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How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar

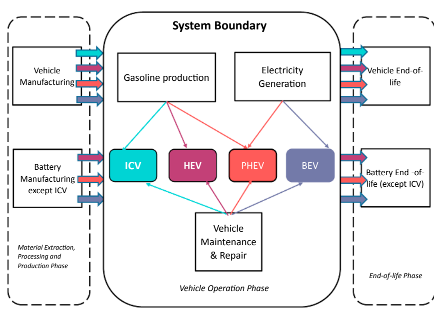
Nuri Cihat Onat[a,*], Murat Kucukvar[b], Nour N.M. Aboushaqrah[a], Rateb Jabbar[a]

[a] Qatar Transportation and Traffic Safety Center, College of Engineering, Qatar University, Doha, Qatar
[b] Mechanical and Industrial Engineering, College of Engineering, Qatar University, Doha, Qatar

HIGHLIGHTS

- A Novel Life Cycle Sustainability Assessment Approach is developed.
- Sustainability impacts of electric vehicles in Qatar are quantified.
- Battery electric vehicles does not favor macro-economic indicators.
- Electric vehicle alternatives can significantly reduce environmental impacts.
- Electric vehicles have slightly less ownership cost then conventional vehicles.

GRAPHICAL ABSTRACT



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ABSTRACT

Electric mobility is a trending topic around the world, and many countries are supporting electric vehicle technologies to reduce environmental impacts from transportation such as greenhouse gas emissions and air pollution in cities. While such environmental impacts are widely studied in the literature, there is not much emphasis on a comprehensive sustainability assessment of these vehicle technologies, encompassing the three pillars of sustainability as the environment, society, and economy. In this study, we presented a novel comprehensive life cycle sustainability assessment for four different support utility electric vehicle technologies, including hybrid, plug-in hybrid, and full battery electric vehicles. A hybrid multi-regional input-output based life cycle sustainability assessment model is developed to quantify fourteen sustainability indicators representing the three pillars of sustainability. As a case study, we studied the impacts for Qatar, a country where 100% of electricity generation is from natural gas and have a very unique supply-chain, mainly due to a wide range of exported products and services. The analysis results showed that all-electric vehicle types have significant potential to lower global warming potential, air pollution, and photochemical oxidant formation. A great majority (above 90%) of the emissions occurs within the region boundaries of Qatar. In the social indicators, internal combustion vehicles performed better than all other electric vehicles in terms of employment generation, compensation of employees, and taxes. The results highlighted that adoption of electric vehicle alternatives doesn't favor macro-economic indicators and they have slightly less for a life-cycle cost. The proposed assessment methodology can be useful for a comprehensive regionalized life cycle sustainability assessment of alternative vehicle technologies and developing regionalized sustainable transportation policies worldwide.

* Corresponding author.
E-mail address: onat@qu.edu.qa (N.C. Onat).

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1. Introduction

Electric mobility (e-mobility) is an emerging and important topic relevant to efficient use of energy for mobility, as well as for overcoming the grand challenges of sustainability including global warming, air pollution in cities, employment shifts in important energy sectors due to structural changes in the supply chains of energy sectors. Creating sustainable strategies for efficient use of energy resources requires a complete evaluation of three important pillars of sustainability; society, economy, and the environment. While the literature is abundant with the studies focusing on technical or the environmental aspects of e-mobility, there are few research efforts providing a comprehensive sustainability assessment where all these three pillars are considered. From a socio-economic perspective, widespread adoption of electric vehicles is expected to cause a structural change in the energy industry from employment shifts in the supply chains of different energy sectors (shift from petroleum to electricity generation) to tax balances and profitability. Environmentally and economically, there are still questions about the potential environmental and economic benefits of electric vehicle technologies. In this regard, government interventions are extremely important [1]. Sustainable energy development plans for governments and utilizing renewable energy sources are vital strategies to maximize potential environmental benefits can be achieved by the widespread adoption of electric vehicles [2,3]. The potential environmental benefits that could be derived from the adoption of these alternative technologies are highly dependent on the source of electricity generation [4], for example, adopting such technologies in regions that rely primarily on coal or petroleum for generating electricity could be worse than using fossil fuel vehicles [5,6]. Therefore, policy development for the adoption of electric vehicle technologies requires robust, informed decisions using a comprehensive sustainability assessment.

Electric vehicle technologies are attractive and eco-efficient alternatives to conventional gasoline vehicles due to their great potential to minimize the externalities arising from road transportation including air pollution and associated health impacts on urban population [7], global climate change [8], energy consumption [9] material use [10], and water footprint [11]. There is a growing movement toward alternative vehicles technologies around the world. Countries such as Spain, Portugal, Denmark, Ireland, the Netherlands, Austria, Japan, and South Korea have electric vehicle sales targets in place, according to the International Energy Agency (IEA). Furthermore, China, India, France, Britain, Germany, and Norway are racing to ban gasoline and diesel vehicles in favor of electric vehicles [12]. Among the Gulf states, Qatar targets 10% electric vehicle sales by 2030 [13]. In spite of the fact that the emerging electric vehicles have the capability to mitigate or minimize the environmental impacts from road transportation, there are some certain technological and infrastructure related limitations against the widespread adoption of these technologies. These challenges include lack of infrastructure for charging electric vehicles, charging time, range anxiety, operational issues, a high purchase price of BEVs, and uncertainties associated with the potential benefits of these vehicles [14,15]. From a socio-technical perspective, experiences showed that commercial fleets can be early adaptors and might help to widespread adoption of electric vehicles [16].

Qatar national vision 2030 aims to balance the accomplishments that achieve economic growth with social prosperity and environmental management, the three pillars of sustainable development [17]. In other words, Qatar seeks to sustain the economic and social growth, while simultaneously, preserving the environment through minimizing the adverse environmental impacts arising from development activities. According to the Intergovernmental Panel on Climate Change (IPCC) reports, Qatar is the largest CO_2 emitter per capita in the world, with 45 tons of CO_2 emissions per capita per year [18]. While Qatar recently tenders a large-scale solar power plant with 350 Mega Watts capacity [19], currently almost 100% of electricity generation relies on natural gas [20]. Furthermore, Doha is one of the world's most polluted cities in terms of air quality, placed at number 12 by the World Health Organization of the top 20 cities in terms of the annual mean concentration of particulate matter formation (PM2.5 and PM10). These air emissions pose significant health risks to people [21]. Although Qatar is committed to developing alternative transportation modes such as the multi-billion dollar Qatar Rail Subway project, currently the main mode of transportation is personal vehicles. For this reason, the transportation sector is significantly contributing to air pollution in Qatar [22]. While Qatar aims to continue enhancing the access to goods and services towards supporting economic and social growth, Qatar must simultaneously mitigate the environmental, economic and social impacts resulting from the transportation sector. In this regard, this study presents a comprehensive literature review about transportation studies in Qatar as well as initiatives towards achieving the adoption of electric vehicles in Qatar. Along with the same lines, a novel multi-regional input-out based life cycle sustainability assessment framework is developed to assess and compare potential social, economic, and environmental impacts of alternative electric vehicle options in Qatar.

1.1. Towards sustainable transportation: The case for Qatar

1.1.1. The literature review of sustainable transportation studies in Qatar

Sustainable transportation has been an important challenge for Qatar and a number of studies focused on different aspects of transportation issues in Qatar. A comprehensive literature review is conducted to explore the issues, challenges, and knowledge gaps in transportation literature for Qatar. According to the literature review ("Sustainable" OR "Sustainability" AND "mobility" OR "transportation" OR "transport" AND "Qatar" in either title, abstract, or keywords for time span between 2000 and 2018, accessed on 30 October 2018 in Scopus database), 12 out of 21 studies focused on infrastructure development and transportation systems, public transportation projects, urban planning strategies, transportation initiatives, and alternative transport fuels, while the rest is completely out of scope of transportation. In addition, three studies found in Google Scholar database covered different topics in transportation field in Qatar, such as transportation systems [23], urban development [24], and public transportation services [25]. However, no study found in this literature search, addressing the transportation externalities of road mobility in Qatar. Table 1 provides a summary of transportation studies in Qatar between 2000 and 2018 using the Scopus database.

According to the comprehensive literature review, only several studies analyzed the past and future of the transportation systems and infrastructure in Doha, capital of Qatar. Shaaban K, Radwan [23] have discussed the importance of rebuilding the transportation system in the city of Doha to accommodate the vast change in Doha's urban expansion over the last few decades. Besides, Azzali and Sabour [26] proposed a comprehensive framework to improve the existing mobility system within Qatar University toward a more sustainable mode, via conducting a review of the literature on transport policies and initiatives. However, their research did not cover many issues related to the mobility system of Qatar University. Abdelwarith [27] conducted a thorough review of the literature on sustainable transportation systems and initiatives to investigate which of the existing transportation sustainability assessment systems can be applicable to Qatar, and based on the results driven, none of the current transportation initiatives is applicable to the case of Qatar. On the other hand, the fourth European Telecommunications Standards Institute's (ETSI) workshop on intelligent transport systems (ITSs) that took place in Doha, Qatar, on 7–9 February 2012, placed increasing emphasis on using cooperative intelligent transport systems ITSs towards more safe, smart and sustainable traffic [28]. The past and current urban infrastructure in Qatar has been reviewed in the paper of [24], besides, a comparison between Doha and Dubai in terms of mega-urban developments has been conducted and it was shown how Qatar had put special efforts to fulfill its

Table 1
Summary of sustainable transportation studies in Qatar in between 2000 and 2018 (Scopus database).

ID#	Title	Reference	Year	Study Focus	Article Type
1	"Where Is Qatar from Complete Streets?"	[30]	2019	Urban Street Planning (complete streets policies)	Book series, Conference paper
2	"Who Is Going to Ride the Upcoming Metro in Qatar?"	[32]	2019	Public Transportation (potential metro rail rider survey)	Book series, Conference paper
3	"A framework for improving sustainable mobility in higher education campuses: The case study of Qatar University"	[26]	2018	Transportation Systems (mobility system within Qatar University)	Journal, Article in Press
4	"Urban regeneration in Qatar: A comprehensive planning strategy for the transport-oriented development of Al-Waab"	[34]	2017	Urban planning (adoption of an integrated planning strategy for the regeneration of Al-Waab transport oriented development)	Journal, Article
5	"Light rail transit (LRT) and transit villages in Qatar: A planning strategy to revitalize the built environment of Doha"	[29]	2017	Urban planning (investigating to what extent public light rail transit and transit villages strategies are applicable in Qatar)	Journal, Article
6	"Urban planning in Qatar: strategies and vision for the development of transit villages in Doha"	[33]	2016	Urban planning (Assessing the level at which transit-oriented development strategy is applicable in Doha)	Journal, Article
7	"Demonstrating the Worth of Recycled Aggregates - A Case Study from Qatar"	[75]	2016	Construction (contribution of recycled aggregates in sustainable road construction, a case of trial road construction in Qatar)	Conference Proceedings, Conference paper
8	"The need for biofuels"	[36]	2015	Biofuels (lignocellulosic biofuel as an alternative transportation fuel)	Trade publications, Article
9	"A new paradigm of urban development: envisioning sustainable futures in Qatar, 6th International Conference on Sustainable Development and Planning, SDP 2013"	[35]	2013	Urban Architecture (integration of local Qatari architecture with a contemporary architecture)	Journal, Article
10	"Natural gas as an alternative fossil fuel; the prospect and the market in 2020"	[37]	2012	Natural gas (Natural gas as alternative fossil fuel)	Conference Proceedings, Conference paper
11	"Review of existing transportation sustainability initiatives and their applicability to Qatar"	[27]	2012	A review of the literature on sustainable transport initiatives	Conference Proceedings, Conference paper
12	"ETSI ITS workshop has global reach"	[28]	2012	European telecommunications standards institute's (ETSI) workshop on Intelligent Transport Systems	Journal, Review

modernization through emulating Dubai's success. Furlan and Sipe [29] have discussed how public transit systems and land use fit into urban transformation and redevelopment in Doha. In other work, Shaaban and Khalil [30] have evaluated three local neighborhoods in Qatar; an old neighborhood, a recently developed neighborhood, and an under-development neighborhood in order to identify where is Qatar from the complete streets policy that encourages a safe, comfortable and integrated mobility network for all users regardless of mode of transportation, which in turn contributes to sustainability.

Some studies found in the literature focused on the public transportation in Qatar and Furlan [29] revealed the need for using public transportation services in order to smooth the existing traffic flow as well as to relieve the expected heavy congestion during the FIFA World Cup 2022. Shaaban and Khalil [25] have conducted a survey to investigate the quality of existing Qatar's public bus service and the users' level of satisfaction with this service from various aspects, and the survey results showed how necessary it is to encourage the Qatari nationals to use this service in the future in order to resolve even if partially the issue of the traffic congestion. In fact, the most important projects proposed to support the public transportation in Qatar are still under development, such as Qatar National Railway System, Doha Metro Network and Lusail light rail transit (LLRT) [31]. Furlan and Sipe [29] have discussed the progress and implications of the establishment of the new public light rail transit system for the built environment of Doha. Shaaban and Rania [32] have conducted a survey aimed at identifying the prospective passengers' demographics for the upcoming metro service in Qatar, and the results revealed the need to attract more users to this service as this would reduce the traffic congestion caused primarily by the private vehicle dependency.

Three of the reviewed studies addressed the use of transit villages/transit-oriented development planning strategy in Qatar to expand public transportation use and to encourage transit ridership. For instance, [29,33] have investigated to what level transit-oriented developments are considered good strategies for sustainable urbanism in Doha. In other work, [34] have focused on formulating an integrated urban planning strategy for the regeneration of Al-Waab's (a city in Qatar) transit-oriented development toward minimizing the cars' use, reducing the sprawl development, and providing sustainable multimodal transport systems. However, due to the fact that most of the urban planning concepts are imported from the west, the study of [35] emphasized on the idea of maintaining the principles of Qatari traditional architecture while taking the advantage of the advances in technology through integrating the identity of local Qatari architecture within the urban contemporary environment.

Whereas, only two studies found in the literature concerning alternative transportation fuels, [36,37]. Osokogwu [37] have envisioned considerable growth in natural gas market in 2020, which contributes towards making it an attractive fossil fuel alternative, especially with the emergence of gas to liquids (GTL) technology and the recent projects made based on this technology from countries like Qatar that is currently establishing its GTL plants to increase the production and supply of highly demanded liquid hydrocarbons. In contrast, Dale [36] discussed how necessary it is to develop and deploy renewable energy systems at a large-scale, as fossil fuels are unsustainable resources which will eventually decline in production and run out, and according to the authors the conversion of renewable lignocellulose biomass to liquid transportation fuels can be an attractive alternative to fossil fuels.

To this end, it would be good to note that while there are efforts in the multiple domains such as infrastructure development, public transportation services, urban planning, transport initiatives, and alternative transportation fuels, no study found particularly addressing the externalities resulting from road transportation in Qatar.

1.1.2. Green vehicle initiatives in Qatar

Many countries around the world are increasingly moving toward the adoption of sustainable transportation strategies such as the green vehicle technologies, as these alternative vehicles have a great potential in mitigating the adverse impacts of road transportation including GHG emissions and air pollution. The use of electricity as an energy source for operating vehicles should be the preferred option, as it is considered the most efficient energy carrier compared to other sources [38]. In turn, electricity needs to be generated from renewable energy sources, and for the case of Qatar, based on its geographic conditions, the wind and particularly solar power are possible renewable sources for producing electricity [39]. According to Reiche, (2010), “the conditions for solar energy potential in the GCC are among the most favorable in the world”. However, it is worth mentioning that Qatar is ranked as the third largest natural gas reserves in the world and that natural gas is the sole energy source of electricity in the nation, where the total electricity net generation from natural gas source reached 39 billion kilowatt hours in 2015 [40]. Hence, considering the fact that Qatar has rich natural gas reserves, electric vehicles will be expected to mitigate emissions from tailpipe (burring petroleum) to natural gas power plants. In this regard, the potential benefits will be the trade-off between natural gas and petroleum, which have different fuel-pathways and different amounts of environmental, social, and economic impacts. In this regard, the potential economic, environmental, and social impacts of alternative vehicle technologies should be further investigated to develop effective sustainable mobility strategies.

The Ministry of Energy and Industry, Ministry of Transport and Communications, and Qatar General Electricity and Water Corporation (KAHRAMAA); represented in National Program for Conservation and Energy Efficiency (Tarsheed) have signed a memorandum of understanding (MoU) to launch a major initiative of “Green Car” on May 2017, towards achieving sustainable transportation in Qatar [13]. The aim of the initiative is to disseminate electric vehicles in the local market as an eco- friendly option as well as to manage the infrastructure and provide charging stations to supply those cars with energy. This initiative seeks to make 10% of the total cars on Qatar roads operate by green energy by 2030. This initiative aims to provide a cleaner and healthier environment, to diversify of the energy sources for the transport sector, and to reduce carbon emissions [13]. Indeed, this initiative comes as part of the National Program (Tarsheed) objectives to minimize the harmful carbon emissions in Qatar by 7% from the total targeted percentage of all sectors (17%) by 2022 [41]. On the other hand, there is no clear assessment showing the real benefits of adopting electric vehicle technologies in case of 10% penetration. Hence, this study will also aid policymaking by revealing the environmental, social, and economic benefits of adopting electric vehicle technologies in Qatar.

1.2. Integrated sustainability assessment framework

In this study, we employed and developed an environmentally extended multi-regional input-output based life cycle assessment (LCA) method. While LCA is a widely applied technique for assessing the environmental impacts of products and services over its entire life cycle, it doesn’t take the economic and social impacts into consideration. Due to this limitation, a new framework; “Life Cycle Sustainability Assessment (LCSA)” is emerged, where environmental, economic, and social dimensions of sustainability are assessed in an integrated way. LCSA aims to track and analyze the environmental, economic and social sustainability of product/service systems, which are also commonly called the triple bottom lines (termed as TBL) of sustainable development [42,43]. LCSA framework embraces the three techniques: environmental life cycle assessment (LCA), economic life cycle costing (LCC) and social life cycle assessment (S-LCA), in which these techniques are jointly used for an integrated sustainability assessment [44]. LCSA integrates the TBL to quantify the sustainability impacts and benefits taking into account the product’s/service’s whole life cycle [45].

LCSA is still a relatively new sustainability assessment framework and hence, needs further developments, particularly in terms of case studies/applications. According to a review study on LCSA, the majority of the LCSA studies are lacking in applications or case studies, they rather focus on methodical aspects or conceptual discussions [44]. LCSA is an interdisciplinary framework for integration of models rather than a method itself, and therefore the usefulness of the integrated LCSA lies in the fact that various tools and methods can be integrated within LCSA framework to improve the LCSA applicability [42,43]. Practical applications of LCSA requires the use of various integrated system-based tools and methods such as Multiregional input–output (MRIO) approach, a multi-criteria decision-making tool, and system dynamics modeling [44]. Multi-Region Input-Output (MRIO) is an improved version of single region IO modeling approach, that allows broadening the scope of system boundary, through estimating the life-cycle impacts of a product/service at a global scale. Use of input-output based modeling in conjunction with LCA helps covering the entire global supplies chain-related sustainability impacts and eliminates the cut-off error [46]. Although there are multiple MRIO databases such as, EoRA, EXIOBASE, GRAM, WIOD and GTAP that are widely used to capture and analyze the regional and global environmental, economic and social impacts of economic activities, the integration of MRIO modeling approach with LCSA methodology is often limited [44]. Therefore, this study is used a novel Multi-regional input-output based life-cycle sustainability assessment framework (LCSA) to holistically evaluate the impacts of electric vehicle technologies.

According to the literature, the limitations of LCA have been overcome through broadening the indicators by including economic and social indicators, besides the environmental impacts, as well as by expanding the system boundary of analysis from a micro-level to macro-level [44]. Especially, the analysis of alternative vehicle technologies needs a holistic LCSA that integrates a broad set of sustainability indicators and evaluates the global impacts. In the literature, the great majority (if not all) of studies applied life cycle based approaches to quantify the environmental impacts of alternative vehicle technologies [47,48], while only a handful of studies analyzed the social and economic aspects of these technologies. In fact, the LCSA framework tracks the sustainability impacts by looking at each sustainability dimension, separately. Due to that fact, the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) have been working on possible methodological approaches and metrics towards integrating the triple bottom line dimensions of sustainability into a single-dimensioned LCSA framework [49].

In the literature, the sustainability assessment of electric vehicles has been widely studied. For example, Onat, Kucukvar, and Tatari [50], have developed a comprehensive LCSA model for alternative passenger vehicles in the U.S. to quantify different indicators of sustainability at macro level, including environmental indicators (GWP, water withdrawal, energy consumption, hazardous waste generation, PMF, fishery, grazing, forestry, cropland, CO_2), economic indicators (business profit, import, GDP, air emission cost), and social indicators (employment, government tax, injuries, income, human health). Furthermore, several studies advanced [51–53] advanced the LCSA approach for sustainable transportation literature, and used a holistic single region input-output model for passenger vehicles in the U.S to evaluate the impacts of different indicators representing three pillars of sustainability. In other work, Onat, Kucukvar, and Tatari [54] have quantified macro-level environmental (GWP, PMF, photochemical oxidant formation, global atmospheric temperature rise), economic (ownership cost, GDP, life cycle costing), and social (employment, human health, public welfare) indicators of alternative vehicle technologies in the U.S. through using integrated dynamic LCSA model. Besides, system dynamics modeling was developed in the paper to study the dynamic relationships between the considered sustainability indicators. Onat, Kucukvar, and Tatari [53] have developed an uncertainty-embedded dynamic LCSA to address methodological challenges, issues, and uncertainties in an assessment of the electric vehicles. Several multi-objective decision-making models are developed to evaluate several macro-level environmental, economic, and social indicators for alternative vehicles options through utilizing multi-objective optimization and multi-criteria decision-making techniques with the LCSA model.

1.3. Motivation and research objectives

While the majority of the reviewed studies in LCSA of electric vehicles employed integrated sustainability assessment approaches, no study employed a Multi-regional input-output based hybrid LCA approach. All of the input-output based works stated above relies on single region models and therefore, they were not able to capture the impacts throughout the global supply chains of the processes involved in the assessment. To this end, MRIO based LCSA methodology is applied in this paper due to its capability to capture and quantify the macro-level environmental, economic, and social impacts associated with the entire global supply chain, in addition to the direct impacts of alternative vehicles, as well as to eliminate the cut-off error. Furthermore, according to the comprehensive literature review on sustainable transportation studies in Qatar, there was no study found assessing the alternative vehicle technologies in Qatar. Hence, this study will also fill the knowledge gap in this field by analyzing the sustainability impacts of electric vehicles for the first time for Qatar.

As Qatar aims to achieve 10% electric vehicle by 2030, this study fills the knowledge gap by providing a basis for comparison and reveals the potential economic, social, and the environmental benefits of electric vehicle technologies. Along with the same lines, Qatar aims to achieve a carbon natural FIFA World Cup in 2022, which requires industry-specific carbon inventories and revealing potential benefits of electric vehicles as they are one of the options to be used in the World Cup in 2022. On the other hand, there is no clear assessment showing the real benefits of adopting electric vehicle technologies in case of 10% penetration. Hence, this study will also aid policymaking by revealing the environmental, social, and economic benefits of adopting electric vehicle technologies in Qatar.

In accordance with the comprehensive literature review of sustainable transportation studies in Qatar and applications of integrated sustainability assessment framework, this study aims to fill the knowledge gaps and improve the state-of-the-art in the field by realizing the following objectives;

1) To reveal, assess, and compare the environmental, social, and economic impacts of various electric and gasoline support-utility vehicles (SUV) in Qatar.
2) To assist policy making by revealing the potential benefits can be achieved by 10% electric vehicle market penetration policy goal set by government authorities in Qatar
3) To reveal the environmental, economic, and social impact hotspot throughout the supply-chain (fuel supply inside Qatar, other sectors inside Qatar, and outside Qatar) of the operation phase of the vehicle types.
4) To contribute to the state-of-the-art in LCSA literature by presenting an application of hybrid MRIO LCSA model
5) To provide a comprehensive regionalized life cycle sustainability assessment methodology for assessing alternative vehicle technologies and developing regionalized sustainable transportation policies worldwide.

2. Methods

In this study, a hybrid MRIO-based LCSA model is developed to quantify and compare the macro-level sustainability impacts of the alternative vehicle options as well as the impacts and benefits of the adoption of 10% electric vehicle technologies in Qatar by 2030. To realize this goal, first, the scope and system boundary of the analysis are defined. Second, fourteen sustainability indicators, representing the three pillars of sustainability, the environmental, economic and social indicators, are introduced and briefly described. Third, data sources and calculations related to alternative electric vehicles during the operation life cycle phase are presented. Fourth, the alternative electric vehicle options are analyzed and compared with gasoline conventional vehicles in accordance with the results derived for each sustainability indicator. We also conducted market penetration scenarios including 10% official goal to estimate the potential benefits. Lastly, a sensitivity analysis is conducted to measure the sensitivity of input parameters on selected indicator categories for each vehicle type.

2.1. Scope of analysis

In this study, four SUV types representing different vehicle technologies, internal combustion vehicles (ICV), Hybrid electric vehicles (HEV), Plug-in hybrid electric vehicles (PHEV), and Battery electric vehicles (BEV) are considered. While these vehicles are generic, we used the vehicle features of the Toyota Land Cruiser (ICV), Lexus (HEV), BMW (PHEV), and Tesla (BEV) to represent each vehicle technology. In Qatar, a great majority of personal vehicles are SUVs and they are less fuel-efficient compared to sedan type vehicles. Table S1 in the supplementary information (SI) summarizes the characteristics of the studied vehicles. The vehicles are evaluated and compared based on fourteen sustainability indicators (please see Section 2.2. for the full description of the indicators). As noted, the vehicles considered in this study are either powered with gasoline or electricity and hence, analyzing the impacts of gasoline production and combustion and electricity supply are the most significant parts of this study. The functional unit of this study is 1 km of vehicle travel, in other words, the sustainability impacts are calculated and reported in grams per kilometer.

The system boundary of the analysis is shown in Fig. 1. This study focuses on vehicle's operation phase as it is the most influential phase in terms of the environmental impacts in the life cycles of all of the analyzed vehicles [55,56], while phases of vehicle manufacturing and end of life are not included in the scope of analysis due to data limitations and their relatively fewer impacts. As all vehicle types are imported to Qatar and the manufacturing of these vehicles takes place in the producing countries, estimating vehicles' manufacturing impacts is very challenging. In addition, there is no data about the vehicles' end of life-related impacts in Qatar, as most of the vehicles at the end of their useful life do not undergo recycling processes, but rather they go directly to the landfill. On the other hand, life cycle cost analysis encompasses all life-cycle-phases. When quantifying the impacts of operation phase, two main sub-phases are analyzed; Well-to-Tank (WTT) and Tank-to-Well (TTW). WTT refers to the upstream (supply chain) impacts including extraction of raw material, fuel production, electricity generation, and fuel/electricity distribution and delivery, while the TTW represents the direct impacts (e.g. tailpipe emissions) during vehicle travel. Furthermore, using the MRIO modeling, WTT sub-phase is investigated further under three major components as; (i) inside Qatar fuel supply (impacts of producing gasoline or electricity at the power plant); (ii) inside Qatar sectors (excluding fuel supply); and (iii) outside Qatar sectors. (all impacts occurring in the global supply chains). As can be seen in Fig. 1, each color represents one vehicle type, and the arrows refer to the relationship between each vehicle type and its corresponding processes. For example, the electricity generation process is related to PHEVs and BEVs only, while gasoline production process is related to ICVs, HEVs, and PHEVs.

2.2. Sustainability indicators

In this study, 14 macro-level indicators representing the three dimensions of sustainability, environmental, economic, and social impacts are quantified. Table 2 presents the selected indicators and their brief description.

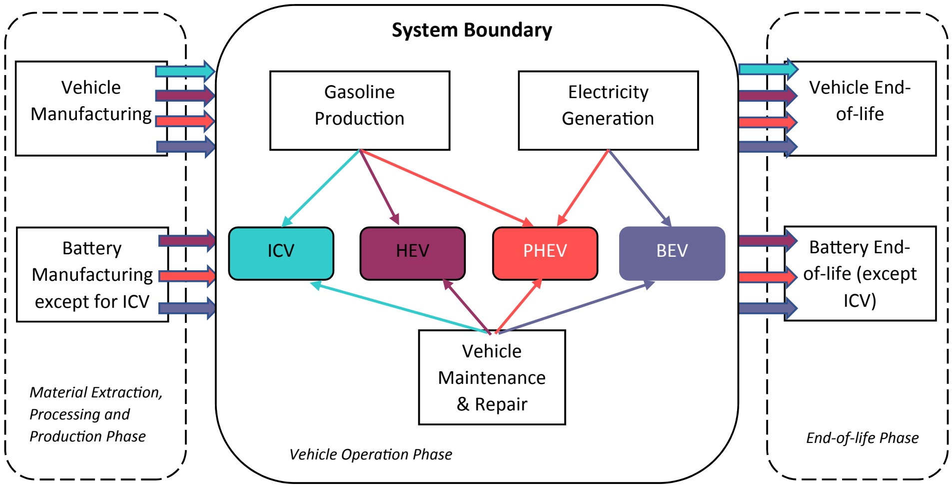


Fig. 1. System boundary for life cycle sustainability assessment of the vehicles.

2.3. Life cycle inventory

Direct and indirect impacts of the vehicle's operation phase activities including gasoline supply and electric power generation are calculated using the hybrid MRIO-LCSA model, as this model is capable to capture the global supply chain related activities of the operation phase. The upstream impacts resulting from the production and combustion of a liter of gasoline are calculated by using the upstream impact factors extracted from the MRIO model, using EXIOBASE 3.4. This emission database is used to calculate the upstream impacts for inside Qatar fuel supply, inside Qatar sectors, and outside Qatar sectors. EXIOBASE database. The upstream impact factors that are used for calculating the impacts from gasoline supply and the impacts from other sectors, inside and outside Qatar, are presented in Table S2 in the supplementary information (SI) file available at the journal's website. Due to the fact that Natural gas is the sole energy source for generating electricity in Qatar, the upstream impacts from the generation of 1 kWh of electricity from Natural gas source is calculated using the hybrid MRIO based LCSA model. The impacts from the electricity generation by the natural gas power plant and the impacts from other sectors inside and outside Qatar are calculated by using upstream impact factors taken from the hybrid MRIO based LCSA model. Table S3 in the supplementary file presents the upstream impact factors to generate per kWh of electricity from Natural gas energy source that would be used for calculating the impacts per km travel. However, tailpipe emissions (direct emissions) that release due to the combustion of a liter of gasoline during vehicle operation are collected from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. In the supplementary file, Table S2 presents also the tailpipe emission factors that are used to calculate the impacts of gasoline consumption in Qatar. The detailed calculation steps associated with Well-to-Tank (WTT) and Tank-to-Wheel (TTW) operation sub-phases are provided in the following subsections.

2.3.1. Well-to-Tank operation sub-phase

In WTT phase, the impacts are calculated using the environmental extended MRIO model, which allowed us to estimate impacts through the global supply chains of electricity generation and petroleum production in Qatar. Three main components of WTT phase includes; (i) inside Qatar fuel supply, (ii) inside Qatar sectors, and (iii) outside Qatar sectors.

Multiregional input–output (MRIO) analysis is advanced and extended versions of single region input-output models [57]. Both models are integrated with life cycle assessment to calculate the direct and

Table 2
The brief description of sustainability indicators for the Environment, Society, and Economy.

Sustainability Aspect	Sustainability Indicator	Unit	Brief Description
Environmental	Global Warming Potential (GWP)	g CO_2-eqv	The total Greenhouse gas emissions for GWP100.
	Particulate Matter Formation (PMF)	g PMF-eqv	The mixture of solid and liquid pollutant particles in the atmosphere
	Photochemical Ozone Formation (POF)	g POF-eqv	The mixture of pollutants formed as a result of photochemical reactions between nitrogen oxides and Volatile Organic Compounds
	Land use	Km^2	The series of operations carried out by humans on land for the purpose of gaining benefits through using land resources
	Energy Inputs from Nature	TJ	The total energy content input from natural resources
	Water Consumption	liter	The amount of water removed for use from its source permanently.
	Water withdrawal	liter	The amount of water withdrawn from a water source for use and then returned to its source.
Economic	Operating Surplus	QAR	The available capital of organizations, which enables them to pay taxes, repay creditors, and finance investments
	Gross Domestic Product (GDP)	QAR	The market value of all the final goods and services produced within and outside Qatar sectors
	Life Cycle Cost (LCC)	QAR	The total costs incurred throughout the lifecycle of owning a product.
Social	Human Health	DALY (Disability-Adjusted Life Year)	The number of years of life lost due to disability, ill-health, or early death
	Total Tax	QAR	The total taxes generated by each sector inside and outside Qatar
	Compensation	QAR	The amount of money given as an equivalent for service, loss, injury, debt, etc.
	Employment	1000 person	The number of employees in each sector within and outside Qatar

supply chain driven indirect impacts of products or sectors [58]. However, MRIO models can capture the impacts of the global economy considering global supply chains of traded products through their life cycles [59]. MRIO models primarily comprise of trade flow matrices covering different regions or countries worldwide. Therefore, global trade-related sustainability impacts among trading countries are important due to the fact that today's economies are globally integrated and complex global supply chains of world economies should be traced to consider the role of technological differences in production of traded products in different regions of the world [60]. MRIO models are therefore superior to single region models and the economic transactions consisting of sector-wise imports and exports are presented as monetary flows for each country. By merging all flows of imports and exports, a reliable and accurate financial accounting framework can be developed and many global multiregional databases such as Eora, WIOD, EXIOBASE, and GRAM are compiled and data quality is advanced over the past few years [61].

In this research, the EXIOBASE version 3.41 is used to as a high country and sector resolution multiregional input-output database [62,63]. Using this database, we obtained a symmetric industry-by-industry input-output table at basic prices and associate economic transactions for world economies including the Middle East as a region. EXIOBASE version 3.41 provides a time series of symmetric multinational input-output tables encompassing 43 countries, 5 rest-of-the-world regions (including Qatar under the World Middle East region) and 163 industries, covering approximately the entire global economy [64]. EXIOBASES's MRIO datasets are constructed using the Supply and Use Tables at current prices with a fixed product sales assumption and consist of national and global IO tables and obtain its raw data from the UN's System of National Accounts and Comtrade databases as well as numerous national agencies such as Eurostat [65]. After the MRIO model is constructed, social, economic and environmental impacts can be estimated by multiplying the output of each sector by its sustainability impacts per economic output [66]. For further methodological details about MRIO modeling and developing a symmetric industry-by-industry MRIO model, please refer to [65].

In this paper, a global MRIO model has been created to measure the life cycle sustainability impacts of alternative vehicle technologies and internal combustion vehicles in Qatar. Although MRIO analysis is widely used to quantify life cycle assessment of alternative vehicle technologies such as carbon footprint, energy and material consumption [67,68], there is no study found in the literature using MRIO analyses for a detailed life cycle sustainability assessment of EV technologies. In our model, input-output tables show the relationships, in other words, inputs, and outputs, within an economy, using the Leontief's inverse formula:

$$x = (I - A)^{-1}y \tag{1}$$

In Eq. (1), an output vector, **x** is defined as a function of **I**, **A**, and **y**, where **y** is the column vector of total demand (in M.Eur), A is the input-output coefficient matrix (in M.Eur/M.Eur), I is the identity matrix and x is the column vector of total output (in M.Eur). The term $(\mathbf{I} - \mathbf{A})^{-1}$ is also known as the Leontief inverse, denoted as capital **L** showing the total requirements matrix.

In the direct requirement matrix of **A**, each element shows the total inputs required for producing one unit of output of the sector. Using this relationship and sector-specific environmental satellite accounts (such as energy use, water consumption, carbon emissions, resource use, etc.) and socioeconomic accounts (such as tax, employment, income, value added, etc.), a global MRIO model accounts for the impacts associated with a unit of output of a particular sector as well as indirect impacts stemming from the international supply chains of the industry by using the total requirement matrix.

In Eq. (2), a vector of environmental, economic and social impacts generated by each industry per unit of economic output (M. Euro) is represented by **B** as follows:

$$B = E * (\mathrm{diag}(x))^{-1} \tag{2}$$

where we can denote the totals with **x** (in M. Euro) and the satellite accounts with the letter **E**. Therefore, **B** is the matrix of intensities in terms of per M. Euro. With diagonal, **I** indicate that the vector **x** has to be diagonalized. By multiplying **B** of Eq. (1) by**L**and**y**, we can also obtain the Eq. (3) as follows:

$$r = BLy \tag{3}$$

In this equation, **r** vector is calculated by multiplying **L**by **B** (intensity matrix per unit of output), and further multiplying by **y**which represents the total output of each sector (final output vector). By using Eq. (3), **r** vector quantifies the direct plus indirect social, economic and environmental impacts sectors. To this end, the Eq. (3) lets us keep tracking the sustainability impacts throughout the regional and international supply chains. To perform all matrix operations, a powerful Python programming language is used to handle big matrix data and obtain sectorial multiplier for two sectors such as petroleum production, electricity production from natural gas. The researchers later hybridized the carbon footprint and other air pollutants obtained from developed MRIO model. For example, regional and global supply chain related carbon footprints and air pollutants such as PM10 and PMF of electricity production from natural gas for Qatar are calculated using the developed MRIO model and then tailpipe emissions from internal combustions vehicle are added to the sectorial emissions to calculate both sectorial and direct emissions from vehicle operations. For a detailed method for developing a hybrid life cycle models for electric vehicles, please refer to [68].

WTT analysis is performed for both gasoline combustion and supply, and electricity generation and distribution, since all vehicle types considered in this study are run on either gasoline or electricity. Gasoline is consumed fully by ICVs and HEVs, and partially by PHEVs. The fuel efficiency of each vehicle type indicates the fuel requirement (either gasoline or kWh of electricity or both for PHEVs) to travel 1 km. Fuel Efficiency values are presented in Table 3.

The upstream impact factors obtained from MRIO model for the production of a liter of gasoline are shown in Table S2, in the supplementary file. The total impacts per km of travel that is associated with gasoline supply are calculated by multiplying the fuel efficiency of each vehicle (L/km) with the associated upstream impact factor.

Electricity supply is the second main part of WTT analysis. Electricity is used for operating EVs and the electric mode portion of PHEVs. Although electricity use in EVs and PHEVs does not cause any tailpipe emissions, the variations in the resulting environmental impacts from operating vehicles in electric mode are highly dependent on the source(s) of electric power generation. For the case of Qatar, natural gas is the sole energy source for generating electricity. The total WTT impacts can be calculated by multiplying the electricity required to travel 1 km (Fuel efficiency) with the associated impact factors to generate per kWh of electricity from natural gas obtained from the MRIO model, presented in Table S3, in the supplementary file. Eq. (4) shows how the total WTT impact per vehicle km travel is calculated;

$$(\mathrm{SI})_i = (\mathrm{FE})_j * [(\mathrm{IF}_{\text{fuel supply}})_{i,} + (\mathrm{IF}_{\text{inside Qatar sectors}})_{i,} + (\mathrm{IF}_{\text{outsideQatarsectors}})_i] \tag{4}$$

Table 3
Fuel Efficiency values of vehicle alternatives.

Fuel Efficiencies	ICV	HEV	PHEV-AER 22 km		EV
			Electricity mode	Gasoline mode	
Liter Per Kilometers (L/100 KM)	14.5	7.84	37.4*	9.8	22.5*
Miles per gallon (MPG)	16.24	30	56	24	93

* The unit is kWh/km for electricity mode.

Table 4
Summary of the considered Cost elements for Life Cycle Cost Analysis of each vehicle technology.

Life Cycle Costs	ICV	HEV	PHEV	BEV
Initial/Purchase Price (QR)	259,000 QR	QR 199,344.75	QR 232,145.63	289,499.25 QR
Fuel Usage (L/100 km)	14.5 Lt ≈ 6.9 km/L	7.84 Lt ≈ 12.76 km/L	37.4 kwh electricity ≈ 2.67 km/kwh 9.8 L gasoline ≈ 10.2 km/L	22.5 kwh ≈ 4.444 km/kwh
Annual Fuel Costs (QR/Year)	22,000 km/6.9 km/L ≈ 3188.41 L/year * 2 QR/L ≈ 6376.82 QR/year	22,000 km/12.76 km/L ≈ 1724.14 L/year * 2 QR/L ≈ 3448.28 QR/year	Electric mode: 22,000 km/2.674 km/kwh ≈ 8227.37 kwh/year * 0.085 QR/kwh ≈ 699.33 QR/year Gasoline mode: 22,000 km/10.2 km/L ≈ 2156.86 L/year * 2 QR/L ≈ 4313.72 QR/year Total Cost: 0.35(699.33) + 0.65(4313.72) = 3048.68 QR/Year	22,000 km/4.44 km/kwh ≈ 4954.95 kwh/year * 0.085 QR/kwh ≈ 421.17 QR/year
Average Maintenance Costs (QR/Year)	283.1 QR	374.43 QR	728.22 QR	748.85 QR

where

SI: Sustainability impact
i: represents the sustainability impact category for 13 indicators
j: Vehicle types of ICV, HEV, or BEV
FE: represents the fuel efficiency of a vehicle
IF: Impact factors for the sectors (either for gasoline production or electricity generation and for their supply chain) in the supply chain of operation phase, obtained from the MRIO model

Eq. (1) can be used to calculate the total WTT impact of ICVs, HEVs, and EVs. On the other hand, emissions produced by PHEVs are calculated in a different way, as they are capable to run on both gasoline and electric mode. The electric mode portion of PHEV is determined by the utility factor (UF), that is the percentage of daily travel distance in electric mode. The utility factor of PHEV-22 km in Qatar is assumed to be 35%. The total WTT impacts of PHEVs can be calculated as follows;

$$
\begin{aligned}
(SI)_{i} &= UF * (FE)_{\text{electricity mode}} \\
&* [(IF_{\text{fuel supply}})_{i,} + (IF_{\text{inside Qatar sectors}})_{i} + (IF_{\text{outside Qatar sectors}})_{i}]_{\text{electricity generation}} \\
&+ (1 - UF) * (FE)_{\text{gasoline mode}} \\
&* [(IF_{\text{fuel supply}})_{i} + (IF_{\text{inside Qatar sectors}})_{i} + (IF_{\text{outside Qatar sectors}})_{i}]_{\text{gasoline production}}
\end{aligned} \tag{5}
$$

where

SI: Sustainability impact
i: represents the impact category,
FE: represents the fuel efficiency of a PHEV for two different modes (electricity or gasoline
IF: Impact factors for the electricity generation or petroleum production

The first part of Eq. (5) calculates the WTT impacts from electricity consumption, while the second part calculates the WTT impacts from gasoline consumption.

2.3.2. Tank-to-Wheel operation sub-phase

Because BEVs and PHEV in electricity mode don't have tailpipe emissions, TTW impacts are directly associated with the gasoline amount used during vehicle operation, and tailpipe emission released per gasoline combusted during a kilometer of travel. To calculate the TTW impacts, the fuel efficiency of each vehicle type is multiplied by the associated tailpipe emission factors that are presented in Table S2, in the supplementary file. The TTW impacts for each vehicle type except for PHEVs can be calculated using the following equation,

$$(SI)_{i} = (FE) * [\text{Direct emissions (or tailpipe emissions)}]_{i} \tag{6}$$

It is worth mentioning that, TTW impacts for EVs and electric mode portion of PHEVs are zero. Hence, the TTW impacts associated with the gasoline mode portion of PHEVs can be calculated as follows,

$$(SI)_{i} = (1 - UF) * (FE) * [\text{Direct emissions (tailpipe emissions)}]_{i} \tag{7}$$

2.3.3. Life cycle costing

Life-cycle costing (LCC) is a method of economic, aims to estimate all the costs that are likely to be incurred over the entire useful life of a project, product or service. LCC helps in making logical decisions and can be used to evaluate and compare among different options as well as to make tradeoffs between the alternatives. LCC analysis includes various cost elements such as initial costs, operating, maintenance, and repair costs (OM&R), replacement costs, residual costs, energy costs, etc. In this study, initial costs, annual fuel costs, maintenance costs, insurance costs, and salvage values of the studied vehicle options are considered for the analysis of LCC. The key assumptions for this analysis are presented in the supplementary information document. The steps of performing LCC analysis is carried out as follows; first, the data on cost element costs, and useful life are gathered and estimated for each vehicle option. Next, economic parameters such as interest rate, inflation rate, inflation-adjusted interest rate, and vehicle depreciation are estimated and used in the analysis. Then, trough using present worth analysis, the present value for each cost element is calculated on a yearly basis. Finally, the LCC of each vehicle option is calculated by adding the present value of costs of each cost element every year. This comparative financial analysis (LCC) is performed in this study to select the alternative with the lowest overall lifecycle costs, i.e. the most cost-effective vehicle option over the anticipated lifetime. Table 4 provides a summary of the cost elements considered in the LCC analysis.

3. Results

The results are presented in the following subsections representing each impact category (environmental, economic, social) for fourteen sustainability indicators. The potential savings can be achieved by alternative SUV vehicle technologies are compared to the internal combustion engine SUV for varying market penetration rates, including the 10% of official goal.

3.1. Environmental impacts

The environmental impacts of each alternative vehicle technology are presented in Fig. 2. The quantification of GWP, PMF and POF emissions of each vehicle technology is illustrated in Fig. 2(a–c), respectively. According to the results, the contribution of direct (tailpipe) impacts (TTW) dominates the total emissions for ICVs, HEVs, and PHEVs. On the other hand, BEVs do not produce any tailpipe emissions, and therefore the majority of EV emissions stem from the electricity generation supply chain, while the rest (very low) of the upstream emissions associated with BEVs came from the other sectors inside and outside Qatar. The analysis results show that the majority of impacts occur inside Qatar. Overall, the global supply chain related impacts account for around 1% for all vehicle types for GWP and POF, while it ranges between 1 and 4% for PMF. The impacts of suppliers within Qatar for electricity generation and the petroleum production sectors have an impact of 2–8% of the total operation phase impacts for GWP. It indicates that a great majority of GWP, PMF, and POF occurs inside Qatar. In comparison, BEV performs better the other alternatives, as BEV has zero tailpipe emissions and most of the BEV-related impacts are limited to regional boundaries of the electric power plant, which makes the residential exposure to PMF emissions limited. HEVs have the least GWP, PMF, and POF emissions generated from the fuel supply-chain, while BEVs produces the highest GWP, PMF, and POF in the fuel supply (emission from electricity generation in the natural gas power plant). All vehicle options have considerable low upstream emissions associated with the sectors inside and outside Qatar; where ICVs produce the highest amount of GWP, PMF, and POF inside and outside Qatar sectors. ICVs produce the highest GWP, PMF, and POF amount in TTW, while PHEVs produce the least in this stage. The results show that HEVs, PHEVs, and BEVs have substantially lower GWP, PMF, and POF emissions compared to ICVs.

The water withdrawal and water consumption are shown in Fig. 2(d and e), respectively. According to the results, the contribution of fuel supply impacts dominates the total Water withdrawal for PHEVs and BEVs, while the contribution of (inside Qatar sectors) impacts dominates the total water withdrawal for ICVs and HEVs. This result implies that there is a significant water withdrawal for electricity generation, which worsens the performance of BEVs in terms of water withdrawal per km. On the other hand, the supply chain of petroleum production and extraction involves water-intensive processes overseas (outside the regional boundaries of Qatar) and worsens the performance of ICV in terms of water consumption. The majority (more than 90% of total water consumption for all vehicle types) of water consumption occurs outside of Qatar's regional boundaries. In water withdrawal impact category, BEVs or PHEVs performs worse than ICV, mainly due to water withdrawals occurs in the process of electricity generation from natural gas. In this category, the best alternative is HEV, mainly due to lower water withdrawal from petroleum production and it's supply chain. In water consumption category, the best alternative is BEVs, while ICV is the worst. However, the great majority of the water consumption doesn't take place inside Qatar, embedded in the global supply chains of the sectors in Qatar.

The Energy input from nature impact is presented in Fig. 2(f). As can be seen, inside Qatar fuel supply impact is the highest contributor to Energy inputs impact for all vehicle options, where ICVs have the highest impact, and BEVs account for the least. All vehicle options have considerable low Energy inputs impacts inside and outside Qatar sectors. All vehicle types have no tailpipe impacts. The Land use impact is presented in Fig. 2(g). As shown, more than 95% of total land use occurs outside Qatar (in the global supply chains of the sectors inside Qatar). In this category, ICVs have the highest impact, and BEVs have the least. All vehicle options have considerable low land use impacts inside Qatar.

3.2. Social impacts

The social impacts; total Tax, compensation, employment, and Human health impact categories are illustrated in Fig. 3(a–d), respectively. In comparison, ICVs have the highest benefit in terms of taxes, employment, and compensation, which implies that the petroleum extraction and all supply chain related benefits in terms of above-mentioned categories generate more employment, tax, and compensation. Moreover, roughly more than 60% of the employment occurs in the regional boundaries of Qatar, while 30–40% of the employment occurs in the global supply chains. In compensation and tax generation categories, approximately 90% of the total tax and compensation benefits occur within regional boundaries of Qatar. On the other hand, in human health impact category, the vehicle types show the quite different distribution in terms of the location of impacts. Human health impacts of ICVs occur while driving through tailpipe emissions and this composes of a great majority of the ICVs human health impacts with 94% of ICV's total. For BEVs, human health impacts are attributed to electricity generation sub-phase. In comparison, electrification of the vehicle fleet favors the human health impact category, as the impacts decrease from ICV to BEV. However, electrification doesn't favor the social indicators of employment, tax, and compensations.

3.3. Economic impacts

Economic indicators of the operating surplus and GDP are presented in Fig. 4(a and b), respectively. The results show that fuel supply (Petroleum extraction and production and electricity generation in Qatar) dominates the contribution to GDP and operating surplus for all vehicle types. ICVs are better options for these two macro-level economic indicators, mainly due to more added value and operating surplus in the fuel supply. Furthermore, more than 90% of economic benefits occur within the regional boundaries of Qatar. For BEVs, contribution to GDP occurs mainly in the electricity generation and its supply chain inside Qatar, accounting for roughly 48% and 49% of its total GDP contribution. In operating surplus category, the contribution of fuel supply for ICV, HEV, and PHEV dominate the total contribution of each alternative with at least 80% of each vehicle type's total contribution to operation surplus. Overall, the results highlighted that the adoption of electric vehicle alternatives doesn't favor macro-economic indicators.

Fig. 5 compares the life cycle ownership costs for four vehicle types based on a present value analysis per kilometer basis. The vehicles in Qatar travels an average of 22,000 km per year and the useful lifetime

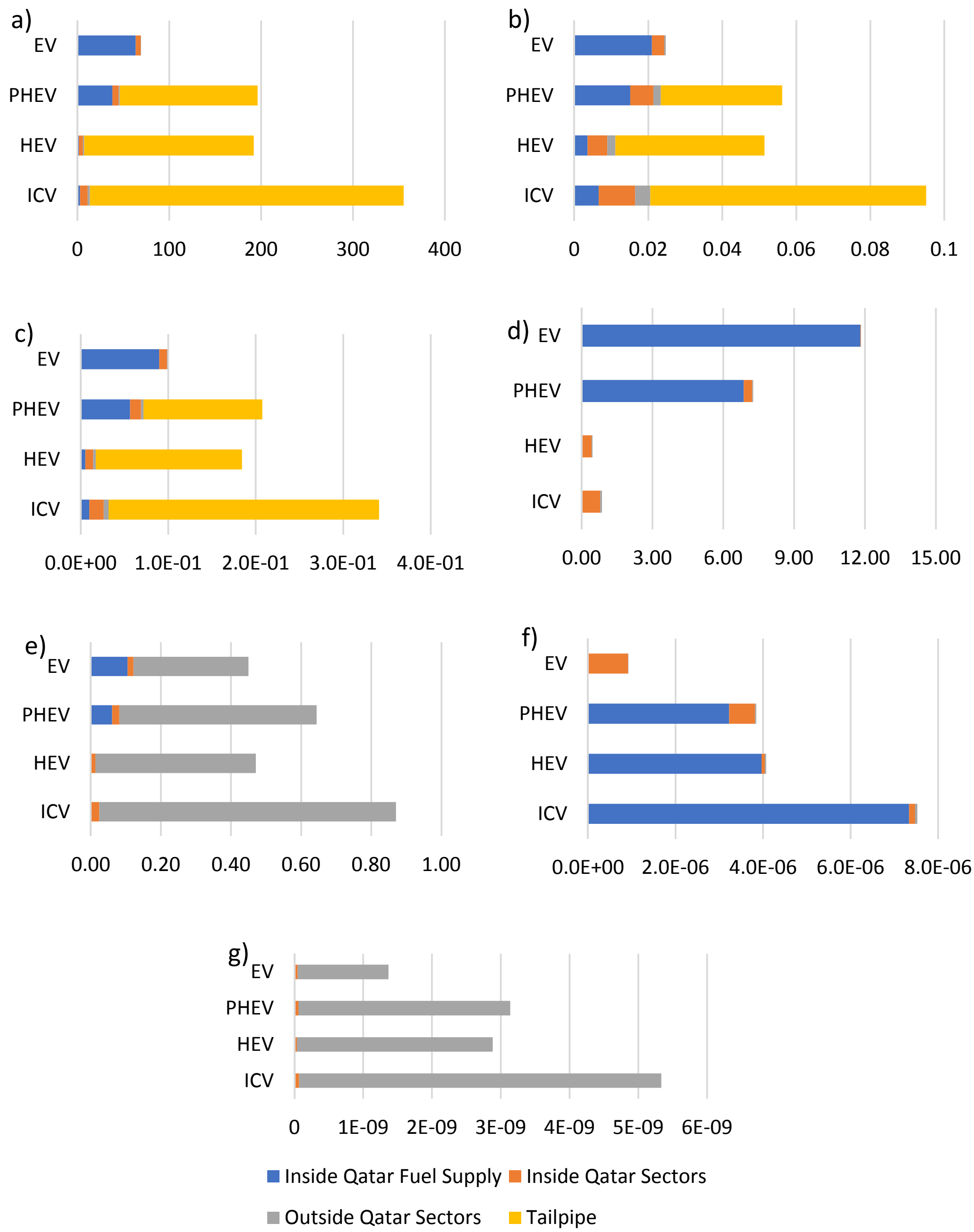


Fig. 2. Environmental impacts of alternative vehicle technologies: (**a**) GWP (gCO2-eqv. per Km); (**b**) PMF (gPMF-eqv. per Km); (**c**) POF (gPOF-eqv. per Km); (**d**) Water withdrawal (liter per Km); (**e**) Water Consumption (liter per Km); (**f**) Energy Inputs from Nature (TJ Per Km.); (**g**) Land Use (Km2 Per Km.).

assumed to be 12-years. The developed LCC model incorporates various cost elements such as vehicle's purchase price, fuel cost, maintenance cost, insurance cost, and salvage value. The model also includes some economic factors such as vehicle depreciation, interest rates, and inflation rates. As shown, BEV has the highest initial cost, while HEV has the lowest. According to the results, there is a significant variation in fuel costs over the alternatives, where ICV has the highest fuel cost of 0.312 QAR/km, and BEV has the least with 0.023 QAR/km. The low fuel cost of BEV is due to the lower electricity cost compared to gasoline cost. Salvage value varies insignificantly between 0.222 QAR/km for the BEV and 0.152 QAR/km for HEV. For the maintenance cost, ICV has the lowest cost, while BEV has the highest. Moreover, BEV has the highest insurance cost, while HEV has the lowest insurance cost. The total LCC results show that the lowest cost option is the HEV followed by PHEV, while ICV has the highest cost and BEV has the second largest LCC.

3.4. Scenario analysis: Revealing the potential benefits

While the scenario of 10% market penetration is an official target for Qatar, the full potential at varying market penetration rates and corresponding potential benefits or impacts are revealed. Fig. 6 illustrates the potential relative reduction of each electric vehicle technology under different market penetration rates ranging from 0% to 100%. All reduction potentials are relative to internal combustion vehicles. In other words, the percentage reduction potential of replacing a BEV with an ICV at different market penetration rates are estimated.

The market penetration analysis results showed that the GWP, PMF and POF emission reduction potentials of BEVs are relatively higher than those of HEVs and PHEVs. The findings demonstrated that when the penetration rate of electric vehicles is 10%, the GWP would be reduced by 12% if BEV is adopted. For the same scenario, the potential

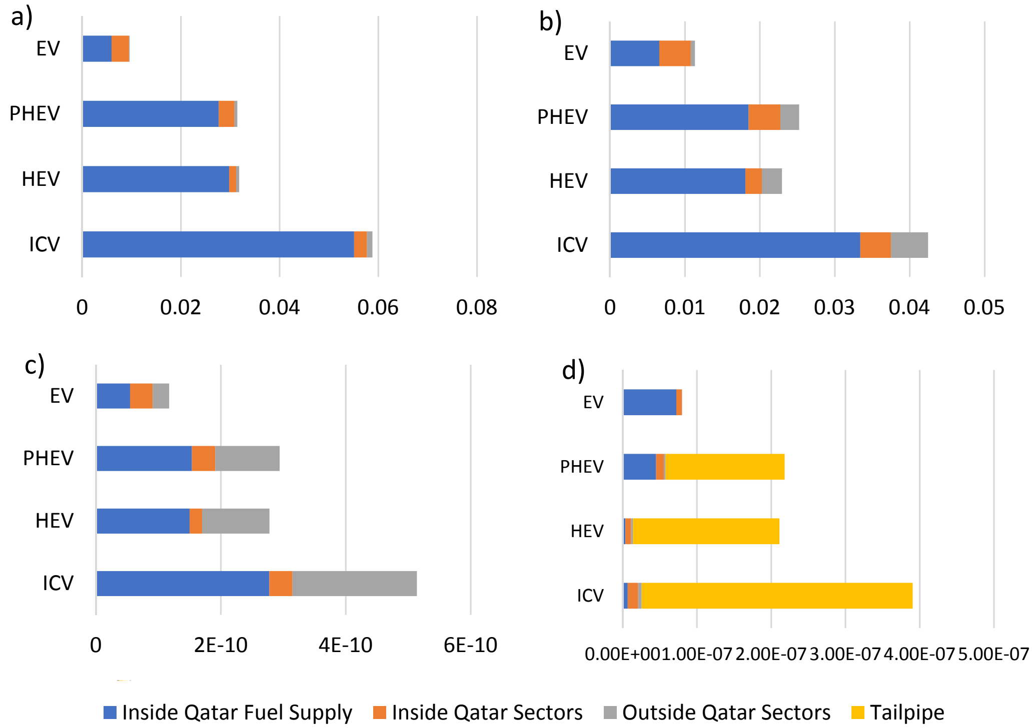


Fig. 3. Social impacts of alternative vehicle technologies: (**a**) Total Tax (QAR per Km); (**b**) Compensation (QAR per Km); (**c**) Employment (1000 P per Km); (**d**) Human Health (Daly per Km).

GWP reduction is 4% and 8% for HEVs and PHEVs. Besides, HEVs, PHEVs, and BEVs have PMF and POF emission reduction potential of 5%, 4%, and 7%, respectively. As their market penetration increases, the GWP, PMF, and POF emission reduction can be achieved by increasing the adoption of BEVs, which have a higher slope than the other options. However, in terms of water consumption, environmental impact category, BEVs and HEVs are relatively better options as opposed to PHEVs. The adoption of 10% of electric vehicles would reduce the water consumption of PHEVs by 3% and by 5% for both HEVs and PHEVs. On the other hand, adoption of BEVs adversely affects the water withdrawal. In the case of 10% market penetration, the BEVs can cause additional roughly 1.3 times more water withdrawal, mainly due to high water withdrawal rates for electricity generation and it's supply chain. BEVs are superior to HEVs and PHEVs in terms of energy inputs from nature. The penetration of 10% electric vehicle would reduce the energy consumption of BEVs by 9% and by 5% for both HEVs and PHEVs. Similarly, BEVs are superior to HEVs and PHEVs in terms of land use, and the results indicated that BEVs, HEVs, and PHEVs have a land use reduction potential of 7%, 5%, and 4% respectively for 10% market penetration.

Regarding human health, social impact category, the results showed that BEVs are relatively better options than HEVs and PHEVs, and the adoption of 10% electric vehicles would achieve 8% reduction of human health impact by BEVs, and 4% and 5% reduction by PHEVs and HEVs, respectively. On the other hand, in total tax category (a positive social indicator), BEVs cause a reduction, relatively higher than those of HEVs and PHEVs. The results of the market penetration analysis showed that when market penetration rate for electric vehicles is 10%, the total tax would be reduced by 5% for both HEVs and PHEVs, and by 8% for BEVs. On the other hand, in terms of employment and compensation, social impact categories, PHEVs and HEVs are relatively better options as opposed to BEVs. Because, at market penetration of 10%, BEVs, HEVs, and PHEVs would reduce employment by 8%, 5%, and 4% respectively, and would reduce employment compensation by 7%, 5%, and 4% respectively. In other words, the employment and compensation impact categories would be impacted adversely in case of adoption of any type of electric vehicles, while among those, PHEVs cause the least employment and compensation loss

In operating surplus and GDP, economic impact categories, HEVs, PHEVs, and BEVs have a reduction potential of 5%, 5%, and 9%, respectively for 10% market penetration. In other words, the operating surplus and GDP would be reduced if BEVs are adopted. Hence, in terms

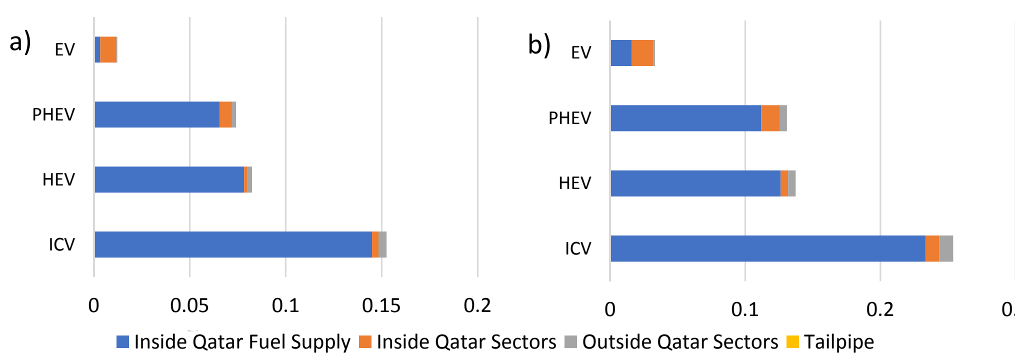
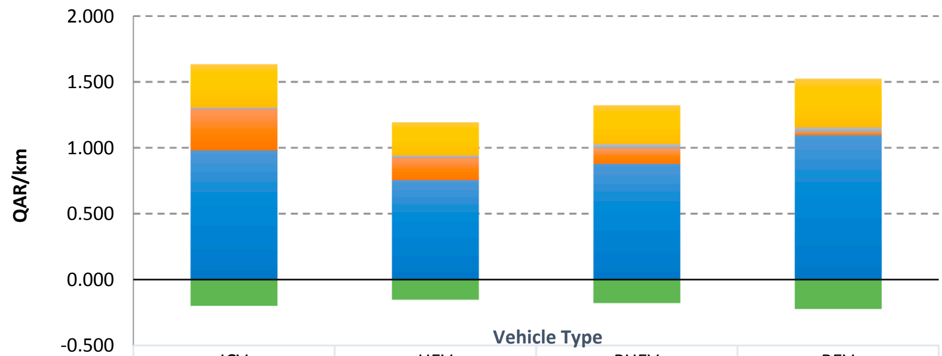


Fig. 4. Economic impacts of alternative vehicle technologies: (**a**) Operating surplus (QAR per Km); (**b**) GDP (QAR per Km).



	ICV	HEV	PHEV	BEV
Salvage value	-0.198	-0.152	-0.178	-0.222
Insurance Costs	0.328	0.253	0.294	0.367
Maintenance Costs	0.014	0.018	0.036	0.037
Fuel Costs	0.312	0.169	0.114	0.023
Initial/Purchase Price	0.981	0.755	0.879	1.097

Initial/Purchase Price Fuel Costs Maintenance Costs Insurance Costs Salvage value

Fig. 5. Life Cycle Cost breakdown of life-cycle phases for each vehicle type (QAR/km).

of operating surplus and GDP, BEVs are worse than HEVs and PHEVs. Furthermore, in LCC, BEVs performs the worst compared to other alternative vehicle technologies. The potential LCC reductions are 3%, 2%, and 1% for HEV, PHEV, and BEVs, respectively. While HEVs have greater potential for reducing LCC compared to other electric vehicle types, no significant LCC reduction potential is observed for 10% market penetration

3.5. Sensitivity analysis

A sensitivity analysis (10,000 iterations using Monte Carlo simulation) is conducted to measure the sensitivity of input parameters on certain outputs such as GWP, Employment, and LCC impact categories. Fig. 7 shows the sensitivity results for each vehicle type in GWP impact category. According to the sensitivity analysis results, fuel consumption

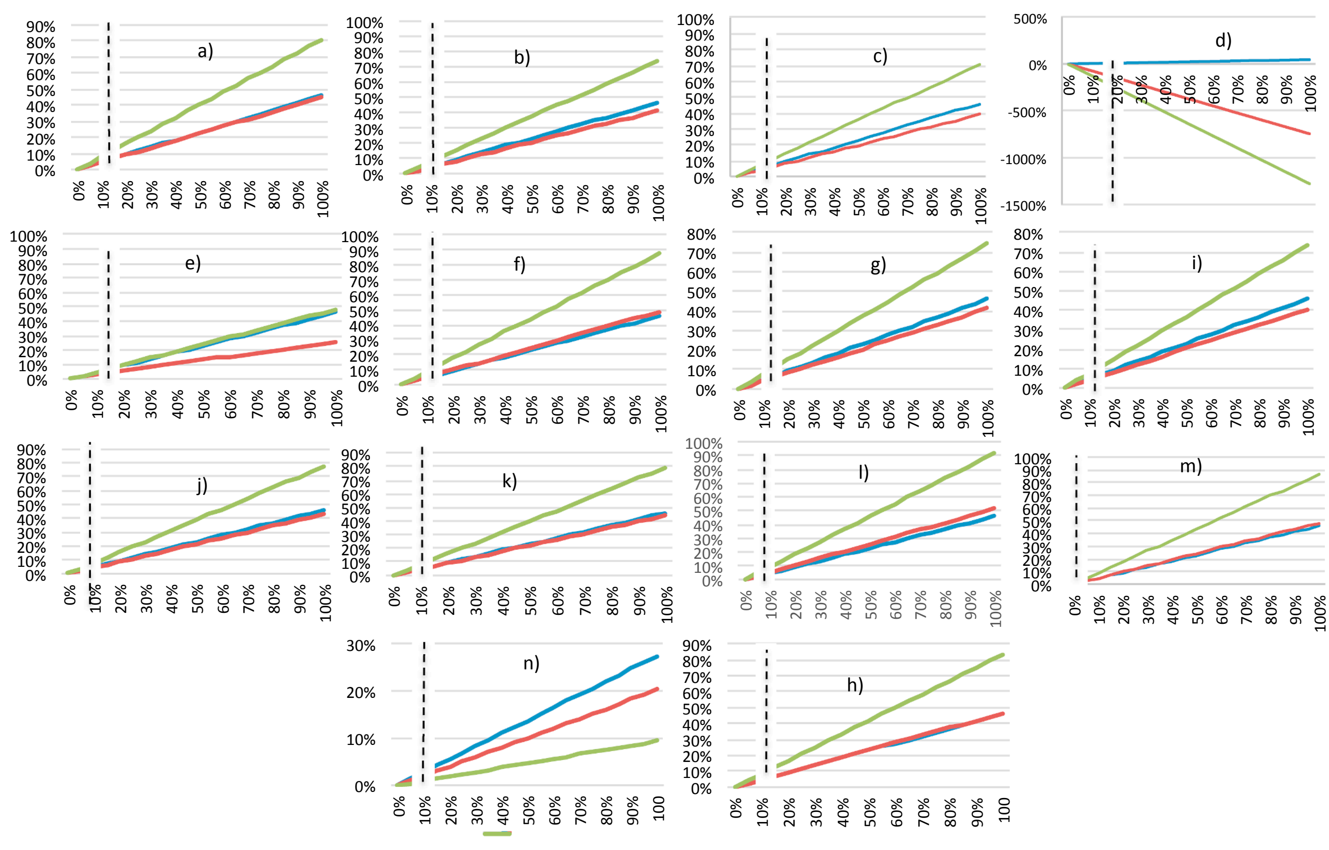


Fig. 6. Percentage Reduction potentials as a function of market penetration rates, (**a**) GWP emissions; (**b**) PMF emissions; (**c**) POF emissions; (**d**) Water withdrawal; (**e**) Water Consumption; (**f**) Energy Inputs from Nature; (**g**) Land Use; (**h**) Total Tax; (**i**) Compensation; (**j**) Employment; (**k**) Human Health; (**l**) Operating Surplus; (**m**) GDP; (**n**) LCC.

Fig. 7. Sensitivity analysis for GWP (a) ICV; (b) HEV; (c) PHEV; (d) BEV.

is the most sensitive input parameter for all vehicle types. Tailpipe emissions are the second most influential parameter affecting the GWP of ICV, HEV, and PHEV. On the other hand, the indicator "Inside Qatar Fuel Supply" for BEV, referring to electricity generation from natural gas, is the second most influential parameter affecting the GWP of BEVs. The results for GWP showed that the most effective parameters, in other words, the highest potential for improvement, is embedded in the fuel efficiency of the vehicle types.

Sensitivity analysis for employment impact category is presented in Fig. 8. According to the results, fuel consumption is the most sensitive input parameter on results. Unlike the GWP, the input parameter "Inside Qatar Fuel Supply", representing either gasoline production or electricity generation, is the second most sensitive parameter on employment generation. Direct fuel requirement of vehicles is the main determinant of the employment generation in upstream fuel supply chains, whereas the employment generation inside Qatar sectors (excluding fuel supply) has a negligible impact compared to the outside Qatar sectors. This result also indicates the employment generation through exports in the upstream supply chain for fuel production.

Fig. 9. shows the sensitivity of input parameters for LCC for each vehicle type. Results highlight that the most important initial purchase price by far is the most sensitive parameter for all vehicle types. This is mainly because of the low-cost fossil fuels in Qatar, making the operation phase costs less sensitive for overall LCC. Because the insurance rate is a function of the value of the vehicle throughout its life cycle, it is one of the most sensitive parameters for the total LCC. Annual VKT is another important sensitive input parameter for ICV and HEV, relatively due to their relative contribution to the LCC of ICV and HEV is greater compared to that of PHEV and BEV.

4. Conclusions and future work

To fill the knowledge gaps in the field and to provide better and informed decisions, a novel multi-regional regional input-output based life cycle sustainability framework is developed and applied to quantify fourteen sustainability indicators for four different types of support utility vehicles. To provide a better understanding of the potential benefits or adverse effects, the impacts are evaluated based on varying market penetration scenarios. Overall, according to the analysis results, the following points are highlighted;

- Battery electric vehicles, Plug-in hybrid electric vehicles, and hybrid electric vehicles have substantially lower global warming potential, particulate matter formation, and photochemical oxidant formation compared to internal combustion vehicles. The analysis revealed that a great majority (above 90%) of the emissions occurs within the region boundaries of Qatar. According to the 10% market penetration scenario, BEVs are the best options for the impact categories of global warming potential, particulate matter formation, and photochemical oxidant formation. For the official goal of 10% market penetration, and they can reduce up to 8%, 7%, and 7% of the global warming potential, particulate matter formation, and photochemical oxidant formation, respectively.
- Battery electric vehicles performed worse than internal combustion vehicles and all other alternative vehicles in the water withdrawal category with around 12-liter water withdraw consumption per

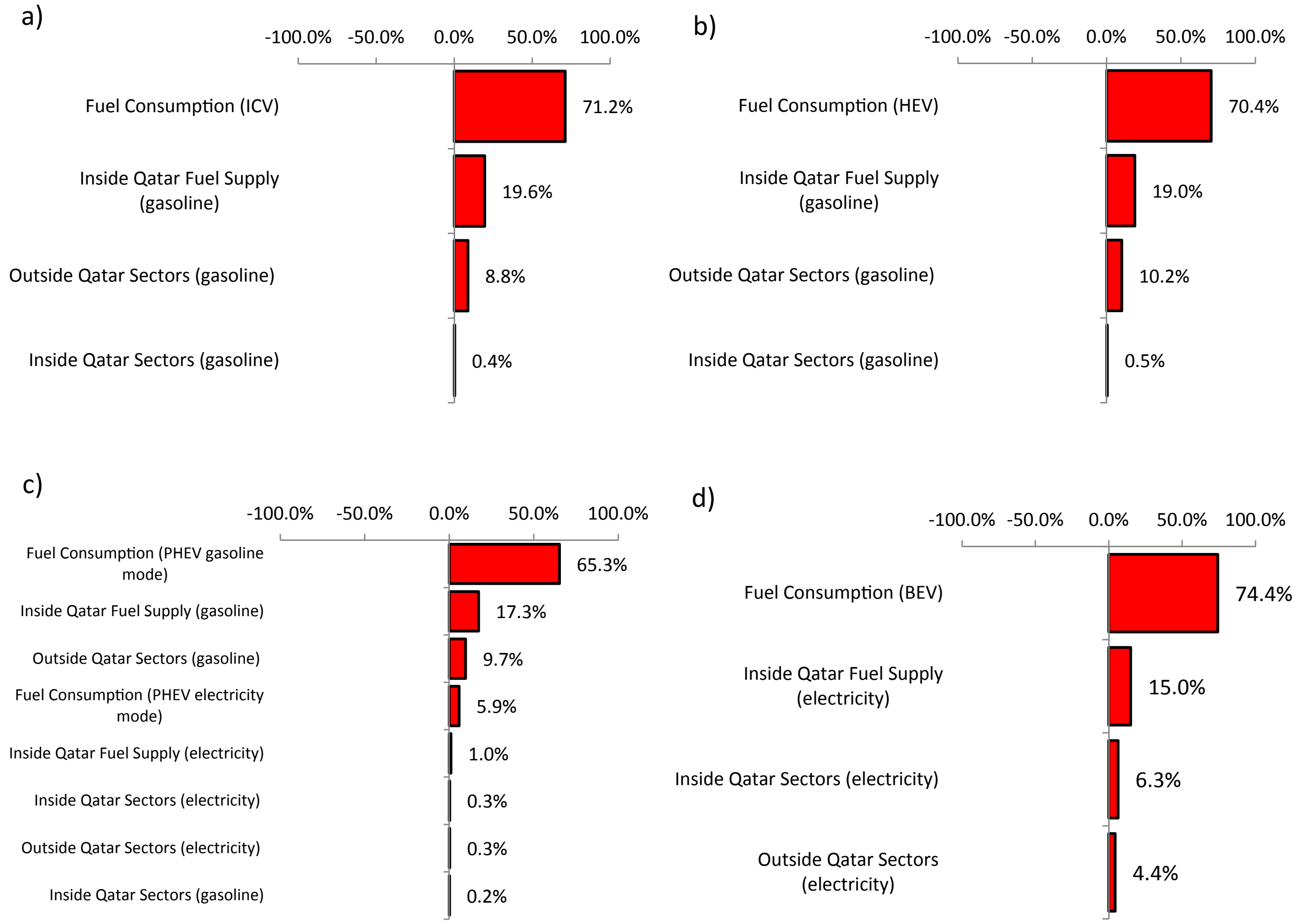


Fig. 8. Sensitivity analysis for Employment (a) ICV; (b) HEV; (c) PHEV; (d) BEV.

kilometer driven. On the other hand, in the water consumption category, internal combustion vehicles are found to be the worst vehicle alternative. It should be also noted that more than 90% of the total water consumption impact occurs outside of Qatar's regional boundaries, attributed to the global supply chains of the associated sectors, while water withdrawals occur within the regional boundaries of Qatar.

- Similarly, in the land use category, battery electric vehicles have the lowest land use, while internal combustion vehicles have the highest. However, more than 95% of this impact occurs outside of the regional boundaries of the Qatar, which implies the impact of imports on the global supply chain of Qatar's petroleum production and electricity generation sectors.
- In the social indicators, internal combustion vehicles perform better than all other alternative vehicles in terms of employment generation, compensation, and taxes. On the other hand, they perform the worst in the human health impact category. Hence, from a socio-economic perspective, a 10% market penetration for battery electric vehicles cause employment, compensation, and tax loss up to 8%, 7%, and 9%, respectively. However, in the same market penetration scenario, they can reduce human health impacts up to 8%. It should be also noted that the majority of these impacts occurs within the regional boundaries of Qatar.
- The results highlighted that the adoption of electric vehicle alternatives doesn't favor macro-economic indicators. Overall, the battery electric vehicles perform worse in terms of contribution to gross domestic product and operation surplus, while they are slightly better for life-cycle ownership cost compared to internal combustion vehicles, and can reduce only up to 1% of life cycle cost in case of 10% market penetration scenario. It should be noted that there are also design parameters [69] and subsidies in different countries [70], which can significantly influence the cost of ownership for electric vehicle types Such parameters can further be investigated in future studies.

Considering that there are fourteen different indicators influencing the selection of best vehicle alternative, effective policy development requires consideration of all these indicators together. For the case of Qatar, the importance of these indications should be prioritized in coordination with the stakeholders. By developing multi-criteria decision-making models such as multi-objective optimization, optimal vehicle mix on road can be determined. Future work should focus on developing a compromise programming approach to estimate the optimal distribution (mix) on Qatar's roads [71]. The boundary selection is also an important factor affecting the impacts of the alternatives [46]. Therefore, the optimal mix should be investigated for varying boundary definitions (from smaller boundary to larger), as the impacts of alternatives are distributed either within regional boundaries or global supply chains of the operation phase impacts. In addition, a scenario where electric vehicles are charged through solar energy should be investigated to account for potential benefits can be achieved by utilizing significant solar capacity of Qatar.

The quantification of the selected indicators that have been performed in this paper does not consider the dynamical relationships between indicators and future estimations. Therefore, the proposed multi-regional input-output based Life Cycle Sustainability Assessment can be improved by integration of system dynamics modeling to reveal the interconnections and the dynamic relationships between the

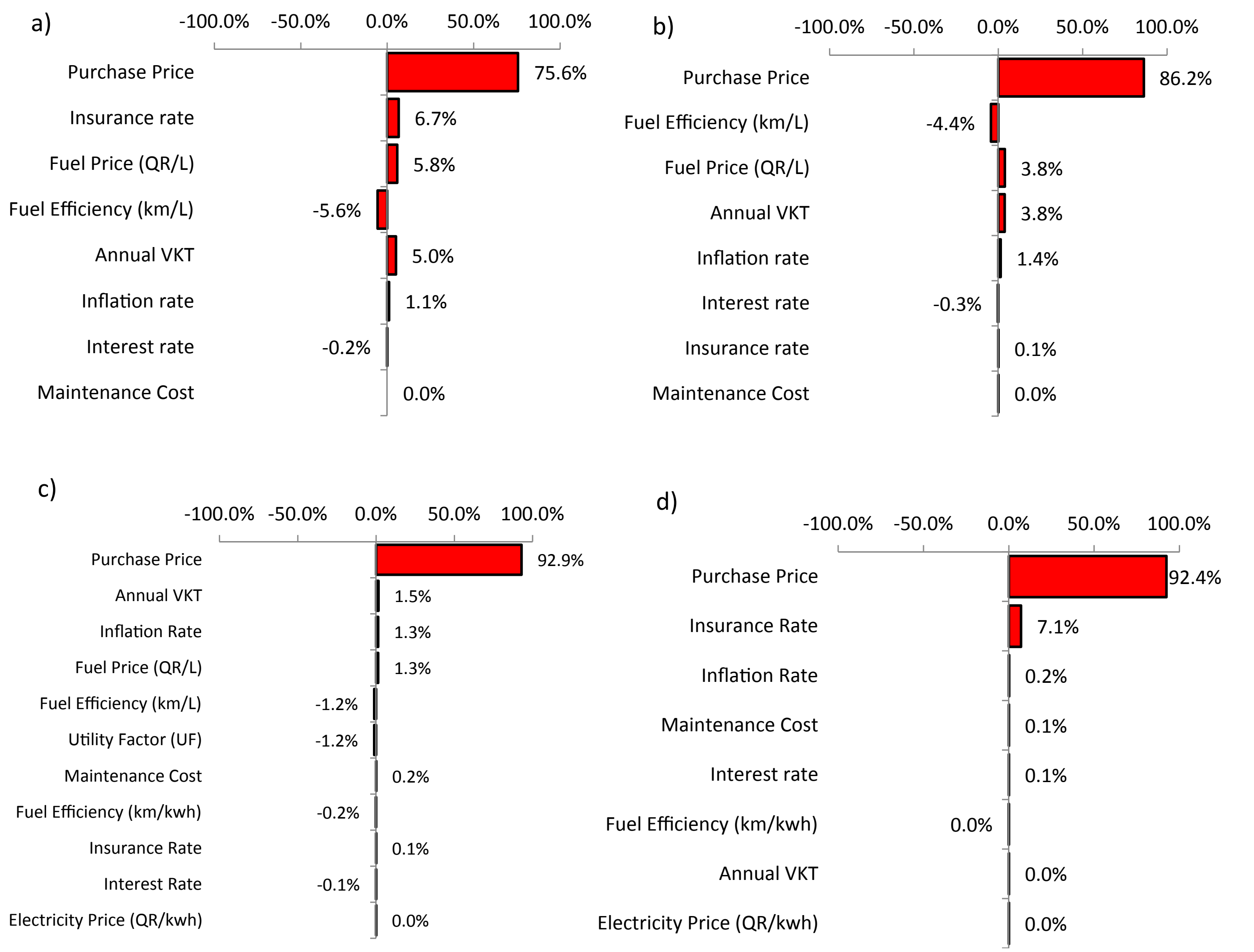


Fig. 9. Sensitivity analysis for LCC (a) ICV; (b) HEV; (c) PHEV; (d) BEV.

environmental, economic, and the social indicators [72,73]. The proposed multi-regional input-output based Life Cycle Sustainability Assessment framework can be further enhanced by the inclusion of system dynamics modeling to reveal the complex interconnections and dynamic relationships between sustainability indicators as well as uncertainties in electric vehicle policies [74].

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.05.076.

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