates. Although they are for general use and not specific to Qatar, these sources may shed light on some of the global patterns and technological advances that could reasonably be anticipated to impact or mirror developments in Qatar. This entails studying these global trends and then customizing them with due recognition of the considerations of economics, environmental, and infrastructure standards. In this regard, the initiative utilizes the worldwide information obtained from international investigations and considers the restriction brought about by the absence of locally generated information. Through this procedure, it is possible to develop realistic and evidence-based trajectories for ambition in Qatar concerning the world's best practices, which cannot be replaced by scarce local information.

Transparency of the selected sources is vital for the carbon calculator project, especially since there is much data from various global regions. All the publications sourced for this project are relevant to its objectives, scientifically rigorous, and from credible publishers or authors. This encompasses articles from reputed journals, extensive industry reports, and credible scholarly research. This way, the selection process is not arbitrary but is based on a thorough evaluation

of each source's content, quality, and relevance. This enhanced transparency helps make the research process more dependable and comprehensible to stakeholders or other researchers regarding the basis for assumptions and projections used by the carbon calculator.

The next section of this research concentrates on the abovementioned levers and provides an extensive analysis, turning to a more detailed understanding. Also, the segment sets out to describe a lever, providing its essential features and purpose. It provides a necessary theoretical basis for understanding the lever and sets the stage for subsequent analysis.

After introducing the lever, a literature review discusses the current state of the lever. The present part of the section examines the available academic discussion to paint a picture of how lever is doing worldwide, providing an overall review of current research targeting more relevant and recent data. The next part of this section continues the literature review but shifts the focus toward future scenarios. It examines and anticipates the academic predictions of the usage of the lever and its effects by 2050 in different situations. This gives it a long-term outlook on how the lever can contribute to low GHG emissions through road transport and its future as the years pass by.

The current situation and 2050 forecasts are specifically drawn upon global literature to provide an understanding of the current situation and future forecasts of the lever. This approach has been taken primarily due to a lack of specific literature focused on Qatar. Literature from various regions, including the United States, Europe, China, and more, offers a broader and global perspective. This viewpoint aids in comprehending the complexities and potential of the lever in diverse contexts and scenarios. Despite its geographical focus, this global literature can offer valuable insights into trends and strategies that could potentially be applicable or adaptable to Qatar. This global approach, therefore, allows for an informed understanding of the lever's potential, bridging the knowledge gap caused by the dearth of literature specific to Qatar.

Subsequent to these literature-based explorations, the section then incorporates feedback from a range of stakeholders. Discussions were held with various academics from different universities in Qatar, professionals working at the Ministry of Transportation, Ministry of Environment and

Climate Change, the Traffic Department at the Ministry of Interior, and Qatar General Electricity & Water Corporation. The inclusion of these diverse viewpoints enriches the understanding of the lever, adding practical insights and expert opinions to the theoretical foundations established earlier.

The final part of this section presents the suggested Ambition Levels for this study, which are designed based on the examination of the list described above. These suggested levels are drawn from the evaluation of preceding discussions, including the lever's theoretical underpinnings, current state, future predictions, and practical feedback from stakeholders.

Overall, this section provides an understanding of the lever and its potential different pathways that demonstrate possible changes in Qatar's road transport sector by 2050. It integrates theoretical knowledge, future projections, and real-world insights to offer a perspective on the lever's role in achieving a more sustainable future.

5.4.1 Light duty vehicles - travel demand

Lever description

The passenger transport demand lever expresses annual passenger travel activity per capita in pkm/person. When all else is equal, a decrease in passenger demand results in decreased carbon emission.

Current situation

Khalili et al. (2019) investigate the developments in the transport sector, as well as alternative transportation technologies and how they influence the energy demand and travel demand. They use the data provided by the ICCT, as well as the International Marine Organization, to estimate passenger activity, and consider the role of GDP and country's population in the travel demand predictions. They consider four modes of transport – road, rail, marine and aviation, and estimate the global passenger travel demand in 2015 as about 5.8 x 10^7 million passenger-kilometers [p-km], out of which 23,137 billion p-km were attributed to light-duty vehicles (around 40%).

Chen and co-author focus on passenger travel demand in large cities with the population higher than 300,000 people (G. Chen & Kauppila, 2017). The employed data of the new International Transport Forum's global urban passenger transport model takes into account 5 modes of transportation: private car, public transport, motorcycle, walking, and cycling. According to their estimates, the travel demand in 2015 equaled 18,042.6billion *p-km*, in North America about 80% of that was attributed to cars, while in the European Economic area the share of cars was about 60%.

Various scenarios for 2050

Most of the researchers predict a drastic increase in passenger travel demand by 2050. Khalili and co-authors predict the global passenger travel demand almost tripling by 2050, as compared to 2015: increasing to almost 16 x 10^7 million p-km, out of which 62,942 billion p-km were attributed to light-duty vehicles (Khalili et al., 2019). Chen and co-author predict a higher mobility demand caused by the growing urbanization of the planet (G. Chen & Kauppila, 2017). According

to their predictions under the baseline scenario, the travel demand will increase from 18,042.6 billion p-km in 2015 to 35,279.8 billion p-km in 2050, about 55% of which (19,403.9 billion p-km) were attributed to cars. Apart from the baseline scenario, they considered 2 additional scenarios – one scenario took into account the local policies aimed to limit the use of private cars, while the other scenario also integrated "sustainable urban transport development and a joint land use policy." They have discovered that those additional policies negatively influence the usage of private vehicles, however, the total travel demand increases due to the higher availability of public transportation options. Scenario 1 predicted the total travel demand of 42,053.5 b p-km, about 25% of which were attributed to cars; the second scenario predicted the total travel demand of 38,208 b p-km, about 20% of which (7,641.6 b p-km) were attributed to cars.

One study stated that the most rapid increase in transportation demand will come between 2010 and 2030 as a result of economic activities driving further expansion of the sector (Capros et al., 2016). Another study estimated an expected rise in passenger demand of up to 200% by 2050 through their thorough evaluation of over 20 mobility scenarios (Skinner et al., 2010).

Feedback from stakeholders

During a consultation, experts highlighted the importance of dividing cars into different types in order to obtain accurate results for GHG emissions. The experts noted that different types of cars have vastly different emissions profiles, depending on factors such as their fuel source, engine size, and weight. It was highlighted that by dividing cars into different types, policymakers and researchers can better understand the sources of GHG emissions from the transportation sector and develop more targeted strategies to reduce these emissions.

It was noted that accurate data on GHG emissions from cars is essential for policymakers to make informed decisions about transportation policies and regulations. For example, data on emissions profiles can inform policies that incentivize the use of low-emissions vehicles, such as electric or hybrid cars, or policies that discourage the use of high-emissions vehicles, such as taxes on gasoline or diesel fuel. Accurate data can also help policymakers evaluate the effectiveness of existing policies and make adjustments as needed to achieve emissions reduction targets.

Ambition Levels

Typically, an increase in travel demand inevitably leads to an increase of GHG (primarily CO_2) emissions into the atmosphere. Since many parts of the world are currently actively trying to reduce GHG emissions, the future travel demand estimates often consider several different scenarios: a baseline scenario, describing an increase in passenger travel demand if no additional measures are taken, and several modified scenarios, describing the effects of implementing various policies aimed at promoting public transportation and reducing the use of private vehicles.

In the below table, Level 1 corresponds to the baseline scenario which was calculated in Chapter 3. The values were converted from pkm to vkm in order to directly lead to overall emission impacts. In this scenario, no additional measures to reduce travel demand are implemented. Level 2 in this table is obtained using the rate change of Level 1 and 2 in travel demand used in the EU-Calc (Taylor et al., 2020). Level 4 corresponds to the scenario where the local policies were enhanced with “sustainable urban transport development and a joint land use policy“ (G. Chen & Kauppila, 2017). Level 3 is a half point located exactly between Level 2 and Level 4.

Table 5.7: Ambition Levels for LDVs passenger travel demand in 2050.

Ambition Levels	1	2	3	4
Passenger travel distance (vkm)	7.77E+10	7.42E+10	5.96E+10	4.51E+10

5.4.2 Light duty vehicles - mode of transport

Lever description

The mode of transport lever analyzes the breakdown of passenger travel across different types of transportation modes. This lever examines both the total passenger distance travelled and the share of pkm accounted for by each mode. The goal is to understand modal split - how much travel volume is occurring via private vehicles versus public transit versus active transport modes.

Tracking mode share over time provides insight on shifts between transportation modes and patterns in travel behaviour. Growth in private VKT versus public transit ridership has implications for congestion, emissions, and accessibility. Changes in active transport indicate urban planning and commuting patterns.

According to different studies, modal share is commonly influenced by a wide range of factors such as (Fulton et al., 2017; Santos et al., 2013):

- Cost of various transportation modes
- Ownership of a vehicle
- Travel time
- Parking space prices and restrictions
- Availability, dependability, and regularity of public transportation

According to Maltha et al. (2017), household income and size are the two primary factors affecting vehicle ownership in the Netherlands. In 1987, household income was the most influential element; in 2014, household size became somewhat more significant. Similarly, family size and income are the two most significant elements impacting vehicle modal share.

Current situation

Currently private cars remain the most common mode of transportation worldwide. Astegiano et al. (2019) used 2015 as their base year which show that for trips under 50 km in the EU28 countries, the modal share of private cars constituted 70.4%.

According to research, at least 78% of the population in Qatar has at least one private vehicle (S. S. Mohammed, 2017). It is worth noting that 94% of those who responded to the study are not Qataris. Given that Qataris earn significantly more than non-Qataris on average, it is projected that more than 78% of the population owns a car.

In another survey conducted by Shaaban in 2020 in Qatar, the author asked whether the residents in about their main and daily mode on transportation. The 868 responses indicated that the most common mode of transport is private vehicles, ride-sharing services, and taxis with 82.4%, 10.4%, and 3.3% respectively. The study also indicated that buses are only used regularly by 2.6% of the respondents (Shaaban, 2020).

In 2015, road vehicles emerged as the most prevalent mode of transportation in the European Union, accounting for 78% of the overall transportation share. This pattern was reflected in different magnitudes across the region, with these vehicles constituting 64% of the transportation modalities in Hungary and 88% in Lithuania (Taylor et al., 2020). Moreover, Fountas et al. (2020) made an elaborate database on transport modal shares for 131 countries worldwide up to 2020, taking into account the changes that the COVID-19 pandemic has brought to the mobility levels (Fountas et al., 2020). They demonstrate the current share of private cars of 94% in North America, 72.7% in Europe and Central Asia, and 71.5% in Middle East and North Africa.

Various scenarios for 2050

A 2019 study focused on the influence of electric bikes on the mobility share in Europe, and the projected mobility shares for 2050 for four different types of transportation: regular bikes, e-bikes, private cars and public transportation (Astegiano et al., 2019). They considered 2 scenarios – a baseline scenario, and a scenario involving introducing certain charges to the cars entering urban areas. According to the predictions of this study, for travel distances less than 50 km within the EU, private cars will remain the main mode of transport, with a modal share of 67.9% in the baseline scenario and 66.5% in the policy scenario. The modal shares for bikes, e-bikes and public transport in the baseline scenario were predicted to be 18%, 2.7% and 11.3% respectively.

Another paper has also considered France as a case study for alternative modal transport futures. In this paper, the proximobility scenario is introduced as an aspirational scenario which predicated that the travel demand would diminish due to the idea that people's lifestyles will slow down. This scenarios also includes modal shifts from single-occupancy car use to alternative approaches which leads to a more environmentally sustainable lifestyle (Kaufmann & Ravalet, 2016).

Feedback from stakeholders

Experts have stated that Qatar is experiencing rapid urbanization and population growth. As countries and cities become more crowded, the demand for efficient transportation options increases. Public transport can provide a solution by offering a reliable and affordable means of commuting, particularly in densely populated areas. With the initiation of the national metro system in 2019, this mode of transportation has become one of the public transport options along with buses. New cities such as Lusail has its own tram system which consists of an underground rail system with multiple stops around the city. Qatar has also implemented policies and incentives to encourage public transport usage. These measures include affordable ticket prices, dedicated lanes for buses and trams, and improved connectivity between different modes of transport. However, experts have pointed out that the metro and tram system are not very popular options at the moment, and their future remains uncertain.

It has been pointed out that Qatar has traditionally been dominated by a car-centric culture, where private car ownership is high. The convenience, privacy, and flexibility associated with private vehicles make them a preferred choice for many individuals. Changing this mindset and shifting towards public transport may require significant efforts in terms of awareness campaigns and mindset change. in addition, the country experiences extremely hot climates for a significant part of the year, which can be a deterrent to using public transport, especially for outdoor journeys. The reliance on air-conditioned private vehicles may continue to be preferred by some individuals, particularly if public transport systems do not adequately address these weather-related challenges.

Ambition Levels

A survey conducted in Qatar indicated that 78% of the residents in the country own at least one car. Even though the study does not state that the remaining 22% use public transport (as they could be using taxis and other private mobility services), this value will be used as a Level 1 Ambition (S. S. Mohammed, 2017). Level 3 is based on the data of Astegiano et al. (2019), focusing on travel distances of less than 50 km within the EU. This scenarios corresponds to a future with additional policies introducing extra charges for cars entering urban areas. Level 4 relies on the proximobility scenario, which was introduced earlier, while Level 2 is the halfway point between Levels 1 and 3.

Table 5.8: Ambition Levels for car share predictions in 2050.

Ambition Levels	1	2	3	4
Car modal share (%)	78	72.3	66.5	54.4

5.4.3 Light duty vehicles - occupancy rate

Lever description

The mean value for people in a vehicle is determined by the passenger occupancy rate lever. In a typical situation, this stage converts pkm to VKT. However, given that the VKT was already provided by FAHES, this step is skipped. When travel demand and other parameters, such as vehicle size, fuel economy, and technology are constant, higher occupancy rate will lead to reduced energy demand, and thus, reduced GHG emissions. The occupancy rate lever is only used in this model for cars, and later in the chapter for buses.

Vehicle occupancy is influenced by a wide range of elements. For road vehicles, consider the following (Levine & Wachs, 1998):

- Time of day
- Day of week
- Geographical location
- Density of traffic
- Purpose of the trip (work-related, educational, social, etc.)
- Travel distance

The rate of car occupancy is primarily influenced by cultural and behavioural factors, and can undergo major shifts as new travel trends emerge, including self-driving vehicles, carpooling, and tailored incentive programs. Additionally, cultural behaviours can contribute to these changes, such as by granting priority to carpooling vehicles on freeways.

Current situation

Vehicle occupancy rates in developed countries are currently very low, which inevitably has a negative effect on the amount of GHG emissions. Stanley et al. (2011) investigated vehicle occupancy rate in Australia and demonstrated that in 2007 it was as low as about 1.4 travelers per vehicle. During the busy morning rush hours that occupancy rate decreased even further and reached the value of 1.14.

Truong et al. (2017) demonstrated that the average car occupancy rates have been decreasing in the last 10 years, reaching 1.55 in 2015 in the case of Victoria, Australia. While another group of researchers reported an average occupancy rate of 1.5 in the UK in 2015 Marsden et al., 2019).

Various scenarios for 2050

Due to the fact that cars will most likely remain the primary mode of transportation up to at least 2050, increasing vehicle occupancy rates is an obvious solution to reducing emissions (Schafer & Victor, 1999). Stanley et al. (2011) researched different scenarios with the aim to achieve Australia's goal of 80% emission reduction by 2050 (as compared to 2000 levels). They considered three different scenarios with varying vehicle emission improvements, and demonstrated that to achieve the goal of 80% in emissions, vehicle occupancy should increase to 1.7, while the cars emission intensity should improve by 92%. The other two scenarios aimed at reaching 84% and 75% of improvements in car emission intensities, and required increasing vehicle occupancy rates up to 2.6 and 2.8 respectively.

Pan et al. (2021) considered various scenarios for the shared use of transport in the US and presented the following assumptions for the average number of passengers per trip in 2050:

- 1.2 for private cars;
- 1.3 and 1.8 for taxis (depending on the scenario in question)
- 1.2 for private automated cars

Truong et al. (2017) assumed that the tendency of vehicle occupancy decrease will continue in the future; in the case of Victoria, Australia, the average number of travelers per vehicle will decrease from 1.55 (as of 2015) to 1.3 in 2050.

According to a study conducted in the US, car occupancy for shared vehicles might reach roughly 1.7 people per vehicle by 2050 (Fulton et al., 2017). Furthermore, it has been predicted that by 2050, vehicle occupancy for urban and interurban trips might reach 2.1 and 2.5, respectively (Peterson et al., 2009).

In 2019 the UK Commission on Travel Demand published a report emphasizing the importance of shared mobility in the future (Marsden et al., 2019). They demonstrated that implementing certain policies supporting shared mobility can increase the average occupancy rate from 1.5 (as of 2015) to 1.7 (in 2050). While the absence of the necessary policies can lead to a further decrease of vehicle occupancy rate to 1.3 (in 2050).

Feedback from stakeholders

Similar to other Arabian Gulf countries, Qatar has been experiencing significant population growth and rapid urbanization. As cities become more crowded and space becomes limited, there is a possibility that the occupancy rate per vehicle could increase. Experts believe that carpooling or ride-sharing initiatives might become more popular as a means to alleviate traffic congestion and optimize vehicle utilization in the future. Traditionally, there has been a strong preference for car ownership in Qatar, with a high rate of private vehicle ownership per capita. However, attitudes towards car ownership are evolving, especially among younger generations. Factors such as rising costs of car ownership, increased awareness of environmental concerns, and the convenience of alternative transportation options may lead to a shift in preferences. However, the people consulted believe that this shift is still slow and unnoticed.

Ambition Levels

5.9 demonstrates different predictions for vehicle occupancy rates for private cars. Level 1 is based on the data of the business as usual (BAU) scenario of (Pan et al., 2021). Level 2 is based

on the data of the UK Commission on Travel Demand, introducing a policy framework promoting shared car use in the UK . Levels 3 and 4 describe two ambitious scenarios including achieving 84% and 75% of improvements in car emission intensities respectively correspond to the data of (Stanley et al., 2011).

Table 5.9: Ambition Levels for vehicle occupancy rate predictions in 2050.

Ambition Levels	1	2	3	4
Car occupancy rate (persons/car)	1.2	1.7	2.6	2.8

5.4.4 Light duty vehicles - vehicle technology

Lever description

The aim of the vehicle technology lever is to determine the technology mix, including ICEV and BEV of cars in the market. The value in vkm per mode is converted into vkm per mode and per technology. A larger alternative vehicle technology share will consequently correspond to a greater number of vkm driven by low-emissions technologies.

Current situation

Electrification of LDV is universally considered an important contributing factor in achieving the global emission reduction goals. Habib et al. (2020) presented the 2018 data of the IEA, reporting the global sales of electric vehicles in 2017 exceeding 1 million, leading to the global stock of electric vehicles reaching 3.1 million, while the total number of passenger vehicles is estimated as 1.13 billion in 2011 (Habib et al., 2020).

In recent years, the global automotive market has witnessed an unprecedented surge in BEV sales, reflecting an accelerating transition towards greener transport solutions. The quantity of electric cars on the roads, including BEVs and PHEVs, soared to over 26 million in 2022, marking a 60% increase from 2021 and a more than five-fold rise compared to the stock in 2018. In particular, the surge in sales has been exponential, with sales numbers jumping from 100,000 to 1 million within a five-year period from 2012 to 2017. By 2022, the total sales of electric cars outpaced 10 million, which was calculated as a 55% increase from 2021, elevating the share of electric cars in total car sales from 9% in 2021 to 14% in 2022. This was over ten times the share reported in 2017. Notably, China has become a frontrunner in this electric revolution, hosting around half of the world's electric cars in 2022. Sales of BEVs in China escalated by 60% in 2022 compared to 2021, reaching 4.4 million, while PHEV sales nearly tripled to hit 1.5 million (IEA, 2023).

Various scenarios for 2050

Many researchers have demonstrated the projected influence of increasing the number of BEVs on the global climate change mitigation. Already in 2015, Nic Lutsey published a working paper demonstrating the contribution of BEVs to different nations' climate goals (Lutsey, 2015). According to the presented projections, most of the biggest automobile markets in the world will fully transition to electrically powered vehicles by 2050. That includes Norway, the Netherlands, France, Japan, Germany, the UK, the US, China and Canada. They further assume that several other countries in the world will follow the development of those markets with a certain delay, projecting about 76% of BEVs in the total mix of those countries by 2050. The predicted global average value amounted to about 88% BEVs.

Since 2022, Indonesia has enforced a policy mandating government vehicles to be electric, introducing subsidies for EV purchases a year later in 2023. The Seychelles has set ambitious goals for sustainable transportation, intending 30% of new vehicle sales to be electric by the year 2030. Furthermore, an upcoming National Electric Mobility Strategy envisages that all buses will be electric by 2050. In Panama, targets have been set for 40% of specific public vehicle fleets to transition to electric power by 2030. Meanwhile, Vietnam has committed to achieving zero emissions in transportation by 2050, aiming for complete reliance on vehicles powered by electricity and green energy. This goal includes prohibiting the production, assembly, and importation of vehicles powered by fossil fuels by 2040. In a similar vein, Ghana has unveiled a new strategy that sets progressive targets for EV sales: 4% by 2025, 16% by 2030, and 32% by 2050 (IEA, 2023).

Habib et al. (2020) investigated three different scenarios for the development of global passenger vehicles demand – baseline, moderate and stringent. For 2050 they predicted a 73% share of BEVs for the stringent scenario, and a 32% share for the moderate scenario.

Alarfaj et al. (2020) estimated the amount of GHG emissions in 2050 in the US, taking into account various rates of electrification, ride sharing and potential vehicle automation. They considered three scenarios with different BEVs penetration rates: 100% BEVs by 2050, 80% BEVs by 2050, 67% BEVs by 2050 (the lower bound necessary for meeting the 80% climate target), and an additional scenario extrapolating the data for 2050 from a predicted 42% share of EVs in 2040.

Feedback from stakeholders

Specialists have expressed that, at this time, there are several factors that support the widespread adoption of BEVs in the coming decades. Firstly, environmental concerns and the need to combat climate change have become increasingly urgent. Electric vehicles produce zero tailpipe emissions, reducing GHG emissions and air pollution. Many countries have already announced plans to ban the sale of ICEVs in the coming years, incentivizing consumers to choose electric alternatives.

Secondly, technological advancements in battery technology and charging infrastructure are rapidly progressing. Electric vehicle ranges are increasing, alleviating range anxiety, and charging times are decreasing. As these improvements continue, the barriers to BEV adoption will diminish, making them more accessible and convenient for the average consumer. Considering these factors, experts shared that vehicle electrification can reach 80% by 2050, which is similar to the middle scenario proposed by (Alarfaj et al., 2020).

Ambition Levels

Table 5.10 presents different predictions for the share of electric vehicles in the vehicle technology mix. Level one assumes that the goal set by Kahramaa is to electrify 10% of the fleet is achieved by 2050. Level 2 corresponds to the moderate scenario by Habib et al. (2020), targeted at keeping a moderate representative concentration pathways (RCPs) level. Level 4 is based on the data of the stakeholder feedback which is also equivalent one of the scenarios which was forecasted by Alarfaj et al. (2020). Level 3 is evaluating the impact if half of the entire fleet was composed of BEVs.

Table 5.10: Ambition Levels for the share of electric passenger in 2050.

Ambition Levels	1	2	3	4
Share of BEVs in fleet (%)	10	32.6	50	80

5.4.5 Light duty vehicles - vehicle efficiency

Lever description

The purpose of the vehicle efficiency improvements lever is to determine the vehicle's energy usage per vkm. The lever assists in converting vkm per vehicle type and technology into energy usage per fuel type such as diesel, gasoline, and electricity. Better energy efficiency will consequently equate to lower energy consumption for the same travel distance, represented in vkm, and the same share of technology.

Current situation

The EPA has been recording fuel economy data since 1975, and in their 2022 Automotive Trends Report, it was stated that in 2021, the real world fuel economy for a conventional vehicle was 9.3 l/100km (U.S. EPA, 2022). Moreover, on their website, the IEA has shown that the current fuel economy of a new LDV is around 7 l/100km (IEA, 2021). Islam et al. (2020) reported the data for 2015 fuel consumptions of conventional vehicles in the range of 6.8 l/100km to 10 l/100km, depending on the vehicle category and fuel type. In addition, the author also reported various data points for 2015 BEVs energy consumption, ranging from 214 Wh/mile ((133 Wh/km) to 225.7 Wh/mile ((140 Wh/km) (Islam et al., 2020).

Various scenarios for 2050

The IEA has also evaluated fuel efficiencies for new LDVs until 2050. Three distinctive pathways have been formulated: the Stated Policies Scenario, the Announced Pledged Scenario, and the Net Zero Emissions by 2050 Scenario. These propositions project that, by the year 2050, the fuel economies of LDVs will achieve efficiency ratings of 4 l/100km, 3 l/100km, and 2 l/100km, respectively, under each respective scenario (IEA, 2021).

Krause et al. (2020) investigated various decarbonization possibilities under different conditions – in the urban environment, rural environment and on the highways, and estimated the conventional vehicle fuel consumption for small and medium cars in 2050 as 0.06 l/km. The study also discusses a basic scenario for BEVs and Fuel Cell Hybrid Electric Vehicles (FCHEVs), assuming

no advancements in vehicle efficiency. Initially, small cars are estimated to consume 155 Wh/km, while larger cars consume 189 Wh/km. The authors also suggest that improvements in vehicle weights and aerodynamics could reduce energy consumption. For small cars, the projected consumption could be either 74 Wh/km or 109 Wh/km, depending on various factors. Similarly, larger cars might reduce their consumption to either 96 Wh/km or 135 Wh/km in different scenarios (Krause et al., 2020).

For the US, the 2045 predicted energy consumption values of battery BEVs for small vehicles constituted 148.4 Wh/mile (92.2Wh/km) for premium vehicles and 140.0 Wh/mile (87.0 Wh/km) for base vehicles for a scenario assuming a high level of technological progress, and 174.0 Wh/mile (108.1 Wh/km) for premium vehicles versus 164.6 Wh/mile (102.3 Wh/km) for base vehicles assuming a low level of technological progress (Islam et al., 2020).

Feedback from stakeholders

The feedback obtained from specialist state that the evolution of vehicle efficiency is primarily contingent on a confluence of factors including technological innovations, policy measures, and market dynamics. Advancements in engine technology, transmission systems, vehicular aerodynamics, and the use of lightweight materials can dramatically enhance vehicle efficiency. Moreover, governments around the world are tightening fuel economy standards, compelling automotive manufacturers to invest in fuel-saving technologies. Such regulatory pressures are likely to persist, driving continuous improvements in vehicle efficiency. Also, consumer preference is increasingly tilting towards fuel-efficient vehicles due to the rising cost of fuel and growing environmental consciousness. Given these considerations, experts think it is plausible that ICEV vehicle efficiency could improve by approximately 20% to 30%, and BEV vehicle efficiency could improve by 10% to 30% by 2050 compared to average current levels.

Ambition Levels

Table 5.11: Ambition Levels for LDV efficiency improvements in 2050.

Ambition Levels	1	2	3	4
ICEV energy efficiency improvements (%)	-14	-26	-39	-51
BEV energy efficiency improvements (%)	0	-10	-30	-43
Metro system energy efficiency improvements (%)	0	-12.9	-25.7	-38.6

.11 presents vehicle efficiency values expressed in fuel consumption rates for conventional vehicles and energy consumption rates for BEVs as well as the Metro in Qatar. For the conventional vehicles Ambition Level 1, this study uses the average value of the current fuel economy reported in the EPA Automotive Trends Report and the IEA as a benchmark (IEA, 2021; U.S. EPA, 2022). The IEA Announced Pledges Scenario is used to represent Ambition Level 4 (IEA, 2021). Level 2 and 3 are 1/3 and 2/3 respectively between Levels 1 and 4.

For BEVs, Level 1 is derived from the research conducted by Krause et al. (2020), with Level 1 corresponding to a baseline scenario in which energy consumption in 2050 matches that of 2015. Subsequently, Level 2 represents a scenario with a 10% improvement in vehicle efficiency, this was indicated as the lower limit based on the stakeholders' feedback. In contrast, Level 3 corresponds to the upper limit as articulated by the stakeholders, aligning simultaneously with one of the scenarios proposed in the work of Krause et al. (2020). Notably, Level 4 utilizes data from a study conducted by Islam et al. (2020). All these designated levels correspond to projections for the year 2050, with the sole exception of Level 4 for BEVs, which is intended for the year 2045.

For the metro, the International Union of Railways (UIC) created general efficiency targets that countries should adopt by certain years in order to reach carbon neutrality by 2050. The targets state that by 2030 and 2050, efficiency improvements will need to be reduced by 38.6% and 54% respectively in comparison to 1990 levels (International Union of Railways, 2019). Given that the metro system in Qatar was recently opened, improvements on the current system are unlikely. With that said, Level 1 corresponds to no changes occurring to the current system, while Level 4

is taken from the 2030 goal sent by the UIC. Levels 2 and 3 are 1/3 and 2/3 between Levels 1 and 4.

Table 5.11: Ambition Levels for LDV efficiency improvements in 2050.

Ambition Levels	1	2	3	4
ICEV energy efficiency improvements (%)	-14	-26	-39	-51
BEV energy efficiency improvements (%)	0	-10	-30	-43
Metro system energy efficiency improvements (%)	0	-12.9	-25.7	-38.6

5.4.6 Heavy duty vehicles - travel demand

Lever description

The HDV travel demand lever is represented in pkm. Generally, the HDV travel demand can either be computed using tkm or vkm as units. In this study, vkm is used with an average emission factor that accounts for the weight in HDVs. This lever depends highly on the economy and trade in the country. A large volume of HDV enters the country via the land border with Saudi Arabia or via the international ports. Under low-carbon scenarios, HDV activity could be disturbed by a number of factors:

- Local economy trading: increased economic trading within local areas which reduces demand for products from further cities. On the other hand, the opposite which result in an increase for HDV travel demand.
- Construction activity: more construction projects require more trucks to transport equipment, materials, waste, etc.
- E-commerce growth: the growth of online shopping results in more delivery trucks for induvial packages.
- Infrastructure investment: expanded highways and logistics encourages enable more long-haul HDV activities.

- Environmental regulations: stricter environmental on trucks could restrict HDV access and routes.

Current situation

Khalili et al. (2019) estimates the 2015 freight travel demand as 12,708 billion ton-kilometers (b t-km), based on the data of the International Council of Clean Transportation.

Various scenarios for 2050

Similar to passenger travel demand, freight travel demand is also predicted to significantly increase by 2050. Khalili et al. (2019) forecasted the overall transportation demand to almost triple in 2050, as compared to 2015. The authors made their predictions based on the data from the ICCT, while taking into account the changes in population of the countries under investigation. Moreover, they considered the economic development of the researched regions through estimating the influence of the GDP on the transport demand predictions. According to their predictions, the freight travel demand will increase from 12,708 billion ton-kilometers (b t-km) (as of 2015) to 19,066 b t-km in 2030 and 32,156 b t-km in 2050. The authors investigated the transport demand of three types of heavy-duty trucks: light, medium, and heavy.

In 2016, the European Commission published the EU reference scenario, discussing energy, transport and GHG emission projections (Capros et al., 2016). According to their predictions, the road freight traffic will increase by about 57% by 2050, as compared to 2010 levels.

Yan et al. (2021) made predictions on the future freight travel demand, as well as on the emission and energy consumption levels. They also investigated the projected influence of various climate policies on the values listed above. The authors developed an extensive model to cover several possible scenarios (Yan et al., 2021):

1. Baseline scenario, with no additional policies and consistent technological improvement trends

2. Energy price scenario, taking into account diesel price growth according to the EU Reference Scenario 2016
3. Carbon tax scenario, taking into account increased governmental carbon tax policies
4. Diesel rebate scenario, removing the controversial diesel rebate policy
5. Fuel efficiency scenario, taking into account reduced emissions from vehicles

Feedback from stakeholders

For this lever, there was no particular feedback or changes requested.

Ambition Levels

Generally, the Ambition Levels below follow a similar approach to that of passenger vehicles. Level 1 is taken from Khalili et al. (2019) as they predict that 2050 levels are 2.5 times greater than current levels. HDV travel demand was also calculated in Chapter 3, and will be used in the table below to represent Ambition Level 2. Moreover, Levels 3 and 4 correlate to the change in freight transport demand found in the EU-Calc (Taylor et al., 2020).

Table 5.12: Ambition Levels for HDV travel demand predictions in 2050.

Ambition Levels	1	2	3	4
HDV travel distance (vkm)	4.32E+09	3.58E+09	3.45E+09	3.33E+09

5.4.7 Heavy duty vehicles - vehicle technology

Lever description

The type of truck powertrain is influenced by the vehicle technology lever for HDVs, which determines the technology mix such as ICE, BEV, etc. Based on this lever and historical fleet data, the project can calculate the percentage of each vehicle technology in the overall fleet. This step in the model divides vkm by mode into vkm by mode and by technology. A larger technology share will consequently correspond to a greater number of vkm travelled by higher energy efficient alternatives for the same vehicle distance.

Current situation

HDVs remain the most energy-consuming mode of road transport on a per vehicle basis, and their electrification is not a very straightforward process. Currently-used batteries are generally not powerful enough to charge HDVs, and introducing electric freight vehicles would require improvements not only of the trucks themselves, but of the whole heavy-duty transport sector. Nevertheless, some researchers investigate this possibility (Çabukoglu et al., 2018).

Khalili et al. (2019) investigated fuel shares of the road mode for LDVs as well as HDVs, and reported that both in 2015 and 2020 the in-stock HDVs were exclusively powered by liquid fuels (internal combustion engines), with small percentages of newly-sold HDVs in 2020 being FCEVs, PHEVs, or BEVs. Another study conducted by the ICCT stated that in 2021, only 1% of the entire EU fleet was composed of zero-emission HDVs, while the majority of vehicles operate of diesel fuel (O'connell et al., 2023).

The IEA reported that in 2021, the registration numbers for electric HDVs saw an upward movement in regions like China, Europe, and the United States. The worldwide sales for electric medium and heavy-duty trucks saw a twofold increase from the sales figures of 2020, even though the total sales volume stayed relatively stable compared to the previous year (IEA, 2022b).

Various scenarios for 2050

According to a PwC report released in October 2022, the market share of zero-emission trucks (electric and hydrogen) will reach a third in Europe, North America, and China by 2050 and reach 70% of the market part by 2035 as a result of the growth of regulatory restrictions and the decrease in the total cost over the cycle of life of these vehicles, which will be lower by 30% than that of conventional vehicles by that same year (PwC, 2022).

In their paper which discusses near and long-term initiatives to decarbonize HDVs in China, Khanna et al. (2021) introduces an early and late adoption scenarios for electric HDVs. As indicated by the name, the early adoption scenario states that the deployment of battery HDVs is set to begin as early as 2020, with the goal of reaching 30% of electric HDVs by 2050. It is expected that the adoption rate of battery HDVs will be approximately twice as fast as fuel cell trucks due to the faster pace of technology maturity. This is supported by the abundance of existing models of electric HDVs that are currently being demonstrated in pilot projects around the world, and the shorter anticipated timeline for commercial production by major companies. Furthermore, existing fueling infrastructure launch initiatives are expected to expedite the adoption of battery HDVs (Khanna et al., 2021). On the other hand, in the late adoption scenario of electric HDVs, the adoption commences later in 2020 and progresses at a slower rate until 2050, at which point it is projected to comprise 14% of the overall stock (Khanna et al., 2021).

In response to the pressing need for immediate action, a coalition comprising 19 jurisdictions in both the U.S. and Canada has pledged to reduce GHG emissions and air pollution by expediting the market for zero-emission buses, vans, and trucks. To facilitate a swift and effective transition, the involved jurisdictions are devoted to having at least 30% of new HDV sales to be zero-emission by 2030, with a target of 100% of new HDV sales to be zero-emissions by 2050. The coalition believes that the fast electrification of HDVs and buses will result in a substantial reduction in GHG emissions and air pollution, as well as provide significant economic and employment prospects (Northeast States for Coordinated Air Use Management, 2022).

Feedback from stakeholders

The stakeholders believe that major logistics and shipping companies have recognized the importance of sustainability and are integrating it into their business strategies. Companies are setting ambitious targets to reduce emissions and transition to electric or low-emission fleets. As industry leaders adopt electric trucks and demonstrate their feasibility, it will encourage wider adoption across the trucking sector. Moreover, governments worldwide are introducing policies and incentives to accelerate the adoption of electric trucks. Subsidies, tax incentives, and grants can significantly reduce the upfront costs of electric truck purchases, making them more financially viable for trucking companies. Experts believe that Qatar is not too behind in this, and estimate that by 2050, around 40% of HDVs could be electric.

Ambition Levels

Table 5.13 presents different predictions for the penetration rate of electric HDVs. Levels 1 and 2 represent the late and early adoption scenario proposed by Khanna et al. (2021), while Level 4 is based on the 70% electrification scenario proposed by PwC. It is important to note that PwC's projection states that 70% will be achieved in 2045, however, since this rate is ambitious, this study assumes that this rate will be achieved in the Level 4 scenario by 2050. Finally, Level 3 is ½ between Levels 2 and 4.

Table 5.13: Ambition Levels for the share of electric HDVs in 2050.

Ambition Levels	1	2	3	4
Share of electric HDV in fleet (%)	14	30	50	70

5.4.8 Heavy duty vehicles - vehicle efficiency

Lever description

The vehicle efficiency improvement lever for heavy duty vehicles helps determine how much energy a vehicle consumes per vkm for trucks. In this step, the model converts vkm per vehicle type and technology into energy consumption per fuel type such as gasoline, diesel, electricity, etc. Better energy efficiency will consequently translate to reduced energy consumption for the same travelling distance and same technology share, stated in vkm.

Current situation

Krause et al. (2020) performed extensive research on tank-to-wheel vehicle efficiencies of various types of vehicles in the EU. For the conventional heavy-duty vehicles, they obtained the following fuel consumption values for 2015: 0.25 l/km for driving in rural areas, 0.38 l/km for driving in urban areas, 0.24 l/km for driving on the highway. Taking into account the road type shares (0.12 for urban share, 0.25 for rural share and 0.63 for highway share), those numbers added up to a total baseline fuel consumption of 0.26 l/km, which corresponds to CO_2 emissions of 678 gCO_2/km. On the other hand, due to the higher efficiency of their electric components, electric buses can offer potential savings in fuel expenditures. Modern light-duty electric vehicles, depending on their usage, can achieve more than 130 miles per gallon equivalent (MPGe) and are capable of covering a distance of 100 miles while only using between 25 and 40 kilowatt-hours of energy.

Moreover, a test performed in Germany examined the Volvo FH Electric, a vehicle producing zero exhaust emissions with a continuous power output of 490 kilowatts and a gross combination weight of 40 tonnes. Over the entirety of the course, the Volvo FH Electric maintained an average speed of 80 km/h, and with energy consumption as low as 1.1 kilowatt-hours per km, the electric truck had a travel range of 345 km on a single charge. According to the test, the Volvo FH Electric utilized 50% less energy in the Green Truck Route than a Volvo FH equipped with a comparable diesel engine. Furthermore, Volvo Trucks has set ambitious goals, projecting that by 2030,

electric vehicles will constitute half of its truck sales, and by 2040, it anticipates a 100% reduction in WTW CO2 emissions for newly sold trucks (Volvo Trucks, 2022).

Various scenarios for 2050

Krause et al. (2020) also considered several measures aimed at transport reduction and vehicle efficiency enhancements, and employed the data to make predictions for several possible scenarios up to 2050. The 2050 baseline scenario was based on the assumption that the average fuel consumption of a conventional vehicle would be equivalent to the 2015 consumption. Furthermore, they considered several types of technical improvements and calculated energy reduction potentials for each measure separately. For the highway-driving they obtained the following values for the share of energy consumption reduction of 2050 vehicles relative to 2015 vehicles:

- Improving diesel engines led to 0.04 or 0.09 energy reduction, depending on the scenario.
- Improving waste heat recovery led to 0.04 reduction for both scenarios.
- Improving vehicles' aerodynamics led to 0.05 or 0.1 energy reduction.
- Improving several driving conditions, such as speed smoothening and avoiding the stops, led to 0.05 or 0.15 energy reduction, depending on the scenario.

Karali et al. (2017) investigated the possibilities of heavy-duty vehicles efficiency improvements in India; they considered seven possible scenarios and obtained the average fuel efficiency values in 2050 in the range of (4.1 – 7.1) km/l (or 0.24 – 0.14) l/km, which led to CO_2 emission reductions of 12.5% to 41.1%, depending on the scenario.

Askin et al. (2015) presented an analysis of the future of HDVs in the U.S. and came to the conclusion that conventional diesel-powered vehicles will still dominate the heavy-duty transport sector in 2050. They demonstrated that decreasing the purchase price of natural-gas-powered vehicles would influence their penetration rates more than increasing their efficiency, and came to the final conclusion that increasing the efficiency of all energy supplies (including both conventional diesel and alternative sources of energy) will be more beneficial in the long run than focusing only on one energetic aspect.

A paper by Jadun et al. (2017) looks at the fuel economies of electric HDVs leading to 2050 in three different scenarios (slow advancement, moderate advancement, and rapid advancement). Based on this, the fuel economy is forecasted to improve by 25%, 45%, and 65% in the slow, moderate, and rapid scenarios respectively while using the year 2020 as baseline year. In a different study that predicts scenarios to 2050, for electric HDVs, the average fuel economy of the fleet improves from the present average amount of 1.5 kWh/km to today's best available fuel consumption of 1.25 kWh/km, which has been achieved by the Semi tractor trailer introduced by Tesla (Khanna et al., 2021).

Feedback from stakeholders

For HDV efficiency, common principles for passenger vehicles such as technological advancements, regulatory measures and market dynamics apply here. In addition, ICE HDVs predominantly use diesel engines. In the future, advancements in diesel engine technology could lead to significant efficiency improvements. These could include low-temperature combustion regimes, and advanced exhaust after-treatment systems. This could lead to vehicle efficiency improvements between 20% and 30% by 2050. For electric HDVs, battery technology is the cornerstone of efficiency. Future advancements such as solid-state batteries could offer higher energy densities, faster charging times, and better safety profiles than current lithium-ion batteries, leading to improved range and efficiency. Also, ongoing research and development in power electronics, including inverters and converters, as well as electric motors, can lead to efficiency improvements. With that said, experts reckon that electric HDV efficiency can improve by 30% to 50% by 2050.

Ambition Levels

5.14 presents freight vehicle efficiency values expressed in fuel consumption rates. For the conventional trucks, Levels 1 and 3 are based on the data of Krause et al. (2020), where Level 1 corresponds to the baseline scenario, and Level 3 – to the 0.15 energy reduction caused by improving the driving conditions. Levels 2 and 4 are based on two of the scenarios of (Karali et al., 2017). Level 2 corresponds to the baseline scenario in this paper and then is referenced back

to the Kruse et al. (2020) paper, where the values were calculated using engine data specific for India, vehicle specification information obtained from the manufacturers, and industry experts estimates. Level 4 corresponds to a scenario predicting various technological advancements, including a 5% reduction in weight, using advanced low rolling resistance tires, improved engines, automatic tire inflation systems, hybrid-electric powertrain, and advanced truck aerodynamics. For electric HDVs, Level 1 is obtained from the study presented by Khanna et al. (2021) while the slow, moderate, and rapid advancements shown in study performed by Jadun et al. (2017) represent Levels 2, 3, and 4 respectively.

Table 5.14: Ambition Levels for HDV efficiency improvements in 2050.

Ambition Levels	1	2	3	4
ICEV energy efficiency improvements (%)	0	-7.7	-15.4	-46
BEV energy efficiency improvements (%)	-16.7	-25	-45	-65

5.4.9 Buses - travel demand

Lever description

The bus travel demand lever is denoted in vkm. For this analysis, vkm is employed with an average emission factor that takes into account the general capacity of buses. A significant number of buses operate within city limits, connecting various parts of the country. Assuming all other factors remain constant, a reduction in the need for bus transport leads to a corresponding drop in carbon emissions.

Current situation

Khalili et al. (2019) investigated the global transportation demand and its projections up to 2050. They estimated the global bus travel demand in 2015 as 18,619 b pkm. In Qatar, buses are used by two different entities for two different purposes. The first group category is “Mowasalat” (exclusive taxi and public transport operator in Qatar), while the second category is referred to in this project as “Other” which represents all the other buses used in the country for different purposes such as for schools, industries, etc. In 2022, Mowasalat’s fleet consisted of 25% electric buses with an annual travel demand of circa 94,192 km, and in 2023, the entire bus fleet became electric. On the other hand, the “Other” category is entirely conventional with an annual vkm of 18,712 km.

Various scenarios for 2050

According to the researchers’ predictions (based on the data provided by the International Council on Clean Transportation), the global bus travel demand will increase from 18,619 b p-km as of 2015 to 42,498 b p-km in 2050 (Khalili et al., 2019).

Girod et al. (2013) performed a comparison of five different transport models in terms of CO_2 emissions, fuel use and travel demand. The study focused on the baseline projections of the included models; to compare the models, the authors ran calculations with similar input data for world population and global income. All considered models demonstrated an extremely steep increase in transportation demand by 2050: from (34-41) trillion pkm as of 2015 to (86-141)

trillion pkm projected for 2050. It should be noted that even though similar assumptions for population and income were made in this comparison, different models used different values for travel mode shares; the differences in modal shares were particularly big for buses, as the most wide-spread form of public transport in developing countries. The global bus share for base year (2015) varied from about 20% (Kyle & Kim, 2011) to more than 30% (Fulton et al., 2009). The predictions for 2050 ranged from about 15% (Fulton et al., 2009) of the total passenger travel demand of about 110 trillion pkm, to about 22% (Kitous et al., 2010) of the total travel demand about 140 trillion pkm, to about 30% (Girod et al., 2013) of the total travel demand of more than 160 trillion pkm. Most of the scenarios in question predicted a decrease in bus travel demand over the years, which was attributed to carbon tax having a greater influence on bus and air travel, than on LDVs, because of the fact that energy costs constitute the majority of the total travel costs.

Feedback from stakeholders

During a consultation, experts emphasized that buses serve various purposes, ranging from urban public transit to school bus service, and intercity transportation (intercity transportation does not apply in Qatar). Each of these purposes entails different travel patterns and distances. Urban buses, for example, primarily operate within city limits and cover relatively shorter distances on fixed routes. in contrast, school buses predominantly cover shorter distances for transporting students to and from educational institutions.

Considering these variations in travel distances is essential when calculating GHG emissions from buses. The experts emphasized that accurate data on travel distances allows for more precise estimations of fuel consumption and emissions. This information is important for policymakers and researchers in developing effective strategies and policies to reduce emissions and improve the environmental sustainability of bus transportation.

Accurate calculations of GHG emissions rely on reliable data on fuel consumption, which is closely tied to travel distance. By knowing the distance covered by buses, it becomes possible to estimate the amount of fuel consumed and subsequently calculate the associated emissions. This

knowledge serves as a crucial foundation for setting emission reduction targets, evaluating the effectiveness of existing policies, and identifying opportunities for improvement in the bus transportation sector.

Ambition Levels

Table 5.15 demonstrates different predictions for the global bus travel demand in 2050. The bus travel demand which was calculated in Chapter 3 is used in this table to represent Ambition Level 1. Girod et al. (2013) modeled 3 scenarios for bus transport demand in 2050. The first scenario will be used as a benchmark where the rate of improvement in comparison to other scenarios will be used with the travel demand to create Ambition Level 4. Then, the same rate of improvement from Khalili et al. (2019) will be used to model Ambition Level 3. Finally, Level 2 will mark the halfway point between Levels 1 and 3.

Table 5.15: Ambition Levels for bus travel demand in 2050.

Ambition Levels	1	2	3	4
Mowasalat buses (vkm)	5.19E+08	4.90E+08	4.60E+08	3.34E+08
Other buses (vkm)	8.79E+06	8.29E+06	7.79E+06	5.65E+06

5.4.10 Buses - occupancy rate

Lever description

The typical count of passengers in a bus is gauged by the bus occupancy rate lever. At this juncture, the model employs this lever and translates pkm into vkm. Presuming bus travel demand and other factors like bus size, fuel efficiency, and technology remain fixed, a higher occupancy rate will result in a decrease in energy consumption, subsequently leading to a reduction in GHG emissions.

Current situation

Pan et al. (2021) reported the average occupancy rate for road public transport in the US in 2015 is 10.9 passengers per vehicle.

Various scenarios for 2050

Shared mobility combined with the more extensive usage of public transportation are very important factors of emission reductions strategies. Pan et al. (2021) investigated the possibility of the shared use of electric autonomous vehicles, as well as their influence on the air quality and various health factors in the United States. The study considered several scenarios, the most ambitious of which included three factors of improvement – increasing the number of electrified vehicles, automating the vehicles and increasing the shared use of vehicles. The authors assumed the vehicle occupancy rates of 10.9 and 14.4 for buses (depending on the scenario in question) (Pan et al., 2021).

While most researchers incorporate some increase in the occupancy rate of buses in their scenarios, some mention that public transportation vehicles in the developing countries are already often overcrowded; therefore, increasing vehicle occupancy rates is not always a feasible solution to achieve emission reductions. Multiple studies focus on other emission reduction strategies, while keeping the public transport occupancy rates the same. Ankur et al. (2022) developed a model to analyze the influence of various occupancy rates (varying from 0 to 100%) on the energy demands; however, they also performed various calculations assuming that the

occupancy rates for buses will not significantly change in the future. They used a default occupancy rate of 19% (Ankur et al., 2022).

Feedback from stakeholders

For this lever, there was no particular feedback or changes requested.

Ambition Levels

The tale below presents different predictions for vehicle occupancy rates for buses. Level 1 and Level 4 of this table correspond to the different scenarios discussed in (Pan et al., 2021). Level 1 corresponds to the business-as-usual scenario, with the predicted occupancy rates equal to the occupancy rates of 2015, and Level 4 corresponds to a “three revolutions” scenario by Fulton et al. (2017), implying “automation, electrification, and sharing”. Levels 2 and 3 are at 1/3 and 2/3 respectively between Levels 1 and 4. While the increase difference between Levels 1 and 4 might not be big, this is mainly due to the factors mentioned before which makes the use of buses both uncomfortable and inefficient in Qatar.

Table 5.16: Ambition Levels for buses occupancy rates in 2050.

Ambition Levels	1	2	3	4
Bus occupancy rate (persons/car)	10.9	12	13.2	14.4

5.4.11 Buses - vehicle technology

Lever description

The purpose of the vehicle technology lever in the context of buses is to establish the blend of technologies, including conventional and electric buses within the market. This lever utilizes historical bus stock data within the calculator to determine the proportion of different bus technologies in the total stock. Subsequently, the value in vkm per mode is divided into vkm per mode and per technology.

Current situation

In the majority of the world, buses are still mainly powered by diesel. For example, Skytte et al. (2019) focuses on the Danish transport sector and reports a bus vehicle mix for 2012 consisting of 100% diesel-powered vehicles. On a global level, Khalili et al. (2019) reports the following data for the penetration of different types of vehicle technology for buses:

- In 2015, about 10% of both in-stock and newly-sold buses are electric, about 1% of all buses are represented by PHEVs, with the rest of the vehicles being ICEs.
- In 2020, about 14% of in-stock vehicles and about 20% of newly-sold vehicles are electric, 1-2% are represented by PHEVs, and the rest of the vehicles are represented by ICEs.

For the case of Qatar, it was mentioned earlier that in 2022, 25% of the Mowasalat bus fleet was electric, and that by 2023 the entire fleet was electrified (Ministry of Transport, 2022). On the other hand, the “Other” bus fleet remains entirely conventional.

Various scenarios for 2050

There are several ways that public bus technology can improve in the future including the usage of electric buses, hydrogen buses, switching from conventional diesel to biodiesel or biogas fuel. Skytte et al. (2019) investigated how electric and hydrogen-powered vehicles can aid in achieving Denmark’s goal of being completely independent from fossil fuels by 2050. The authors have considered two scenarios, with one scenario focusing on a pathway of widespread EVs

implementation, while the other scenario focused on the use of hydrogen for transportation, as well as a carbon-neutral scenario, as defined by the Nordic Energy Technology Perspectives. Currently Denmark's bus fleet consists of 100% diesel-powered buses. In the carbon-neutral scenario presented by, the shares of bus technologies consisted of about 70% biodiesel-powered buses and about 30% of biogas-powered buses (Nordic Energy Research & IEA, 2013). In Skytte et al. (2019) electric vehicles-focused scenario, the shares of bus technologies were as follows: about 42% of buses were powered by electricity, about 30% of buses were powered by biogas, and the remaining 28% were powered by biodiesel. The values were obtained as percentages of the fuel consumption for person transportation. In the hydrogen scenario, the researchers deduced the following values for the percentage of fuel consumption for bus transportation – about 30% for biogas, about 40% for hydrogen, about 28% for biodiesel, and the remaining 2% for electricity(Skytte et al., 2017).

García et al. (2022) investigated several pathways of achieving the EU CO_2 emission reductions goals in bus transit in a case study of Valencia, Spain. They considered multiple scenarios using the data of the ten most popular bus lines in the city, including vehicle speed information provided by GPS. The scenarios in question included the case of employing 100% hybrid buses, as well as the case of 100% electrified fleet.

Walmsley et al. (2015) studied several ways of reducing GHG emissions caused by the transport sector in New Zealand up to 2050. They considered three different scenarios aimed at achieving the goal of reducing emissions to 1990 level by 2050. Two of those scenarios assume that 40% of the bus fleet will be constituted by hybrid vehicles, while the third scenario assumes that only 20% of the bus fleet will be represented by hybrid vehicles, while the remaining travel demand will be met with oil, coal and biofuels.

Khalili et al. (2019) also looked at the different penetration rates of renewable bus technologies in 2050 and obtained the following values: about 90% of both stock and newly-sold buses were represented by battery electric buses; furthermore, about 3% and 2% were represented by ICEVs for stock and newly-sold buses respectively; and finally, about 7% and 8% were represented by PHEVs for stock and newly-sold buses, respectively.

Another research investigated various scenarios concerning increasing the buses average occupancy rate and introducing more electrically-powered vehicles, and came to the conclusion that in the case of China, the benefits of converting to a vehicle fleet with 50% electric vehicles will surpass the benefits of increasing the buses' occupancy rate (Silva, 2013).

Feedback from stakeholders

Qatar has shown a keen interest in electric buses, with 25% of the Mowasalat fleet being electric in 2022. Stakeholders have also stated that there would be a complete transition in Mowasalat buses to 100% electric by 2023. This Ambition is supported by technological advancements and increasing climate change awareness. Experts predict that by 2050, it is reasonable to assume that 80% of Qatar's entire bus fleet will be electric.

Ambition Levels

Table 5.17 presents different predictions for the share of different types of buses in the bus vehicle technology mix. The "Other" fleet ambition scenarios is based on the stock shares reported by Khalili et al. (2019), where the values in Level 1 are assumed to represent the baseline scenario, where no improvements are made in the future and vehicle fleet of 2050 directly corresponds to the vehicle fleet of 2015. Level 3 corresponds to the authors' predictions for 2050, and Level 2 is halfway between Levels 1 and 3, while Level 4 presents a 100% electric bus share. The Mowasalat bus fleet is currently at 100% electrification and will remain the same across the different Ambition Levels.

Table 5.17: Ambition Levels for the share of electric buses in 2050.

Ambition Levels	1	2	3	4
Share of electric buses in Mowasalat fleet (%)	100	100	100	100
Share of electric buses in Other fleet (%)	10	50	90	100

5.4.12 Buses - vehicle efficiency

Lever description

The vehicle efficiency lever for buses is designed to quantify the bus's energy consumption per vkm. This lever aids in translating vkm per bus type and technology into energy usage per fuel type, including diesel and electricity. Improved vehicle efficiency will thus correspond to decreased energy usage for the same journey distance, articulated in vkm and vehicle technology. This ensures that even with the same amount of bus travel and the same technological makeup, higher vehicle efficiency can lead to energy savings.

Current situation

The public transport sector of road traffic is currently using fossil fuels as the primary source of energy (Schwertner & Weidmann, 2016). However, during the last decade various renewable energy alternatives have been investigated and even successfully implemented. The new technologies include fuel cell electric (FCE) buses, battery electric buses and hybrid electric buses. PHEVs have very different efficiencies, depending on the operation mode – electric or powered by the internal combustion engine. Khalili et al. (2019) calculated the TTW efficiencies of various types of buses and reported an efficiency of 33% for ICE buses in 2015. The TTW efficiency of FCE buses is estimated to be 44% in 2015.

Various scenarios for 2050

Khalili et al. (2019) predict an increase in TTW efficiency for ICE buses from 33% in 2015 to 37% in 2050. The battery electric buses TTW efficiency is expected to reach 90% by 2050. The efficiency of PHEVs operating in the ICE mode is equivalent to the efficiency of ICE buses – 37%, while in the electric mode the TTW efficiency is equivalent to the efficiency of battery electric buses – 90%. The authors also discussed WTT efficiencies of various energy sources, with diesel, gasoline and electricity (including fossil, nuclear and renewable) being the relevant ones for buses. According to a study focusing on land freight, the highest efficiency gain for buses by 2030 would be a 30% decrease in fuel use (Transport & Environment, 2017).

Feedback from stakeholders

In addition to what was mentioned for passenger vehicles and HDVs, buses typically operate in stop-and-go urban conditions, making the transmission system critically important. Advances in automatic and continuously variable transmissions (CVTs) can provide smoother shifts and operate the engine closer to its optimal efficiency point. Thus, experts believe that by 2050, ICE buses can improve their efficiency by 10-20%, while electric buses have the potential to improve by 20-30% which is representative in the range proposed by the different levels of ambition.

Ambition Levels

The predicted TTW efficiencies of various types of buses as modeled by Khalili et al. (2019), are presented below. Level 1 corresponds to 2020 efficiency values, while Level 3 corresponds to 2050 values. Level 2 is the halfway point between Levels 1 and 3, while Level 4 is linearly extrapolated at the end.

Table 5.18: Ambition Levels for bus efficiency improvements in 2050.

Ambition Levels	1	2	3	4
ICEV energy efficiency improvements (%)	0	-6.1	-12.1	-18.2
BEV energy efficiency improvements (%)	0	-9.2	-18.4	-27.6

5.4.13 All vehicles - fuel type

Lever description

The fuel type lever takes different types of fuels such as diesel, gasoline, natural gas as well as electricity and determines how much of each energy vector they contain. It looks at the share and quantity of each type of fuel consumed by road vehicles. This lever examines and differentiates between various fuel sources, including traditional fuels such as diesel or natural gas, and modern energy vectors such as electricity. By doing so, it offers a complete view of the energy composition each fuel type possesses. For example, it would show how much diesel, gasoline, natural gas and electricity are used across all fuels and vehicle types. The fuel type level provides data to evaluate pathways to reduce the carbon intensity of fuels by substituting electricity for natural gas.

Economic activity has been growing faster than energy consumption for some years now due to technological advancements and the initial measures made in the transition to a new energy mix. Furthermore, this pattern appears to be continuing. According to the U.S. Energy Information Administration (EIA), during the next 12 years, global GDP will expand at a 3.1% yearly rate, while primary energy consumption will grow at a 0.9% yearly rate (U.S. Energy Information Administration, 2021). These data depict the predicted increases in energy savings, which will have substantial ramifications in advanced nations because it is precisely in these economies that energy consumption per capita is highest. Thanks to the larger weighting of renewable and natural gas over coal, the new energy mix is projected to be more efficient. The energy used in the extraction process will be reduced, and the negative consequences of pollution are expected to decrease.

Current situation

The types of vehicles considered in this study are passenger vehicles, HDVs, and buses. Currently, all passenger vehicles run on gasoline, while all HDVs run on diesel fuel. However, the bus fleet in Qatar is both electric or conventional which means that some buses operate on electricity, and some operate on diesel. The composition of gasoline and diesel is entirely conventional where

no biofuel or e-fuel is used. Electricity in Qatar is generally 100% produced from LNG, however, in 2022, Qatar announced the opening of its first PV solar farm aiming to supply the country with 10% of its peak electricity demand (TotalEnergies, 2022).

Other countries around the world are using PV as a source of electricity production. For instance, Australia reached a milestone of having 50% of its electricity produced from renewables in 2019 for a brief time. Of the 50%, 32.5% was met by solar energy (23.7% from rooftop solar and 8.8% from large scale solar), while wind and hydro contributed to 15.7% and 1.9% respectively (Readfearn, 2019). Generally, PV is the third largest renewable source of energy after hydropower and wind as it produces 3.6% of global electricity (IEA, 2022c).

Various scenarios for 2050

On a global level, forecasts indicate that by 2024, 33% of electricity will be supplied from renewable energy sources as PV accounts for 60% of its composition (IEA, 2019). A study published by the US Solar Energy Technologies Office (SETO) and the National Renewable Energy Laboratory (NREL) states that with the help of suitable policies, strict cost reductions, and widespread electrification, solar energy could cover 40% of the national electricity needs by 2035, and reach 45% by 2050. In order to achieve this goal, solar energy would require an annual growth rate of 30 GW between the year 2021 until 2025, and then increase to an annual growth of 60 GW between 2025 and 2030. The study indicates that reaching these levels would require the following initiatives (US Department of Energy, 2021):

- Technological improvements and no price increases
- Fast deployment of clean energy
- Developments in storage, transmission, and maintenance
- Availability of land

In their paper, Lawrenz et al. (2018) examines electricity pathways for a low-carbon transition in India by 2050. The authors model three scenarios to represent the different pathways India might follow in order to lower their GHG emissions:

- Limited Emissions Only: describes the path India should take in order to align itself with a 2 °C warming scenario.
- Business As Usual: describes a path where the Indian government commits to the goals and treaties it is part of.
- 100% Renewable Energy Sources: describes a path where the entire electricity is produced from renewable energy.

In the Limited Emissions Only scenario and the Business As Usual scenario, the leading source for electricity generation is solar PV. The power produced from PV is 69% for the Limited Emissions Only scenario and it is 66% for the Business As Usual scenario as fossil fuels are being reduced over time (Lawrenz et al., 2018). In another study, researchers explored pathways for Germany to make its low-carbon transition by 2050. This study also included three different scenarios where each scenarios has its own storyline based on patterns occurring in climate politics. The models include the European Island scenario, the Green Democracy scenario, and the Survival of the Fittest scenario. By 2050, the Survival of the Fittest scenario includes a 95% share of renewable energy, while the other two scenarios use 100% renewable energy to generate electricity. The main generators of electricity in the mentioned scenarios are hydropower, wind and solar PV (Bartholdsen et al., 2019).

Feedback from stakeholders

During the consultation with different stakeholders, it was acknowledged and deemed reasonable to assume that PV solar power would play a role in the energy landscape, with an estimated contribution of 60% of electricity generation by the year 2050. The stakeholders recognized that PV has demonstrated remarkable growth and cost reduction over the past few decades, making it one of the most promising sources of clean and sustainable electricity. This statement comes after Qatar has starting the operation of its first solar PV station in 2022, and with the announcement of new PV station projects expected to be completed between 2030 and 2040.

Multiple factors contributed to stakeholders' confidence in the role of PV solar power in the future energy mix. Firstly, the continuously declining costs of PV technology, driven by economies of scale, technological advancements, and increased production capacity, have rendered solar power increasingly competitive compared to conventional energy sources. This cost-effectiveness, coupled with the abundance of solar energy resources in the region, further solidified stakeholders' belief in the growth potential of PV solar power.

It should be noted that while the assumption of 60% electricity generation from PV solar power by 2050 was deemed reasonable by stakeholders, there are still challenges to address. These include the need for robust infrastructure development, energy storage solutions, grid integration, and overcoming intermittency issues associated with solar power. However, stakeholders expressed confidence in the ongoing technological advancements and the collective efforts to address these challenges.

Ambition Levels

The table below represents the different ambition used for fuel type in the model. The composition for gasoline and diesel will remain the same over the years, which means that no biofuels are used and the environmental footprint remains the same, while on the other hand, electricity production changes. Ambition Level 1 for electricity indicates that 10% of the energy produced will be from solar PV. Qatar currently has the solar capacity to produce electricity which meets 10% of the peak demand. Levels 3 and 4 are used the low-carbon transformation scenarios of India and Germany (Bartholdsen et al., 2019; Lawrenz et al., 2018). Finally, Ambition Level 2 is the halfway point between Levels 1 and 3.

Table 5.19: Ambition Levels for fuel type in 2050.

Ambition Levels	1	2	3	4
Gasoline (% of conventional composition)	100%	100%	100%	100%
Diesel (% of conventional composition)	100%	100%	100%	100%

Electricity (% of solar PV)	10%	39.50%	69%	95%

5.5 Results and discussion

This section presents a detailed analysis of CO2 emissions within Qatar's transportation sector. The results methodically investigate CO2 emissions for LDVs, HDVs, and buses across four different Ambition Levels, each comprising an increasing degree of mitigation effort. The analysis extends beyond mere emission figures as they examine potential emissions avoided due to different factors under Ambition Levels 2, 3, and 4 compared to the baseline 'business-as-usual' scenario of Ambition Level 1. This comparison is crucial in understanding the impact of specific interventions and strategies on emissions reduction in each vehicle category.

Additionally, the section includes an evaluation of LDV emissions both with and without behavioral changes, emphasizing the role of human behavior in emission outcomes. Moreover, it provides insights into the overall progression of emissions by examining the percentage change in emissions by 2050 relative to 2022 values, offering a clear perspective on the advancement or setback in each Ambition Level. These findings calculate the emissions across various vehicle categories and Ambition Levels in order to shed light on the effectiveness of different mitigation strategies. The comparative analysis of emissions, considering both technological changes and behavioral shifts, offers insights that will inform the ensuing discussion on effective pathways for Qatar to achieve its sustainability goals and transition towards a low-carbon future.

CO2-eq emissions from road transport

Figure 5.2 shows the projected CO2-eq emissions from Qatar's road transportation sector for the period 2022 to 2050, incorporating the four distinct Ambition Levels previously outlined. This projection is grounded in the operating emissions framework, focusing exclusively on emissions produced during the vehicle operation phase. The ambit of these levels spans from a business-as-usual scenario to a transformative paradigm, including the adoption of low-emission technologies and practices. Initially, in 2022, all four scenarios (Ambition Levels) begin with an identical emission figure of around 11 Mt CO2-eq yr^{-1}, acting as a baseline for comparative analysis. This uniform, baseline starting point is used as a reference to evaluate the effectiveness and impact of the different Ambition Levels over time.

In the business-as-usual scenario (Ambition Level 1), emissions are constantly on the uptrend, culminating at 17 Mt CO2-eq yr^{-1} by 2050. This trend indicates that emissions will progressively escalate without significant behavioral shifts or technological improvements, driven by increased transportation demand, continued reliance on traditional fuels, and more. Conversely, Ambition Level 2 gradually declines from the baseline over time. Under this scenario, emissions are projected to diminish incrementally, reaching 10.7 Mt CO2-eq yr^{-1} in 2025, 10.5 Mt CO2-eq yr^{-1} in 2030, and 10.3 Mt CO2-eq yr^{-1} by 2035. By 2050, efforts made in Ambition Level 2 will result in CO2-eq yr^{-1} emission levels peaking below 9 Mt CO2-eq.

The advanced ambition scenario (Ambition Level 3) portrays a more optimistic outlook, where emissions demonstrate a consistent decrease, reaching 3.8 Mt CO2-eq yr^{-1} by 2050. This reduction from the baseline demonstrates the potential impact of substantial adoption of low-emission technologies and practices, including a shift to cleaner fuels and improved vehicle efficiency. Finally, the most aggressive scenario, Ambition Level 4, estimates that a dramatic reduction in emissions is possible, culminating in just 1.2 Mt yr^{-1} by 2050. While the Ambition Level 4 scenario does not meet net zero, it indicates a drastic transformation of the transportation sector with highly ambitious policies put in place.

To realize the lower emission scenarios, especially Ambitions Levels 3 and 4, Qatar's transportation policies must rapidly adopt electric vehicles, enhance public transport infrastructure, implement strict fuel efficiency standards, and foster sustainable mobility behaviors among the populace. Additionally, financing renewable energy sources to power electric vehicles and public transportation systems would be pivotal in achieving these ambitious targets.

In conclusion, Figure 5.2 illustrates the potential impact of varying levels of Ambition in behavior and technology adoption on CO2 emissions in Qatar's transportation sector. It stresses the need for concerted technological innovations and societal behavior changes to achieve significant reductions in GHG emissions.

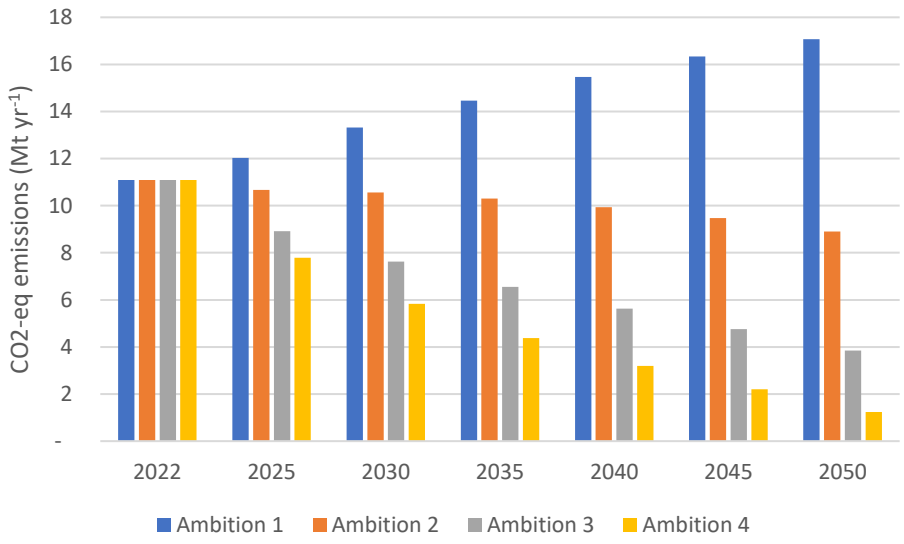

Figure 5.2: Annual CO2-eq emissions from road transport under different Ambition Levels 2022-2050.

CO2-eq emissions from LDVs

Figure 5.3 details CO2-eq emissions from LDVs in Qatar's transportation sector from 2022 to 2050 under various Ambition Levels is shown below. The 2022 baseline emissions for all Ambition Levels in 2022 are 9 Mt CO2-eq yr^{-1}. Under Ambition level 1, representing a continuation of existing practices, there is a progressive increase in emissions, peaking at 12.8 Mt CO2-eq yr^{-1} by 2050. Ambition Level 2, which introduces moderate developments, initially follows a steady decrease, ending at 5.8 Mt yr^{-1} by 2050. In Ambition 3, a more pronounced decline in emissions is evident, with the figure dropping to 1.8 by Mt CO2-eq yr^{-1} 2050. This scenario indicates an accelerated adoption of improved vehicle technologies, a significant increase in the use of electric vehicles, and a broader shift towards more sustainable transport modalities. The most profound impact is seen under Ambition 4, where by 2050, emissions drastically reduce to 0.44 Mt yr^{-1}. This scenario implies a transformative approach, potentially including a near-total shift to electric vehicles, groundbreaking innovation in vehicle technology, and a fundamental alteration in transport behavior.

The figure illustrates that while gradual changes can produce positive results, achieving drastic reductions in emissions requires adopting multiple strategies. A complete approach is needed to achieve the lower emission figures in Ambitions 3 and 4. This would involve not only the promotion of BEVs and the enhancement of public transportation but also the implementation of robust fuel efficiency standards and a cultural shift towards embracing sustainable transportation practices.

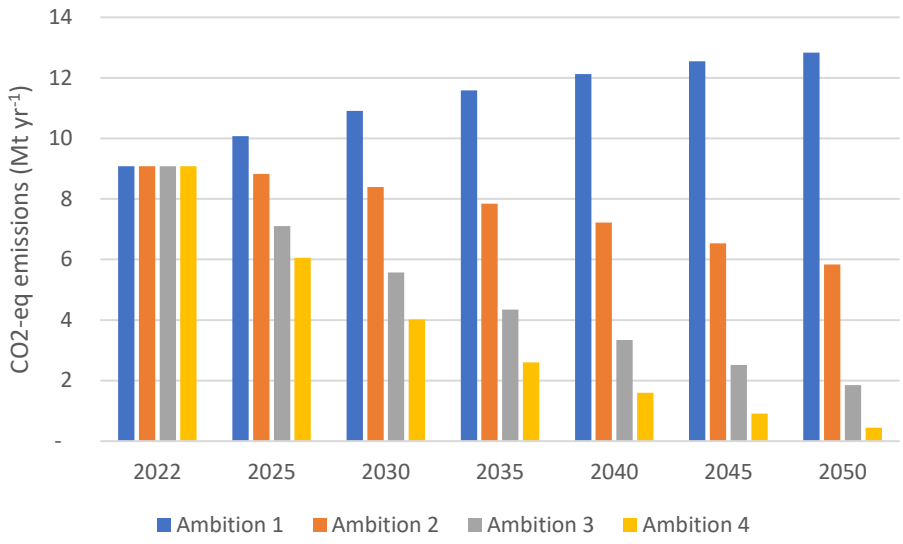

Figure 5.3: Annual CO2-eq emissions from LDVs under different Ambition Levels 2022-2050.

CO2-eq emissions from HDVs

Figure 5.4 summarizes projected CO2 emissions from HDVs in Qatar, spanning from 2022 to 2050, and is categorized into the four different Ambition Levels. In 2022, the emissions from HDVs are all set at 1.9 Mt CO2-eq yr^{-1}, establishing a baseline for the following comparisons and allows for a clear view of the effectiveness of each Ambition Level over the time period.

Under Ambition 1, the emissions from HDVs exhibit an increasing trend, peaking at 3.5 Mt CO2-eq yr^{-1} by 2050. This gradual rise indicates that without alterations in the approach towards HDV emissions, there will be a significant increase, likely influenced by factors such as growth in HDV usage and limited improvements in fuel efficiency or alternative fuel adoption. Ambition Level 2 demonstrates a different trajectory, where emissions initially decrease in 2025 but then rise, reaching 2.5 Mt CO2-eq yr^{-1} by 2050. This scenario includes implementing mild emission reduction strategies, including enhancements in vehicle efficiency, gradual adoption of cleaner fuel options, or modest shifts in HDV operation patterns. The leveling off of emissions in later years hints at a balance between HDV usage growth and these moderate interventions' effectiveness.

Ambition 3 describes a more optimistic outlook, with a consistent decrease in emissions, culminating at 1.6 Mt CO2-eq yr^{-1} by 2050. This decline implies a robust commitment to reducing emissions through more aggressive strategies, such as widespread adoption of low-emission vehicle technologies, substantial shifts towards alternative fuels, or a notable reduction in HDV usage through logistics optimization. The most dramatic change is observed under Ambition 4, where emissions sharply reduce to around 0.6 Mt yr^{-1} by 2050. This ambitious scenario reflects a transformative approach, which could incorporate widespread changes such as near-complete electrification of HDVs (70%) and breakthroughs in emission reduction technologies in different vehicle powertrains.

The varying emissions trajectories across these Ambition Levels illustrate the substantial impact that different policy and technological intervention levels can have on HDV emissions. While incremental changes under Ambition 2 lead to a moderate reduction, the data indicates that

more ambitious measures, as seen in Ambitions 3 and 4, are essential for achieving further reductions in emissions.

The emissions trajectory for HDVs in Qatar underlines the sector's unique challenges. The increasing emissions under Ambition 1 highlight the insufficiency of current practices in curbing emissions growth, necessitating a reevaluation of strategies. The significant emissions reduction observed in Ambitions 3 and 4 reflects the potential effectiveness of aggressive policy measures, such as extensive adoption of low-emission technologies and a shift to alternative fuels. This suggests that to achieve substantial emissions reductions in the HDV sector, Qatar may need to explore more targeted and optimized approaches.

The data indicate that to achieve lower emissions in the HDV sector, a combination of advanced vehicle technologies, cleaner fuel adoption, and optimization of HDV operations is necessary. Policies that support technological innovation, incentivize the use of cleaner fuels, and encourage efficient logistics practices are crucial. Additionally, considering the operational demands and technical complexities of HDVs, tailored strategies specific to this sector are essential.

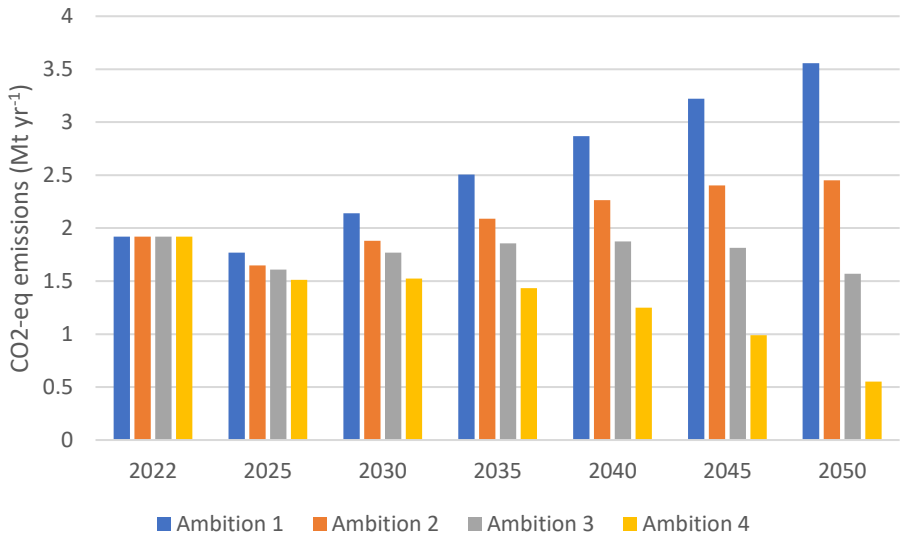

Figure 5.4: Annual CO2-eq emissions from HDVs under different Ambition Levels 2022-2050.

CO2-eq emissions from buses

Figure 5.5 illustrates GHG emissions from buses in Qatar from 2022 to 2050 under the same four Ambition Levels. Notably, Qatar's bus transport incorporates two segments: Mowasalat, the primary transport services provider, and other bus services, including school and privately owned buses. In 2023, Mowasalat's transition to an all-electric bus fleet marked a shift in Qatar's public transportation landscape. It is important to note that this move forms a part of the initiatives included in Ambition Level 1. However, this change was not mirrored across the rest of the bus sector.

Similar to the previous cases, all Ambition Levels start with the exact emissions figure of 91 kt CO2-eq yr^{-1}. This figure includes emissions from both Mowasalat and the other bus categories combined. The first scenario (Ambition Level 1) demonstrates a continuous rise in emissions, reaching 687 kt CO2-eq yr^{-1} by 2050. This trend could indicate that despite Mowasalat's shift to electric buses, the emissions from the entire bus fleet continue to grow. In Ambition Level 2, emissions also increase but at a slightly slower pace, peaking at 618 kt CO2-eq yr^{-1} in 2050. The variation from the first scenario is due to some level of intervention, incremental upgrades in fuel efficiency, and the electrification of 50% of the fleet of buses outside the Mowasalat fleet. Moreover, a more noticeable reduction in emissions is observed in Ambition Levels 3 and 4, where emissions decline to 437 and 245 kt CO2-eq yr^{-1} respectively by 2050. In Ambition Level 4, the entire bus fleet is considered electric and running on electricity generated from PV. This scenario implies that all the CO2-eq emissions associated with the bus fleet would be attributable to the emissions from power stations. This shift displays a strategic change from direct vehicular emissions to a centralized emission source at the power generation stage. It is also important to note that in the case of buses in Qatar, all Ambition Levels have higher emissions in 2050 compared to 2022 values.

The progression of emissions in these Ambition Levels highlights the impact of different levels of intervention in the bus sector on overall CO2 emissions. Mowasalat's transition to an all-electric fleet represents a significant step towards sustainability. However, the actions taken by a single operator, while impactful, are not sufficient to bring about sector-wide emissions reductions. The

results from the different Ambition Levels indicate that broader, more comprehensive strategies are needed to lower emissions from the entire bus sector. These might include expanding electrification efforts to private and school buses, coupled with policies that support cleaner fuel adoption and efficiency improvements. The findings also highlight the need for policies that extend beyond the electrification of public buses. Strategies should include incentives for the adoption of electric buses in the non-Mowasalat fleet, investment in charging infrastructure, and policies promoting clean fuel technologies.

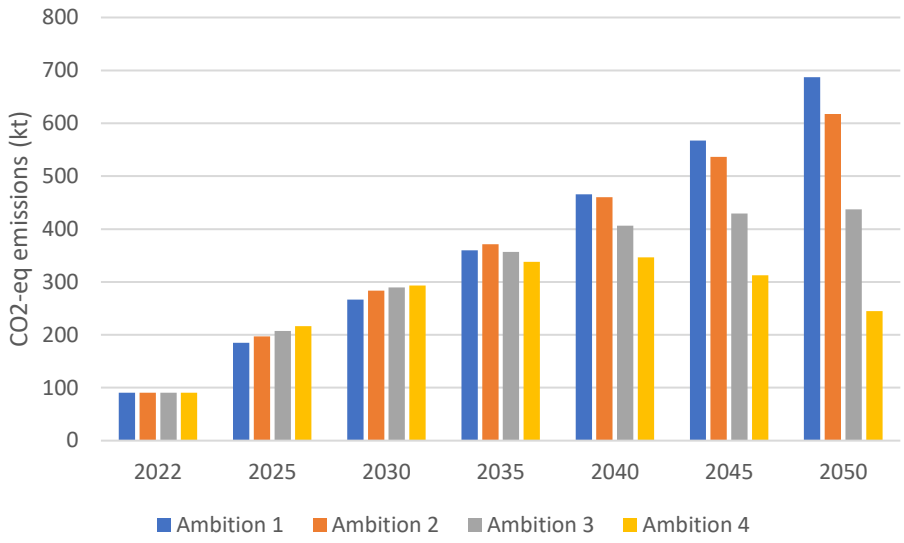

Figure 5.5: Annual CO2-eq emissions from buses under different Ambition Levels 2022-2050.

Avoided CO2-eq emissions for LDVs

Figure 5.6 below quantifies cumulative emissions avoided in Qatar's LDV sector from 2022 to 2050. This figure compares Ambition Levels 2, 3, and 4 against the baseline scenario of Ambition Level 1 in 2050. Each factor (travel demand, mode of transport, occupancy rate, vehicle technology, vehicle efficiency, and fuel type) contributes differently to the overall emissions reduction in each Ambition Level.

In Ambition 2, the cumulative emissions avoided due to travel demand are 0.47 Mt CO2-eq. This figure is lower than the emissions avoided in Ambition 3 (1.79 Mt CO2-eq) and Ambition 4 (2.46 Mt CO2-eq), indicating an increase in the influence of travel demand management in more ambitious scenarios. Similarly, the mode of transport contributes to avoiding 0.76 Mt CO2-eq of emissions in Ambition 2, compared to 1.13 Mt CO2-eq in Ambition 3 and 1.78 Mt CO2-eq in Ambition 4. This pattern indicates that shifting from personal vehicles to more sustainable modes of transport becomes increasingly impactful in higher-ambition scenarios.

The occupancy rate shows the highest emissions avoidance in Ambition 2 at 3.02 Mt CO2-eq, increasing in Ambition 4 to 3.35 Mt CO2-eq. This implies a saturation point where further increasing occupancy rates yields diminishing returns regarding emissions reduction. Transportation system efficiency plateaus beyond a certain occupancy level due to diminishing returns. Increased occupancy initially improves per capita energy use and emissions efficiency, but reaches an optimum. Under Ambition Level 4, this occupancy-efficiency saturation has several explanations. Widespread BEV adoption and vehicle efficiency improvements establish a high baseline operation efficiency, minimizing occupancy impact. Additionally, cleaner fuels shift emissions away from vehicles towards cleaner power generation. Reduced driving frequency from behavioral changes also reduces the emissions improvement from higher occupancy. Together, these trends under Ambition Level 4 clarify why higher occupancy correlates less directly with lower emissions.

Further, advancements in vehicle technology play a vital role across all Ambition Levels. Ambition 2 contributes to avoiding 1.15 Mt CO2-eq of emissions, increasing to 1.52 Mt CO2-eq in Ambition

3 and further to 2.04 Mt CO2-eq in Ambition 4. Also, vehicle efficiency is another critical factor, with 1.44 Mt CO2-eq emissions avoided in Ambition 2, growing to 2.20 Mt CO2-eq in Ambition 3, and reaching 2.52 Mt CO2-eq in Ambition 4. This shows the importance of improving fuel efficiency in reducing emissions, which becomes increasingly more effective in avoiding emissions in higher ambition scenarios.

Lastly, changes in fuel type from natural gas to solar PV for electric powertrains contributes the least emissions avoidance across all Ambition Levels but still show an upward trend. In Ambition 2, the emissions avoided are 0.15 Mt CO2-eq, increasing to 0.22 Mt in Ambition 3 and 0.24 Mt in Ambition 4. This indicates that while shifting to cleaner fuels is beneficial, its impact is relatively smaller compared to other factors.

In analyzing the cumulative avoided CO2-eq emissions for LDVs, the significant role of increased vehicle occupancy, notably through carpooling and shared mobility solutions, is illustrated. This finding opens up a broader discourse on the impact of individual and collective behavioral changes on environmental outcomes. To increase occupancy rates, a multifaced approach including both technological and policy-driven strategies is proposed. In addition to incentivizing ride-sharing apps and implementing dedicated lanes for high-occupancy vehicles, creative strategies could include integrating carpooling with gamification techniques to engage users. For instance, developing a reward system that offers incentives based on the number of carpool trips or the amount of emissions saved could be explored. This combined approach synergizes technological suggestions and behavioral motivations to promote higher vehicle occupancy.

Furthermore, the integration of smart city technologies to optimize traffic flow and improve the efficiency of shared transportation systems could also play a role. The use of real-time data analytics to inform travelers of the most sustainable transport options based on current traffic conditions, weather, and vehicle availability might further reduce unnecessary trips. Additionally, the results from Ambitions 3 and 4 suggest that travel demand management can highly reduce emissions. This could involve more radical policy interventions, such as implementing congestion pricing in urban centers or providing subsidies for electric bike-sharing programs to encourage a

shift away from personal vehicle use. The potential of telecommuting policies, especially in the post-pandemic context, to reduce travel demand should also be considered.

The findings indicate a need for policies that are multi-faceted and adaptive. For instance, integrating urban planning with transportation policy could enhance the effectiveness of carpooling and shared mobility initiatives. Creating 'mobility hubs' where different modes of transport converge (e.g., carpooling, public transit, bike-sharing) could simplify and incentivize the use of sustainable transport options. On the technological front, continued support for research and development in vehicle efficiency and alternative fuel technologies is essential. Policies that encourage the automotive industry to accelerate the development of low-emission vehicles, coupled with incentives for consumers to adopt these technologies, could be impactful. This could include tax rebates for purchasing electric vehicles or subsidies for retrofitting existing vehicles with more efficient engines.

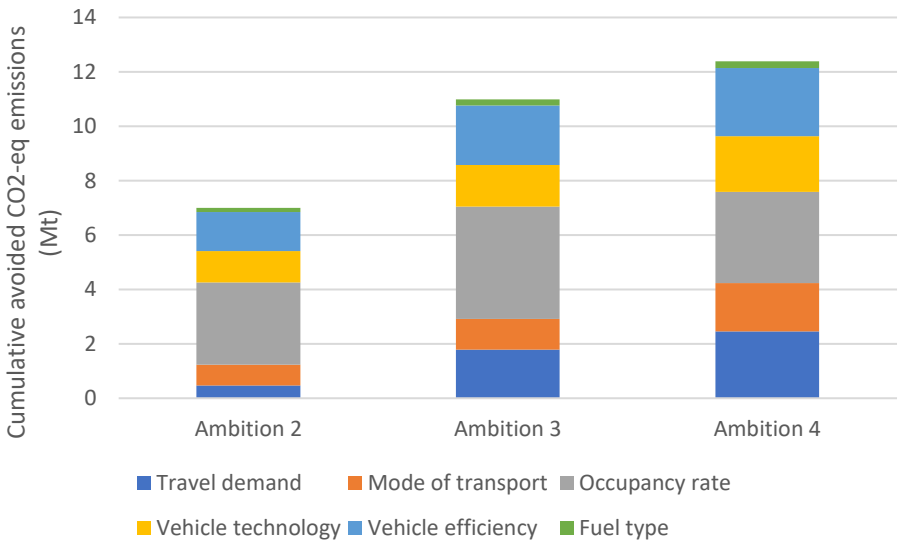

Figure 5.6: Cumulative avoided CO2-eq emissions for LDVs from 2022 to 2050 compared to the baseline scenario of Ambition Level 1.

Avoided CO2-eq emissions for HDVs

The figure below shows the effects of the three Ambition Levels on several aspects related to HDV emissions avoidance in Qatar by 2050. Regarding travel demand, Ambition 2 displays a 0.64 Mt CO2-eq avoidance, which rises to 0.84 Mt CO2-eq in Ambition 3 and then increases somewhat to 0.87 Mt CO2-eq in Ambition 4. While vehicle technology is identified as one of the methods to reduce emissions, its contribution, particularly in the context of HDVs, remains the smallest factor when compared to other measures. This is evident in the progression from Ambition 2 through Ambition 4, where the emission reductions attributable to vehicle technology increase from 0.024 Mt to 0.061 Mt and then to 0.08 Mt, respectively. Despite these increases, the role of technical improvements in HDVs plays a less dominant part in the overall strategy for reducing emissions.

Vehicle efficiency has a more noticeable effect. Emissions averted increased from 0.30 Mt in Ambition 2 to 0.75 Mt in Ambition 3 and jumped to 1.69 Mt in Ambition 4. These figures indicate the importance of improving the fuel economy of HDVs to reduce emissions, particularly in the higher Ambition Levels. Finally, changing the fuel type also contributed to reducing emissions as it begins in Ambition 2 with 0.15 Mt CO2-eq of avoided emissions, rises to 0.34 Mt CO2-eq in Ambition 3, and ultimately reaches 0.42 Mt CO2-eq in Ambition 4. As part of a holistic plan to reduce emissions in the HDV sector, it is crucial to move to cleaner fuels, as this constant growth highlights.

The analysis stresses the potential for significant emissions reduction in Qatar's HDV sector through targeted strategies. Vehicle efficiency improvements, particularly in adopting newer, cleaner engine technologies and aerodynamic enhancements, stand out as the primary driver of emissions reduction. This observation opens up avenues for exploring creative solutions, such as the integration of more efficient powertrains which can provide higher fuel economies. Moreover, managing travel demand through efficient route planning and load optimization presents a critical opportunity for reducing emissions. Innovative ideas, such as the use of AI and big data analytics for real-time route optimization and load balancing, could enhance operational efficiencies. Additionally, policies encouraging off-peak travel can help reduce congestion and

associated emissions, suggesting a need for flexible scheduling and incentivization mechanisms within the logistics industry.

To effectively reduce emissions in the HDV sector, policies should prioritize vehicle efficiency improvements and the management of travel distances. Emphasizing fuel economy, these policies could mandate enhanced fuel efficiency standards for HDVs, ensuring a significant reduction in fuel consumption per mile. Concurrently, measures to reduce travel distances are essential. This could involve optimizing logistical routes and encouraging the consolidation of loads to minimize unnecessary mileage. By focusing on these two critical areas, the policies can achieve a more targeted and impactful approach to emission reduction in the HDV sector.

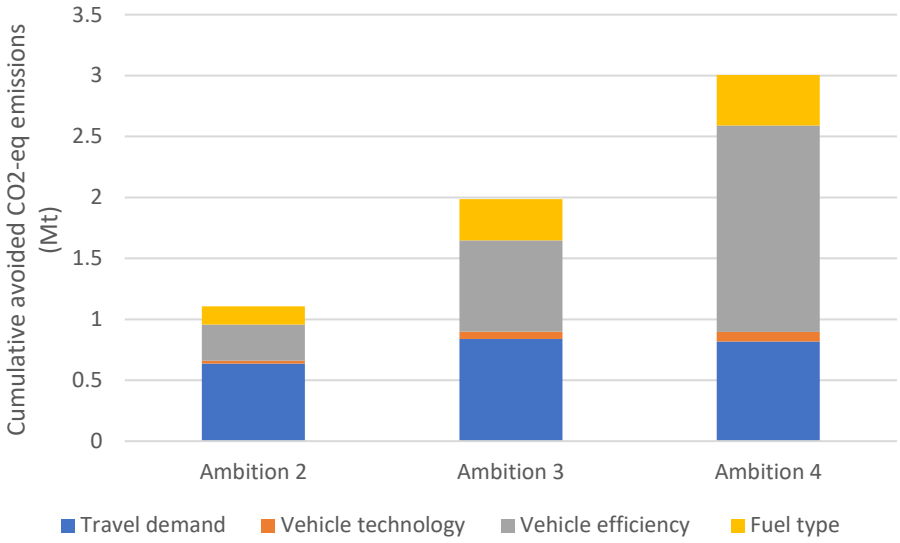

Figure 5.7: Cumulative avoided CO2-eq emissions for HDVs from 2022 to 2050 compared to the baseline scenario of Ambition Level 1.

Avoided CO2-eq emissions for buses

The differences in impacts can be observed after examining the results shown in the figure about emissions reduction in Qatar's bus industry by 2050. The data shows the extent to which changes in travel demand, vehicle technology, vehicle efficiency, and fuel type contribute to reducing emissions compared to a reference scenario (Ambition level 1). In Ambition Level 2, emissions reduction resulting from changes in travel demand is comparatively low, amounting to 0.02 Mt CO2-eq. However, this number experiences a relative spike in Ambition Level 3, reaching 0.07 Mt CO2-eq, and further climbs to 0.20 Mt CO2-eq in Ambition Level 4. These numbers propose that managing travel demand becomes increasingly impactful in more ambitious scenarios, potentially reflecting greater shifts towards public transit use or more efficient routing.

The enhancement of bus technology also reduces emissions, beginning with a total of 0.04 Mt CO2-eq in Ambition Level 2. The surge is particularly noticeable in Ambition Level 3, reaching 0.11 Mt CO2-eq, but exhibits a marginal increase to 0.12 Mt CO2-eq in Ambition Level 4. This trend implies that while technological developments are essential, their ability to reduce emissions is limited at a particular stage. Moreover, the Ambition Levels demonstrate a consistent rise in emissions avoidance due to vehicle efficiency improvements. The avoidance rate increases from 0.03 Mt CO2-eq in Ambition Level 2 to 0.09 Mt CO2-eq in Ambition Level 3 and to 0.13 Mt CO2-eq in Ambition Level 4. This tendency emphasizes the continuous significance of improving fuel economy in buses to decrease emissions. The shift in fuel type has also significantly reduced emissions, resulting in a total of 0.06 Mt CO2-eq of emissions averted at Ambition Level 2. The amount increases rapidly to 0.17 Mt in Ambition Level 3 and 0.23 Mt in Ambition Level 4. These statistics highlight the essential need for shifting towards cleaner fuel options. This is especially pertinent as this scenario demonstrates an all-electric bus fleet charged from electricity generated by 95% PV.

The main finding drawn from this study on emissions avoidance within Qatar's bus sector highlights the necessity for a range of strategies to achieve meaningful emissions reduction. A key aspect is the transition to electric buses, however, to optimize this transition, it is crucial to consider the source of electricity powering buses. Generating electricity from PV sources rather

than traditional natural gas will increase the emissions reduction potential of electric buses. This shift towards cleaner energy sources for electric bus charging infrastructures not only complements the move towards electrification but also ensures a more complete approach to sustainability. The impact of different factors on emissions avoidance for buses are relatively close, indicating the importance of a multifaceted approach. Deploying strategies such as optimizing bus routes using advanced GPS tracking and analytics, implementing demand-responsive transit systems, and enhancing the interconnectivity between different modes of public transport can contribute significantly to emissions reduction.

Reflecting upon the study's findings, which reveal that a multitude of factors, beyond just the electrification of buses, are crucial for emissions reduction, it becomes evident that policy initiatives should extend beyond mere fleet electrification. This includes developing infrastructure like dedicated bus lanes and advanced charging facilities, as well as policies that incentivize the adoption of clean technologies in the private bus sector. Financial incentives, tax rebates, or grants could be offered to private bus operators for upgrading to electric or hybrid models. Further, urban planning policies should also take into account the unique weather conditions. For instance, the integration of shaded or air-conditioned waiting areas at bus stops and the strategic planning of bus routes to minimize exposure to the sun can enhance the appeal of public transport. This can be further supported by regulatory measures that ensure new buses not only meet high environmental and efficiency standards but are also equipped to handle extreme heat.

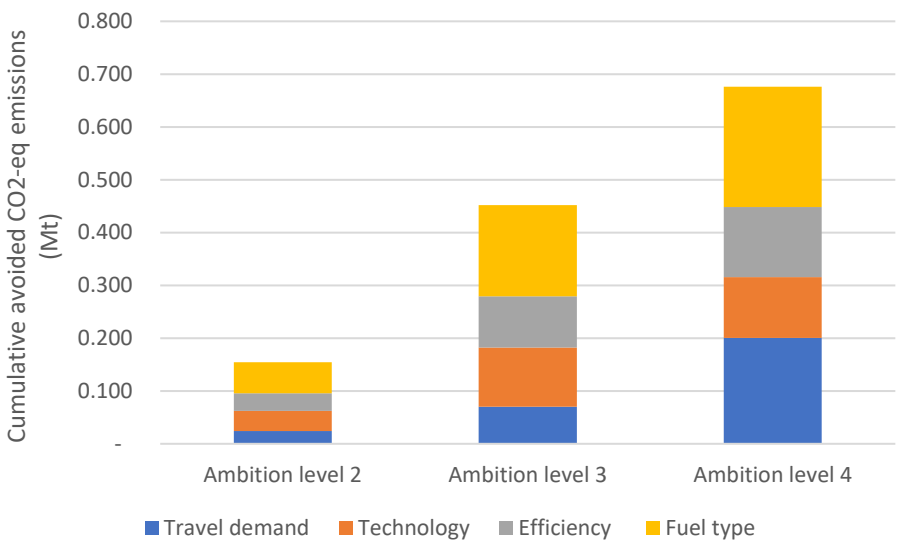

Figure 5.8: Cumulative avoided CO2-eq emissions for buses from 2022 to 2050 compared to the baseline scenario of Ambition Level 1.

Avoided CO2 emissions for road transport

Figure 5.9 summarizes all the avoided emissions from LDVs, HDVs, and buses in Qatar, presenting an aggregated view of the impact of various Ambition Levels on overall emissions reduction by 2050. These figures offer a holistic perspective on the cumulative effect of emissions reduction strategies across different vehicle categories under three distinct Ambition Levels.

In Ambition 2, the cumulative emissions avoided across all vehicle types amount to 8 Mt CO2-eq. This figure reflects the collective impact of reasonable improvements in various factors such as vehicle efficiency, fuel type, and travel demand management. It indicates that significant emissions reductions can be achieved even with mild policy changes and technological progression. The cumulative emissions avoidance increases in Ambition 3, reaching 13 Mt CO2-eq. This jump establishes that more aggressive strategies and interventions across the transportation sector yield a markedly higher impact on emissions reduction. The strategies involve more enhanced technological improvements, greater shifts in travel behavior, and generally more efforts made.

Ambition 4 showcases the most profound level of cumulative emissions avoidance, totaling 16 Mt CO2-eq. This highest figure reflects a transformative approach towards transportation and emissions management. It implies the implementation of highly ambitious and potentially groundbreaking policies and technologies, indicating a holistic shift towards a sustainable and low-carbon transportation sector. The figure highlights the incremental yet significant impact of escalating Ambition Levels on emissions reduction. It shows the magnitude of integrated and ambitious approaches through all vehicle groups to achieve meaningful reductions in CO2-eq emissions.

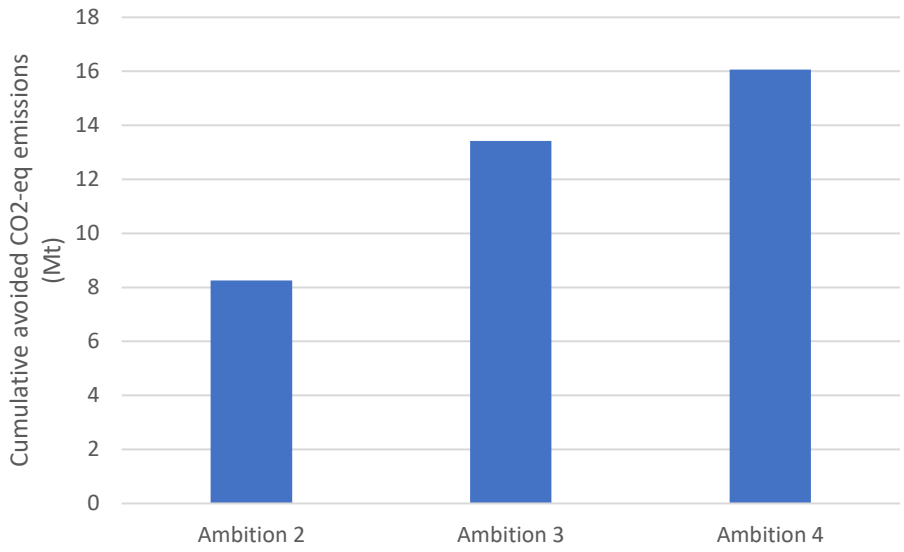

Figure 5.9: Cumulative avoided CO2-eq emissions for road transport from 2022 to 2050 compared to the baseline scenario of Ambition Level 1.

CO2-eq emissions for road transport with and without behavioral changes

The analysis of LDV emissions in Qatar under various Ambition Levels, both with and without incorporating behavioral changes, offers insights into the interplay between technology and behavioral factors in emissions reduction. This analysis is important for framing policies and understanding the potential trajectory of emissions in the context of Qatar's environmental goals. In Ambition 1, serving as the business-as-usual baseline, emissions stand at 12.8 Mt CO2-eq yr^{-1} in 2050, setting the stage for understanding the relative impact of interventions in subsequent scenarios. Ambition 2 showcases a significant impact of behavioral changes. Without these changes, emissions are noted at 9.3 Mt CO2-eq yr^{-1}, but with behavioral modifications, such as increased public transport use, increasing vehicle occupancy rate, and reduced individual vehicle usage, emissions are reduced to 5.8 Mt CO2-eq yr^{-1} which represents a 37.2% decrease. This level of reduction underscores the effectiveness of integrating behavioral strategies with technological improvements.

The trend becomes even more pronounced in Ambition 3, where emissions decrease from 6.0 to 1.8 Mt CO2-eq yr^{-1} in 2050, marking a 69.2% reduction when behavioral changes are factored in. This steep decline demonstrates the synergistic effect of combining advanced technological measures with significant changes in societal transportation habits and preferences. The most dramatic shift is observed in Ambition 4. In this scenario, emissions plummet from 2.4 to 0.44 Mt CO2-eq yr^{-1} – an 81.2% reduction – when behavioral changes are implemented. This decrease reflects not just the role of overarching technological improvements but also the profound impact of widespread and significant changes in both individual and societal transportation behaviors.

With that said, this analysis demonstrates the pivotal role of behavioral changes in amplifying the effectiveness of technological advancements in achieving emissions reduction targets in the LDV sector. The significant reductions seen across the ambition levels, particularly in Ambitions 2, 3, and 4, illustrate that technological solutions, while crucial, reach their full emissions reduction potential only when coupled with behavioral shifts.

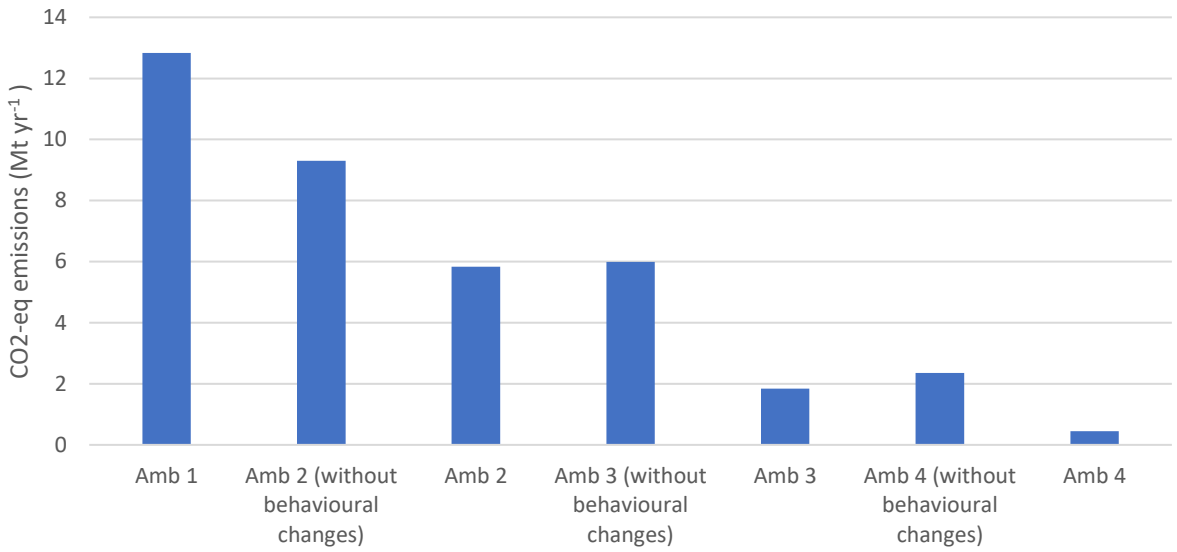

Figure 5.10: CO2-eq emissions with and without behavioural changes in 2050.

Percentage change in emissions in 2050 compared to 2022 values

The graph below shows the projected percentage change in emissions by 2050 compared to 2022 under the four Ambition Levels. These figures are used to understand the long-term impact of different environmental policies and initiatives in Qatar.

In the scenario of Ambition 1, there is an increase of 54% in emissions by 2050 compared to the values in 2022. This rise indicates that continuing current practices without changes or interventions in the transportation sector will lead to a considerable escalation in emissions. Such an increase would likely be driven by factors like growth in the number of vehicles, persisting dependence on fossil fuels, and increasing transportation demand. Conversely, Ambition 2, shows a decrease in emissions by 20% in 2050 compared to 2022.

In addition, Ambition Level 3 demonstrates a more extensive reduction, with emissions decreasing by 65% compared to 2022. This decline reflects the impact of stricter behaviors and technological innovations. Finally, the most significant decline is seen in Ambition 4, with an 89% reduction in emissions by 2050. This decrease proposes a transformative approach toward the transportation sector, involving sweeping technological advancements, major shifts in energy sources, and profound changes in societal transportation patterns.

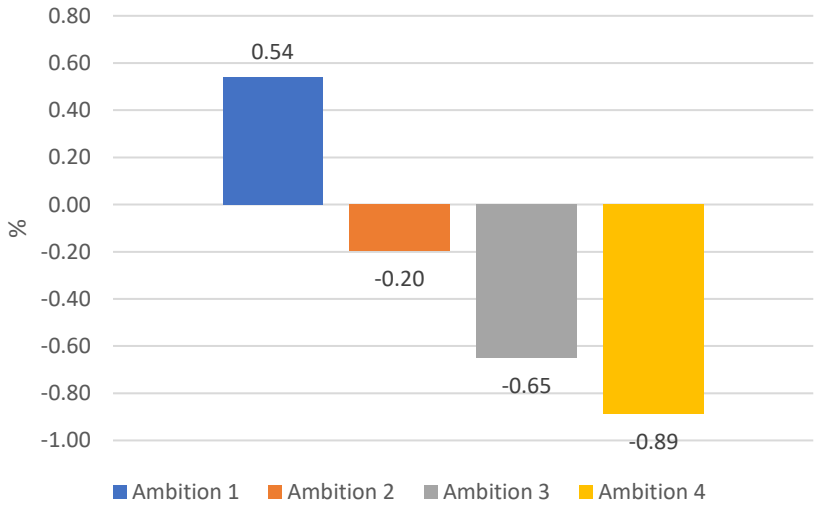

Figure 5.11: Percentage change in emissions in 2050 compared to 2022 values.

5.6 Conclusion

This chapter has explored various emission scenarios in Qatar's transportation sector through the lens of the carbon calculator, and several key insights emerge. The vehicle population is witnessing a sharp rise in Qatar, which will likely lead to increased energy consumption and GHG emissions. Therefore, suitable and practical policy actions are needed to decrease energy use and emissions in the transport sector.

This study uses the carbon calculator for road transport in Qatar to develop constructive pathways to visualize potential carbon emission scenarios at country level by 2050. The research discussed the multiple transportation levers in detail and introduced four different levels of ambition. The investigation presents urban cities and developing regions such as Qatar with a flexible framework for future transportation research and decision making. The analysis, spanning LDVs, HDVs, and buses under four distinct Ambition Levels, provides a nuanced understanding of the potential trajectories for CO2-eq reduction. The study distinctly highlights that achieving high reductions in CO2 emissions across all transportation sectors requires a multifaceted approach. The simulation outcomes demonstrate that every facet of the sector plays a critical role in the overall emissions narrative; there are no ‘silver bullets’.

For LDVs, the analysis indicates that behavioral changes, including a reduction in travel demand, increased occupancy rates, and a transition towards public transportation, have the potential to yield emissions reductions. Depending on the Ambition Level considered, these reductions represent 60.8% to 64.1% of the overall avoided emissions. In the case of HDVs, the data shows the significance of operational efficiencies, including enhanced route planning and optimization. This is complemented by technological advancements, such as adopting cleaner engine technologies and electrification. The study reveals that in Ambition Level 2, behavioral changes account for approximately 57.5% of the emissions avoided. However, for Ambition Levels 3 and 4, the impact of these behavioral changes diminishes, with technological improvements playing an increasingly larger role in emissions reduction. Conversely, the analysis indicates a more balanced impact of different measures on emissions avoidance for buses. The data suggests that

while various levers contribute relatively the same to reducing emissions, there is a slight edge in the effectiveness of changing the fuel type.

While a valuable tool for policymakers, corporate leaders, NGOs, and researchers, the carbon calculator inherently possesses certain constraints due to its design and scope. Developed to clarify complex interrelationships within the transportation system into a more accessible format, the model inevitably simplifies some aspects of these interactions. Future enhancements to the carbon calculator could increase the accuracy of its underlying assumptions and provide more detailed representations. This might include incorporating confidence ranges for projected data, offering a more nuanced understanding of the model's predictions. The inclusion of such improvements would not only refine the tool's utility but also align it more closely with the evolving needs of its diverse user base.

This chapter adds to the scholarly discussion on reducing emissions in the transport sector and provides practical ideas for developing policies that align with Qatar's and the global community's environmental objectives. This highlights the requirement for cooperative, inventive, and comprehensive approaches in planning a sustainable and adaptable future for the transportation industry. Moreover, this analysis presents findings and suggestions aimed at fulfilling Qatar's national objectives of limiting GHG emissions from road transport by the year 2030 and leading a transition towards a sustainable, low-carbon transport system by the year 2050. These findings are helpful for policymakers and stakeholders in Qatar, signaling the necessity for integrated strategies that holistically address both technological innovation and behavior modification to realize a sustainable and low-carbon transportation future.

6 Discussion

6.1 Introduction

This discussion chapter serves as the nexus of this research, synthesizing the findings from the preceding chapters to evaluate the effectiveness of Qatar's current road transport policies in reducing GHG emissions. The primary focus of this research is to assess the potential of these policies to meet Qatar's national emissions reduction target for 2030 and explore strategies to sustain and enhance these reductions through 2050.

The complex nature of decarbonizing the transport sector requires a multifaceted analysis. The thesis has approached this challenge through three distinct but interconnected methodologies: Scenario Analysis for Road Transport, comparative LCA of vehicles, and Carbon Calculator modeling. The discussion integrates these diverse strands of analysis to provide an understanding of Qatar's current position and future potential in reducing transport-related emissions. By bringing together quantitative projections, life cycle impacts, and scenario modeling, this analysis offers a nuanced view of the challenges and opportunities facing Qatar's transport sector. This integrated approach forms the foundation for conclusions and recommendations in the next chapter, providing policymakers and stakeholders with insights to guide future decision-making in Qatar's journey towards a sustainable transportation system.

6.2 Synthesis of Findings

This chapter synthesizes the key findings from Chapters 3, 4, and 5 to provide a comprehensive discussion on Qatar's current emissions from road transport and future projections under different scenarios. This integration offers a nuanced view of the effectiveness of various policies and explores future strategies to enhance emission reductions, addressing both immediate and long-term impacts.

The scenario analysis in Chapter 3 demonstrated the significant impact of different ICEV ban scenarios on CO2-eq, NOx, and PM2.5 emissions. The results emphasized the importance of early policy implementation. For instance, a 2030 ICEV ban scenario showed the most substantial reduction, potentially lowering road CO2-eq emissions to 11.8 Mt yr^{-1} by 2030, which is a 12% reduction from the projected 13.4 Mt yr^{-1} under a BAU scenario. Furthermore, a 2030 ban could lead to a 34% reduction in cumulative CO2-eq emissions by 2050 compared to the BAU scenario, illustrating the long-term benefits of timely policy action. Delayed bans for 2035 and 2040, while still beneficial, provide smaller reductions, highlighting the need for timely implementation. For instance, the 2035 ban scenario would reduce emissions by only 5.5% in 2030 to 12.7 Mt CO2-eq yr^{-1}, while a 2040 ban would result in a 2.4% reduction to 13.1 Mt CO2-eq yr^{-1} in 2030. Looking further ahead, a 2035 ban would decrease emissions to 12 Mt CO2-eq yr^{-1} in 2035, a 17.4% reduction from the anticipated 14.5 Mt yr^{-1}. Similarly, a 2040 ban would lower emissions to 12.2 Mt CO2-eq yr^{-1} in 2040, a 22% drop from the projected 15.6 Mt CO2-eq yr^{-1}. These projections indicate that while the current policies are directionally correct, their effectiveness is highly dependent on the timing of their implementation. Additionally, the ICEV ban scenarios positively impacted air quality by reducing NOx and PM2.5 emissions, although the reductions in these pollutants were less pronounced than those for CO2-eq emissions. The steady decrease in vehicle NOx emissions with increased BEV adoption highlights the potential for air quality improvements over time.

The analysis also explored Qatar's policy to electrify 10% of its road fleet by 2030. Electrifying sedans alone could reduce CO2-eq emissions by 411 kt yr^{-1} in 2030 compared to the no-electrification scenario. Extending this policy to include all LDVs, such as SUVs and sports vehicles,

could lead to an additional reduction of 564 kt yr^{-1} by 2030. These findings demonstrate the effectiveness of targeted electrification policies in reducing emissions. The analysis suggests that electrifying 10% of the road fleet by 2030 is a step in the right direction but may not be sufficient to meet the national 2030 target of 25% emissions reduction. The analysis indicates that more aggressive measures, such as an earlier ICEV ban and higher electrification rates, would be necessary to approach this target. To achieve the 25% emissions reduction target through vehicle electrification by 2030, this study suggested a specific fleet composition. This included around 2,000 BEV buses, 14,000 ICEV HDVs, 90,000 ICEV SUVs, 70,000 ICEV sports vehicles, and 148,000 ICEV sedans.

Moreover, the LCA in Chapter 4 provides context for the findings in Chapters 3 and 5. While the scenario analysis and carbon calculator predominantly focus on operational emissions, the LCA offers a more comprehensive view of the environmental impacts across the entire life cycle of vehicles. This is particularly important when considering the transition to BEVs, as highlighted in both the ICEV ban scenarios and the carbon calculator analysis. In terms of GWP, BEVs demonstrated lower impacts compared to ICEVs. Projections for 2050 show BEV sedans emitting 1.54E-01 kg CO2-eq/km compared to 1.63E-01 kg CO2-eq/km for ICEV sedans. This difference is even more pronounced for SUVs, with BEVs showing almost half the carbon footprint of their ICEV counterparts. However, the LCA revealed more nuanced results regarding air quality and human health impacts. BEVs showed higher emissions of fine particulate matter compared to ICEVs. In 2050, BEV sedans are projected to emit 3.03E-04 kg PM2.5-eq/km, while ICEV sedans are expected to emit 1.29E-04 kg PM2.5-eq/km. BEVs also showed higher potential for ozone formation, impacting both human health and terrestrial ecosystems. In terms of resource scarcity, BEVs performed better regarding fossil resource scarcity but showed higher mineral resource scarcity due to battery production. The temporal dynamics revealed in the LCA indicated that the environmental performance of both BEVs and ICEVs is expected to improve over time due to technological advancements and efficiency improvements, with the relative benefits of BEVs over ICEVs projected to increase as the electricity grid becomes cleaner.

The LCA conducted in this study offers an evaluation of the environmental impacts associated with ICEVs and BEVs in Qatar. This evaluation extends beyond GHG emissions to include various environmental impact categories such as human toxicity, ecotoxicity, particulate matter formation, and resource depletion. The findings indicate that while BEVs exhibit lower GWP, they present higher impacts in categories such as human toxicity and particulate matter formation, primarily due to the materials and processes involved in battery production.

The human carcinogenic toxicity potential for sedan BEVs is projected to slightly decrease over time but remains higher than that of ICEVs, marked at 2.97E-02 kg 1,4-DCB by 2050. Policymakers should be concerned about this level of emissions as part of a broader strategy, but they must balance efforts with other significant environmental and health priorities. Although the difference in carcinogenic emissions may seem marginal, the cumulative health impacts over a large population and extended period could be larger. Tackling this issue would align with long-term public health goals and support a more holistic approach to emissions reduction. Similarly, eco-toxicity measures reflect concerns related to the extraction and processing of metals such as lithium, cobalt, and nickel used in batteries. The production phase of BEVs is particularly impactful due to intensive mining and processing activities required for battery materials, contributing significantly to human and ecotoxicity. Conversely, the operational phase of BEVs, due to zero tailpipe emissions, shows a marked improvement in local air quality and reduced human exposure to harmful pollutants.

This analysis reveals important trade-offs and synergies between different environmental impacts resulting from the adoption of BEVs. The increase in mineral resource scarcity, reflected in the heightened BEV impacts in this category (from 3.56E-03 kg Cu eq per kilometer in 2022 to 3.46E-03 kg Cu eq in 2050 for BEVs), could present a higher risk factor for achieving ICEV replacement targets. Therefore, there is a need for sustainable resource management practices to reduce this risk. These practices could include developing more efficient battery technologies, improving recycling rates of critical minerals, and ensuring environmentally responsible mining practices. Qatar, which relies heavily on imports for vehicles, faces unique challenges in aligning its environmental goals with global supply chains. Since vehicles and their components are

produced abroad, Qatar has limited control over manufacturing processes, which can vary widely in environmental standards. As a result, broader environmental impacts related to BEV production are displaced to manufacturing countries.

This situation demonstrates the importance of international cooperation and supply chain management in aligning vehicle manufacturers' environmental standards with Qatar's sustainability objectives. To optimize the benefits of transitioning to a more sustainable transport system, Qatar should prioritize adopting BEVs while addressing associated ecological challenges. This involves enhancing local infrastructure, public awareness, establishing import regulations favoring vehicles with lower lifecycle environmental impacts, negotiating agreements with exporting countries to improve manufacturing practices, and encouraging manufacturers to adopt greener technologies and materials. By engaging in these strategies, Qatar can mitigate negative impacts related to mineral resource depletion, human toxicity, and terrestrial acidification.

While reducing CO2-eq emissions is a vital goal in mitigating climate change, this study highlights the value of adopting a transportation policy approach that considers a broader range of environmental and health impacts. The LCA results reveal that focusing solely on GHG emissions may overlook other environmental and health concerns. Therefore, policymakers and stakeholders in Qatar's transportation sector must consider a set of environmental and health indicators when developing and implementing sustainable transport strategies. This approach not only leads to more robust policy-making but also ensures that decisions are based on a holistic understanding of the impacts. By adopting this balanced perspective, Qatar can work towards a sustainable transportation system that not only reduces GHG emissions but also minimizes negative impacts on human health and the broader environment, while simultaneously strengthening the resilience and effectiveness of its transportation policies.

The LCA findings demonstrate the complexity of impacts associated with the transition to electric vehicles. While BEVs offer advantages in reducing GHG emissions and potentially improving local air quality due to zero tailpipe emissions, they also pose challenges in terms of human toxicity, ecotoxicity, and mineral resource depletion. Future policies and research in Qatar should adopt

the multi-criteria decision-making approach suggested in this study, focusing on promoting BEV adoption while implementing holistic strategies to mitigate adverse impacts. This could include innovations in vehicle design, battery technology, and responsible material sourcing. Enhancing international cooperation and sustainable supply chain management will be crucial in aligning global environmental standards with Qatar's sustainability objectives. By pursuing these multifaceted efforts, Qatar can work towards a truly sustainable transportation system that optimizes across various environmental and health indicators, as recommended by this study.

In addition to local emissions, transboundary pollutants also contribute to making air pollution a critical public health issue in Qatar. Local emissions from the transport sector contribute to air quality challenges, with NOx and PM2.5 emissions posing direct health risks. The problem is compounded by transboundary pollution from neighboring countries, where industrial activities, petrochemical operations, and dust storms contribute to the regional movement of pollutants, exacerbating respiratory and cardiovascular health issues, especially in densely populated urban areas.

Qatar’s geographical location and atmospheric conditions make it especially vulnerable to pollutants carried across borders. Seasonal wind patterns transport fine PM from industrial sources in nearby countries, adding to local pollution. This highlights the necessity of addressing air quality issues both at the local and regional levels. Even with Qatar’s efforts to reduce local emissions, transboundary pollution remains a challenge, making regional cooperation essential to improving air quality.

ICEVs emit large amounts of NOx and PM2.5, and their proximity to human populations in densely populated areas amplifies health risks. The proximity of transport emissions to densely populated areas further exacerbate public health risks. Urban transport corridors bring emissions close to where people live and work, intensifying the public's exposure to PM.

The results of this thesis, which emphasize the role of transport emissions in contributing to PM, have significant public health implications. These emissions, when combined with transboundary pollution, increase the exposure of urban populations to harmful pollutants, particularly in

densely populated areas like Doha. The thesis demonstrates that reducing transport emissions through policies such as ICEV bans could mitigate some health risks, but additional efforts are needed to address non-exhaust emissions and transboundary pollution.

To mitigate the public health impacts of transport emissions, Qatar could implement low-emission zones (LEZs) in urban centers. Such zones would restrict high-polluting vehicles and encourage cleaner alternatives like BEVs and hybrid vehicles, reducing public exposure to harmful pollutants. Additionally, electrifying public transport, particularly buses and taxis, would reduce NOx and PM2.5 emissions in high-traffic areas. Moreover, Qatar could further enhance urban planning and transport policies to shield its population from the compounded effects of local and transboundary pollution. Introducing green buffer zones around major transport corridors and industrial areas, as well as increasing urban vegetation, would help filter pollutants and improve air quality. Investing in technologies that minimize PM impacts, such as dust suppression systems and advanced street cleaning technologies, would also mitigate the health risks associated with both local and regional pollution.

Moreover, the Carbon Calculator analysis in Chapter 5 provided insights into various emissions scenarios under different levels of climate mitigation ambition. Under the BAU scenario (Ambition Level 1), transport sector emissions were projected to reach 17 Mt CO2-eq yr^{-1} by 2050. In contrast, Ambition Level 2, incorporating moderate measures, showed a reduction to 8.91 Mt CO2-eq yr^{-1}, representing a 47.8% decrease from the baseline. Ambition Level 3, with more aggressive strategies, projected a 77.4% reduction to 3.85 Mt CO2-eq yr^{-1}. The most dramatic decrease was observed in Ambition Level 4, representing a transformative approach, which showed emissions dropping to 1.24 Mt CO2-eq yr^{-1}, an 85.2% reduction from the baseline.

The analysis across vehicle categories revealed that LDVs had the highest potential for emissions reduction across all Ambition Levels. HDVs demonstrated potential for emissions reduction through improved efficiency and electrification, while buses showed varied results with electrification playing an important role in emissions reduction. A crucial finding from this analysis was the impact of behavioral changes such as reducing travel activity, changing mode of transport, and increasing vehicle occupancy rates on emissions reduction. For LDVs, behavioral

changes accounted for 60.8% to 64.1% of overall avoided emissions, depending on the Ambition Level. This finding highlights that while technological improvements are vital, combining these with behavioral changes leads to more significant emissions reductions.

On the other hand, for scenarios where behavioral changes are minimal or absent, CCS can potentially represent a technological pathway for achieving emissions reductions. In such scenarios, CCS could play a role by capturing emissions at the point of origin—whether from fuel combustion in vehicles or from power generation that supports BEVs. By integrating CCS into power generation (where fossil fuels are still in use), it could offset the emissions that behavioral changes would have reduced.

Similarly, renewable energy can potentially be important in reducing emissions in scenarios that do not rely on behavior-driven reductions. The adoption of renewable energy sources such as solar and wind for powering BEVs can mitigate emissions. Even in the absence of behavioral shifts, the transition to renewable-powered electrification could reduce the emissions from LDVs, HDVs, and buses, particularly as Qatar continues to expand its solar capacity. Renewables, when integrated into the energy mix, could address emissions from vehicles powered by electricity. The more the energy grid shifts towards renewable energy, the more effective the no-behavioral-change scenarios would become in meeting emissions reduction goals.

Thus, while behavioral changes significantly amplify the effectiveness of emissions reduction strategies, CCS and renewables offer pathways to achieving reductions in no-behavior-change scenarios. They provide a technological safety net, allowing for progress even in contexts where societal and individual behavior changes are limited. Incorporating a brief discussion on these technologies reinforces the holistic approach to achieving Qatar's GHG emissions reduction goals.

The scenario analysis in Chapter 3 and the carbon calculator analysis in Chapter 5 both show the importance of early and decisive action in reducing emissions. The 2030 ICEV ban scenario from Chapter 3 aligns closely with the more ambitious levels (3 and 4) in the carbon calculator analysis, both projecting considerable emissions reductions. This correlation reinforces the potential

effectiveness of stringent policy measures in achieving Qatar's emissions reduction targets. A holistic approach that addresses both vehicle technology and the electricity grid's decarbonization is necessary. A tailored strategy for different vehicle categories (LDVs, HDVs, and buses) is required, as detailed in the carbon calculator analysis, providing insights into the most effective measures for each sector.

The LCA findings from Chapter 4 support the push for electrification but caution against viewing it as a panacea. The lower GWP of BEVs aligns with Qatar's emissions reduction goals, but the higher impacts in other categories such as particulate matter emissions and mineral resource scarcity suggest that a transition to BEVs should be accompanied by efforts to mitigate these other environmental impacts. This understanding is essential when interpreting the emissions reduction potentials presented in Chapters 3 and 5, as it highlights the need for a holistic approach to environmental impact assessment in policy-making. Chapter 5's Carbon Calculator analysis further demonstrates the importance of an approach that combines technological advancements with behavioral changes.

Qatar's wealth also influences its adoption of BEVs and its journey towards reducing harmful emissions. As a country with financial resources, Qatar is well-positioned to invest in the necessary infrastructure, incentives, and technologies to accelerate the transition to electrified mobility. For example, Qatar's wealth enables investment in BEV charging infrastructure, which is important for supporting BEV adoption. The country can afford to build a widespread and accessible network of charging stations, alleviating one of the primary concerns potential BEV buyers have regarding range anxiety. The country's small geographic size and urban concentration could facilitate the deployment of charging infrastructure and make BEVs a more practical option for many consumers. Moreover, the application of financial incentives, such as subsidies for BEV purchases, tax exemptions, and rebates for installing home charging stations, are generally more feasible in wealthier economies.

However, while wealth could facilitate the transition to BEVs, reliance on fossil fuel revenues poses a strategic challenge. Qatar's efforts to diversify its economy may influence the pace and emphasis of its transition to electrified transport, as the country balances its traditional energy

sectors with new, sustainable initiatives. Also, affluence can affect consumer behaviour, with a potential preference for luxury or high-performance vehicles, which may limit the market for BEVs if available models do not meet these preferences. However, the increasing availability of high-performance and luxury BEVs could mitigate this concern.

In general, the driving performance of BEVs, especially in terms of torque and acceleration at low speeds, are commonly regarded as superior to those of ICEVs. This attribute may be desirable among car enthusiasts. The performance advantages of BEVs can effectively alter public opinion and cultivate a stronger acceptance and interest for them. If effectively managed, this change in perspective can serve as a potential driver for the transition to BEVs. Emphasising these advantages in marketing techniques and consumer involvement could speed up the acceptance of BEVs.

On another note, the successful implementation of the ICEV ban requires an approach that considers the integration of the electricity grid, charging infrastructure, and production capacity. According to Kahramaa, the country's electricity grid should be able to handle the increased stress caused by the ICEV ban and the widespread adoption of BEVs (Kahramaa, 2021). This assessment suggests that the risk of bottlenecks or saturation points in the sustainable transition is relatively low, increasing the likelihood of the policy's effectiveness in reducing emissions.

Despite the potential benefits, transitioning to BEVs poses challenges, making it unlikely to achieve the target ahead of schedule. Factors such as developing renewable energy capacity within a constrained timeframe and meeting the rising demand for vehicles could prove to be substantial barriers to early adoption. The case study of Qatar is particularly relevant, as it sheds light on the challenges faced by countries heavily dependent on fossil fuels for electricity generation. The dominance of natural gas in Qatar's energy mix directly impacts the environmental benefits of BEVs, as the emissions associated with charging these vehicles are tied to the carbon intensity of the electricity grid. This study emphasizes the need for an approach to decarbonization, recognizing that the success of BEV adoption in reducing emissions is intrinsically linked to the transformation of the energy sector towards cleaner sources. As Qatar and other nations with similar energy landscapes navigate the path to sustainable transportation,

the insights from this study can inform policy decisions and highlight the importance of integrating renewable energy sources to maximize the environmental benefits of BEV adoption. Policymakers must carefully consider these challenges and develop a comprehensive strategy to overcome them while capitalizing on the environmental benefits of electrified mobility.

6.3 Conclusion

This research shows that Qatar's current road transport policies are an important step in the right direction but require further enhancement and timely implementation to meet the 2030 targets and sustain emissions reductions through 2050. The analysis reveals several key notions: early and decisive action is crucial as implementing stringent measures sooner, such as ICEV bans and aggressive electrification targets, yields significantly greater emissions reductions. A holistic approach is necessary; while vehicle electrification is important, it must be accompanied by grid decarbonization and efforts to mitigate other environmental impacts associated with BEVs. Behavioral changes are as important as technological advancements, with encouraging sustainable transportation behaviors leading to substantial emissions reductions across all vehicle categories. Tailored strategies for different vehicle types are needed, as LDVs, HDVs, and buses each present unique challenges and opportunities for emissions reduction. Continuous policy review and adjustment is essential, given the rapid pace of technological change in the transport sector.

Looking forward, Qatar should focus on developing an integrated strategy that combines early policy interventions, technological advancements, and initiatives to promote behavioral changes. This approach should include accelerating the transition to BEVs while simultaneously decarbonizing the electricity grid, and implementing an ICEV ban by 2030 or 2035, supported by policies to facilitate the transition. Additionally, Qatar should develop environmental impact management strategies, launch initiatives to promote sustainable transportation behaviors, create sector-specific strategies for LDVs, HDVs, and buses, and establish a framework for regular policy review and adjustment. This research highlights the need for a balanced and nuanced policy environment that addresses both immediate and long-term objectives, ensuring that Qatar can effectively reduce GHG emissions and transition to a sustainable future.

By adopting this comprehensive approach, Qatar can not only meet its 2030 emissions reduction targets but also ensure sustained reductions through 2050. This strategy aligns with the nation's broader vision for environmental sustainability and economic growth, positioning Qatar as a leader in sustainable transportation in the region.

7 Conclusions

This thesis embarked on a journey to evaluate the effectiveness of Qatar's road transport policies in reducing GHG emissions to meet the national target for 2030 and to explore potential strategies that can sustain and enhance these reductions through 2050. The research addressed three key aspects of this overarching question. Firstly, the research evaluated the impacts of Qatar's current road transport policies on reducing CO2-eq emissions, including an in-depth analysis of various internal combustion engine vehicle ban scenarios planned for 2030, 2035, and 2040, and their projected influence on CO2-eq emissions. These scenarios were used to understand the future trajectory of road transport emissions under different policy implementations. They highlight the effectiveness of timely early policy interventions in achieving Qatar's decarbonization goals, with earlier implementation leading to more substantial emissions reductions.

Additionally, the Scenario Analysis Chapter probed two distinct aspects of Qatar's road transport policy. The first aspect examined the specific impact of Qatar's policy to electrify 10% of its road fleet by 2030. The study also explored what fleet configuration of Battery Electric Vehicles would achieve the national goal of reducing 25% of road transport-based greenhouse Gas emissions by 2030. This aspect of the research was instrumental in gauging the overall efficacy of Qatar's emissions reduction strategy within the broader framework of decarbonizing the road transport sector. It provided insights into how different elements of road transport policy work towards achieving Qatar's greenhouse gas reduction targets and leads to the conclusion that the current 10% electrification goal, while positive, falls short of the 25% emissions reduction target.

Secondly, the thesis included a time-dynamic Life Cycle Assessment from cradle to grave, comparing the environmental impacts of battery electric vehicles and internal combustion engine vehicles operating in Qatar. This comparison helped elucidate the implications of adopting different vehicle technologies in Qatar. The results show that battery electric vehicles demonstrate lower Global Warming Potential, with 2050 battery electric vehicle sedans projected to emit 154g CO2-eq/km compared to 163g CO2-eq/km for internal combustion engine

vehicle sedans. This difference is even more pronounced for SUVs, where battery electric vehicles show almost half the carbon footprint of their internal combustion engine vehicles counterparts. In addition, for internal combustion engine vehicles, emissions are almost entirely produced at the exhaust, directly impacting local air quality. In contrast, most emissions associated with battery electric vehicles occur at the point of electricity production, which offers greater potential for future reductions through grid decarbonization. These findings show the importance of considering both the quantity of CO2-eq emissions and its location in policy decisions, as the transition to battery electric vehicles presents opportunities for centralized emission control and overall environmental improvement.

However, when considering air quality and human health impacts, the results are more nuanced. Battery electric vehicles show higher emissions of fine particulate matter 2.5 and higher potential for ozone formation compared to internal combustion engine vehicles. This impacts both human health and terrestrial ecosystems. Regarding resource scarcity, battery electric vehicles perform better in terms of fossil resource scarcity. These findings show the importance of addressing the entire life cycle of vehicles when assessing their environmental and health impacts.

Finally, employing the carbon calculator method, the research evaluated the potential impact of various measures and initiatives on the CO2-eq emissions reduction potential of Qatar's road transport by 2050. This analysis provided insights into the long-term strategies that could effectively steer Qatar toward its goal of a sustainable, low-carbon transport system. In this analysis, Ambition Level 1 serves as the baseline which assumes current practices continue without further mitigation efforts. On the other hand, Ambition Level 2 sees emission reductions with moderate measures. More aggressive strategies under Ambition Levels 3 and 4 result in even greater cuts. These findings show the importance of ambitious policies for achieving more emissions reductions and support a sustainable transition to low-carbon transport.

Throughout this research, various data sources, analytical tools, and theoretical perspectives were employed to evaluate the effectiveness of Qatar's transport policies in reducing GHG emissions. The findings of this study not only shed light on the current state of affairs but also offer insights into potential strategies that could improve emissions reductions through 2050. As

this thesis concludes, it is imperative to reflect on the key insights gleaned, their implications for future policy-making, and the emergent avenues for ongoing research in this vital domain. This conclusion section provides key recommendations based on the findings, a discussion of the limitations of the study, and suggestions for future research directions to build upon this work and reduce the uncertainty associated with the recommendations.

7.1 Recommendations

The upcoming recommendations section is divided into three parts, each based on the results and analyses arising from this thesis. This section is crafted following an analysis of CO2-eq emissions in Qatar's road transport sector. It aims to provide specific and nuanced strategies for the efficient and material reduction of emissions from light duty vehicles, heavy duty vehicles, and buses. These recommendations provide a clear approach to the identification of effective mitigation policies in the transport sector, aligning with Qatar's commitment to a sustainable and environmentally responsible future.

7.1.1 Scenario Analysis for Road Transport

A suite of recommendations designed to expedite Qatar's progression towards a sustainable and low-carbon transport ecosystem is provided. It highlights pathways through which these recommendations can contribute to materially reducing harmful climate and air quality emissions within Qatar's road transport sector, aligning with the nation's targeted goals to balance economic growth with environmental stewardship.

Accelerate the Transition to Electrified Mobility

A strategic phase-out of internal combustion engine vehicles is central to reducing CO2-eq emissions within Qatar's road transport sector. Projections have shown the environmental benefits of instituting internal combustion engine vehicle bans by 2030, 2035, and 2040. An analysis of these timelines indicates that a 2030 ban could yield the most emissions reductions, positioning it as the most effective target date for mitigating climate impact. A comparison of implementing internal combustion engine vehicle bans in the three alternative target years identified above, reveals a progressive reduction in emissions, with the 2030 timeline naturally offering the most aggressive curtailment, followed by 2035 and 2040, respectively.

To support this transition, a legal framework should be developed to progressively reduce and eventually prohibit the sale of new internal combustion engine vehicles by the designated year. This framework could include a gradually declining cap on internal combustion engine vehicle sales, with clearly defined yearly targets to provide a transparent trajectory towards the ultimate goal. Additionally, it would serve as a signal to consumers and manufacturers alike to begin the shift towards electric vehicles, thereby fostering an environment that encourages investment in battery electric vehicle technology and infrastructure. In tandem with phasing out internal combustion engine vehicles, it is crucial to make electricity production less carbon-intensive to maximize the environmental benefits of electrified mobility. Transitioning to renewable energy sources and improving energy efficiency for electricity generation will ensure that battery electric vehicles operate on a cleaner energy grid, further reducing overall greenhouse gas emissions.

Moreover, a multifaceted approach should be adopted to manage the transition, addressing potential economic and social impacts. This could involve retraining programs for automotive industry workers, trade-in schemes to support the replacement of internal combustion engine vehicles with electric vehicles, and educational campaigns to inform the public about the benefits and practicalities of electric mobility. This transition will not only reduce greenhouse gas emissions but also improve air quality by reducing pollutants such as nitrogen oxides and particulate matter, which are closely associated with internal combustion engine vehicles. Enhanced air quality can lead to better public health outcomes and contribute to environmental sustainability in urban areas. These tangible benefits to public health and quality of life are important in promoting public acceptance and backing the shift to battery electric vehicles. This increased public support might potentially accelerate the rate of adoption and policy implementation.

This timeline offers a clear comparative advantage over the later dates. While the 2035 and 2040 timelines provide additional preparation time, they do not match the emissions reduction potential demonstrated by the 2030 target. By initiating the earlier ban, Qatar can capitalize on the reduction of emissions sooner, contributing to a cumulative positive environmental impact over time. To achieve this, a policy package is required. It should foster consumer readiness and market receptivity, ensuring that the automotive sector's evolution is both economically viable and environmentally sound. It is through these strategic directives that Qatar can affirm its commitment to sustainable transport and realize its vision for a reduced-carbon future.

Establish battery electric vehicle mandates for government fleet

Further, government fleets utilized by various ministries and agencies should adhere to a battery electric vehicle mandate. Initiating with the replacement of non-essential light duty vehicles with electric alternatives, the mandate would progressively expand to encompass heavy duty vehicles, mandating that all new procurements prioritize electric models. Such a move by government agencies would serve as an example, illustrating the practicality and environmental benefits of battery electric vehicles in everyday use. For effective implementation, an approach involving baseline assessments to inventory existing vehicles, strategic infrastructure planning for

necessary charging facilities, and the development of incentive programs to support the transition is required.

Furthermore, fostering public-private partnerships could leverage private sector innovation and investment, enhancing the efficiency and scalability of electric public transport solutions. Capacity building efforts, including training programs for vehicle maintenance, charging station operation, and fleet management, are also vital to ensure a skilled workforce is ready to support this transition.

Fleet renewal programs

Based on the findings of this study, a potential strategy for accelerating battery electric vehicle adoption in Qatar could focus on sectors with high vehicle usage and rapid turnover rates. One creative approach worth exploring is the implementation of fleet renewal programs aimed at incentivizing commercial fleets to adopt battery electric vehicles. Such programs could offer financial incentives, like tax credits, low-interest loans, or grants, to businesses committing to replace their internal combustion engine vehicles with electric alternatives. While the effectiveness of this approach in Qatar's specific context would require further research, it presents an intriguing possibility for lowering financial barriers to battery electric vehicle adoption and demonstrating governmental support for sustainable transportation solutions.

Recognizing the diversity within commercial fleets, it's crucial to tailor these fleet renewal programs to the specific needs and circumstances of different sectors. Factors such as the age of the current fleet, the average mileage of vehicles, and the specific operational requirements of businesses should be taken into account. For instance, a relatively new fleet with a high turnover rate might benefit more from direct purchase incentives, while an older fleet might require additional support for charging infrastructure development. Moreover, the design of these programs should consider the total cost of ownership of battery electric vehicles, which can be lower than internal combustion engine vehicles over their lifetime due to reduced fuel and maintenance costs. Providing businesses with clear, accessible information about the total cost

of ownership savings associated with battery electric vehicles can help overcome initial hesitations related to the higher upfront costs of electric vehicles.

To ensure the effectiveness of fleet renewal programs, collaboration with vehicle manufacturers, financial institutions, and energy providers is key. This would help in aligning the incentives with the market availability of suitable battery electric vehicle models, ensuring that financing options are attractive and accessible, and that the necessary charging infrastructure can be developed in tandem with the growing battery electric vehicle fleet. Implementing fleet renewal programs requires a phased approach, starting with pilot projects in sectors most amenable to electrification, such as delivery services, taxis, and public transport fleets. Success in these sectors can provide valuable insights and serve as a model for broader implementation across the commercial transport ecosystem.

In summary, fleet renewal programs represent a possible strategic intervention to accelerate the transition to electric mobility within the commercial sector. By providing targeted financial incentives and taking into account the specific needs of different fleet types, these programs can contribute to reducing transportation-related emissions.

Strengthen Supporting Infrastructure

The transition to battery electric vehicles necessitates a parallel advancement in infrastructure to ensure the shift is seamless, sustainable and has societal support. Central to this infrastructure development is the expansion of the battery electric vehicle charging network. A strategic deployment plan should ensure that charging stations are evenly distributed and readily accessible, mitigating the concern of range anxiety among potential battery electric vehicle adopters. This network should be capable of supporting the expected increase in battery electric vehicle usage, with high-density urban areas and key transport corridors prioritized for station placement.

In tandem with the charging network, modernizing the power grid is essential to handle the increased demand from battery electric vehicles. Investments should be channeled towards enhancing grid capacity and stability, as well as integrating renewable energy sources. This

modernization should be carefully planned to prevent grid overloads, particularly during peak charging times, and to ensure that the environmental benefits of battery electric vehicles are not compromised by increased fossil fuel consumption in electricity generation. Moreover, if or when renewables are used, thorough research is needed to accommodate the increase in intermittent energy supplies from renewables, ensuring the grid can effectively manage and utilize this additional capacity.

Additionally, the government should consider establishing policies that encourage the construction of new buildings with battery electric vehicle charging capabilities and the retrofitting of existing structures. This would embed battery electric vehicle charging infrastructure into the fabric of urban development, making it a standard feature of parking facilities. Collectively, these infrastructural enhancements will provide the backbone for Qatar's transition to an electrified transport system, supporting the country's broader environmental goals and reinforcing the reliability and appeal of battery electric vehicles as a practical alternative to internal combustion engine vehicles.

Strengthen Regulatory Frameworks

In concert with the proposed internal combustion engine vehicle ban policies, the introduction and enforcement of rigorous emissions standards for all new vehicles is needed to ensure overall emission reductions. This measure is not merely complementary but integral to the phased internal combustion engine vehicle ban, establishing a regulatory environment that promotes the adoption of cleaner technologies and paves the way for a gradual reduction in the carbon footprint of the transport sector. The standards set should be progressive, becoming increasingly stringent over time, and should apply to a broad spectrum of vehicle emissions, including but not limited to CO2-eq, nitrogen oxides, and particulate matter. These regulations would not only encourage the development and sale of low-emission vehicles but also incentivize advancements in fuel efficiency and alternative fuel technologies.

By synchronizing emissions standards with internal combustion engine vehicle ban timelines, Qatar can ensure a dual-front approach to emissions reduction. For instance, as the 2030

deadline for the internal combustion engine vehicle ban approaches, emissions standards can be tightened to hasten the transition away from high-emission vehicles. This approach allows for a smooth transition by gradually preparing the market for the impending shift, rather than causing a sudden disruption. Moreover, stringent emissions standards would have the added benefit of influencing the entire vehicle lifecycle. They would drive improvements in manufacturing processes, operational efficiency, and even end-of-life vehicle disposal. Such standards would not only mitigate the immediate environmental impact of transportation but also contribute to long-term sustainability goals.

To support these standards, a robust monitoring and compliance framework must be established in parallel with the ban legislation. This framework would include periodic vehicle inspections, certification processes for new vehicles, and penalties for non-compliance. It would also facilitate data collection for ongoing policy evaluation and refinement, ensuring that Qatar's emissions standards remain at the forefront of environmental stewardship. Through such regulatory measures, the nation can achieve a harmonious balance between its economic aspirations and its environmental commitments.

7.1.2 Life Cycle Assessment

The segment of the recommendations section addresses the outcomes derived from the life cycle assessment study. Insights gained from this study inform a series of suggestions aimed at reducing environmental impacts.

Lifecycle Vehicle Policies

Based on the results of this chapter, promoting the adoption of battery electric vehicles emerges as a key recommendation for reducing greenhouse gas emissions in Qatar's road transport sector. The impact assessments reveal that battery electric vehicles consistently exhibit lower GWP compared to internal combustion engine vehicles across various vehicle categories, including sedans, sports vehicles, SUVs, heavy duty vehicles, and buses, over the forecast period from 2022 to 2050. This advantage is particularly pronounced for larger vehicles. Specifically, battery electric vehicles show a progressive decrease in CO2-eq emissions, highlighting their potential to contribute to Qatar's greenhouse gas emission reduction targets. Additionally, the assessments of fossil resource scarcity underscore battery electric vehicles' role in mitigating the dependency on oil, aligning with broader environmental sustainability goals.

However, a balanced approach must address both climate mitigation and human health/air quality aspects. While battery electric vehicles demonstrate improvements in fine particulate matter formation, especially for larger vehicles, contributing to better air quality, they also show higher human carcinogenic and non-carcinogenic toxicity impacts due to battery production. This highlights the importance of considering the entire lifecycle environmental impact of vehicles for effective policy formulation.

To maximize environmental benefits while minimizing potential negative impacts, Qatar should implement a phased transition to battery electric vehicles, prioritizing larger vehicles for maximum climate impact. This transition should be supported by policies that encourage battery electric vehicle adoption, such as financial incentives, infrastructural development for charging facilities, and public awareness campaigns. Simultaneously, investments in renewable energy

sources could further reduce the carbon footprint of battery electric vehicles and improve overall air quality.

Policies should not only incentivize the adoption of vehicles with lower operational emissions but also support the development and adoption of technologies and practices that minimize environmental impacts across the entire vehicle lifecycle. This includes encouraging research and development of more sustainable battery technologies to help reduce mineral resource scarcity and toxicity impacts, promoting recycling and second-life applications for vehicle components, and considering the environmental implications of vehicle disposal.

During the transition period, implementing stringent emission standards for internal combustion engine vehicles would help minimize adverse air quality impacts. By carefully balancing these factors and addressing the varied impacts observed across different life stages of both internal combustion engine vehicles and battery electric vehicles, Qatar can work towards achieving its environmental greenhouse gas reduction goals while safeguarding public health.

Target Specific Vehicle Categories for Emission Reductions

The analysis of environmental impacts across various vehicle categories highlights the need for targeted emission reduction strategies in Qatar's road transport sector. Results suggest that certain vehicle types, particularly SUVs, heavy duty vehicles, and buses exhibit higher environmental impacts in terms of global warming potential, resource scarcity, and toxicity measures compared to sedans and sports vehicles. This differentiation points towards the potential for more significant emission reductions by focusing policy measures on these specific categories. For example, SUVs, known for their larger size and generally less fuel-efficient characteristics, contribute disproportionately to CO2 emissions. Moreover, these larger vehicles also have more significant direct air quality impacts, such as higher emissions of particulate matter and nitrogen oxides, which can have substantial implications for human health. Similarly, heavy duty vehicles and buses, integral to commercial transport and public transit systems, represent key areas where improvements in fuel efficiency, adoption of cleaner technologies, or a shift towards electric alternatives could yield substantial environmental benefits. Therefore,

implementing stricter emission standards and efficiency requirements for new SUVs and heavy duty vehicles, alongside incentives for transitioning to electric buses within public transportation fleets, could be highly effective. Such measures would contribute to reducing greenhouse gas emissions and also address other environmental impacts, including air quality and resource depletion. Tailoring policies to address the specific challenges and opportunities presented by different vehicle categories will enable more efficient and effective reductions in the transport sector's overall environmental footprint.

Balancing Climate, Health, and Ecological Goals

Given the complex interplay of environmental and health impacts associated with different transport options, policymakers in Qatar should adopt a multi-criteria decision-making approach when evaluating and implementing transport policies. Such an approach should weigh climate change mitigation alongside other crucial factors such as human health impacts, ecological consequences, and resource sustainability. This multi-faceted evaluation could be implemented through tools such as multi-criteria decision analysis or Life Cycle Sustainability Assessment. By employing such comprehensive assessment methods, Qatar can develop a more robust and sustainable transport strategy that optimizes across various environmental and health objectives.

Building on the findings of this study, it is crucial that future research in Qatar's transport sector aims to optimize across multiple environmental and health objectives, rather than focusing solely on greenhouse gas reductions. Future research should develop more comprehensive models that can simultaneously assess and optimize for various environmental and health outcomes, including greenhouse gas emissions, air quality, human toxicity, ecosystem health, and resource depletion. This could involve integrated assessment models that combine climate projections with air quality modeling and health impact assessments. Additionally, future studies should explore potential synergies and trade-offs between different environmental and health objectives in the context of Qatar's specific geographical, economic, and social conditions.

On the policy front, decision-makers should work towards creating a regulatory framework that incentivizes holistic improvements across multiple environmental and health dimensions. This might include developing a composite sustainability index for vehicles that accounts for their full life-cycle impacts or implementing policies that simultaneously target reductions in both greenhouse gases and other air pollutants. By broadening the scope of both research and policy development, Qatar can work towards a truly sustainable transport system that not only contributes to global climate goals but also enhances local environmental quality and public health.

Continuous Monitoring and Adaptation of Policies

The evolving nature of vehicle technologies and their environmental impacts necessitates an attentive approach to policy development and implementation. Continuous monitoring and adaptation of policies are important to ensure that Qatar's road transport strategies remain effective in reducing greenhouse gas emissions and other environmental impacts. This approach involves establishing a robust framework for tracking the performance of vehicles across different categories over time, taking into account advancements in vehicle technologies, changes in energy sources, and shifts in user behavior. Such a framework should include regular assessment of emissions data, environmental impact studies, and the effectiveness of current policies in achieving their intended outcomes. By analyzing this data, policymakers can identify trends, assess the efficacy of existing measures, and pinpoint areas where adjustments or new initiatives may be required. For example, if certain vehicle categories show slower progress in emission reductions, targeted interventions can be designed. Similarly, as new technologies emerge, such as advancements in battery efficiency or alternative fuels, policies can be updated to incorporate these developments. Engaging stakeholders, including vehicle manufacturers, energy providers, and the public, in a continuous dialogue can help ensure that policies are aligned with technological capabilities and societal needs. This adaptive policy approach allows for the iterative refinement of strategies, ensuring that Qatar's road transport policies remain aligned with environmental objectives and are resilient to future changes.

Encourage research and development

In addition, the results from the tables highlight areas within the automotive sector where further research and development (R&D) could enhance the environmental sustainability of vehicles. Given the variability and uncertainty in the environmental impacts of both internal combustion engine vehicles and battery electric vehicles—particularly concerning human toxicity, ecotoxicity, and resource scarcity—targeted R&D efforts can help guide more effective policies and technological innovations. These efforts should focus on improving battery technology to reduce reliance on scarce minerals and decrease toxicity, enhancing the recyclability of vehicle components, and developing more efficient powertrains for internal combustion engine vehicles. Also, exploring alternative fuels and advanced materials for vehicle construction could lead to reductions in lifecycle emissions and resource use. By fostering collaborations between government, academia, and the private sector, Qatar can stimulate innovation in sustainable transport solutions. This collaborative approach could include funding for research projects, creation of innovation hubs, and incentives for companies that develop and implement green technologies. Moreover, it ensures that the nation's policies and infrastructure investments are supported by a foundation of scientific research and technological innovation, enabling a more informed and effective response to the challenges of reducing transport emissions.

Enhance Public Awareness and Education

Raising public awareness about the benefits and practicalities of battery electric vehicles will accelerate their adoption and help overcome barriers such as range anxiety and the perception of high initial purchase costs. In the context of Qatar, where electricity tariffs are notably low, emphasizing the cost-effectiveness of battery electric vehicles in operation relative to internal combustion engine vehicles could influence consumer attitudes. Additionally, the transition to battery electric vehicles enhances the surrounding urban air quality by eliminating vehicle exhaust emissions. Furthermore, battery electric vehicles contribute to a quieter urban environment by minimizing noise pollution, a non-trivial benefit given the increasing global concern over noise pollution in densely populated areas.

7.1.3 Carbon Calculator

In this section, a range of strategic recommendations are provided aimed at catalyzing Qatar's advancement toward an environmentally sustainable and carbon-efficient transportation framework. The mechanisms through which the implementation of these strategies could facilitate the nation's commitment to curbing harmful emissions, thereby contributing to the global of combating climate change, are highlighted.

Promote behavioral changes

To effectively reduce CO2 emissions in Qatar's light duty vehicle sector, a recommendation is to promote behavioral changes among the populace. The results from the research underscore the importance of incorporating behavioral change outcomes if a significant reduction in CO2-eq emissions is to be achieved, especially for light duty vehicles. Encouraging the use of public transportation and carpooling emerges as a critical strategy. For instance, the implementation of policies that incentivize carpooling can significantly reduce the number of single-occupancy vehicles on the road. This could be achieved through measures such as enforcing congestion charges for single-occupancy vehicles or establishing high-occupancy vehicle lanes. Additionally, bolstering the public transport infrastructure to make it more accessible and convenient can lead to a shift from personal vehicle use to public transit. Such a shift not only contributes to emissions reduction but also alleviates traffic congestion and improves urban air quality. However, the arid hot weather of Qatar will have to included in the overall planning.

These behavioral changes are further supported by data from Ambition Level 2, where emissions decrease by 37.2% (from 9.3 to 5.8 Mt CO2-eq yr^{-1}) with the inclusion of behavioral changes. This trend continues in Ambition Level 3, demonstrating a 69.2% reduction in emissions (from around 6 to 1.8 Mt CO2-eq yr^{-1}). These figures illustrate the impact that changing travel habits and transportation preferences can have on reducing CO2-eq emissions in the light duty vehicle sector. Therefore, implementing policies and initiatives that encourage and facilitate these behavioral changes is essential for Qatar to achieve emission reductions in the road transportation sector.

In Qatar's hot and arid climate, the comfort and convenience of public transport users, especially those utilizing buses, are important. One approach to enhance the user experience and encourage the use of public buses is the installation of air-conditioned waiting rooms at bus stops or the strategic placement of bus stops near buildings and areas that provide shelter from the heat and sun. This initiative would be particularly beneficial during the sweltering summer months, where temperatures can soar to extreme levels, making waiting for buses in open, unshaded areas uncomfortable and potentially hazardous. Air-conditioned waiting areas would not only offer relief from the heat but also make public bus transport a more attractive option, potentially increasing ridership. The locating of bus stops near existing structures like general stores, offices, or public buildings where people can wait comfortably would be a practical solution that utilizes existing infrastructure.

The Doha Metro, with its relatively low ticket prices of around $0.55 per trip, suggests that the primary goal of the metro system is not to generate substantial profit but to facilitate transportation and alleviate traffic congestion. This opens up an opportunity for the government to further encourage metro usage by reducing barriers to access. One strategy could be to make the metro service even more affordable, or potentially free, to increase ridership.

Making the metro free for users could boost its appeal and usage, particularly in densely populated urban areas where traffic congestion is an issue. This approach aligns with the broader objective of promoting public transport as a sustainable alternative to personal vehicles. The financial implications of offering free metro services are likely to be manageable, given that the current revenue from ticket sales is not a major income source for the state (based on the current low metro ridership). Furthermore, the long-term environmental and social benefits of increased metro use, such as reduced road traffic, lower emissions, and improved air quality, could outweigh the immediate financial costs.

Improve vehicle efficiency

To effectively harness the potential of vehicle efficiency in reducing CO2-eq emissions for light duty vehicles in Qatar, a multi-faceted approach is essential. The data indicates improving vehicle

efficiency is the second highest category for avoided CO2-eq emissions, as evidenced by the potential avoidance of 2.5 Mt CO2-eq yr^{-1} emissions under Ambition Level 4. To capitalize on this, it is crucial to enforce rigorous fuel efficiency standards for light duty vehicles. In parallel, financial incentives for consumers to purchase high-efficiency or electric vehicles can encourage people. Providing tax rebates, lowering registration fees, or offering subsidies could make efficient vehicles an attractive and economically viable option, thereby encouraging a shift in consumer preferences.

Advancing vehicle efficiency in heavy duty vehicles is a critical recommendation for reducing CO2 emissions in Qatar's transportation sector. The analysis of emission scenarios reveals that improvements in vehicle efficiency in heavy duty vehicles present the most significant potential for emissions reduction, particularly under higher ambition levels. For example, in Ambition Level 4, focusing on vehicle efficiency leads to an emissions avoidance of approximately 1.70 Mt CO2-eq, the highest among the factors analyzed for heavy duty vehicles. In Ambition Level 3, the focus on vehicle efficiency results in an avoidance of 0.75 Mt CO2-eq, which is also significant. These figures highlight the increasing importance of vehicle efficiency improvements as the Ambition Levels rise.

It is important to recognize that heavy duty vehicles are not manufactured in Qatar; instead, they are imported from other countries. This situation means that Qatar does not have direct control over vehicle development and technological advancements in heavy duty vehicles. However, the nation can exert influence through regulatory measures and market incentives. By implementing stringent fuel efficiency standards and providing incentives for importing cleaner, more efficient heavy duty vehicles, Qatar can drive demand for vehicles that meet higher environmental standards. Moreover, Qatar can also play a role in supporting research and development in heavy duty vehicle technologies through international collaborations. The country can partner with global manufacturers and technology developers to influence and contribute to the development of next-generation heavy duty vehicles that are both efficient and environmentally friendly.

The emphasis on vehicle efficiency in heavy duty vehicles, as demonstrated by the emissions reductions at higher ambition levels, aligns with the broader goal of transitioning to a more

sustainable and low-carbon transportation system in Qatar. By prioritizing advancements in heavy duty vehicle efficiency, strides can be made in reducing the road transportation sector's overall emissions footprint.

Accelerate electrification of buses

Accelerating the electrification of buses is another recommendation for reducing CO2 emissions in Qatar's transportation sector. The analysis shows that transitioning to electric buses, especially under higher ambition levels, has a large impact on emissions reduction. Given Qatar's hot climate, the electrification of buses should also consider the efficiency and resilience of electric buses under extreme temperature conditions. This involves ensuring that the electric buses are equipped with robust cooling systems and battery technology optimized for high temperatures. Furthermore, similar to light duty vehicles and heavy duty vehicles, Qatar does not manufacture buses domestically and relies on imports, thus, there is an opportunity to influence the market through policy and procurement strategies. By setting high environmental standards for public transportation vehicles and offering incentives for the import and use of electric buses, Qatar can drive the demand for cleaner, more sustainable public transport options. Moreover, investing in the necessary infrastructure for electric buses, such as charging stations and maintenance facilities, is also essential. These should ideally be powered by renewable energy sources, aligning with Qatar's broader sustainability goals.

Encourage adoption of renewable energy sources

Encouraging the adoption of renewable energy sources is a pre-condition for the meaningful reduction of CO2-eq emissions in Qatar's road transport sector. Given Qatar's high solar energy potential, as well as the current established efforts, focusing on Photovoltaic (PV) systems specifically emerges as a particularly promising strategy. To leverage this renewable energy source effectively, policies could be implemented to support the installation of solar PV panels at transportation infrastructure sites, such as metro and bus stations, as well as at electric vehicle charging stations. This would not only ensure a cleaner energy supply for these facilities but also set a precedent for integrating renewable energy into public transport systems more broadly.

Moreover, incentivizing the private sector to invest in renewable energy technologies can accelerate this transition. Financial incentives, tax rebates, or subsidies for companies that incorporate solar power into their operations, particularly in the road transport sector, can stimulate a shift towards cleaner energy sources. This approach can be complemented by awareness campaigns to stakeholders that highlight the environmental and economic benefits of renewable energy, fostering a culture of sustainability and eco-consciousness among the public and private entities alike.

7.2 Limitations

The research undertaken in this thesis presents useful insights into the current and future implications of Qatar's road transport policies. However, it is important to acknowledge the limits of this analysis. The constraints arise from several sources, such as the fundamental assumptions that form the basis of the study, the methods used, and the accessibility and level of detail of the data. To ensure an understanding of the study's scope and the context of its findings, it is important to discuss these limitations systematically. The general limitations that affect the study's overall conclusions and the specific constraints associated with each of the three results chapters is explored.

One of the general limitations of this study stems from the technological assumptions regarding the evolution of battery electric vehicles and battery technologies. These assumptions are based on current trends and projections, which inherently carry a degree of uncertainty about the pace and direction of future technological advancements. Rapid breakthroughs in battery electric vehicle efficiency, battery storage capacity, or charging technology could accelerate the adoption of electric mobility. Conversely, unforeseen challenges or slower-than-expected progress in these areas could hinder the transition to electrified transport, affecting Qatar's ability to meet its emissions reduction targets. Qatar faces risks associated with BEV technological developments occurring beyond its influence, primarily due to its reliance on imported vehicles. This displays the importance of continuously monitoring technological developments and remaining flexible in policy planning to accommodate and leverage new innovations as they emerge. It also highlights the need for supportive policies that foster research and development in clean vehicle technologies, ensuring that the transition to a low-carbon transport sector is both feasible and aligned with global technological advancements.

Another limitation of the current model is its lack of consideration for the economic aspects of the transition to electrified mobility. Specifically, the model does not incorporate techno-economic indicators that could provide insights into the cost-effectiveness, financial sustainability, and economic impact of electrification. Such indicators are aid in understanding the broader implications of the transition, including investment requirements, potential cost

savings over time, and the economic viability of scaling up EV infrastructure and technologies. While Qatar's relative wealth may render it less sensitive to the immediate economic pressures of such a transition compared to less affluent nations, the inclusion of economic considerations remains important in order to get the full scope of policy impacts. Future research could therefore benefit from integrating techno-economic analyses to complement environmental impact assessments, offering a more comprehensive view of the transition's feasibility, optimizing resource allocation for maximum benefit, and enabling learning-by-doing for effective course correction as needed.

The primary focus of this thesis on battery electric vehicles and its implications for the whole electricity system results in the exclusion of hydrogen fuel cell electric vehicles from the model. Incorporating fuel cell electric vehicles would increase the model's complexity and application scope, introducing assumptions about hydrogen fuel that increase uncertainty (Howarth & Jacobson, 2021). According to Staffell et al. (2019), fuel cell electric vehicles are expected to play an important part in road transportation in the near future, but this has not occurred yet. Battery electric vehicles dominate fuel cell electric vehicles by a factor of almost 300 to 1 in 2021 (IEA, 2022b). In the future, studies could raise significant questions about the number and adoption rate of fuel cell electric vehicles. Hydrogen production methods with differing environmental impacts could also be examined in future research.

In the same manner as fuel cell electric vehicles, synthetic fuel types and alternate fuel types compatible with internal combustion engine vehicles were excluded from this study. The uncertainty regarding the large-scale availability of these fuels to meet decarbonization targets makes it challenging to plan for a diverse mix of alternative fuels and vehicles. This exclusion highlights an important area for future research, identified by this work, to explore the feasibility and scalability of these alternative fuel options. An additional factor to take into account is the anticipated influence of synthetic fuels on emissions of air pollutants (Transport & Environment, 2017). Currently, Qatar does not utilize any synthetic fuel types or alternate fuel types in its road transport sector. Given the absence of these fuel types in Qatar's current road transport

landscape, their exclusion from the study is justified to maintain the analysis's relevance and applicability to the country's specific context.

The study's scope does not account for the nuances of driving habits and conditions that influence vehicle fuel economy and, consequently, emissions. Variations in driving behavior, such as aggressive acceleration, speed fluctuations, and frequent braking, as well as external conditions including road type, and traffic congestion can affect a vehicle's fuel efficiency. Incorporating these factors into the analysis would enhance the precision of emissions estimates, providing a more detailed and accurate depiction of the potential impact of policy changes on the environment. However, comprehensive and reliable data on driving habits and conditions were unattainable at the time of this research, presenting a challenge to integrating these variables into the study. The lack of such data demonstrates a gap in current research and shows an area for future investigation that could refine the understanding of emissions from road transport.

The study's findings are contingent upon the current policy and regulatory landscape, which presents another layer of complexity and uncertainty. The dynamic nature of policy and regulation means that future changes, whether in the form of new environmental mandates, adjustments to existing laws, or shifts in international climate agreements, could influence the trajectory and outcomes of Qatar's emissions reduction strategies. For instance, more stringent global emissions standards or enhanced international collaboration on climate change could provide additional impetus for Qatar to accelerate its transition to electrified mobility. On the other hand, relaxation of regulations or shifts in policy focus could slow progress.

7.2.1 Scenario Analysis for Road Trasport

The study acknowledges the limitations inherent in the Vehicle Stock Mode particularly its reliance on current technological and economic trends as well as the environmental, fuel and energy characteristics. Further innovation in vehicle technology and the energy sector introduces a degree of uncertainty in the model's projections. Additionally, the study boundary for greenhouse gases is limited to scope 1 and scope 2 emissions, which primarily account for direct

emissions from fuel combustion in vehicles and emissions associated with electricity generation for charging battery electric vehicles. Future research could broaden the scope to include the full fuel supply chains, incorporating scope 3 emissions related to the extraction, processing, and transportation of fossil fuels and the upstream emissions associated with natural gas production. Therefore, future research could aim to incorporate more granular data on consumer behavior, repeat this type of model calculations for different geographies or represent different degrees of technological advancements to refine this study's accuracy. While this study focuses on Qatar, the insights can provide broader applicability. The Middle East, with its unique socio-economic landscape and environmental conditions, has often been omitted from comparable studies yet is part of the countries seeking to navigate the complex terrain of sustainable transportation.

The findings regarding air pollutants in Chapter 3 do not account for the geographical distribution of vehicle usage and the resultant emissions. This omission does not allow for a focus on policies aimed at reducing vehicle kilometers travelled in specific areas, such as establishing zero-emission zones or promoting active transportation in a specific geographical location.

In the model, the vehicle kilometers travelled for battery electric vehicles is assumed to be the same as for internal combustion engine vehicles, although current evidence to support this assumption is insufficient. The vehicle kilometers travelled rates for buses, heavy duty vehicles, and motorcycles have been set considering a broad spectrum of distribution, with an emphasis on the need for accurate, real-world kilometer driven data. As such data for heavy duty vehicles and motorcycles in Qatar are not publicly available, these vehicles should be prioritized for data collection.

Another limitation of this study is the exclusion of Aftermarket Emission Control Device failure over time. This factor could potentially become impactful, particularly after 2035, as these devices might emerge as a predominant source of nitrogen oxide emissions in aging vehicle fleets. Current estimates suggest failure rates between 1.2% and 3.3% for light duty vehicles (Y. Chen & Borken-Kleefeld, 2016). However, this study employs a Tier 2 methodology, which does not account for this degradation, unlike the EMEP/EEA's speed-dependent Tier 3 methodology for calculating degradation rates (Ntziachristos & Samaras, 2019). Consequently, the potential

increase in emissions as vehicles age due to this factor is not captured in our current analysis. This limitation presents an opportunity for more detailed analysis in future research.

For light duty vehicles, which utilize similar technology and undergo type approval testing, their nitrogen oxide emissions are likely comparable across different registration years. Similarly, non-exhaust emissions for light duty vehicles may also show resemblance between registration years due to similarities in vehicle size and curb mass. An underestimation of uncertainty in model outputs could result from assuming parameters are independent, whereas in reality, some parameters are interrelated.

For well-established parameters like nitrogen oxide emissions, relationships between various parameters can be determined using vehicle samples from the fleet. However, non-exhaust emissions currently have a high level of uncertainty, making it difficult to assess such relationships. Future vehicle stock models may thus be able to handle the relationships and effects of various variables for certain inputs used in this chapter.

7.2.2 Life Cycle Assessment

Pragmatic data collection within the framework of the life cycle assessment aims to streamline the gathering of environmental impact data across the production chain. This approach is often necessary due to the extensive scope of life cycle assessment studies, which require data from various stages of a product's life cycle, from raw material extraction through manufacturing, use, and disposal. However, while pragmatic data collection facilitates a more efficient acquisition of information, it introduces certain compromises, especially in terms of the precision and specificity of data for complex unit operations.

Potential effects of technological advancements on the environmental performance of both vehicle types is another area which is worth exploring in future research. For instance, the development of solid-state batteries could improve the energy density and safety of battery electric vehicle batteries, reducing their environmental impact and influence the vehicle weight, which in turn scales down the energy needs. Similarly, the advancement of carbon capture and storage technologies could potentially reduce the emissions from fossil fuel-based electricity

generation, which would also lower the environmental impact of battery electric vehicles in regions like Qatar.

In the context of life cycle assessment, accurately quantifying the direct emissions from specific production systems and handling processes is crucial for evaluating a product's overall environmental impact. However, direct measurement of these emissions in situ (i.e., within the actual operational context) often presents significant challenges. These challenges can rise from logistical constraints, the cost of measurement, the complexity of the production processes, or the lack of available technology for precise measurement. As a result, life cycle assessment practitioners frequently resort to modeling emissions data as a practical solution.

The statistical treatment of data, including the calculation of means, medians, standard deviations, and confidence intervals, also introduces uncertainty. The degree of confidence in life cycle assessment results is directly related to the quality and quantity of underlying data. In many cases, data gaps are filled with assumptions or data from similar processes, which may not accurately reflect the specific case being studied. The standard error of the mean provides a measure of the precision of the estimate, but it cannot account for systematic errors in data collection or inherent biases in source data.

7.2.3 Carbon Calculator

In examining CO2-eq emissions across Qatar's transportation sector, the carbon calculator presents some limitations that require attention. A critical aspect of the study's methodology involves assuming a linear progression in technology adoption and behavioral changes across the forecast period, stretching from 2022 to 2050. The study's approach means that the anticipated improvements in vehicle efficiency, shifts towards more sustainable modes of transportation, and the integration of renewable energy sources are all modeled to progress at a constant rate toward the Ambition Level targets set for 2050. Such a linear approach simplifies complex trajectories of change, potentially overlooking the nuanced and often non-linear nature of technological innovation, societal adaptation, and policy implementation.

The analysis also sets aside the potential impact of external factors that could disrupt the expected linear progression. Global economic shifts, for instance, can influence both the availability of funding for green technologies and the public willingness to adopt them. Oil price fluctuations directly affect the cost-competitiveness of electric vehicles compared to traditional fossil-fuel-powered models. Geopolitical events could disrupt supply chains for critical components of battery electric vehicles or renewable energy systems, affecting both their price and availability. Such events could lead to emissions trajectories that deviate markedly from the linear paths anticipated in the study. Furthermore, while the study utilizes emissions data and projections up to 2050, the rapidly evolving landscape of transportation technology and climate policy may render some assumptions outdated. The unpredictable pace at which new technologies are developed and adopted could significantly alter the anticipated emissions reductions.

Another limitation is the omission of urban planning's impact on transportation systems, as urban design influences transport efficiency and the reliance on private vehicles. While Ambition Level 4 aims for transformational changes within the transportation sector, including major technological breakthroughs and rapid adoption of impactful initiatives, it did not extend to exploring urban planning. This focus was specifically on direct transportation interventions, such as advanced vehicle technologies and enhancements in public transportation, rather than on the broader, interdisciplinary approach that includes urban planning.

Future research should consider how urban planning strategies can align with transport policies to achieve decarbonization goals, especially as Qatar continues to develop. This would involve studying the integration of compact city designs, robust public transport systems, and pedestrian-friendly infrastructures alongside transportation policies. Incorporating the health benefits of active travel modes into urban planning not only complements environmental efforts but also enhances public health outcomes, making the adoption of such strategies more appealing and effective across the community. Including these modes into urban design could lead to reduced healthcare costs and improved overall community well-being, providing a strong case for their inclusion in future urban planning and transport strategies.

7.3 Future research

Due to limitations in time and resources, a number of intriguing questions that emerged during the research process could not be investigated in greater depth. Future research should consider the spatial distribution of emissions from transportation and their impact on human health. While chapter 3 (Scenario Analysis for Road Transport) has focused on the overall emissions reductions potential of battery electric vehicles in Qatar, it is important to recognize that the spatial and temporal distribution of these emissions can have significant implications for public health, particularly in urban areas with high population density and traffic congestion. Future studies could employ spatial analysis techniques, such as Geographic Information Systems (GIS) and dispersion modeling, to map the distribution of transportation emissions and identify hotspots of air pollution. This could help to prioritize areas for interventions, such as the deployment of battery electric vehicles or the implementation of low-emission zones, to maximize the health benefits of emissions reductions. Furthermore, future research could explore the potential health impacts of different battery electric vehicle adoption scenarios and policy measures, using epidemiological models to estimate the burden of disease associated with air pollution from transportation. This could inform the public about the health co-benefits of transitioning to battery electric vehicles and help to build support for more ambitious emissions reduction targets.

At this point, this thesis does not consider the potential societal impacts of a shift from internal combustion engine vehicles to battery electric vehicles or potential changes on fleet level. For example, such a shift could have implications for the oil and gas industry, which is a major part of Qatar's economy. On the other hand, it could also lead to new opportunities in areas such as renewable energy and electric vehicle infrastructure alongside the need for additional dispatchable power and electricity storage capacity.

Future research in the field of life cycle assessment should aim at advancing the in-situ measurements of emissions, as there's a clear need to refine the integration of site-specific databases with literature data. This could involve the development of modeling techniques that better account for the variability and complexity of production processes. Research should focus

on enhancing the granularity and accuracy of secondary data sources, enabling them to more closely reflect actual operational conditions.

For the Carbon Calculator, future research should aim to employ more dynamic modeling techniques that can better capture the complex, non-linear progression of technology adoption, behavioral changes, and policy impacts within the transportation sector. Such models should consider variable rates of change, potential breakthroughs in technology, and shifts in societal behaviors that could accelerate or hinder progress towards emissions reduction targets. Incorporating scenario analysis that accounts for socio-economic, cultural, and political barriers, as well as the potential impact of external factors like global economic shifts, oil price fluctuations, and geopolitical events, will provide a more nuanced understanding of possible future emissions trajectories. Additionally, expanding the scope of analysis to include a wider range of transportation modes and considering the cross-sectoral impacts of transportation policies on urban development, energy systems, and societal well-being could offer comprehensive insights into the multifaceted challenge of achieving sustainable transportation.

Understanding public acceptance of new transportation technologies and policies is important. Research in this area could explore factors influencing consumer preferences for electric vehicles, willingness to adopt car-sharing services, or reactions to policies like congestion pricing. Surveys, focus groups, and pilot studies could be used to gauge public sentiment and identify potential barriers to the adoption of sustainable transportation practices. This research would provide valuable insights into how policy measures can be designed and communicated to maximize public buy-in and effectiveness.

Future research could investigate the public's perception of utilizing mass transit options such as buses and metros, thereby identifying factors influencing their choices. This exploration could extend to evaluating effective incentives to encourage the adoption of public transportation, covering both monetary and non-monetary benefits. Furthermore, investigations into strengthening the appeal and convenience of public transport systems could yield insights into infrastructure and service enhancements needed to bolster public interest.

The study of vehicle emissions in Qatar primarily focuses on the potential impact of different technological and policy interventions without delving deeply into the economic and logistical aspects of their implementation. The complexity of the sector, including the varied nature of vehicles and their usage patterns, poses unique challenges not fully addressed in the analysis. There is an urgent need for studies that examine the economic viability, logistical feasibility and transitional risks of implementing emissions reduction strategies in the road transport sector. This involves evaluating the cost implications of transitioning to low-emission technologies for businesses, the government, and other stakeholders. Research should also examine the logistical challenges, such as the infrastructure needed for alternative fuel vehicles, the impact on local and global supply chains, and the readiness of the workforce for technological shifts. Investigating case studies of other countries that have successfully implemented similar strategies could offer practical insights. Additionally, examining the potential economic benefits, such as job creation in new technology sectors or savings from reduced fuel costs, could provide a more balanced view of these strategies' overall impact.

References

Abdmouleh, Z., Gastli, A., & Ben-Brahim, L. (2018). Survey about public perception regarding smart grid, energy efficiency & renewable energies applications in Qatar. *Renewable and Sustainable Energy Reviews*, *82*, 168–175. https://doi.org/10.1016/J.RSER.2017.09.023

Aboushaqrah, N. N. M., Onat, N. C., Kucukvar, M., & Jabbar, R. (2020). Life cycle sustainability assessment of sport utility vehicles: The case for Qatar. *Advances in Intelligent Systems and Computing*, *1091 AISC*, 279–287. https://doi.org/10.1007/978-3-030-35543-2_22

Ahmad, S., Balaban, O., Doll, C. N. H., & Dreyfus, M. (2013). Delhi revisited. *Cities*, *31*, 641–653. https://doi.org/10.1016/J.CITIES.2012.12.006

Al Mamun, A., Abouzeid, A., Al-Yafei, H., Hussain, S., Ahmad, A. M., Aseel, S., Kucukvar, M., & Onat, N. C. (2021). Sustainable Transportation in Qatar. *2021 IEEE 8th International Conference on Industrial Engineering and Applications, ICIEA 2021*, 583–588. https://doi.org/10.1109/ICIEA52957.2021.9436707

Al-Aali, I., & Modi, V. (2022). Decarbonizing the electricity sector in Qatar using PV combined with ice thermal and battery storage. *Energy Strategy Reviews*, *44*, 101014. https://doi.org/10.1016/J.ESR.2022.101014

Alarfaj, A. F., Griffin, W. M., & Samaras, C. (2020). Decarbonizing US passenger vehicle transport under electrification and automation uncertainty has a travel budget. *Environmental Research Letters*, *15*(9), 0940c2. https://doi.org/10.1088/1748-9326/AB7C89

Al-Buenain, A., Al-Muhannadi, S., Falamarzi, M., Kutty, A. A., Kucukvar, M., & Onat, N. C. (2021). The Adoption of Electric Vehicles in Qatar Can Contribute to Net Carbon Emission Reduction but Requires Strong Government Incentives. *Vehicles*, *3*(3), 618–635. https://doi.org/10.3390/vehicles3030037

Al-Hemoud, A., Gasana, J., Al-Dabbous, A., Alajeel, A., Al-Shatti, A., Behbehani, W., & Malak, M. (2019). *Exposure levels of air pollution (PM 2.5) and associated health risk in Kuwait*. https://doi.org/10.1016/j.envres.2019.108730

Al-Noaimi, F., Al-Ansari, T., & Bicer, Y. (2023). Toward a Long-Term Low Emission Development Strategy: The Case of Energy Transition in Qatar. In *Global Challenges* (Vol. 7, Issue 6). John Wiley and Sons Inc. https://doi.org/10.1002/gch2.202200229

Al-Saffar, A., & Van der Beeuren, M. (2020). *The case for energy transitions in major oil- and gas-producing countries – Analysis - IEA*. https://www.iea.org/commentaries/the-case-for-energy-transitions-in-major-oil-and-gas-producing-countries

Al-Siddiqi, A., & Dawe, R. A. (1999). QATAR'S OIL AND GASFIELDS: A REVIEW. *Journal of Petroleum Geology*, *22*(4), 417–436. https://doi.org/10.1111/J.1747-5457.1999.TB00477.X

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

Al-Thawadi, F. E., & Al-Ghamdi, S. G. (2019). Evaluation of sustainable urban mobility using comparative environmental life cycle assessment: A case study of Qatar. *Transportation Research Interdisciplinary Perspectives*, *1*(2019), 100003. https://doi.org/10.1016/j.trip.2019.100003

Al-Thawadi, F. E., Weldu, Y. W., & Al-Ghamdi, S. G. (2020). Sustainable Urban Transportation Approaches: Life-Cycle Assessment Perspective of Passenger Transport Modes in Qatar. *Transportation Research Procedia*, *48*, 2056–2062. https://doi.org/10.1016/j.trpro.2020.08.265

Ankur, A. K., Kraus, S., Grube, T., Castro, R., & Stolten, D. (2022). A Versatile Model for Estimating the Fuel Consumption of a Wide Range of Transport Modes. *Energies*, *15*(6), 2232. https://doi.org/10.3390/EN15062232/S1

Argonne National Laboratory. (2016). Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways. *Journal of Chemical Information and Modeling*, *53*(9), 210. https://doi.org/10.1017/CBO9781107415324.004

Askin, A. C., Barter, G. E., West, T. H., & Manley, D. K. (2015). *The heavy-duty vehicle future in the United States: A parametric analysis of technology and policy tradeoffs*. https://doi.org/10.1016/j.enpol.2015.02.005

Astegiano, P., Fermi, F., & Martino, A. (2019). Investigating the impact of e-bikes on modal share and greenhouse emissions: a system dynamic approach. *Transportation Research Procedia*, *37*, 163–170. https://doi.org/10.1016/J.TRPRO.2018.12.179

Atabani, A. E., Silitonga, A. S., & Mahlia, T. M. I. (2012). Cost benefit analysis and environmental impact of fuel economy standards for passenger cars in Indonesia. *Renewable and Sustainable Energy Reviews*, *16*(5), 3547–3558. https://doi.org/10.1016/J.RSER.2012.01.001

Axon, C. J., & Darton, R. C. (2021). Sustainability and risk – a review of energy security. *Sustainable Production and Consumption*, *27*, 1195–1204. https://doi.org/10.1016/J.SPC.2021.01.018

Baldino, C., Tietge, U., Muncrief, R., Bernard, Y., & Mock, P. (2017). *ROAD TESTED: COMPARATIVE OVERVIEW OF REAL-WORLD VERSUS TYPE-APPROVAL NO X AND CO 2 EMISSIONS FROM DIESEL CARS IN EUROPE*. www.theicct.orgcommunications@theicct.orgACKNOWLEDGMENTS

Bandivadekar, A., Miller, J., Kodjak, D., Muncrief, R., Yang, Z., Jong, R. De, & Fabian, B. (2020). *VEHICLE EFFICIENCY AND ELECTRIFICATION: A GLOBAL STATUS REPORT*.

Baptista, P. C., Silva, C. M., Farias, T. L., & Heywood, J. B. (2012). Energy and environmental impacts of alternative pathways for the Portuguese road transportation sector. *Energy Policy*, *51*, 802–815. https://doi.org/10.1016/J.ENPOL.2012.09.025

Barchasz, C., Molton, F., Duboc, C., Leprêtre, J. C., Patoux, S., & Alloin, F. (2012). Lithium/sulfur cell discharge mechanism: An original approach for intermediate species identification. *Analytical Chemistry*, *84*(9), 3973–3980. https://doi.org/10.1021/AC2032244/SUPPL_FILE/AC2032244_SI_001.PDF

Bare, J. (2011). TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technologies and Environmental Policy*, *13*(5), 687–696. https://doi.org/10.1007/S10098-010-0338-9

Bartholdsen, H. K., Eidens, A., Löffler, K., Seehaus, F., Wejda, F., Burandt, T., Oei, P. Y., Kemfert, C., & von Hirschhausen, C. (2019). Pathways for Germany's Low-Carbon Energy Transformation Towards 2050. *Energies 2019, Vol. 12, Page 2988*, *12*(15), 2988. https://doi.org/10.3390/EN12152988

Bartolozzi, I., Rizzi, F., & Frey, M. (2013). Comparison between hydrogen and electric vehicles by life cycle assessment: A case study in Tuscany, Italy. *Applied Energy*, *101*, 103–111. https://doi.org/10.1016/J.APENERGY.2012.03.021

Bauer, C., Hofer, J., Althaus, H. J., Del Duce, A., & Simons, A. (2015). The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework. *Applied Energy*, *157*, 871–883. https://doi.org/10.1016/j.apenergy.2015.01.019

Bauer, G., Hsu, C.-W., Nicholas, M., & Lutsey, N. (2021). *CHARGING UP AMERICA: ASSESSING THE GROWING NEED FOR U.S. CHARGING INFRASTRUCTURE THROUGH 2030*.

Bayram, I. S., Saffouri, F., & Koc, M. (2018). Generation, analysis, and applications of high resolution electricity load profiles in Qatar. *Journal of Cleaner Production*, *183*, 527–543. https://doi.org/10.1016/J.JCLEPRO.2018.02.084

Benveniste, H., Boucher, O., Guivarch, C., Le Treut, H., & Criqui, P. (2018). Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: uncertainty analysis and distribution of emissions. *Environmental Research Letters*, *13*(1), 014022. https://doi.org/10.1088/1748-9326/AAA0B9

Bicer, Y., & Dincer, I. (2018). Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2018.01.036

Bohra, M., & Shah, N. (2019). Optimizing Qatar's energy system for a post-carbon future. *Energy Transitions*, 1–19. https://doi.org/10.1007/s41825-019-00019-5

Boretti, A. (2019). Advantages and Disadvantages of Diesel Single and Dual-Fuel Engines. In *Frontiers in Mechanical Engineering* (Vol. 5). Frontiers Media S.A. https://doi.org/10.3389/fmech.2019.00064

Bouoiyour, J., & Selmi, R. (2019). The Qatar-Gulf Crisis and Risk Management in Oil and Gas Markets. *Hal Archives-Ouvertes*, *April*, 1–26. https://doi.org/10.13140/RG.2.2.26173.72161

Brand, C., Anable, J., Ketsopoulou, I., & Watson, J. (2020). Road to zero or road to nowhere? Disrupting transport and energy in a zero carbon world. *Energy Policy*, *139*. https://doi.org/10.1016/j.enpol.2020.111334

Bras, B., Tejada, F., Yen, J., Zullo, J., & Guldberg, T. (2012). Quantifying the life cycle water consumption of a passenger vehicle. *SAE Technical Papers*. https://doi.org/10.4271/2012-01-0646

Bui, T. D., & Tseng, M.-L. (2022). A Data-Driven Analysis on Sustainable Energy Security. *Journal of Global Information Management*, *30*(6), 1–38. https://doi.org/10.4018/jgim.287608

Burchart-Korol, D., Jursova, S., Folęga, P., Korol, J., Pustejovska, P., & Blaut, A. (2018). Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. *Journal of Cleaner Production*, *202*(October 2014), 476–487. https://doi.org/10.1016/j.jclepro.2018.08.145

Çabukoglu, E., Georges, G., Küng, L., Pareschi, G., & Boulouchos, K. (2018). Battery electric propulsion: An option for heavy-duty vehicles? Results from a Swiss case-study. *Transportation Research Part C: Emerging Technologies*, *88*, 107–123. https://doi.org/10.1016/J.TRC.2018.01.013

Canals Casals, L., Martinez-Laserna, E., Amante García, B., & Nieto, N. (2016). Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction. *Journal of Cleaner Production*, *127*, 425–437. https://doi.org/10.1016/J.JCLEPRO.2016.03.120

Capros, P., Vita, A. De, Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., Nakos, C., & Paroussos, L. (2016). *EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050*.

Chatterton, T., Barnes, J., Wilson, R. E., Anable, J., & Cairns, S. (2015). Use of a novel dataset to explore spatial and social variations in car type, size, usage and emissions. *Transportation Research Part D: Transport and Environment*, *39*, 151–164. https://doi.org/10.1016/J.TRD.2015.06.003

Chaudhary, A., Verones, F., De Baan, L., & Hellweg, S. (2015). Quantifying Land Use Impacts on Biodiversity: Combining Species-Area Models and Vulnerability Indicators. *Environmental Science and Technology*, *49*(16), 9987–9995. https://doi.org/10.1021/ACS.EST.5B02507/SUPPL_FILE/ES5B02507_SI_004.XLSX

Chen, G., & Kauppila, J. (2017). Global Urban Passenger Travel Demand and CO2 Emissions to 2050: New Model. *Https://Doi.Org/10.3141/2671-08*, *2671*, 71–79. https://doi.org/10.3141/2671-08

Chen, W., Liang, J., Yang, Z., & Li, G. (2019). A review of lithium-ion battery for electric vehicle applications and beyond. *Energy Procedia*, *158*, 4363–4368. https://doi.org/10.1016/j.egypro.2019.01.783

Chen, X., Shen, W., Tu, T. V., Cao Zhenwei, & Kapoor, A. (2012). *An Overview of Lithium-ion Batteries for Electric Vehicles*.

Chen, Y., & Borken-Kleefeld, J. (2016). NOx Emissions from Diesel Passenger Cars Worsen with Age. *Environmental Science and Technology*, *50*(7), 3327–3332. https://doi.org/10.1021/ACS.EST.5B04704/SUPPL_FILE/ES5B04704_SI_001.PDF

Chen, Y., Ding, Z., Liu, J., & Ma, J. (2019). Life cycle assessment of end-of-life vehicle recycling in China: a comparative study of environmental burden and benefit. *International Journal of Environmental Studies*. https://doi.org/10.1080/00207233.2019.1618670

Chiodi, A., Gargiulo, M., Deane, J. P., Lavigne, D., Rout, U. K., & Ó Gallachóir, B. P. (2013). Modelling the impacts of challenging 2020 non-ETS GHG emissions reduction targets on Ireland's energy system. *Energy Policy*, *62*, 1438–1452. https://doi.org/10.1016/J.ENPOL.2013.07.129

Climate Change Committee. (2018). *Government's Road to Zero Strategy falls short, CCC says - Climate Change Committee*. https://www.theccc.org.uk/2018/07/10/governments-road-to-zero-strategy-falls-short-ccc-says/

Climate Change Committee. (2024). *COP28: Key outcomes and next steps for the UK*.

Committee on Climate Change. (2020). *The Sixth Carbon Budget The UK's path to Net Zero*. www.theccc.org.uk/publications

Cooper, E. M., Lefevre, B., & Li, X. (2016). CAN TRANSPORT DELIVER GHG REDUCTIONS AT SCALE? AN ANALYSIS OF GLOBAL TRANSPORT INITIATIVES. *World Resources Institute*. http://www.wri.org/publication/transport-ghg-initiatives.

Cox, B., Bauer, C., Mendoza Beltran, A., van Vuuren, D. P., & Mutel, C. L. (2020). Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. *Applied Energy*, *269*, 115021. https://doi.org/10.1016/J.APENERGY.2020.115021

Craglia, M., & Cullen, J. (2019). Do technical improvements lead to real efficiency gains? Disaggregating changes in transport energy intensity. *Energy Policy*, *134*, 110991. https://doi.org/10.1016/J.ENPOL.2019.110991

Craglia, M., & Cullen, J. (2020). Modelling transport emissions in an uncertain future: What actions make a difference? *Transportation Research Part D: Transport and Environment*, *89*, 102614. https://doi.org/10.1016/J.TRD.2020.102614

Creutzig, F., Jochem, P., Edelenbosch, O. Y., Mattauch, L., van Vuuren, D. P., McCollum, D., & Minx, J. (2015). Transport: A roadblock to climate change mitigation? *Transport Reviews*, *36*(3), 341–360. https://doi.org/10.1080/01441647.2015.1079277

Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., Bruine De Bruin, W., Dalkmann, H., Edelenbosch, O. Y., Geels, F. W., Grubler, A., Hepburn, C., Hertwich, E. G., Khosla, R., Mattauch, L., Minx, J. C., Ramakrishnan, A., Rao, N. D., Steinberger, J. K., Tavoni, M., Ürge-Vorsatz, D., & Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, *8*(4), 268–271. https://doi.org/10.1038/S41558-018-0121-1

Da Pan, Tao, L., Sun, K., Golston, L. M., Miller, D. J., Zhu, T., Qin, Y., Zhang, Y., Mauzerall, D. L., & Zondlo, M. A. (2020). Methane emissions from natural gas vehicles in China. *Nature Communications*, *11*(1), 4588. https://doi.org/10.1038/S41467-020-18141-0

Del Pero, F., Delogu, M., & Pierini, M. (2018). Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car. *Procedia Structural Integrity*, *12*, 521–537. https://doi.org/10.1016/J.PROSTR.2018.11.066

Deng, D. (2015). Li-ion batteries: basics, progress, and challenges. *Energy Science & Engineering*, *3*(5), 385–418. https://doi.org/10.1002/ESE3.95

Department for Environment Food & Rural Affairs. (2020). *Emissions of air pollutants - GOV.UK*. https://www.gov.uk/government/statistics/emissions-of-air-pollutants

Dhingra, R., Overly, J. G., & Davis, G. A. (1999). *Life-cycle Environmental Evaluation of Aluminun and Composite Intensive Vehicles*.

Dornoff, J., Tietge, U., & Mock, P. (2020). *On The Way to "Real-World" CO2 Values: The European Passenger Car Market in its First Year After Introducing the WLTP*. www.theicct.org

Ecoinvent. (n.d.). *Impact Assessment*. Retrieved October 6, 2023, from https://ecoinvent.org/the-ecoinvent-database/impact-assessment/#1661420435296-03a17d13-bc0e16614291937081661429832917

Elizondo, A., Pérez-Cirera, V., Strapasson, A., Fernández, J. C., & Cruz-Cano, D. (2017). Mexico's low carbon futures: An integrated assessment for energy planning and climate change mitigation by 2050. *Futures*, *93*, 14–26. https://doi.org/10.1016/j.futures.2017.08.003

Ellingsen, L. A. W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valøen, L. O., & Strømman, A. H. (2014). Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *Journal of Industrial Ecology*, *18*(1), 113–124. https://doi.org/10.1111/JIEC.12072

Ellingsen, L. A. W., Singh, B., & Strømman, A. H. (2016). The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. *Environmental Research Letters*, *11*(5), 054010. https://doi.org/10.1088/1748-9326/11/5/054010

Encyclopedia Britannica. (2019). *Economy of Qatar*. https://www.britannica.com/place/Qatar/Economy

European Commission. (2020). *Vehicle categories | Internal Market, Industry, Entrepreneurship and SMEs*. https://ec.europa.eu/growth/sectors/automotive/vehicle-categories_en

European Commission-JRC-IES. (2010). International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment -- Detailed guidance. In *Constraints*. https://doi.org/10.2788/38479

European Environment Agency. (2021). *Greenhouse gas emissions from transport in Europe*. https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12

Façanha, C., Blumber, K., & Miller, J. (2012). *Global Transportation Energy and Climate Roadmap*.

Faria, R., Marques, P., Moura, P., Freire, F., Delgado, J., & De Almeida, A. T. (2013). Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renewable and Sustainable Energy Reviews*, *24*, 271–287. https://doi.org/10.1016/J.RSER.2013.03.063

Faria, R., Moura, P., Delgado, J., & De Almeida, A. T. (2012). A sustainability assessment of electric vehicles as a personal mobility system. *Energy Conversion and Management*, *61*, 19–30. https://doi.org/10.1016/J.ENCONMAN.2012.02.023

Fountas, G., Sun, Y.-Y., Akizu-Gardoki, O., & Pomponi, F. (2020). How Do People Move Around? National Data on Transport Modal Shares for 131 Countries. *World 2020, Vol. 1, Pages 34-43*, *1*(1), 34–43. https://doi.org/10.3390/WORLD1010003

Fuels Institute. (2022). *Life Cycle Analysis Comparison ELECTRIC AND INTERNAL COMBUSTION ENGINE VEHICLES*.

Fulton, L., Cazzola, P., & Cuenot, F. (2009). IEA Mobility Model (MoMo) and its use in the ETP 2008. *Energy Policy*, *37*(10), 3758–3768. https://doi.org/10.1016/J.ENPOL.2009.07.065

Fulton, L., Mason, D. J., Meroux, D., & Davis, U. C. (2017). *Three Revolutions in Urban Transportation*.

Gallo, M. (2011). A fuel surcharge policy for reducing road traffic greenhouse gas emissions. *Transport Policy*, *18*(2), 413–424. https://doi.org/10.1016/J.TRANPOL.2010.11.003

García, A., Monsalve-Serrano, J., Lago Sari, R., & Tripathi, S. (2022). Pathways to achieve future CO2 emission reduction targets for bus transit networks. *Energy*, *244*, 123177. https://doi.org/10.1016/J.ENERGY.2022.123177

Garcia, R. P. (2016). *Dynamic Fleet-Based Life-Cycle Assessment: Addressing Environmental Consequences of the Introduction of Electric Vehicles in Portugal*. *April*, 204 pp. http://hdl.handle.net/10316/30192

Gebrehiwot, M., & Van Den Bossche, A. (2015). Driving electric vehicles: As green as the grid. *IEEE AFRICON Conference*, *2015-November*. https://doi.org/10.1109/AFRCON.2015.7331913

Girardi, P., Gargiulo, A., & Brambilla, P. C. (2015). A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study. *International Journal of Life Cycle Assessment*, *20*(8), 1127–1142. https://doi.org/10.1007/S11367-015-0903-X/TABLES/7

Girod, B., van Vuuren, D. P., & de Vries, B. (2013). Influence of travel behavior on global CO2 emissions. *Transportation Research Part A: Policy and Practice*, *50*, 183–197. https://doi.org/10.1016/J.TRA.2013.01.046

Girod, B., van Vuuren, D. P., & Deetman, S. (2012). Global travel within the 2 °C climate target. *Energy Policy*, *45*, 152–166. https://doi.org/10.1016/J.ENPOL.2012.02.008

GIZ. (2015). *Navigating Transport NAMAs A practical handbook on Nationally Appropriate Mitigation Actions (NAMAs) in the transport sector 2nd revised edition*.

Global Fuel Economy Initiative. (2021). *VEHICLE FUEL ECONOMY IN MAJOR MARKETS 2005-2019*. www.iea.org/t&c/

Global Petrol Prices. (2022). *Gasoline prices around the world, 28-Mar-2022 | GlobalPetrolPrices.com*. https://www.globalpetrolprices.com/gasoline_prices/

Grischkat, S., Hunecke, M., Böhler, S., & Haustein, S. (2014). Potential for the reduction of greenhouse gas emissions through the use of mobility services. *Transport Policy*, *35*, 295–303. https://doi.org/10.1016/J.TRANPOL.2014.06.007

Gupta, A. (2019). *VW Boosts Electric-Car Target by 50% With Budget, China Models – The Leading Solar Magazine In India*. https://www.eqmagpro.com/vw-boosts-electric-car-target-by-50-with-budget-china-models/

Gürsan, C., & de Gooyert, V. (2021). The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition? *Renewable and Sustainable Energy Reviews*, *138*, 110552. https://doi.org/10.1016/J.RSER.2020.110552

Habib, K., Hansdóttir, S. T., & Habib, H. (2020). Critical metals for electromobility: Global demand scenarios for passenger vehicles, 2015–2050. *Resources, Conservation and Recycling*, *154*, 104603. https://doi.org/10.1016/J.RESCONREC.2019.104603

Harrison, R. M., Allan, J., Carruthers, D., Heal, M. R., Lewis, A. C., Marner, B., Murrells, T., & Williams, A. (2021). Non-exhaust vehicle emissions of particulate matter and VOC from road traffic: A review. *Atmospheric Environment*, *262*, 118592. https://doi.org/https://doi.org/10.1016/j.atmosenv.2021.118592

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, *17*(1), 53–64. https://doi.org/10.1111/J.1530-9290.2012.00532.X

He, X., Shen, W., Wallington, T. J., Zhang, S., Wu, X., Bao, Z., & Wu, Y. (2021). Asia Pacific road transportation emissions, 1900–2050. *Faraday Discussions*, *226*(0), 53–73. https://doi.org/10.1039/D0FD00096E

Hill, G., Heidrich, O., Creutzig, F., & Blythe, P. (2019). The role of electric vehicles in near-term mitigation pathways and achieving the UK's carbon budget. *Applied Energy*, *251*, 113111. https://doi.org/10.1016/J.APENERGY.2019.04.107

Howarth, R. W., & Jacobson, M. Z. (2021). How green is blue hydrogen? *Energy Science & Engineering*, *9*(10), 1676–1687. https://doi.org/10.1002/ESE3.956

Huff, S., West, B., & Thomas, J. (2013). Effects of air conditioner use on real-world fuel economy. *SAE Technical Papers*, *2*. https://doi.org/10.4271/2013-01-0551

ICCT. (2019). *CO2 emission standards for passenger cars and light-commercial vehicles in the European Union*. http://www.europarl.europa.eu/news/en/press-room/20181218IPR22101/curbing-co2-

IEA. (n.d.-a). *Kuwait - Countries & Regions*. Retrieved September 30, 2024, from https://www.iea.org/countries/kuwait/emissions

IEA. (n.d.-b). *Middle East – Countries & Regions*. Retrieved October 1, 2024, from https://www.iea.org/regions/middle-east

IEA. (n.d.-c). *Qatar - Countries & Regions*. Retrieved March 12, 2024, from https://www.iea.org/countries/qatar/emissions

IEA. (n.d.-d). *Saudi Arabia - Countries & Regions*. Retrieved September 30, 2024, from https://www.iea.org/countries/saudi-arabia/emissions

IEA. (n.d.-e). *United Arab Emirates - Countries & Regions*. Retrieved September 30, 2024, from https://www.iea.org/countries/united-arab-emirates/emissions

IEA. (2019). *Renewables 2019*. www.iea.org/renewables2019

IEA. (2021). *Trajectories of rated fuel economy of new light-duty vehicles against Global Fuel Economy Initiative targets and IEA scenarios, 2005-2050.* https://www.iea.org/data-and-statistics/charts/trajectories-of-rated-fuel-economy-of-new-light-duty-vehicles-against-global-fuel-economy-initiative-targets-and-iea-scenarios-2005-2050

IEA. (2022a). *Global CO2 emissions from transport by sub-sector in the Net Zero Scenario, 2000-2030*. https://www.iea.org/data-and-statistics/charts/global-co2-emissions-from-transport-by-sub-sector-in-the-net-zero-scenario-2000-2030-2

IEA. (2022b). *Global EV Outlook 2022 Securing supplies for an electric future*. www.iea.org/t&c/

IEA. (2022c). *Solar PV*. https://www.iea.org/reports/solar-pv

IEA. (2023). *Global EV Outlook 2023: Catching up with climate ambitions*. www.iea.org

IHS Markit. (2019). *News Release | IHS Markit Online Newsroom*. https://news.ihsmarkit.com/prviewer/release_only/slug/automotive-average-age-cars-and-light-trucks-us-rises-again-2019-118-years-ihs-markit-

International Trade Administration. (2022). *Qatar - Country Commercial Guide*. https://www.trade.gov/country-commercial-guides/qatar-oil-gas-field-machinery-equipment

International Union of Railways. (2019). *Adoption of new sustainable mobility commitments*.

IPCC. (2006). IPCC Guidelines for National Greenhouse Gas Inventories – Chapter 3: Uncertainties. *Urban Climate Change Crossroads*, 49–56. https://doi.org/10.4324/9781315548906

IPCC. (2015). *Climate Change 2014 Synthesis Report*. http://www.ipcc.ch.

Islam, E. S., Moawad, A., Kim, N., & Rousseau, A. (2020). *Energy Consumption and Cost Reduction of Future Light-Duty Vehicles through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050*. https://doi.org/10.2172/1647165

Jadun, P., Mcmillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., & Mai, T. (2017). *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050*. www.nrel.gov/publications.

Jain, S., Aggarwal, P., Sharma, P., & Kumar, P. (2016). Vehicular exhaust emissions under current and alternative future policy measures for megacity Delhi, India. *Journal of Transport & Health*, *3*(3), 404–412. https://doi.org/10.1016/J.JTH.2016.06.005

Jain, S., & Khare, M. (2009). Construction of fuzzy membership functions for urban vehicular exhaust emissions modeling. *Environmental Monitoring and Assessment 2009 167:1*, *167*(1), 691–699. https://doi.org/10.1007/S10661-009-1085-4

Kamal, A., Al-Ghamdi, S. G., & Koç, M. (2020). Modeling and understanding the impacts of efficiency measures on fleet fuel consumption in vehicle importing countries: A case study of Qatar. *Journal of Cleaner Production*, *259*, 120619. https://doi.org/10.1016/j.jclepro.2020.120619

Karali, N., Gopal, A. R., Sharpe, B., Delgado, O., Bandivadekar, A., & Garg, M. (2017). *Improved heavy-duty vehicle fuel efficiency in India Benefits, costs and environmental impacts*.

Kaufmann, V., & Ravalet, E. (2016). From Weak Signals to Mobility Scenarios: A Prospective Study of France in 2050. *Transportation Research Procedia*, *19*(June), 18–32. https://doi.org/10.1016/j.trpro.2016.12.064

Kay, A. I., Noland, R. B., & Rodier, C. J. (2014). Achieving reductions in greenhouse gases in the US road transportation sector. *Energy Policy*, *69*, 536–545. https://doi.org/10.1016/J.ENPOL.2014.02.012

Khalili, S., Rantanen, E., Bogdanov, D., & Breyer, C. (2019). Global transportation demand development with impacts on the energy demand and greenhouse gas emissions in a climate-constrained world. *Energies*, *12*(20). https://doi.org/10.3390/en12203870

Khandakar, A., Rizqullah, A., Ashraf, A., Berbar, A., Ahmed, M. R., Iqbal, A., Chowdhury, M. E. H., Ashfaq, S. M., & Zaman, U. (n.d.). *A Case Study to Identify the Hindrances to Widespread Adoption of Electric Vehicles in Qatar*. https://doi.org/10.3390/en13153994

Khanna, N., Lu, H., Fridley, D., & Zhou, N. (2021). Near and long-term perspectives on strategies to decarbonize China's heavy-duty trucks through 2050. *Scientific Reports 2021 11:1*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-99715-w

Kiemel, S., Rietdorf, C., Schutzbach, M., & Miehe, R. (2022). How to Simplify Life Cycle Assessment for Industrial Applications—A Comprehensive Review. In *Sustainability (Switzerland)* (Vol. 14, Issue 23). MDPI. https://doi.org/10.3390/su142315704

Kim, S. H. (2016). Comparison of Sensitivity Analysis Methods for Building Energy Simulations in Early Design Phases: Once-at-a-time (OAT) vs. Variance-based Methods. *KIEAE Journal*, *16*(2), 17–22. https://doi.org/10.12813/kieae.2016.16.2.017

Kitous, A., Criqui, P., Bellevrat, E., & Chateau, B. (2010). Transformation Patterns of the Worldwide Energy System -Scenarios for the Century with the POLES Model. *Https://Doi.Org/10.5547/ISSN0195-6574-EJ-Vol31-NoSI-3*, *31*(SPECIAL ISSUE), 49–82. https://doi.org/10.5547/ISSN0195-6574-EJ-VOL31-NOSI-3

Koroma, M. S., Costa, D., Philippot, M., Cardellini, G., Hosen, M. S., Coosemans, T., & Messagie, M. (2022). Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. *Science of The Total Environment*, *831*, 154859. https://doi.org/10.1016/J.SCITOTENV.2022.154859

Krause, J., Thiel, C., Tsokolis, D., Samaras, Z., Rota, C., Ward, A., Prenninger, P., Coosemans, T., Neugebauer, S., & Verhoeve, W. (2020). EU road vehicle energy consumption and CO2 emissions by 2050 - Expert-based scenarios. *Energy Policy*. https://doi.org/10.1016/j.enpol.2019.111224

Kumar, C. (2019). *400 electric car charging stations by 2022 in Qatar - The Peninsula Qatar*. The Peninsula. https://thepeninsulaqatar.com/article/17/01/2019/400-electric-car-charging-stations-by-2022-in-Qatar

Kumar, R., & Chavan, S. (2022). Numerical and Experimental Investigation of Thermal Behaviour for Fast Charging and Discharging of Various 18650 Lithium Batteries of Electric Vehicles. *International Journal of Heat and Technology*, *40*(6), 1492–1499. https://doi.org/10.18280/ijht.400618

Kyle, P., & Kim, S. H. (2011). Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands. *Energy Policy*, *39*(5), 3012–3024. https://doi.org/10.1016/J.ENPOL.2011.03.016

Lanouar, C., Al-Malk, A. Y., & Al Karbi, K. (2016). *Air Pollution in Qatar: Causes and Challenges*.

Lawrenz, L., Xiong, B., Lorenz, L., Krumm, A., Hosenfeld, H., Burandt, T., Löffler, K., Oei, P.-Y., & Von Hirschhausen, C. (2018). Exploring Energy Pathways for the Low-Carbon Transformation in India-A Model-Based Analysis. *Energies*. https://doi.org/10.3390/en11113001

Lebel, L., Garden, P., Banaticla, M. R. N., Lasco, R. D., Contreras, A., Mitra, A. P., Sharma, C., Nguyen, H. T., Ooi, G. L., & Sari, A. (2007). Management into the Development Strategies of Urbanizing Regions in Asia: Implications of Urban Function, Form, and Role. *Journal of Industrial Ecology*, *11*(2), 61–81. https://doi.org/10.1162/JIE.2007.1185

Lee, D., Cho, S.-H., Roberts, R. K., & Lambert, D. M. (2016). Effects of Population Redistribution on Greenhouse Gas Emissions: A Case Study of South Korea. *International Regional Science Review*, *39*(2), 177–202. https://doi.org/10.1177/0160017615571585

Levine, N., & Wachs, M. (1998). Factors affecting vehicle occupancy measurement. *Transportation Research Part A: Policy and Practice*, *32*(3), 215–229. https://doi.org/10.1016/S0965-8564(97)00011-6

Li, C., & Managi, S. (2021). Contribution of on-road transportation to PM2.5. *Scientific Reports 2021 11:1*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-00862-x

Lipsett, M. J., Ostro, B. D., Reynolds, P., Goldberg, D., Hertz, A., Jerrett, M., Smith, D. F., Garcia, C., Chang, E. T., & Bernstein, L. (2011). *Long-Term Exposure to Air Pollution and Cardiorespiratory Disease in the California Teachers Study Cohort*. https://doi.org/10.1164/rccm.201012-2082OC

Lohse-Busch, H., Duoba, M., Rask, E., Stutenberg, K., Gowri, V., Slezak, L., & Anderson, D. (2013). Ambient temperature (20°F, 72°F and 95°F) impact on fuel and energy consumption for several conventional vehicles, hybrid and plug-in hybrid electric vehicles and battery electric vehicle. *SAE Technical Papers*, *2*(1). https://doi.org/10.4271/2013-01-1462

Lucas, K., & Pangbourne, K. (2014). Assessing the equity of carbon mitigation policies for transport in Scotland. *Case Studies on Transport Policy*, *2*(2), 70–80. https://doi.org/10.1016/J.CSTP.2014.05.003

Lutsey, N. (2015). *global climate change mitigation potential from a transition to electric vehicles*. www.theicct.org

M Ahmed, A. F., Al-kuwari, L., Khazndar, A., & Marri, A. AL. (2021). *Assessment of Road Transport Atmospheric Emission of GHGs & Criteria Pollutants in Qatar: BAU Versus Paris Agreement NDC Policy Scenarios*. https://www.motc.gov.qa/en/sectors/land-transport

Mahmood, S., Qouteshat, O., & Al-Abdulla, S. (2021). *Electricity regulation in Qatar: overview*.

Majeau-Bettez, G., Hawkins, T. R., & StrØmman, A. H. (2011). Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environmental Science and Technology*, *45*(10), 4548–4554. https://doi.org/10.1021/ES103607C/SUPPL_FILE/ES103607C_SI_001.PDF

Maltha, Y., Kroesen, M., Van Wee, B., & Van Daalen, E. (2017). Changing influence of factors explaining household car ownership levels in the netherlands. *Transportation Research Record*, *2666*, 103–111. https://doi.org/10.3141/2666-12

Manzetti, S., & Mariasiu, F. (2015). Electric vehicle battery technologies: From present state to future systems. *Renewable and Sustainable Energy Reviews*, *51*, 1004–1012. https://doi.org/10.1016/J.RSER.2015.07.010

Marques, P., Garcia, R., Kulay, L., & Freire, F. (2019). Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. *Journal of Cleaner Production*, *229*, 787–794. https://doi.org/10.1016/j.jclepro.2019.05.026

Marsden, G., Anable, J., Bray, J., Seagriff, E., & Spurling, N. (2019). *Shared mobility-where now, where next? Second report of the Commission on Travel Demand About the Commission on Travel Demand Shared*.

Matheys, J., Van Mierlo, J., Timmermans, J. M., & Van Bossche, P. Den. (2008). Life-cycle assessment of batteries in the context of the EU Directive on end-of-life vehicles. *International Journal of Vehicle Design*, *46*(2), 189–203. https://doi.org/10.1504/IJVD.2008.017182

Mayyas, A., Omar, M., Hayajneh, M., & Mayyas, A. R. (2017). Vehicle's lightweight design vs. electrification from life cycle assessment perspective. *Journal of Cleaner Production*, *167*, 687–701. https://doi.org/10.1016/J.JCLEPRO.2017.08.145

Mccartt, A. T., & Hu, W. (2017). Effects of vehicle power on passenger vehicle speeds. *Traffic Injury Prevention*, *18*(5), 500–507. https://doi.org/10.1080/15389588.2016.1241994

McDuffie, E. E., Martin, R. V., Spadaro, J. V., Burnett, R., Smith, S. J., O'Rourke, P., Hammer, M. S., van Donkelaar, A., Bindle, L., Shah, V., Jaeglé, L., Luo, G., Yu, F., Adeniran, J. A., Lin, J., & Brauer, M. (2021). Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales. *Nature Communications 2021 12:1*, *12*(1), 1–12. https://doi.org/10.1038/s41467-021-23853-y

Mehlig, D., Staffell, I., Stettler, M., & ApSimon, H. (2023). Accelerating electric vehicle uptake favours greenhouse gas over air pollutant emissions. *Transportation Research Part D: Transport and Environment*, *124*, 103954. https://doi.org/10.1016/J.TRD.2023.103954

Meltzer, J., Hultman, N. E., & Langley, C. (2014). Low-Carbon Energy Transitions in Qatar and the Gulf Cooperation Council Region. *SSRN Electronic Journal*, *February*. https://doi.org/10.2139/ssrn.2408743

Messagie, M., Boureima, F.-S., Coosemans, T., Macharis, C., & Mierlo, J. Van. (2014). A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels. *Energies 2014, Vol. 7, Pages 1467-1482*, *7*(3), 1467–1482. https://doi.org/10.3390/EN7031467

Meyer, S. (2024). *Average miles driven per year in the U.S.* https://www.thezebra.com/resources/driving/average-miles-driven-per-year/#average-miles-driven-per-year-by-state

Michiels, H., Mayeres, I., Int Panis, L., De Nocker, L., Deutsch, F., & Lefebvre, W. (2012). PM2.5 and NOx from traffic: Human health impacts, external costs and policy implications from the Belgian perspective. *Transportation Research Part D: Transport and Environment*, *17*(8), 569–577. https://doi.org/10.1016/J.TRD.2012.07.001

Milman, O. (2021). *Car firms agree at Cop26 to end sale of fossil fuel vehicles by 2040 | Cop26 | The Guardian*. https://www.theguardian.com/environment/2021/nov/10/cop26-car-firms-agree-to-end-sale-of-fossil-fuel-vehicles-by-2040

Ministry of Development Planning and Statistics. (2018). *Qatar Second National Development Strategy 2018~2022*. 337.

Ministry of Interior. (2019). *TRANSPORT AND COMMUNICATIONS STATISTICS*.

Ministry of Municipality. (n.d.). *Climate Change Strategy for Urban Planning and Urban Development Sector in the State of Qatar*.

Ministry of Municipality and Environment. (2021). *Nationally Determined Contribution (NDC)*.

Ministry of Transport. (2022). *Delivery of Qatar's Electric Bus Fleet for FIFA World Cup 2022 Completed*. https://www.mot.gov.qa/en/news/delivery-qatars-electric-bus-fleet-fifa-world-cup-2022-completed

Ministry of Transport. (2023). *Transportation Master Plan for Qatar-2050*. https://www.mot.gov.qa/en/land-transport/transportation-master-plan-for-qatar-2050

Mirkin, B. (2010). Population levels, trends and policies in the Arab Region: Challenges and opportunities, Arab Human Development Report. *United Nations Development Programme*, 1–41.

Mohammed, S. (2021). *Qatar's National Emission Inventory Report*. *March*, 222. https://figshare.com/articles/QATAR_S_NATIONAL_EMISSION_INVENTORY_REPORT/4161213/2

Mohammed, S. S. (2017). *Environmental Awareness, Attitudes and Actions: A Baseline Survey of the Citizens and Residents of Qatar*.

Morgan, S. (2019). *EU agrees on 37.5% CO2 reduction for cars by 2030*. https://www.euractiv.com/section/transport/news/eu-agrees-on-37-5-co2-reduction-for-cars-by-2030/

Muneer, T., & García, I. I. (2017). The automobile. *Electric Vehicles: Prospects and Challenges*, 1–91. https://doi.org/10.1016/B978-0-12-803021-9.00001-X

Nanaki, E. A., & Koroneos, C. J. (2013). Comparative economic and environmental analysis of conventional, hybrid and electric vehicles - The case study of Greece. *Journal of Cleaner Production*, *53*, 261–266. https://doi.org/10.1016/j.jclepro.2013.04.010

Nealer, R., Reichmuth, D., & Anair, D. (2015). *Cleaner Cars from Cradle to Grave How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions*. www.ucsusa.org

Newby, D. E., Mannucci, P. M., Tell, G. S., Baccarelli, A. A., Brook, R. D., Donaldson, K., Forastiere, F., Franchini, M., Franco, O. H., Graham, I., Hoek, G., Hoffmann, B., Hoylaerts, M. F., Kü Nzli, N., Mills, N., Pekkanen, J., Peters, A., Piepoli, M. F., Rajagopalan, S., & Storey, R. F. (2015). *Expert position paper on air pollution and cardiovascular disease*. https://doi.org/10.1093/eurheartj/ehu458

Nordelöf, A., Messagie, M., Tillman, A. M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can

we learn from life cycle assessment? *International Journal of Life Cycle Assessment*, *19*(11), 1866–1890. https://doi.org/10.1007/S11367-014-0788-0/TABLES/6

Nordic Energy Research, & IEA. (2013). *Nordic Energy Technology Perspectives*. www.iea.org/etp/nordic

Northeast States for Coordinated Air Use Management. (2022). *MULTI-STATE MEDIUM-AND HEAVY-DUTY ZERO-EMISSION VEHICLE ACTION PLAN: A POLICY FRAMEWORK TO ELIMINATE HARMFUL TRUCK AND BUS EMISSIONS*.

Ntziachristos, L., & Samaras, Z. (2019). Methodology for the Calculation of Exhaust Emissions. *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019 – Update Oct. 2020*, *53*(9), 1689–1699.

O'connell, A., Pavlenko, N., Bieker, G., & Searle, S. (2023). *A COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF EUROPEAN HEAVY-DUTY VEHICLES AND FUELS*. www.theicct.orgcommunications@theicct.org

Odyssee-Mure. (2023). *Sectoral Profile-Transport Energy consumption trends in transport in the EU Energy consumption of transport in selected countries*.

Office of Energy Efficiency and Renewable Energy. (2021). *Fuel Economy in Hot Weather*. https://www.fueleconomy.gov/feg/hotweather.shtml

Okonkwo, E. C., Wole-Osho, I., Bamisile, O., Abid, M., & Al-Ansari, T. (2021). Grid integration of renewable energy in Qatar: Potentials and limitations. *Energy*, *235*, 121310. https://doi.org/10.1016/J.ENERGY.2021.121310

Onat, N. C., Kucukvar, M., Aboushaqrah, N. N. M., & Jabbar, R. (2019). How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar. *Applied Energy*, *250*, 461–477. https://doi.org/10.1016/j.apenergy.2019.05.076

Ou, X., Zhang, X., Zhang, X., & Zhang, Q. (2013). Life Cycle GHG of NG-Based Fuel and Electric Vehicle in China. *Energies 2013, Vol. 6, Pages 2644-2662*, *6*(5), 2644–2662. https://doi.org/10.3390/EN6052644

Pan, S., Fulton, L. M., Roy, A., Jung, J., Choi, Y., & Gao, H. O. (2021). Shared use of electric autonomous vehicles: Air quality and health impacts of future mobility in the United States. *Renewable and Sustainable Energy Reviews*, *149*, 111380. https://doi.org/10.1016/J.RSER.2021.111380

Particle Measurement Programme. (2016). *Terms of reference and rules of procedure for the Informal Working Group on the Particle Measurement Programme*.

Perera, F., & Nadeau, K. (2022). Climate Change, Fossil-Fuel Pollution, and Children's Health. *New England Journal of Medicine*, *386*(24), 2303–2314.

https://doi.org/10.1056/NEJMRA2117706/SUPPL_FILE/NEJMRA2117706_DISCLOSURES.PDF

Peterson, M., Sessa, C., Enei, R., Ulied, A., Larrea, E., Obisco, O., Timms, P., & Hensen, C. (2009). *TRANSvisions Contract A2/78-2007: Report on Transport Scenarios with a 20 and 40 Year Horizon Final Report*.

Plötz, P., Link, S., Ringelschwendner, H., Keller, M., Moll, C., Bieker, G., Dornoff, J., & Mock, P. (2022). *REAL-WORLD USAGE OF PLUG-IN HYBRID VEHICLES IN EUROPE A 2022 UPDATE ON FUEL CONSUMPTION, ELECTRIC DRIVING, AND CO 2 EMISSIONS*. www.theicct.orgcommunications@theicct.org

PRé Sustainability. (2016). *ReCiPe*. https://pre-sustainability.com/articles/recipe/

Proost, S., & Van Dender, K. (2012). Energy and environment challenges in the transport sector. *Economics of Transportation*, *1*(1–2), 77–87. https://doi.org/10.1016/J.ECOTRA.2012.11.001

PwC. (2022). *The Dawn of Electrified Trucking*.

Qader, M. R., Khan, S., Kamal, M., Usman, M., & Haseeb, M. (2022). Forecasting carbon emissions due to electricity power generation in Bahrain. *Environmental Science and Pollution Research*, *29*(12), 17346–17357. https://doi.org/10.1007/S11356-021-16960-2/TABLES/3

Qatar Civil Aviation Authority. (2021). *Meteorological Conditions*. https://www.caa.gov.qa/en-us/Pages/Metrogical.aspx

Qatar General Electricity & Water Corporation (KAHRAMAA). (2018). *KAHRAMAA Launches "Electric Car Charging Stations Project–Phase 1."* https://www.km.qa/MediaCenter/Pages/NewsDetails.aspx?ItemID=266

Rabbi, M. F., Popp, J., Máté, D., & Kovács, S. (2022). Energy Security and Energy Transition to Achieve Carbon Neutrality. *Energies 2022, Vol. 15, Page 8126*, *15*(21), 8126. https://doi.org/10.3390/EN15218126

Readfearn, G. (2019). *Renewables meet 50% of electricity demand on Australia's power grid for first time*. The Guardian. https://www.theguardian.com/environment/2019/nov/07/renewables-meet-50-of-electricity-demand-on-australias-power-grid-for-first-time

Reap, J., Roman, F., Duncan, S., & Bras, B. (2008). A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation. *International Journal of Life Cycle Assessment*, *13*(5), 374–388. https://doi.org/10.1007/S11367-008-0009-9/TABLES/1

Reiter, M. S., Kockelman, K. M., & Schoch, E. P. (2016). *The problem of cold starts: A closer look at mobile source emissions levels*. https://doi.org/10.1016/j.trd.2015.12.012

S. Rangarajan, S., Sunddararaj, S. P., Sudhakar, A. V. V., Shiva, C. K., Subramaniam, U., Collins, E. R., & Senjyu, T. (2022). Lithium-Ion Batteries—The Crux of Electric Vehicles with Opportunities and Challenges. In *Clean Technologies* (Vol. 4, Issue 4, pp. 908–930). MDPI. https://doi.org/10.3390/cleantechnol4040056

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2022). PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable and Sustainable Energy Reviews*, *160*, 112311. https://doi.org/10.1016/J.RSER.2022.112311

Safak Bayram, I. (2019). A Stochastic Simulation Model to Assess the Impacts of Electric Vehicle Charging on Power Generation: A Case Study for Qatar. *ITEC 2019 - 2019 IEEE Transportation Electrification Conference and Expo*. https://doi.org/10.1109/ITEC.2019.8790585

Samaras, C., & Meisterling, K. (2008). Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy. *Environmental Science and Technology*, *42*(9), 3170–3176. https://doi.org/10.1021/ES702178S/SUPPL_FILE/ES702178S-FILE004.PDF

Santos, G., Maoh, H., Potoglou, D., & von Brunn, T. (2013). Factors influencing modal split of commuting journeys in medium-size European cities. *Journal of Transport Geography*, *30*, 127–137. https://doi.org/10.1016/J.JTRANGEO.2013.04.005

Schafer, A., & Victor, D. G. (1999). Global passenger travel: implications for carbon dioxide emissions. *Energy*, *24*, 657–679. www.elsevier.com/locate/energy

Schmuch, R., Wagner, R., Hörpel, G., Placke, T., & Winter, M. (2018). Performance and cost of materials for lithium-based rechargeable automotive batteries. In *Nature Energy* (Vol. 3, Issue 4, pp. 267–278). Nature Publishing Group. https://doi.org/10.1038/s41560-018-0107-2

Schraufnagel, D. E., Balmes, J. R., Cowl, C. T., De Matteis, S., Jung, S.-H., Mortimer, K., Perez-Padilla, R., Rice, M. B., Riojas-Rodriguez, H., Sood, A., Thurston, G. D., To, T., Vanker, A., & Wuebbles, D. J. (2019). *Air Pollution and Noncommunicable Diseases A Review by the Forum of International Respiratory Societies' Environmental Committee, Part 2: Air Pollution and Organ Systems*. https://doi.org/10.1016/j.chest.2018.10.041

Schwertner, M., & Weidmann, U. (2016). Comparison of Well-to-Wheel Efficiencies for Different Drivetrain Configurations of Transit Buses. *Https://Doi.Org/10.3141/2539-07*, *2539*, 55–64. https://doi.org/10.3141/2539-07

Scott, V. (2014). *WHO: Doha ranked among the world's most polluted cities*. https://www.dohanews.co/doha-one-worlds-polluted-cities/

Sen, A. K., Tiwari, G., & Upadhyay, V. (2010). Estimating marginal external costs of transport in Delhi. *Transport Policy*, *17*(1), 27–37. https://doi.org/10.1016/J.TRANPOL.2009.09.003

Shaaban, K. (2020). Why don't people ride bicycles in high-income developing countries, and can bike-sharing be the solution? The case of qatar. *Sustainability (Switzerland)*, *12*(4). https://doi.org/10.3390/su12041693

Shahi, S. K., & Wang, G. G. (2010). Plug-In Hybrid Electric Vehicle Battery Selection for Optimum Economic and Environmental Benefits Using Pareto Set Points and PSAT™. *Proceedings of the ASME Design Engineering Technical Conference*, *1*(PARTS A AND B), 701–713. https://doi.org/10.1115/DETC2010-28972

Shannak, S., & Contestabile, M. (2022). Does Qatar Face a Trade-off Between Economic Growth and CO2 Emissions? *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.855971

Sharma, R., Manzie, C., Bessede, M., Crawford, R. H., & Brear, M. J. (2013). Conventional, hybrid and electric vehicles for Australian driving conditions. Part 2: Life cycle CO2-e emissions. *Transportation Research Part C: Emerging Technologies*, *28*, 63–73. https://doi.org/10.1016/J.TRC.2012.12.011

Silva, C. (2013). At what extent the benefits of introducing alternative light-duty vehicles offset those of increasing the buses average occupancy? *Energy Conversion and Management*, *70*, 211–219. https://doi.org/10.1016/J.ENCONMAN.2013.02.019

Skinner, I., Essen, H. Van, Smokers, R., & Hill, N. (2010). *Towards the decarbonisation of the EU's transport sector by 2050*. https://www.etipbioenergy.eu/databases/reports/95-towards-the-decarbonisation-of-the-eu-s-transport-sector-by-2050

Skytte, K., Pizarro, A., & Karlsson, K. B. (2017). Use of electric vehicles or hydrogen in the Danish transport sector in 2050? *Wiley Interdisciplinary Reviews: Energy and Environment*, *6*(1), e233. https://doi.org/10.1002/WENE.233

Sprei, F. (2018). Disrupting mobility. *Energy Research & Social Science*, *37*, 238–242. https://doi.org/10.1016/J.ERSS.2017.10.029

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P. E., Ekins, P., Shah, N., & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, *12*(2), 463–491. https://doi.org/10.1039/C8EE01157E

Standardization Organization for G.C.C. (2003). *Motor vehicles allowable limits of gaseous pollutants emitted to the atmosphere from unleaded gasoline engined vehicles*.

Stanley, J. K., Hensher, D. A., & Loader, C. (2011). Road transport and climate change: Stepping off the greenhouse gas. *Transportation Research Part A: Policy and Practice*, *45*(10), 1020–1030. https://doi.org/10.1016/J.TRA.2009.04.005

Strapasson, A., Kalas, N., & Woods, J. (2014). *Briefing Paper on Land, Food and Bioenergy of the Global Calculator Project 1*. www.globalcalculator.org

Strapasson, A., Woods, J., Pérez-Cirera, V., Elizondo, A., Cruz-Cano, D., Pestiaux, J., Cornet, M., & Chaturvedi, R. (2020). Modelling carbon mitigation pathways by 2050: Insights from the Global Calculator. *Energy Strategy Reviews*, *29*, 100494. https://doi.org/10.1016/J.ESR.2020.100494

Tagliaferri, C., Evangelisti, S., Acconcia, F., Domenech, T., Ekins, P., Barletta, D., & Lettieri, P. (2016). Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chemical Engineering Research and Design*, *112*, 298–309. https://doi.org/10.1016/J.CHERD.2016.07.003

Taylor, E., Martin, B., Latiers, M., Cornet, M., & Pestiaux, J. (2020). *Transport Module Documentation*.

Texas A&M Transportation Institute. (2016). *Methodologies Used to Estimate and Forecast Vehicle Miles Traveled (VMT)*.

The GHG Protocol. (2019). *Global Protocol for Community-Scale Greenhouse Gas Inventories*.

The Institute of Life Cycle Assessment Japan. (2015). *Databases and guidelines*. https://ilcaj.org/en/database.php

The International Council on Clean Transport. (2020). *Electric Vehicles*. https://theicct.org/electric-vehicles

The Tyre Collective. (2024). *The Tyre Collective*. https://thetyrecollective.com/

The World Bank. (2020). *GDP per capita, PPP (constant 2017 international $)*. https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD?most_recent_value_desc=true&year_high_desc=true

Timmers, V. R. J. H., & Achten, P. A. J. (2016). Non-exhaust PM emissions from electric vehicles. *Atmospheric Environment*, *134*, 10–17. https://doi.org/10.1016/j.atmosenv.2016.03.017

Timmers, V. R. J. H., & Achten, P. A. J. (2018). Non-Exhaust PM Emissions From Battery Electric Vehicles. *Non-Exhaust Emissions*, 261–287. https://doi.org/10.1016/B978-0-12-811770-5.00012-1

Tiwari, G. (2002). Urban Transport Priorities. *Cities*, *19*(2), 95–103. https://doi.org/10.1016/s0264-2751(02)00004-5

TotalEnergies. (2022). *Qatar: TotalEnergies announces the startup of Al Kharsaah (800 MWp), one of the largest solar power plants in the Middle East*.

Transport & Environment. (2017). *Roadmap to climate-friendly land freight and buses in Europe*. www.transportenvironment.org

Trofimenko, Y., Komkov, V., & Trofimenko, K. (2020). Forecast of energy consumption and greenhouse gas emissions by road transport in Russia up to 2050. *Transportation Research Procedia*. https://doi.org/10.1016/j.trpro.2020.10.082

Truong, L. T., De Gruyter, C., Currie, G., & Delbosc, A. (2017). Estimating the trip generation impacts of autonomous vehicles on car travel in Victoria, Australia. *Transportation*, *44*(6), 1279–1292. https://doi.org/10.1007/S11116-017-9802-2/FIGURES/5

UK Energy Research Centre. (2019). *Review of Energy Policy 2019*. https://doi.org/10.2139/ssrn.3291655

Ummelas, O. (2023). *Norway Risks Missing 2025 EV Sales Goal, Federation Says - Bloomberg*. https://www.bloomberg.com/news/articles/2023-11-01/norway-risks-missing-2025-ev-sales-goal-federation-says

United States Department of Energy. (2020). *Argonne GREET Model*. https://greet.es.anl.gov/

US Department of Energy. (2021). *Solar Futures Study*. https://www.energy.gov/eere/solar/solar-futures-study

U.S. Department of Energy, & EPA. (n.d.). *The Official U.S. Government Source for Fuel Economy Information*. Retrieved February 3, 2024, from https://www.fueleconomy.gov/

U.S. Energy Information Administration. (2021). *Annual Energy Outlook 2021*. https://www.eia.gov/outlooks/aeo/

U.S. EPA. (2012). *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) TRACI version 2.1 User's Guide*. www.epa.gov/research

U.S. EPA. (2021). *Greenhouse Gases at EPA | US EPA*. https://www.epa.gov/greeningepa/greenhouse-gases-epa

U.S. EPA. (2022). *The 2022 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975*. www.epa.gov/automotive-trends.

Van den Bossche, P., Vergels, F., Van Mierlo, J., Matheys, J., & Van Autenboer, W. (2006). SUBAT: An assessment of sustainable battery technology. *Journal of Power Sources*, *162*(2), 913–919. https://doi.org/10.1016/J.JPOWSOUR.2005.07.039

Vattanapuripakorn, W., Sonsupap, S., Khannam, K., Bamrungwong, N., Kaewkhiaw, P., Sarasamkan, J., & Bubphachot, B. (2022). Advanced Electric Battery Power Storage for

Motors through the Use of Differential Gears and High Torque for Recirculating Power Generation. *Clean Technologies 2022, Vol. 4, Pages 987-1000*, *4*(4), 987–1000. https://doi.org/10.3390/CLEANTECHNOL4040061

Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., Cosme, N., Cucurachi, S., de Baan, L., Dong, Y., Fantke, P., Golsteijn, L., Hauschild, M., Heijungs, R., Jolliet, O., Juraske, R., Larsen, H., Laurent, A., Mutel, C. L., Margni, M., … Huijbregts, M. A. J. (2020). LC-IMPACT: A regionalized life cycle damage assessment method. *Journal of Industrial Ecology*, *24*(6), 1201–1219. https://doi.org/10.1111/JIEC.13018

Volvo Trucks. (2022). *Volvo's heavy-duty electric truck is put to the test: excels in both range and energy efficiency*. https://www.volvotrucks.com/en-en/news-stories/press-releases/2022/jan/volvos-heavy-duty-electric-truck-is-put-to-the-test-excels-in-both-range-and-energy-efficiency.html

Walmsley, M. R. W., Walmsley, T. G., Atkins, M. J., Kamp, P. J. J., Neale, J. R., & Chand, A. (2015). Carbon Emissions Pinch Analysis for emissions reductions in the New Zealand transport sector through to 2050. *Energy*, *92*, 569–576. https://doi.org/10.1016/J.ENERGY.2015.04.069

Wang, H., Ou, X., & Zhang, X. (2017). Mode, technology, energy consumption, and resulting CO 2 emissions in China's transport sector up to 2050. *Energy Policy*. https://doi.org/10.1016/j.enpol.2017.07.010

Wang, Y., Teter, J., & Sperling, D. (2011). China's soaring vehicle population: Even greater than forecasted? *Energy Policy*, *39*(6), 3296–3306. https://doi.org/10.1016/J.ENPOL.2011.03.020

Wi, H., & Park, J. (2013). ANALYZING UNCERTAINTY IN EVALUATION OF VEHICLE FUEL ECONOMY USING FTP-75. *International Journal of Automotive Technology*, *14*(3), 471–477. https://doi.org/10.1007/s12239−013−0051−x

Williams, T. A., Chigoy, B., Borowiec, J., & Glover, B. (2016). *Methodologies Used to Estimate and Forecast Vehicle Miles Traveled (VMT)*.

Winkler, S. L., Anderson, J. E., Garza, L., Ruona, W. C., Vogt, R., & Wallington, T. J. (2018). Vehicle criteria pollutant (PM, NOx, CO, HCs) emissions: how low should we go? *Npj Climate and Atmospheric Science 2018 1:1*, *1*(1), 1–5. https://doi.org/10.1038/s41612-018-0037-5

World Bank. (2022). *Qatar key conditions and challenges*.

WorldAtlas. (2018). *Countries That Will Ban Gasoline Cars - WorldAtlas*. https://www.worldatlas.com/articles/countries-that-will-ban-gasoline-cars.html

Yan, S., de Bruin, K., Dennehy, E., & Curtis, J. (2021). Climate policies for freight transport: Energy and emission projections through 2050. *Transport Policy*, *107*, 11–23. https://doi.org/10.1016/J.TRANPOL.2021.04.005

Yorifuji, T., Kashima, S., Tsuda, T., Ishikawa-Takata, K., Ohta, T., Tsuruta, K. I., & Doi, H. (2013). Long-term exposure to traffic-related air pollution and the risk of death from hemorrhagic stroke and lung cancer in Shizuoka, Japan. *Science of The Total Environment*, *443*, 397–402. https://doi.org/10.1016/J.SCITOTENV.2012.10.088

Appendix A: Life Cycle Assessment Results

Table A.1: Full ReCiPe Midpoint results, ICEV sedan 2022-2050.

Impact category	Unit	ICEV LDV sedan 2022	ICEV LDV sedan 2030	ICEV LDV sedan 2040	ICEV LDV sedan 2050
Global warming	kg CO2 eq	2.34E-01	2.11E-01	1.87E-01	1.63E-01
Stratospheric ozone depletion	kg CFC11 eq	1.54E-07	1.39E-07	9.83E-08	5.73E-08
Ionizing radiation	kBq Co-60 eq	4.66E-03	4.40E-03	3.78E-03	3.17E-03
Ozone formation, Human health	kg NOx eq	3.53E-04	3.31E-04	2.75E-04	2.29E-04
Fine particulate matter formation	kg PM2.5 eq	2.27E-04	2.09E-04	1.64E-04	1.29E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.82E-04	3.59E-04	3.01E-04	2.52E-04
Terrestrial acidification	kg SO2 eq	5.49E-04	4.97E-04	3.62E-04	2.58E-04
Freshwater eutrophication	kg P eq	6.92E-05	6.51E-05	5.58E-05	4.67E-05
Marine eutrophication	kg N eq	2.58E-06	2.51E-06	2.38E-06	2.29E-06
Terrestrial ecotoxicity	kg 1,4-DCB	1.28E+00	1.24E+00	1.12E+00	1.03E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.14E-02	1.13E-02	1.11E-02	1.10E-02
Marine ecotoxicity	kg 1,4-DCB	1.50E-02	1.49E-02	1.46E-02	1.43E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.22E-02	1.20E-02	1.16E-02	1.12E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.47E-01	1.44E-01	1.38E-01	1.33E-01
Land use	m2a crop eq	8.29E-03	7.88E-03	6.90E-03	5.95E-03
Mineral resource scarcity	kg Cu eq	7.89E-04	7.80E-04	7.48E-04	7.24E-04
Fossil resource scarcity	kg oil eq	8.76E-02	7.90E-02	5.70E-02	3.50E-02
Water consumption	m3	4.55E-04	4.47E-04	4.29E-04	4.17E-04

Table A.2: Full ReCiPe Midpoint results, ICEV sports 2022-2050.

Impact category	Unit	ICEV LDV sport 2022	ICEV LDV sport 2030	ICEV LDV sport 2040	ICEV LDV sport 2050
Global warming	kg CO2 eq	2.65E-01	2.40E-01	2.62E-01	1.92E-01
Stratospheric ozone depletion	kg CFC11 eq	1.83E-07	1.65E-07	1.84E-07	1.01E-07
Ionizing radiation	kBq Co-60 eq	5.43E-03	5.15E-03	5.38E-03	4.21E-03
Ozone formation, Human health	kg NOx eq	4.07E-04	3.83E-04	3.83E-04	2.93E-04

Fine particulate matter formation	kg PM2.5 eq	2.63E-04	2.43E-04	2.35E-04	1.68E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.41E-04	4.15E-04	4.15E-04	3.20E-04
Terrestrial acidification	kg SO2 eq	6.29E-04	5.71E-04	5.47E-04	3.46E-04
Freshwater eutrophication	kg P eq	8.05E-05	7.60E-05	7.98E-05	6.21E-05
Marine eutrophication	kg N eq	3.07E-06	2.99E-06	2.96E-06	2.78E-06
Terrestrial ecotoxicity	kg 1,4-DCB	1.59E+00	1.55E+00	1.53E+00	1.35E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.34E-02	1.34E-02	1.33E-02	1.31E-02
Marine ecotoxicity	kg 1,4-DCB	1.78E-02	1.77E-02	1.76E-02	1.71E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.47E-02	1.44E-02	1.44E-02	1.37E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.72E-01	1.69E-01	1.67E-01	1.59E-01
Land use	m2a crop eq	1.01E-02	9.67E-03	1.00E-02	8.19E-03
Mineral resource scarcity	kg Cu eq	9.21E-04	9.11E-04	9.04E-04	8.57E-04
Fossil resource scarcity	kg oil eq	9.92E-02	8.96E-02	9.97E-02	5.70E-02
Water consumption	m3	5.48E-04	5.39E-04	5.33E-04	5.09E-04

Table A.3: Full ReCiPe Midpoint results, ICEV SUV 2022-2050.

Impact category	Unit	ICEV LDV SUV 2022	ICEV LDV SUV 2030	ICEV LDV SUV 2040	ICEV LDV SUV 2050
Global warming	kg CO2 eq	4.08E-01	3.67E-01	3.31E-01	2.93E-01
Stratospheric ozone depletion	kg CFC11 eq	2.48E-07	2.23E-07	2.02E-07	1.12E-07
Ionizing radiation	kBq Co-60 eq	7.50E-03	7.03E-03	6.65E-03	5.22E-03
Ozone formation, Human health	kg NOx eq	5.57E-04	5.18E-04	4.67E-04	3.54E-04
Fine particulate matter formation	kg PM2.5 eq	3.72E-04	3.39E-04	2.91E-04	2.05E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.00E-04	5.58E-04	5.05E-04	3.85E-04
Terrestrial acidification	kg SO2 eq	9.19E-04	8.24E-04	6.81E-04	4.25E-04
Freshwater eutrophication	kg P eq	1.12E-04	1.05E-04	9.93E-05	7.70E-05
Marine eutrophication	kg N eq	3.86E-06	3.73E-06	3.59E-06	3.38E-06
Terrestrial ecotoxicity	kg 1,4-DCB	2.03E+00	1.97E+00	1.84E+00	1.64E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.66E-02	1.64E-02	1.62E-02	1.88E-02
Marine ecotoxicity	kg 1,4-DCB	2.20E-02	2.18E-02	2.15E-02	2.49E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.84E-02	1.81E-02	1.76E-02	1.67E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	0.21663697	0.2112145	0.20474431	0.30483373

Land use	m2a crop eq	0.01386796	0.0131238	0.01252927	0.01016892
Mineral resource scarcity	kg Cu eq	0.00115518	0.00113845	0.00110293	0.00104538
Fossil resource scarcity	kg oil eq	0.15433493	0.13865292	0.12688148	0.07214022
Water consumption	m3	0.00068383	0.00066929	0.00064823	0.00171281

Table A.4: Full ReCiPe Endpoint results, ICEV sedan 2022-2050.

Damage category	Unit	ICEV LDV sedan 2022	ICEV LDV sedan 2030	ICEV LDV sedan 2040	ICEV LDV sedan 2050
Human health	DALY	4.35E-07	4.01E-07	3.16E-07	2.38E-07
Ecosystems	species.yr	9.69E-10	8.85E-10	6.69E-10	4.64E-10
Resources	USD2013	3.73E-02	3.35E-02	2.36E-02	1.37E-02

Table A.5: Full ReCiPe Endpoint results, ICEV sport 2022-2050.

Damage category	Unit	ICEV LDV sport 2022	ICEV LDV sport 2030	ICEV LDV sport 2040	ICEV LDV sport 2050
Human health	DALY	5.00E-07	4.63E-07	4.78E-07	3.29E-07
Ecosystems	species.yr	1.11E-09	1.02E-09	1.08E-09	6.85E-10
Resources	USD2013	4.21E-02	3.79E-02	4.25E-02	2.33E-02

Table A.6: Full ReCiPe Endpoint results, ICEV SUV 2022-2050.

Damage category	Unit	ICEV LDV SUV 2022	ICEV LDV SUV 2030	ICEV LDV SUV 2040	ICEV LDV SUV 2050
Human health	DALY	7.24E-07	6.63E-07	5.97E-07	4.37E-07
Ecosystems	species.yr	1.66E-09	1.50E-09	1.35E-09	8.77E-10
Resources	USD2013	6.63E-02	5.94E-02	5.42E-02	2.96E-02

Table A.7: Full ReCiPe Midpoint results, BEV sedan 2022-2050.

Impact category	Unit	BEV LDV sedan 2022	BEV LDV sedan 2030	BEV LDV sedan 2040	BEV LDV sedan 2050
Global warming	kg CO2 eq	1.91E-01	1.73E-01	1.62E-01	1.54E-01
Stratospheric ozone depletion	kg CFC11 eq	8.07E-08	7.38E-08	7.01E-08	6.70E-08
Ionizing radiation	kBq Co-60 eq	1.22E-02	1.21E-02	1.19E-02	1.18E-02
Ozone formation, Human health	kg NOx eq	4.70E-04	4.55E-04	4.46E-04	4.39E-04
Fine particulate matter formation	kg PM2.5 eq	3.13E-04	3.08E-04	3.05E-04	3.03E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.40E-04	5.25E-04	5.16E-04	5.08E-04
Terrestrial acidification	kg SO2 eq	7.35E-04	7.23E-04	7.15E-04	7.08E-04
Freshwater eutrophication	kg P eq	1.38E-04	1.37E-04	1.36E-04	1.35E-04
Marine eutrophication	kg N eq	1.15E-05	1.14E-05	1.14E-05	1.13E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.25E+00	3.22E+00	3.19E+00	3.18E+00
Freshwater ecotoxicity	kg 1,4-DCB	5.31E-02	5.20E-02	5.13E-02	5.07E-02
Marine ecotoxicity	kg 1,4-DCB	6.87E-02	6.73E-02	6.64E-02	6.57E-02
Human carcinogenic toxicity	kg 1,4-DCB	3.06E-02	3.03E-02	2.99E-02	2.97E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	8.40E-01	8.30E-01	8.20E-01	8.14E-01
Land use	m2a crop eq	7.15E-03	7.00E-03	6.92E-03	6.85E-03
Mineral resource scarcity	kg Cu eq	3.56E-03	3.52E-03	3.49E-03	3.46E-03
Fossil resource scarcity	kg oil eq	6.66E-02	5.87E-02	5.45E-02	5.10E-02
Water consumption	m3	1.41E-01	1.38E-01	1.34E-01	1.31E-01

Table A.8: Full ReCiPe Midpoint results, BEV sports 2022-2050.

Impact category	Unit	BEV LDV sport 2022	BEV LDV sport 2030	BEV LDV sport 2040	BEV LDV sport 2050
Global warming	kg CO2 eq	2.17E-01	2.01E-01	1.88E-01	1.62E-01
Stratospheric ozone depletion	kg CFC11 eq	8.97E-08	8.42E-08	7.92E-08	6.97E-08
Ionizing radiation	kBq Co-60 eq	1.33E-02	1.31E-02	1.29E-02	1.27E-02
Ozone formation, Human health	kg NOx eq	4.95E-04	4.82E-04	4.71E-04	4.49E-04
Fine particulate matter formation	kg PM2.5 eq	3.25E-04	3.20E-04	3.17E-04	3.10E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.65E-04	5.52E-04	5.41E-04	5.19E-04
Terrestrial acidification	kg SO2 eq	7.66E-04	7.55E-04	7.45E-04	7.29E-04
Freshwater eutrophication	kg P eq	1.44E-04	1.43E-04	1.42E-04	1.40E-04
Marine eutrophication	kg N eq	1.17E-05	1.17E-05	1.16E-05	1.15E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.35E+00	3.32E+00	3.29E+00	3.24E+00
Freshwater ecotoxicity	kg 1,4-DCB	5.53E-02	5.44E-02	5.35E-02	5.19E-02
Marine ecotoxicity	kg 1,4-DCB	7.16E-02	7.04E-02	6.93E-02	6.73E-02
Human carcinogenic toxicity	kg 1,4-DCB	3.20E-02	3.16E-02	3.12E-02	3.07E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	8.89E-01	8.78E-01	8.67E-01	8.54E-01
Land use	m2a crop eq	7.38E-03	7.26E-03	7.15E-03	6.95E-03
Mineral resource scarcity	kg Cu eq	3.74E-03	3.70E-03	3.66E-03	3.61E-03
Fossil resource scarcity	kg oil eq	7.68E-02	7.04E-02	6.48E-02	5.39E-02
Water consumption	m3	1.66E-01	1.62E-01	1.58E-01	1.54E-01

Table A.9: Full ReCiPe Midpoint results, BEV SUV 2022-2050.

Impact category	Unit	BEV LDV SUV 2022	BEV LDV SUV 2030	BEV LDV SUV 2040	BEV LDV SUV 2050
Global warming	kg CO2 eq	2.22E-01	1.98E-01	1.85E-01	1.75E-01
Stratospheric ozone depletion	kg CFC11 eq	9.14E-08	8.26E-08	7.80E-08	7.41E-08
Ionizing radiation	kBq Co-60 eq	1.47E-02	1.45E-02	1.43E-02	1.41E-02
Ozone formation, Human health	kg NOx eq	5.06E-04	4.87E-04	4.75E-04	4.66E-04
Fine particulate matter formation	kg PM2.5 eq	3.35E-04	3.29E-04	3.25E-04	3.22E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.76E-04	5.56E-04	5.45E-04	5.36E-04
Terrestrial acidification	kg SO2 eq	7.94E-04	7.79E-04	7.68E-04	7.60E-04

Freshwater eutrophication	kg P eq	1.52E-04	1.50E-04	1.48E-04	1.47E-04
Marine eutrophication	kg N eq	1.20E-05	1.19E-05	1.19E-05	1.18E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.45E+00	3.40E+00	3.37E+00	3.34E+00
Freshwater ecotoxicity	kg 1,4-DCB	5.67E-02	5.53E-02	5.44E-02	5.36E-02
Marine ecotoxicity	kg 1,4-DCB	7.36E-02	7.18E-02	7.07E-02	6.97E-02
Human carcinogenic toxicity	kg 1,4-DCB	3.35E-02	3.29E-02	3.25E-02	3.22E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	9.49E-01	9.36E-01	9.24E-01	9.14E-01
Land use	m2a crop eq	7.48E-03	7.29E-03	7.19E-03	7.10E-03
Mineral resource scarcity	kg Cu eq	3.95E-03	3.90E-03	3.85E-03	3.82E-03
Fossil resource scarcity	kg oil eq	7.83E-02	6.84E-02	6.31E-02	5.87E-02
Water consumption	m3	2.01E-01	1.97E-01	1.91E-01	1.87E-01

Table A.10: Full ReCiPe Endpoint results, BEV sedan 2022-2050.

Damage category	Unit	BEV LDV sedan 2022	BEV LDV sedan 2030	BEV LDV sedan 2040	BEV LDV sedan 2050
Human health	DALY	9.80E-07	9.50E-07	9.26E-07	9.08E-07
Ecosystems	species.yr	2.90E-09	2.80E-09	2.71E-09	2.64E-09
Resources	USD2013	2.21E-02	1.93E-02	1.78E-02	1.66E-02

Table A.11: Full ReCiPe Endpoint results, BEV sport 2022-2050.

Damage category	Unit	BEV LDV sport 2022	BEV LDV sport 2030	BEV LDV sport 2040	BEV LDV sport 2050
Human health	DALY	1.08E-06	1.05E-06	1.02E-06	9.82E-07
Ecosystems	species.yr	3.33E-09	3.22E-09	3.12E-09	2.98E-09
Resources	USD2013	2.57E-02	2.34E-02	2.14E-02	1.75E-02

Table A.12: Full ReCiPe Endpoint results, BEV SUV 2022-2050.

Damage category	Unit	BEV LDV SUV 2022	BEV LDV SUV 2030	BEV LDV SUV 2040	BEV LDV SUV 2050
Human health	DALY	1.19E-06	1.15E-06	1.12E-06	1.09E-06
Ecosystems	species.yr	3.83E-09	3.70E-09	3.58E-09	3.49E-09
Resources	USD2013	2.61E-02	2.26E-02	2.07E-02	1.92E-02