The International Journal of Life Cycle Assessment (2025) 30:110–120
https://doi.org/10.1007/s11367-024-02381-z

Environmental impacts of battery electric light-duty vehicles using a dynamic life cycle assessment for qatar's transport system (2022 to 2050)

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Received: 30 April 2024 / Accepted: 21 September 2024 / Published online: 10 October 2024
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Abstract

Purpose This study compares the environmental impacts of transitioning from a business-as-usual (BaU) internal combustion engine vehicles (ICEVs) pathway to one adopting battery electric vehicles (BEVs) in Qatar from 2022 to 2050. The analysis is based on geographically representative empirical data, focusing exclusively on the light-duty, personal vehicle sector. The research explores environmental performance trends, uncertainties, and potential implications of transitioning from ICEVs to BEVs within the Qatar National Vision (QNV) 2030 framework.

Methods Utilising the ReCiPe method, this time-dynamic life cycle assessment (LCA) assessed a range of relevant environmental impact categories: global warming potential, particulate matter, human toxicity, acidification and resource depletion. This analysis incorporates different light-duty vehicle (LDV) types such as sedans, sport utility vehicle (SUVs) and sport vehicles. The impacts of potential technological advancements, such as in fuel efficiency for ICEVs and charging electricity supply and/or battery technology for the BEVs, were included to provide a more encompassing view of the environmental implications of both vehicle types.

Results and discussion Decreasing environmental impact for ICEVs and BEVs is observed, with BEVs' greater potential in reducing Qatar's transport sector's carbon footprint. Uncertainties emerged as this potential decrease was not seen in all impact categories, nor vehicle technology or timeframe. This stresses the BEV's transition importance of production location and energy sources. This was observed for the carbon footprint and overarching environmental impact of battery production, exacerbated in regions reliant on fossil fuel electricity. Qatar, endowed with substantial fossil fuel reserves, relies on natural gas for electricity provision; therefore, the potential benefits of introducing BEVs are limited without strong shifts to renewables. Further research in vehicle production, disposal and technological advancements will prove essential, especially in a maturing sector like electric vehicle production and processing.

Conclusions BEVs have the potential to reduce the environmental impacts of Qatar's transport sector. Yet, the short payback period for newer BEVs is linked with the greenhouse gas intensity of electricity production, emphasising the dual challenge for Qatar with its reliance on fossil fuels. Considering environmental, economic and societal facets, a transition taking into account all facets of sustainability and not purely the introduction of BEVs is imperative in aligning with Qatar's 2030 sustainable vision.

Recommendations A clear understanding of the socio-economic and environmental aspects of the ICEV-BEV transition is urgently required, emphasising production, disposal and technological innovations. Exploring alternative batteries and recycling methods can offer pathways to mitigate environmental concerns associated with BEVs. Regions like Qatar are underrepresented in the available literature, yet should be part of the research on sustainable transitions to provide insights on the opportunity and co-benefits that arise from the development of relevant sustainability transition planning.

Keywords Internal combustion engine vehicle · Battery electric vehicle · Comparative analysis · Qatar · Prospective study · Life cycle assessment · Light duty vehicle

Communicated by Xin Sun.

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1 Introduction

While the transition towards more sustainable transportation presents a promising path forward, its feasibility and effectiveness vary across different regions, production chains and technologies. This variability necessitates an examination that covers the complete life cycle of transportation technologies, considering the associated broader implications. Such an analysis is crucial to understand the diverse challenges and opportunities inherent in sustainable transportation transitions. The transportation sector is as an essential part of the overarching transition, representing 23% of global energy-related CO_2 emissions in 2019. The IPCC makes clear that there is significant urgency in moving away from fossil fuel internal combustion engine vehicles (ICEV) (IPCC 2022). Electric vehicles or battery-operated electric vehicles (BEV) are often put forward as the low-carbon alternative to ICEV.

The global momentum towards BEV adoption is not solely driven by environmental imperatives. Economic, geopolitical and human health factors can be synergistic or antagonistic to a diminishing reliance on fossil fuels (Nandanpawar 2017; Costa et al. 2021). Yet, to accomplish this transition as a part of sustainable transportation, the complete value chain has to be in line with this goal. BEVs have zero tailpipe emissions. However, the narrative surrounding BEVs is multifaceted. While zero tailpipe emissions lead to local pollution reductions and reduced fossil fuel consumption and GHG emissions, it is crucial to take all aspects into account, covering both the strengths and weaknesses of the ICEV and BEV from multiple environmental impact assessments.

Qatar seeks to reduce its carbon impact by introducing a BEV adoption strategy, specifically for its personal, light-duty vehicle (LDV) transport fleet. Kahramaa launched the National Program for Energy Conservation and Efficient Used 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 aims to set up 400 charging stations in Qatar by 2022, inspiring the use of BEV and leading the way to transform 4% of Qatar's vehicle fleet into BEVs by 2022 and 10% by 2030 (Kumar 2019). Major urban centres that are especially grappling with the challenges of transportation and pollution are expected to benefit immensely from widespread BEV adoption (Ellingsen et al. 2014; Pipitone et al. 2021; Rajagopal et al. 2022). Nonetheless, there are overarching concerns, particularly the environmental ramifications of battery production, the ethical considerations surrounding mineral extraction for batteries and the long-term challenges associated with battery recycling and disposal (Raugei and Winfield 2019; Hao et al. 2019).

BEVs are expected to have an advantage in energy efficiency, but the definition should be clearly stated, especially if previous definitions (such as the well-to-wheel (WTW) energy efficiency) are not as straightforward in the ICEV-BEV comparison (Albatayneh et al. 2020). Therefore, when comparing ICEV to BEV, the power source has to be further documented as coal or renewables determine whether the WTW energy efficiency remains respectively on par with ICEV (BEV + coal) or increases significantly in the case renewable energy sources are used (40–70% for BEV + renewables) (Albatayneh et al. 2020).

Even though there are many similarities between BEVs and ICEVs, the underlying characteristics can differ widely. Therefore, comparing BEV and ICEV systems should be done with a holistic understanding of these complexities. This necessitates a rigorous life cycle assessment (LCA) from which life cycle phases can be encompassed. LCA can thus offer insights into the environmental footprint of both BEV and ICEV, going beyond a simplified and often political messages on the comparison between BEV and ICEV options.

The aim of this study is to integrate locally relevant data which has not been reported widely in the literature or in comparable studies for Qatar. Fuel consumption of LDV vehicles was derived from the Qatari Ministry of Interior (MoI) while omitting diesel personal vehicles as this fraction is negligible compared to the overall fleet (Kamal et al. 2020). Second-life use of the battery pack at the end-of-life of the vehicle is not considered because of the current low maturity of this sector and the unavailability of data. Recycling of other vehicle components is considered standard practice around the world as this sector is well established, and components such as steel or copper are highly recyclable.

While many studies have ventured into specific facets of this comparison, truly comprehensive and global perspectives remain sparse due to the underlying complexities of detail and data availability (Moro and Helmers 2017; Hernandez et al. 2017; Raugei and Winfield 2019; Bao et al. 2021; Pulido-Sánchez et al. 2022). Additionally, existing research presents a notable gap in addressing Qatar's unique vehicle situation, characterised by the country's high reliance on fossil fuels and a vehicle fleet with a relatively large share of SUVs and sports vehicles, a context different from regions frequently studied, such as the US, China, and Europe (Singh and Strømman 2013; Kawamoto et al. 2019; Franzo and Nasca 2020; Martins et al. 2022; Milovanoff et al. 2022; Tamba et al. 2022). This paper seeks to bridge this knowledge gap by incorporating unique primary data from diverse and local sources, along with employing contemporary LCA methodologies. Such an approach allows for a detailed and relevant comparison

of BEV and ICEV in Qatar as the research covers the broader interplay of potential adoption pathways.

This comparative environmental analysis will focus on location-specific and time-dynamic aspects of ICEVs and BEVs in the 2022–2050 timeframe, in which future technology improvements are encompassed. The analysis will focus on the environmental impacts from different ICEV and BEV setups over this timeframe. From this analysis, specific impact categories were selected such as the carbon footprint and fossil resource scarcity. The goal of this work is to scrutinise both the environmental and supply chain implications of sourcing materials, especially those pivotal for battery production. The manufacturing phase, with its inherent and often critiqued carbon footprint, is taken into account. The operational phase of these vehicle options is examined via a break-even analysis, with a particular focus on the electricity source and its environmental implications. Beyond these direct environmental impacts, this study provides a basis and framework for further research, the broader socio-economic ramifications of electrification and the sustainable transition of the transport sector. Through this paper, the aim of the authors is to support policymakers, industry stakeholders and the broader public with the insights necessary to make informed decisions in the realm of sustainable transportation transitioning.

2 Methodology and data

2.1 General goal and scope description

The primary objective of this research is to conduct an environmental LCA (e-LCA) in which both time-dynamic and location-specific aspects are central to Qatar. In this analysis, an ICEV will be compared to a BEV over the timeframe 2022 to 2050. To give insight into the technological innovations over time, vehicles have been modelled for the years 2022, 2030, 2040 and 2050.

In order to distinguish between the different means of transportation, the choice was made to go beyond broad averages or a single representation of the complete fleet. This research aims to reflect Qatar's unique situation, focusing and providing results for multiple passenger car options, ranging from LDV such as the classic sedan, sports vehicle and SUVs. Thus, it is possible to investigate the impacts related to these vehicle options as well as extrapolate the results on a fleet-wide level, in order to create the basis for a dynamic fleet analysis in future research. As Qatar is the focus, features and data components are aligned with their specific situation. The direction of sustainable transition as put forward by national plans is also taken into account.

A time-dynamic LCA, combining the prospective (2022–2050) angle with the standard LCA framework, consisting of four phases laid out by the ISO 14040/44 guidelines (ISO:14040 2006) was carried out. The system boundaries are cradle-to-grave as shown in Fig. 1. To provide a comprehensive overview of the vehicle service life, both the fuel life cycle and vehicle life cycle are considered. With a cradle-to-grave approach, all stages from raw material extraction through to the end-of-life are encompassed in the life cycle boundaries. Specifically, this covers raw materials such as metals, plastics or minerals for the vehicles; batteries and fossil fuels for processes needed for manufacturing; maintenance and finally its end-of-life processing. As the ICEV and BEV scenarios are located in Qatar, both options are reliant on fossil fuels for their energy supply, ensuring the energy and fuel sourcing schematic representation is valid in both cases. It should be noted that other geographies or locations could differ in their fuel life cycle description in case electricity could be generated from renewable sources. Background and proxy processes such as infrastructure, auxiliary inputs such as transmission and distribution of electricity or maintenance of the vehicles were taken from the Ecoinvent 3.8 database and the LCAs modelled in the SimaPro software. All processes or components are considered state of the art for the basic static scenario with the starting point in 2022. The main reduction potentials of this paper comprise fuel economy, e.g. battery improvements and weight reduction. Possible future technologies such as carbon capture as well as widespread use of innovative battery technologies are acknowledged but are only described in the context of further research in order to focus on the time dynamic aspect for the Qatar geography, laying the basis for further fleet dynamic research.

The functional unit considered in this work is defined as 1 km driven. This unit is used to measure and compare the environmental impacts of the vehicle technologies over an equivalent distance instead of an overall vehicle lifetime, which is subject to change and subject to external factors unrelated to the vehicle itself. The use of this functional unit aligns with standard practices in transportation LCAs, allowing for the consistent comparison of both ICEVs and BEVs over a specified timeframe, integrating with the broader work on dynamic fleet impacts and changes. While this study focuses on light-duty vehicles, future work will expand this functional unit to incorporate heavy-duty vehicles. However, this specific paper is concerned with the operational performance of LDVs in Qatar, influenced by improvements of the 2020–2050 timeframe, aligned with the geographical and policy context of the study.

To compare and contrast the time-dynamic scenarios of interest in this e-LCA, the ReCiPe method (Huijbregts et al. 2017) was implemented, as it covers a wide array of midpoint categories as well as endpoint damage categories. To narrow down categories, the following categories of interest were chosen: global warming (cfr. climate change),

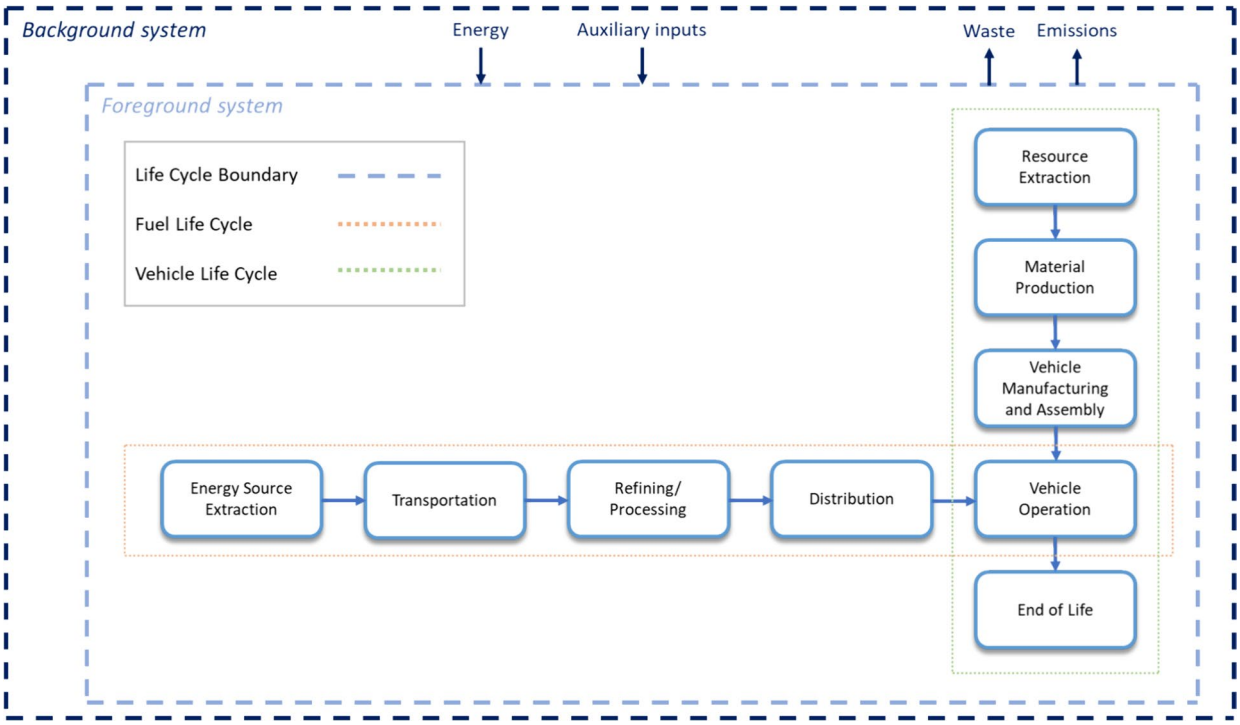


Fig. 1 Schematic representation of life cycle assessment (LCA) system boundaries, covering cradle-to-grave stages for both internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs). Following the GREET model, the boundaries include the complete vehicle and fuel cycles

particulate matter, human toxicity, acidification and resource depletion. The results of all, including the non-focus categories, can be found in the Supplementary Information.

2.2 LCI and model-specific characteristics

Improvements in both ICEV and BEV fuel economy and technologies are modelled for the timeframe 2022–2030–2040 and 2050. Various databases and studies use 150,000 km as a general driving lifetime for vehicles. Background materials and processes, such as vehicle maintenance was gathered from Ecoinvent. The modelling of the vehicles (sedan, sports vehicle and SUV) was based on the GREET model (Kelly and Winjobi 2020) and was checked with current technical sheets from vehicle manufacturers. In terms of vehicle weight, the 2022 starting point for the ICEV was determined to be almost 17% lighter than the BEV. The manufacturing and supply chains of ICEVs and BEVs are broadly seen as similar, aside from the drivetrain. Nonetheless, this only results in more engine components for the ICEV and added weight from the battery in BEV (Yang et al. 2021; Wells and Skeete 2022).

In Qatar, the annual vehicle kilometres travelled (VKT) is 26,330 km for passenger vehicles. This VKT is situated between the VKT for buses (18,645 km, 1 km/l of diesel) and transport or freight trucks (49,720 km, 3 km/l diesel) as reported by Al-Thani et al. (2020). According to the local information provider IHS Markit, the average age of an operational LDV increased from 11.8 to 12.1 years in 2021 (IHS Markit 2019). Regarding changes in fuel economy (technology improvements), its impact is assumed to be mainly on lower fuel requirements per kilometre driven, and no additional links to lowering emissions are included as does increasing environmental standards of the vehicle itself. The environmental emission aspect is reflected in the fuel or vehicle itself, as increasing standards will result in cleaner burning and therefore an overall lowering of the emissions for the fuel. For BEVs, reduction in impacts will result from improvements in energy production, lower energy needs over time of the vehicle, lower vehicle weight and novel or more efficient vehicle technologies, e.g. battery efficiencies and different chemistries (Raja et al. 2021; Hossain et al. 2022; Kim et al. 2022; Forsythe et al. 2023).

For the current vehicle batteries, standard lithium manganese oxide (LiMn2O4) batteries, also known as LMO or Li-ion batteries, were modelled. These had emerged as the preferred choice for electric vehicles, combining high power output and capacity with good thermal stability and thus are a safe option while operating in a wide range of temperatures. LiMn2O4 batteries have a relatively long cycle life, which means they can be charged and discharged many times without significant degradation, crucial for BEVs as

they require batteries that can last for many years of regular use, without high risk of degradation (W. Chen et al. 2019; X. Chen et al. 2012; S. Rangarajan et al. 2022). The mass of a BEV LDV is around 20% heavier than the ICEV alternative (Del Pero et al. 2018). The study focuses on the LMO battery chemistry for consistency and clarity in comparative analysis. While newer chemistries such as NMC, LFP and NCA are gaining prominence, the choice to focus on LMO was driven by its technological maturity and availability in the Ecoinvent database. The broader implications of other battery chemistries are part of ongoing research and future publications.

To model fuel economy improvement, data on fuel type and their improvement through history are compared to projections by the IEA and Global Fuel Economy Initiative (GFEI). Data from FAHES was used to determine the fuel economy of the current Qatari fleet and was categorised according to vehicle types: sedans, sports vehicles and SUVs. Following this classification, the "fuel economy" data from the U.S. Department of Energy (Office of Energy Efficiency and Renewable Energy) was used to ascertain the fuel economies (U.S. Department of Energy and EPA (n.d)). Together with the historical improvements, both the IEA and the GFEI extrapolations on the expected fuel economy improvements of LDVs were derived. From the expected values and historical data, it is clear that deviations are seen in comparison to the reference scenario.

For BEVs, the rate of improvement and thus coupled reduction in weight of the vehicle's operational infrastructure (cfr. battery pack) was assumed to mirror that reported in GFEI historical data—at 1.5%. This assumption has been made due to the absence of a universally accepted benchmark by global institutes. Fuel or energy economy projections were chosen to be comparable to ICEV improvements as no specific data points are proposed by manufacturers or any global institute such as the EPA. All ICEV-BEV fuel and energy economies are given in Table 1.

In Qatar, gasoline petroleum is used for LDVs while diesel fuel is used for both HDVs and buses. With fuel economy improving over the years, the direct emission factor should be assumed to be stable for all dynamic scenarios (2022–2050). The improvement in indirect emissions encompasses reduced impacts from petroleum extraction and higher environmental norms as put forward by the QNP. The complete emission factors for the ICEV and BEV models are given in Table 1.

Overall, the vehicle models used cover both ICEVs and BEVs in the dynamic timeframe 2022–2030–2040–2050. For both vehicle technologies, the full life cycle has been accounted for with the aforementioned characteristics. Specific components, such as the battery pack of the BEV, were modelled after cross-reference with the available Ecoinvent database and processes in which standard configurations are accessible. Where applicable, such as the sourcing of fossil fuels as well as electricity, geographically representative data and environmental standards were applied with the assumption that the sourcing of gasoline would develop to the highest standards currently in use by other nations. This was achieved by the implementation of the Ecoinvent database as part of the SimaPro software. The intrinsic impacts of the electricity production were corroborated by experts active in the Qatar context.

It should be noted that for ICEVs, even though their operation and type-specific emission profile is different, it was

Table 1 Emission factors, fuel efficiencies and energy consumption rates for the dynamic 2022–2050 model, ICEV-BEV (cradle-to-grave approach, including internal burning value of fossil fuels)

ICEV	2022		2030		2040		2050	
	Fuel Emission ($kgCO_2/l$)	Vehicle fuel efficiency (km/l)	Fuel Emission ($kgCO_2/l$)	Vehicle fuel efficiency (km/l)	Fuel Emission ($kgCO_2/l$)	Vehicle fuel efficiency (km/l)	Fuel Emission ($kgCO_2/l$)	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
BEV	2022		2030		2040		2050	
	Electricity emission (kg CO_2/kWh)	Vehicle fuel efficiency (kWh/km)	Electricity emission (kg CO_2/kWh)	Vehicle fuel efficiency (kWh/km)	Electricity emission (kg CO_2/kWh)	Vehicle fuel efficiency (kWh/km)	Electricity emission (kg CO_2/kWh)	Vehicle fuel efficiency (kWh/km)
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

assumed that all vehicles use the same type of gasoline. This way, a difference can be made between the fuel economy changing over time, the impacts related to the fuel inherently as well as the intrinsic emission profile based on the vehicle type. As fuel supply and distribution in Qatar are centralised across vehicle types, this assumption reflects the homogeneity of the gasoline infrastructure in the country, where different vehicle categories (sedans, SUVs and sports vehicles) are supplied with the same grade of gasoline, leading to consistent fuel-related emissions.

Similarly, the electricity used for charging of the BEVs was assumed to come from the central low-voltage national grid, powered by natural gas. Since all BEVs rely on the Qatari grid and the main difference between vehicle options is the efficiency and energy demand, this assumption highlights the greater consistency in the emission calculations across different BEV models. The intrinsic impacts of electricity production were corroborated by experts familiar with Qatar's energy sector, reflecting a natural gas powered grid for the 2020–2050 timeframe.

3 Results and discussion

3.1 ICEV comparison

As a first step in the ICEV-BEV comparison, both vehicle technologies are described separately to get an overview of the underlying differences. The opportunity here is to check specifically which vehicle or technology is the better option, locate internal hotspots, identify improvement options and identify what the main takeaways for each vehicle and timeframe. For the ICEV comparison, specifically the LDV fraction made up of sedans, sports vehicles and SUVs, all subcategories were calculated for the timeframes 2022–2030–2040–2050. For the overview of all vehicles, timeframes and impact categories, refer to the Supplementary Information.

Firstly, from the results of the ICEV sedan 2022–2050 scenario, even with the reported reduction in emissions from fuel and efficiency improvements, the sedan cannot reach its target of climate neutrality by 2050 (Table 2). Even with optimistic fuel efficiency projections, without the help of carbon mitigation strategies, the inherent reliance on fossil fuels is the main bottleneck. Aside from the carbon footprint, the main improvements are in fine particulate matter, acidification and fossil resource depletion, with the latter mainly due to a large improvement in motor efficiency. For the ICEV sedan in 2022, 72% of its carbon footprint is due to the use phase. For this scenario, the impact related to the production of the motor materials 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 with fossil resource scarcity naturally being dominated by gasoline exploration at 83%. In 2050, as lowering fuel demand does not completely fall to zero, the use phase is still responsible for 68% of the carbon footprint with 56% of resource scarcity being due to gasoline exploration. In order to decrease mineral resource scarcity, as well as the toxicity parameters, other aspects of the ICEV would have to be tackled.

The calculation was repeated for the SUV and sports vehicle, as Qatar has a high fleet share compared to other countries. From this analysis, in line with what was found for the ICEV sedan, the carbon footprint reduces with improvements in fuel economy. Yet, the use phase is still dominant in the carbon footprint and fossil resource scarcity due to the nature of fuel exploration. For both the SUV and sports vehicle, the GWP remains higher than a small LDV sedan, resulting in every SUV equalling 1.5 sedans. Overall, significant reductions in impacts could only be seen in fossil resource scarcity, particulate matter and acidification. The GWP for all timeframes and vehicle types states clearly that none of the LDV types can achieve decarbonisation or overall low-carbon targets without additional implementations. It has to be noted that, due to the inconsistency and variability in fuel efficiency 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 reversal is nonetheless not an issue for the overall interpretation of the dynamic scenarios, as this has been established by many

Table 2 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 CO_2 eq	2.34E−01	2.11E−01	1.87E−01	1.63E−01
Fine particulate matter formation	kg PM2.5 eq	2.27E−04	2.09E−04	1.64E−04	1.29E−04
Terrestrial acidification	kg SO_2 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 toxicity	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

authors and governments since the 1990s as the rebound effect, stating that through improvements and easier access, the overall impact still increases.

From the dynamic scenarios, with advances in fuel efficiencies and lower direct fuel emissions, other characteristics/life cycle stages become important. The production of the vehicle represents between 27 and 19% of the carbon footprint in 2050 (sedan and SUV resp.), up from 9 to 11% in 2022.

In order to focus on more than just sedan options, the SUV (ICEV) was further analysed to locate hotspots for this vehicle option over its lifetime. To distinguish from the base case, the 2040 dynamic case was chosen to give an intermediate result. From this, it is clear that the use phase is dominant in the global warming impact category (67% of the relative impact share) while vehicle production is crucial for human toxicity and mineral resource scarcity impact categories. For the latter impacts, vehicle production of the 2040 model would make up more than 70%. In case of impacts related to fossil resource scarcity, the exploration of fossil fuels is the main driver with over 80% of the impact results due to this, while around 50% of fine particulate matter and acidification impacts were due to the fossil fuel well-to-wheel processes.

3.2 BEV comparison

Similar to the ICEV, the BEV scenarios were calculated for the timeframe 2022–2050. It should be noted that the ICEV characteristics of this study are modelled along the GFEI projections, which are deemed optimistic while being unclear if these will be feasible in the long run. The results show that for the base case, in BEV LDV sedans (without a leap in battery and chemistry improvements, carbon capture or large advancements in efficiency), the main reduction is seen in fossil resource scarcity and global warming (Table 3). This is due to the electricity use, located centrally as it is produced by natural gas, and the Qatari grid mix has no renewables. In line with this result, the SUV and sports vehicle also show that, without any additional improvements, fossil resource scarcity and global warming indicator impacts reduce.

It should be noted that differences between the sedan, sports vehicle and the SUV are relatively small with a maximum "premium" of just over 16% increase of the BEV SUV in relation to the sedan in 2022 and less than 5% difference between the sports vehicle and the SUV.

In the hotspot analysis for the BEV vehicle, the impacts resulting from the LDV sedan were further elaborated. From this, it was clear that battery production is the main factor. Impacts range from 32% for global warming to around 50% for mineral resource scarcity and acidification. Other components of the BEV, such as the electric motor and the high amount of copper, do not reach more than 10% of the overall impacts and are thus relatively insignificant in comparison to the main battery and the reinforced steel of the vehicle.

Similarly to the ICEV SUV of 2040, the BEV version was further analysed for specific hotspots in its overall lifetime impacts. Almost 40% of the global warming impact (carbon footprint) is due to electricity (use phase). In comparison, the battery itself would contribute 15%, which is over its lifetime still a significant contribution. Other impact categories such as acidification and mineral resource scarcity remain mainly determined by the battery production and use as the overall use phase of the vehicle has relatively few other inputs. In regard to the fossil resource scarcity, as is the case for the carbon footprint, the electricity use is the main driver with up to 50% of all impacts related to it. As Qatar is expected to remain on the almost-100% natural gas electricity generation pathway, a large reduction in impacts is feasible if switched to renewable sources.

3.3 ICEV-BEV comparison

From the previous sections, it is clear that the direct tailpipe emissions from the ICEV are the dominant driver while the BEV was mostly impacted by car production, battery and repairs/changes over time. In line with available literature, the main potential of BEV seems to originate from lowering the carbon footprint due to a central and potentially optimised energy source. From this analysis, even with

Table 3 Impact assessment BEV sedan 2022–2050, per functional unit

Impact category	Unit	ICEV LDV sedan 2022	ICEV LDV sedan 2030	ICEV LDV sedan 2040	ICEV LDV sedan 2050
Global warming	kg CO_2 eq	1.91E−01	1.73E−01	1.62E−01	1.54E−01
Fine particulate matter formation	kg PM2.5 eq	3.13E−04	3.08E−04	3.05E−04	3.03E−04
Terrestrial acidification	kg SO_2 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 toxicity	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

current technologies, the BEV would be the better option over its complete lifetime. On the other hand, the BEV has the larger impact on mining and mineral resource-related impacts. Thus, the ICEV has some upsides which have to be weighed against its downsides.

Moreover, it should be noted that due to the higher weight and thus lower fuel economy, even with current electricity production, the BEV would remain the better option in reducing greenhouse gas emissions and fossil resource scarcity. However, mineral resources remain very high for the BEV, based on current battery technology and chemistries (Fig. 2).

The global warming potential or carbon footprint is a significant concern, and for this category, BEV SUVs demonstrate a significant advantage with almost half the carbon footprint of their ICEV counterparts. This difference is primarily due to the absence of direct tailpipe emissions and a more pronounced use phase impact due to the well-known higher fuel needs. Mineral resource scarcity is also a critical factor, particularly taking into account the rare earth metals connotated with battery production. Here, ICEVs currently have an advantage as they are less reliant 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 better option, as they do not rely on fossil fuels for operation. Only in the most optimistic 2050 scenario, including dramatic reductions in ICEV fuel needs, do the two technologies become comparable. 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.

3.4 Alternative scenarios and break-even analysis

The primary focus of the break-even analysis in this study is the carbon footprint, as this impact category is a high priority for many national climate and sustainability action plans yet also highly likely to change significantly over time with advancements in vehicle technology and shifts in energy production. In comparison, other impact categories are mainly driven by the battery production which will remain dominant in the BEV scenarios while fossil resource use will stay the dominant factor in the case of ICEV. Therefore, the break-even analysis was focused on the carbon footprint, omitting the other categories at this point. For this analysis, the break-even point refers to the moment when the cumulative carbon emissions of a BEV fall below those of an ICEV, considering both the production and use phases of the vehicles. The break-even analysis accounts for the initial emissions associated with vehicle manufacturing (including battery production for BEVs, upfront burden) and continued operational emissions (gasoline consumption for ICEVs and electricity consumption for BEVs, burdens over time).

Therefore, the carbon break-even calculation is carried out by comparing the total cumulative emissions of each vehicle type over a dynamic number of kilometres driven. For each year under study (2022, 2030, 2040 and 2050), the cumulative carbon footprint of the BEV and ICEV is compared to identify the point where the BEV's emissions become lower than those of the ICEV.

In terms of lifecycle assessment and specific break-even approaches, the inclusion of specific phase assumptions can introduce additional complexities, particularly due to the differences in recycling potential and material

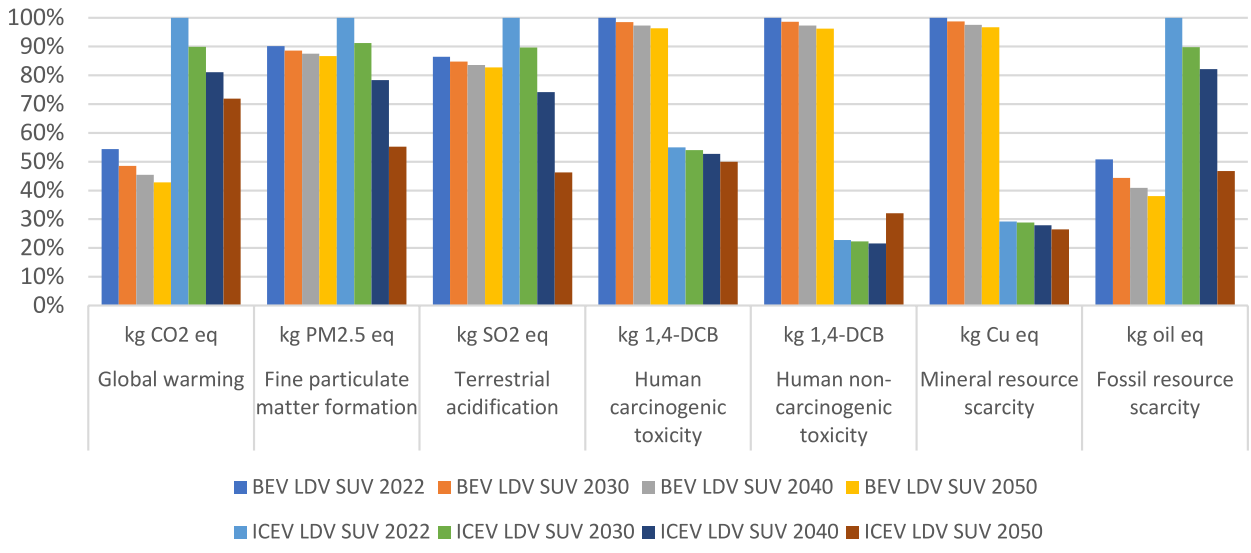


Fig. 2 ICEV-BEV comparison, SUV, per functional unit, ReCiPe method (%, relative impact comp. to max impact)

recovery between ICEVs and BEVs. However, it should be underscored that, even without accounting for potential environmental gains during the end-of-life stage (e.g., battery recycling or reuse), BEVs can still reach a break-even point where they outperform ICEVs in terms of carbon emissions. By focusing on this break-even calculation, the environmental benefits of BEVs during their operational lifetime are highlighted, while acknowledging that end-of-life impacts will require further location-specific investigation.

For this analysis, at the start of the vehicle's lifecycle, the ICEV has the lower initial carbon footprint, with approximately 8.2 CO_2-eq tons compared to the BEV's 11 CO_2-eq tons, resulting in the BEV having around 34% higher emissions at the outset. However, during the operational phase, the BEV's emissions per kilometre are significantly lower, amounting to about 82% of those of the ICEV per kilometre driven for this scenario. As a result of these operational efficiency gains, the BEV surpasses the ICEV in terms of environmental benefits after approximately 75,000 km of use. This marks the break-even point where the cumulative emissions of the BEV fall below those of the ICEV, despite its higher initial impact. With the implemented VKT, this would amount to less than 3 years of vehicle use to fall below the ICEV carbon footprint. In our analysis, we observed that switching to a lighter BEV sourced from European components has potential to further lower the carbon footprint. This finding challenges the prevailing notion of BEVs' environmental cost, particularly incorporating further advances down the line and the options of considering more specific component sourcing to reduce manufacturing impacts.

Looking at the proposed 2050 characteristics, the GFEI (Global Fuel Economy Initiative) targets would suggest a reversal of this break-even, for which ICEVs would theoretically be the better option and the BEV never breaks even. However, the feasibility of these targets is questioned by the authors, given the historical increase of ICEV fuel efficiency improvements and uncertainty if this trend can be maintained. The incremental gains required to meet the 2050 goals would imply a new and significant leap in technological advancement, which appears unlikely as the ICEV sector has a high degree of maturity and a long history of improvements by this point (Kwon 2006; Sivak and Tsimhoni 2009; Delgado et al. 2017). Furthermore, including hybrid vehicles to lower impacts and make those part of the GFEI targets distorts the benefit of such comparative analysis, as the actual improvements are made by the BEV part of the hybrid vehicle.

In the future, the role of battery chemistry will become an ever more critical factor. Current battery technologies vary widely in energy storage capacity, weight, charging speeds as well as practicality and safety characteristics. These directly influence vehicle performance, consumer acceptability and environmental impact as well as cost and lifetimes. With the markets yet to adopt new battery chemistries on a large scale, projections regarding their benefits remain speculative and environmental impacts are uncertain. Nonetheless, the potential for new chemistries warrants attention and investment in further research. In this study (the contemporary Li-ion technology battery), differences were mainly in the expected cycles and stability as well as the energy density. With more than 4000 cycles, prismatic lithium is more stable yet has a lower energy density of around 170 Wh/kg compared to the nickel-manganese alternative (NMC811) with circa 275 Wh/kg yet is currently limited to only 2000 cycles.

Lastly, the reliance of Qatar's electricity grid on natural gas is a significant contributor to the carbon footprint of electric vehicles. A hypothetical shift to renewable energy sources could dramatically alter this. Emissions from BEV can also be reduced from reducing usage, if the goal was to reduce the carbon footprint per kilometre by up to 50% (which is not unfeasible as many renewable energy sources reduce the carbon footprint by a factor of 10 compared to burning natural gas) (Marriott et al. 2010; Nicholson and Heath 2012). Then, this would bring the break-even point of BEVs down to just over 33,000 km or less than 1.5 years of use, which is significantly lower than the average duration of a conventional vehicle lease. This shift not only underscores the importance of energy sources in assessing vehicle impacts but also highlights the transformative potential of renewable energy in the automotive sector.

4 Conclusion and recommendations

This study evaluated the potential environmental impacts and benefits of transitioning from ICEVs to BEVs in Qatar from 2022 to 2050. The findings indicate a general trend of decreasing environmental impacts for both vehicle types, attributed to anticipated technological advancements and improved energy efficiencies. Yet notably, BEVs consistently demonstrate lower impacts in key categories such as global warming potential, fine particulate matter formation, terrestrial acidification and fossil resource scarcity. This challenges the perception that BEVs are environmentally inferior over their lifecycle.

However, BEVs exhibit higher impacts in categories like human carcinogenic toxicity, human non-carcinogenic toxicity and mineral resource scarcity, mainly due to the substantial mineral requirements related to its battery production. This inherent disadvantage does suggest that BEVs will continue to have higher impacts in these categories compared to ICEVs throughout the studied timeframe if not for drastically different battery chemistries.

The carbon footprint break-even analysis reveals that newer BEVs achieve a significantly shorter payback period compared to ICEVs, especially with the introduction of higher standards and lighter vehicle designs. Additionally, integrating renewable energy sources into Qatar's electricity grid could reduce the BEVs' environmental payback period to less than 1.5 years. This insight is crucial for policymakers and stakeholders, underscoring the environmental benefits achievable through BEV adoption if coupled with cleaner energy sources.

In Qatar's context, where electricity generation predominantly relies on centralised natural gas infrastructure, the environmental benefits of BEVs could be hindered by the carbon intensity of the electricity used for charging. The environmental impact of battery production and electricity generation remains critical factors influencing the overall benefits of BEVs. Therefore, the transition to BEVs should be accompanied by efforts to decarbonise the electricity grid to maximise environmental gains.

Technological advancements hold the promise of reshaping the environmental profiles of both vehicle categories. Innovations in battery technology, including NMC and LFP chemistries, could reduce the environmental footprint of BEVs, while improvements in engine efficiency and alternative fuels could enhance the performance of ICEVs. As these new technologies develop and mature, future projections should be reevaluated to incorporate these developments, ensuring that policy decisions are based on the most current data.

In light of these findings, it is recommended that Qatar intensifies its efforts to promote the adoption of BEVs to reduce carbon emissions from light-duty vehicle transportation. This includes implementing purchase incentives to lower the initial cost of BEVs, establishing a comprehensive network of charging infrastructure to improve the convenience of BEV ownership as well as investing in public awareness that address misconceptions about BEVs. Crucially, policies aimed at decarbonising the electricity grid through the integration of renewable energy sources should be pursued in tandem with the promotion of BEVs to fully realise their environmental benefits.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-024-02381-z.

Funding This research was funded by the Qatar Research Development and Innovation Council.

Data availability The data that support the findings of this study are available within the article and its supplementary materials, and additional data are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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References

Albatayneh A, Assaf MN, Alterman D, Jaradat M (2020) Comparison of the overall energy efficiency for internal combustion engine vehicles and electric vehicles. Environ Clim Technol 24:669–680. https://doi.org/10.2478/rtuect-2020-0041

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

Bao Y, Saifullah Mehmood K et al (2021) Global research on the air quality status in response to the electrification of vehicles. Sci Total Environ 795:148861. https://doi.org/10.1016/J.SCITOTENV.2021.148861

Chen X, Shen W, Vo TT, Cao Z, Kapoor A (2012) An overview of lithium-ion batteries for electric vehicles. In: 10th international power and energy conference (IPEC). pp 230–235. https://doi.org/10.1109/ASSCC.2012.6523269

Chen W, Liang J, Yang Z, Li G (2019) A review of lithium-ion battery for electric vehicle applications and beyond. In: Energy Procedia. Elsevier Ltd, pp 4363–4368

Costa E, Horta A, Correia A et al (2021) Diffusion of electric vehicles in Brazil from the stakeholders' perspective. Int J Sustain Transp 15:865–878. https://doi.org/10.1080/15568318.2020.1827317

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. Proc Struct Integ 12:521–537. https://doi.org/10.1016/J.PROSTR.2018.11.066

Delgado O, Rodríguez F, Muncrief R (2017) Fuel efficiency technology in European heavy-duty vehicles: baseline and potential for the 2020–2030 time frame. www.theicct.org

Ellingsen LAW, Majeau-Bettez G, Singh B et al (2014) Life cycle assessment of a lithium-ion battery vehicle pack. J Ind Ecol 18:113–124. https://doi.org/10.1111/JIEC.12072

Forsythe CR, Gillingham KT, Michalek JJ, Whitefoot KS (2023) Technology advancement is driving electric vehicle adoption. Proc Natl Acad Sci U S A 120:e2219396120. https://doi.org/10.1073/PNAS.2219396120/SUPPL_FILE/PNAS.2219396120.SAPP.PDF

Franzo S, Nasca A (2020) The environmental impact of electric vehicles: a comparative LCA-based evaluation framework and its application to the Italian context. 2020 15th International Conference on Ecological Vehicles and Renewable Energies, EVER 2020. https://doi.org/10.1109/EVER48776.2020.9243006

Hao H, Geng Y, Tate JE et al (2019) Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment. Nat Commun 10:1–7. https://doi.org/10.1038/s41467-019-13400-1

Hernandez M, Messagie M, De Gennaro M, Van Mierlo J (2017) Resource depletion in an electric vehicle powertrain using different LCA impact methods. Resour Conserv Recycl 120:119–130. https://doi.org/10.1016/J.RESCONREC.2016.11.005

Hossain MS, Kumar L, El Haj Assad M, Alayi R (2022) Advancements and future prospects of electric vehicle technologies: a

comprehensive review. Complexity 2022:. https://doi.org/10.1155/2022/3304796
Huijbregts MAJ, Steinmann ZJN, Elshout PMF et al (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147. https://doi.org/10.1007/S11367-016-1246-Y/TABLES/2
IPCC 2022 Climate change 2022: mitigation of climate change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change https://doi.org/10.1017/9781009157926.012
ISO:14040 (2006) ISO 14040:2006 - Environmental management - life cycle assessment - principles and framework. https://www.iso.org/standard/37456.html. Accessed 12 Apr 2024
Kamal A, Al-Ghamdi SG, Koç M (2020) Modeling and understanding the impacts of efficiency measures on fleet fuel consumption in vehicle importing countries: a case study of Qatar. J Clean Prod 259:120619. https://doi.org/10.1016/j.jclepro.2020.120619
Kawamoto R, Mochizuki H, Moriguchi Y et al (2019) Estimation of CO2 emissions of internal combustion engine vehicle and battery electric vehicle using LCA. Sustainability 11:2690. https://doi.org/10.3390/SU11092690
Kelly JC, Winjobi O (2020) Update of vehicle material compositions in the GREET model
Kim S, Tanim TR, Dufek EJ et al (2022) Projecting recent advancements in battery technology to next-generation electric vehicles. Energ Technol 10:2200303. https://doi.org/10.1002/ENTE.202200303
Kumar C (2019) 400 electric car charging stations by 2022 in Qatar - The Peninsula Qatar. In: The Peninsula. https://thepeninsulaqatar.com/article/17/01/2019/400-electric-car-charging-stations-by-2022-in-Qatar. Accessed 3 Jun 2020
Kwon TH (2006) The determinants of the changes in car fuel efficiency in Great Britain (1978–2000). Energy Policy 34:2405–2412. https://doi.org/10.1016/J.ENPOL.2005.04.014
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-. Accessed 6 Oct 2021
Marriott J, Matthews HS, Hendrickson CT (2010) Impact of power generation mix on life cycle assessment and carbon footprint greenhouse gas results. J Ind Ecol 14:919–928. https://doi.org/10.1111/J.1530-9290.2010.00290.X
Martins F, Moura P, de Almeida AT (2022) The role of electrification in the decarbonization of the energy sector in Portugal. Energies 15:1759. https://doi.org/10.3390/EN15051759
Milovanoff A, MacLean HL, Abdul-Manan AFN, Posen ID (2022) Does the metric matter? Climate change impacts of light-duty vehicle electrification in the US. Environ Res : Infrast Sustain 2:035007. https://doi.org/10.1088/2634-4505/AC8071
Moro A, Helmers E (2017) A new hybrid method for reducing the gap between WTW and LCA in the carbon footprint assessment of electric vehicles. Int J Life Cycle Assess 22:4–14. https://doi.org/10.1007/S11367-015-0954-Z/FIGURES/5
Nandanpawar HM (2017) Electric vehicles for low carbon sustainable development of transport sector of developing Asia. IRA-Intl J Technol Eng (ISSN 2455-4480) 7:364–372. https://doi.org/10.21013/JTE.ICSESD201735
Nicholson S, Heath G (2012) Life cycle emissions factors for electricity generation technologies. In: National Renewable Energy Laboratory. https://data.nrel.gov/submissions/171. Accessed 24 Apr 2024
Pipitone E, Caltabellotta S, Occhipinti L (2021) A life cycle environmental impact comparison between traditional, hybrid, and electric vehicles in the European context. Sustainability 13:10992. https://doi.org/10.3390/SU131910992
Pulido-Sánchez D, Capellán-Pérez I, de Castro C, Frechoso F (2022) Material and energy requirements of transport electrification. Energy Environ Sci 15:4872–4910. https://doi.org/10.1039/D2EE00802E
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. Accessed 3 Jun 2020
Raja BVK, Raja I, Kavvampally R (2021) Advancements in battery technologies of electric vehicle. J Phys Conf Ser 2129:012011. https://doi.org/10.1088/1742-6596/2129/1/012011
Rajagopal D, Sawant V, Bauer GS, Phadke AA (2022) Benefits of electrifying app-taxi fleet – a simulation on trip data from New Delhi. Transp Res D Transp Environ 102:103113. https://doi.org/10.1016/J.TRD.2021.103113
Rangarajan SS, Sunddararaj SP, Sudhakar AVV et al (2022) Lithium-ion batteries—the crux of electric vehicles with opportunities and challenges. Clean Technol 4:908–930
Raugei M, Winfield P (2019) Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles. J Clean Prod 213:926–932. https://doi.org/10.1016/J.JCLEPRO.2018.12.237
Singh B, Strømman AH (2013) Environmental assessment of electrification of road transport in Norway: scenarios and impacts. Transp Res D Transp Environ 25:106–111. https://doi.org/10.1016/J.TRD.2013.09.002
Sivak M, Tsimhoni O (2009) Fuel efficiency of vehicles on US roads: 1923–2006. Energy Policy 37:3168–3170. https://doi.org/10.1016/J.ENPOL.2009.04.001
Tamba M, Krause J, Weitzel M et al (2022) Economy-wide impacts of road transport electrification in the EU. Technol Forecast Soc Change 182:121803. https://doi.org/10.1016/J.TECHFORE.2022.121803
U.S. Department of Energy, EPA The Official U.S. (n.d.) Government Source for Fuel Economy Information. https://www.fueleconomy.gov/. Accessed 3 Feb 2024
Wells P, Skeete JP (2022) Producing the electric car. Trans Sustain 15:53–69. https://doi.org/10.1108/S2044-994120220000015006/FULL/XML
Yang L, Yu B, Yang B et al (2021) Life cycle environmental assessment of electric and internal combustion engine vehicles in China. J Clean Prod 285:124899. https://doi.org/10.1016/J.JCLEPRO.2020.124899

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