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Integrated modelling for sustainability assessment and decision making of alternative fuel buses

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ABSTRACT

In this paper, a hybrid life cycle sustainability assessment (LCSA) model integrating multi region input–output analysis with novel multi-criteria decision-making techniques is proposed to assess three different fuel alternatives: compressed natural gas (CNG), electric buses (EBs), and diesel buses (DBs). A global hybrid LCSA model first quantified the environmental, economic, and social impacts of alternative fuel buses. The results were investigated in terms of multiple combinations of manufacturing and end-of-life scenarios by encompassing impacts embedded in the global supply chains taking Qatar as a case applied to the proposed model. The Interval-Valued Neutrosophic Fuzzy (IVNF)-Analytic Hierarchy Process with the Combined Compromise Solution (CoCoSo) approach is used to rank the alternative fuel buses based on their corresponding sustainability performance. The proposed model will help in quantitatively capturing the macro-level life cycle socioeconomic and environmental impacts along with optimally selecting alternatives to support sustainable urban transport policy towards a net-zero transportation system globally.

1. Introduction

1.1. Background

The transportation sector emits millions of tons of GHGs, 25 %-30 % of the total (IEA, 2021). In 2019, transport emissions dropped to 0.5 % from 1.9 % in 2000. In 2018, worldwide transport accounted for 21 % of CO2 emissions, according to the IEA (IEA, 2021). Road cars account for 74 % of transport CO2 emissions and 15 % of total CO2. Passenger vehicles account for 45 % of these emissions, and trucks 29 %. (IEA, 2021).

While there is no agreed-upon definition of sustainable transportation, it is generally understood that sustainable transportation entails striking an appropriate balance between present and future environmental, social, and economic elements (Steg and Gifford 2005). There is a shift in the global trend towards a more sustainable transport system by gradually integrating modern technologies and fuel alternatives into the transport fleets. Adopting alternative fuels such as biofuels, electricity, hydrogen, or Compressed Natural

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Table 1
Studies covering the LCSA and MCDM.

Document title	Authors	Selection problem	No. of compared alternative	Consideration of sustainability impacts	Methods considered	Stakeholder Participation	Sensitivity of priorities (weights)
1. "Life cycle sustainability assessment analysis of different concrete construction techniques for residential building in Malaysia."	Balasbaneh and Sher, (2021)	Construction Techniques	3	Env. (5), Eco. (1), Soc.(survey)	TOPSIS, AHP	Yes	Yes
2. "Technology selection for hydrogen production in China by integrating emergy into life cycle sustainability assessment."	Li et al., (2021)	Hydrogen production technologies	4	Env. (2), Eco. (4), Soc. (2)	MAVT	No	Yes
3. "Selection of alternative fuel taxis: a hybridized approach of life cycle sustainability assessment and multi-criteria decision making with neutrosophic sets."	Aboushaqrah, et al., (2021)	Alternative-fuel taxis	4	Env. (7), Eco. (3), Soc. (3)	TOPSIS, AHP	Yes	No
4. "Life cycle sustainability assessment of window renovations in schools against noise pollution in tropical climates."	Balasbaneh et al., (2020)	Noise reduction windows	4	Env. (1), Eco. (1), Soc. (5)	AHP, TOPSIS	Yes	Yes
5. "Incorporating uncertainty into life-cycle sustainability assessment of pavement alternatives."	Zheng, et al., (2020)	Pavement alternatives	3	Env. (6), Eco. (1), Soc. (1)	AHP-ISD	Yes	Yes
6. "Industrial system prioritization using the sustainability-interval-index conceptual framework with life-cycle considerations."		Hydrogen production technologies	5	Env. (2), Eco. (3), Soc. (1)	Multifactor fuzzy best-worst	Yes	Yes
7. "Application of multi-criteria decision-making approach for sustainability assessment of chosen photovoltaic modules."	Krysiak and Kluczek, (2020)	Photovoltaic modules technologies	3	Env. (4), Eco. (3), Soc. (3)	AHP	Yes	No
8. "Multi-criteria decision-making and probabilistic weighting applied to sustainable assessment of beef life cycle."	Florindo et al., (2020)	Animal production	4	Env. (5) Eco. (4), Soc. (5)	VIKOR	Yes	Yes
9. "Life-cycle sustainability assessment of pavement maintenance alternatives: Methodology and case study."	Zheng et al., (2019)	Pavement alternatives	3	Env. (6) Eco. (1), Soc. (8)	AHP-VIKOR	Yes	Yes
10. "Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment."	Ren, (2018)	Electricity generation systems	4	Env. (4) Eco. (3), Soc. (3)	TOPSIS	Yes	Yes

(continued on next page)

Table 1 (*continued*)

Document title	Authors	Selection problem	No. of compared alternative	Consideration of sustainability impacts	Methods considered	Stakeholder Participation	Sensitivity of priorities (weights)
11. "Multiactor multi-criteria decision making for life cycle sustainability assessment under uncertainties."	Ren et al., (2018)	Electricity generation systems	5	Env. (6) Eco. (4), Soc. (4)	ITODIM	Yes	Yes
12. "Life cycle aggregated sustainability index for the prioritization of industrial systems under data uncertainties."	Ren, (2018 a)	Electricity generation systems	4	Env. (4) Eco. (3), Soc. (3)	IMADA, Interval TOPSIS,SWM	No	Yes
13. "Life cycle sustainability decision-support framework for ranking of hydrogen production pathways under uncertainties: An interval multi-criteria decision-making approach."	Ren and Toniolo, (2018)	Hydrogen production	4	Env. (4) Eco. (1), Soc. (2)	ISWM, Interval TOPSIS, DEMATEL, EDAS	No	Yes
14. "Life cycle sustainability assessment (LCSA) for selection of sewer pipe materials.	Akhtar et al., (2015)	Sewer pipe materials	4	Env. (5) Eco. (3), Soc.(0)	AHP	No	Yes
15. Lessons Learned from a Life Cycle Sustainability Assessment of Rare Earth Permanent Magnets."	Wulf et al., (2017)	Rare Earth permanent magnet system	3	Env. (14) Eco. (2), Soc. (15)	Geometric aggregation	Yes	No
16. "Intuitionistic fuzzy multi-criteria decision-making framework based on life cycle environmental, economic, and social impacts: The case of US wind energy."	Gumus et al., (2016)	Wind turbines	4	Env. (4) Eco. (2), Soc. (3)	Fuzzy TOPSIS	No	Yes
17. "Application of the TOPSIS and intuitionistic fuzzy set approaches for ranking the life cycle sustainability performance of alternative vehicle technologies."	Onat et al., (2016a)	Alternative vehicle technologies	4	Env. (10) Eco. (3), Soc. (3)	Fuzzy set, TOPSIS	No	Yes
18. "Combined application of multi-criteria optimization and life-cycle sustainability assessment for optimal distribution of alternative passenger cars in the US."	Onat et al., (2016b)	Alternative vehicle technologies	7	Env. (9) Eco. (3), Soc. (4)	AHP, MODM	Yes	Yes
19. "Ranking the sustainability performance of pavements: An intuitionistic fuzzy decision-making method."	Kucukvar et al., (2014a)	Pavement alternative	4	Env. (10) Eco. (3), Soc. (3)	Fuzzy set, TOPSIS	No	Yes
20. "Stochastic decision modelling for sustainable pavement designs."	Kucukvar et al., (2014b)	Pavement alternative	4	Env. (10) Eco. (3), Soc. (3)	AHP, stochastic optimization	Yes	Yes

(continued on next page)

Table 1 (*continued*)

Document title	Authors	Selection problem	No. of compared alternative	Consideration of sustainability impacts	Methods considered	Stakeholder Participation	Sensitivity of priorities (weights)
21. "Advancing integrated systems modelling framework for life cycle sustainability assessment."	Halog and Manik, (2011)	Energy production technologies	3	Env. (16) Eco. (4), Soc. (15)	AHP, SD	Yes	No
Proposed Study		**Alternative vehicle technologies**	**26**	**Env. (5) Eco. (3), Soc. (4)**	**IVN-AHP integrated CoCoSo SF-AHP integrated CoCoSo PF-AHP integrated CoCoSo**	**Yes**	**Yes**

Gas (CNG) is crucial in cutting down the usage of fossil fuels (Pamucar et al., 2021). Moreover, adopting new technologies into the fleets would positively reduce tailpipe emissions and integrate with sourcing renewable energies, such as battery/chargeable Electric Vehicles (EV), Plug-in Hybrid Electric Vehicles (PHEV), and CNG vehicles (Bartolozzi et al., 2013). Moreover, the power generation mix should be considered since it plays an essential role in the CO_2 intensity related to the electricity used to feed EVs or PHEVs.

The CO_2 intensity varies among EVs, PHEVs, and other conventional vehicles. Moreover, the power consumption mix in a country also plays a role in the CO_2 intensity. Therefore, the optimal choice for new vehicles differs from nation to nation, depending on the energy-generating mix currently in use there (Woo, Choi, and Ahn 2017). Selecting the best vehicle is a complex problem and subjective to several competing factors. Moreover, implementing sustainable decisions to arrive at optimal configurations of road transport fleets requires a coherent multi-criteria framework. This study thus proposes a comprehensive Multi-criteria Decision-Making approach (MCDM). The MCDM method provides an efficient approach to neutralizing the trade-offs between the environmental impacts and the socio-economic benefits of road transport. To this end, this paper presents a novel integrated multi-criteria-based Life Cycle Sustainability Assessment (LCSA) model for the optimal selection of alternative fuel bus technologies (electric, CNG, and diesel buses), applying to a case in the State of Qatar. The ranking analysis evaluates the sustainability impacts of 26 outcomes based on the MRIO-LCSA. This study aims to propose a valuable method for decision-making platforms and assess decision-makers in developing effective policies to achieve Qatar's efforts to minimize the adverse effects of road transportation.

1.2. Literature review

Numerous studies have developed and used several Multiple criteria decision-making (MCDM) tools to solve different problems in diverse fields such as manufacturing, energy production, environment, and sustainability (Mardani et al., 2015). The MCDM has been widely used in research fields since the 1960 s; numerous articles and books have addressed it (Roy, 2005). MCDM is a general term for all methods that help researchers make the best decisions according to different preferences in cases of conflicting criteria (Ho, 2008). MCDM methods allow researchers to solve complex problems by breaking the problem into smaller parts, weighing some external considerations, then finalizing judgments regarding smaller related components, and reassembling the pieces at the end to present the overall situation (Mardani et al., 2015).

The Decision-Making (DM) technique involves making a choice amongst alternatives specified by their aspects. Due to the shortcomings of the DM approach, various MCDM tools and techniques have been developed over time with different theoretical backgrounds. The expansion of MCDM research was enhanced between the 1980s and early 1990s to develop several techniques and approaches. For instance, Saaty (1980) published a comprehensive study on the Analytic Hierarchy Process (AHP), then Saaty (1996) published a development study about the Analytic Network Process (ANP) technique. Roy (1996) summarized the material on Elimination and Choice Expressing Reality (ELECTRE) methods. Moreover, Brauers, (2004) published a study based on the Multi-Objective Optimization by Ratio Analysis (MOORA). Hybrid methods, built on previously well-known methods, are becoming even more central in recent studies. As an illustration, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981), Decision Making Trial and Evaluation Laboratory (DEMATEL) (Huang et al., 2007) and Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) have all emerged in recent scholarship (Opricovic, 1990; Opricovic, 1998).

A review of the literature is conducted in this study to compare the MCDM methods and the sustainability impacts of various studies across different thematic areas. Based on a Scopus database search, there were twenty-one studies covering the "Life cycle sustainability assessment" AND "multi-criteria decision making" in either keywords, abstract, or title for the period between 2011 and 2021, as accessed on 20 September 2021. Table. 1 shows a detailed evaluation of these papers covering the authors' names, studied problems, and the number of sustainability impacts investigated by each article. Also, the assessment covers the stakeholders' participation and whether the paper had applied a sensitivity of priorities for the weighting sustainability impacts or not. Although many studies use

MCDM tools, the research related to alternative fuel vehicles remains limited in the existing scholarly literature. Among the twenty-one articles covered in our literature review, there were only three publications related to alternative vehicle technologies. There was no study published on applying MCDM methods to the study of alternative fuel buses in Qatar or any other region.

Three existing studies have combined MCDM methods and the life cycle sustainability assessment (LCSA) into one framework. More specifically, the combined LCSA and MCDM assessment include the neutrosophic sets and TOPSIS to compare and rank four-vehicle technologies in Qatar (Aboushaqrah et al., 2021). The evaluated vehicle types are conventional gasoline vehicles, hybrid EVs, battery EVs, and CNG vehicles. The results indicate that battery EVs (solar-powered) are the best alternative, followed by CNG vehicles. Furthermore, the work incorporated the results of LCSA into TOPSIS and intuitionistic fuzzy set methods to rank the four vehicle alternatives in the US (Onat et al., 2016). The results reveal that hybrid and plug-in hybrid EVs are the best alternatives based on all the indicators. Lastly, there has been an investigation into seven different vehicle types to determine the optimal fleet mix in the US (Onat et al., 2016 a). The results found that hybrid EVs would have the largest share (91 %) of the optimal fleet when weighing the environmental and socio-economic indicators balanced with the existing electric power infrastructure. However, in the case of using a solar charging station for electric power generation, the optimal fleet mix consists of 100 % of plug-in hybrid EVs. Based on the data presented in Table 1, 9 articles studied diverse energy production methods and 5 articles focused on different construction projects. Hence, energy production forms, and construction projects were commonly investigated. Additionally, ten studies employed AHP methods, which is the most common methodology represented in the existing published scholarly literature. The second most common method was the TOPSIS with nine studies. The third most common method was the Fuzzy method, which was only applied in four studies. The participation of stakeholders is highly effective since more than 60 % of the papers have included stakeholders in their investigation. Furthermore, around 80 % of the articles have tested the sensitivity of priorities by examining different weights.

1.3. Knowledge gaps and novelty

Alternative fuel vehicle technologies will continue to be at the heart of the United Nations Agenda for Sustainable Development. Life Cycle Sustainability Assessments (LCSA) is one of the superior quantitative sustainability assessment frameworks that can help understand the long-term sustainability impacts of new emerging transportation technologies. MCDM techniques facilitate high flexibility in the process of decision-making when more than one criterion is involved to select the optimal alternative. Based on these notions, in this study, a hybrid LCSA model combining Interval Valued Neutrosophic (IVN)-AHP integrated CoCoSo method is proposed to rank three different alternative city fuel bus technologies, taking the State of Qatar as a case application. A comparative analysis is carried out to test the robustness and reliability of the results obtained from the proposed IVNF-AHP & CoCoSo model with the results from using the Spherical Fuzzy (SF)-AHP & CoCoSo model and the Pythogorean Fuzzy (PF)-AHP & CoCoSo model. Furthermore, it can be seen from the literature review those 21 studies have investigated integrating different MCDM methods with the results of LCSA. However, the review of the literature and these methods reveal several gaps and shortcomings. The following highlights of this study demonstrate the novelty of the approach proposed with the respective gaps identified in the current-art knowledge:

(a) This study applies unique ranking models and frameworks that do not exist in previous literature. One of the primary objectives of this study is to integrate the CoCoSo ranking approach with three different methods to determine indicator weights: the NF-AHP, the SF-AHP, and the PF-AHP, among others.
(b) This study evaluates and ranks six alternatives, which is many more options when compared to previous studies, as shown in Table 1.
(c) The NF-AHP allows decision-makers to assess their reservations about creating a membership function. All other logic is an extension of neutrosophic logic. Its definition consequently requires additional parameters, and its Truthiness (T), Indeterminacy (I), and Falsity (F) aspects provide more information about the studied situation. The suggested interval-valued neutrosophic-AHP technique in this study may handle decision-makers' (DMs') optimistic (O), pessimistic (P), and neutral (N) points of view with decreased uncertainty.
(d) Regarding the problem of selection, this research focused on the different alternatives to city buses; however, only a few studies in the literature have focused on evaluating alternative vehicle technologies. Those that were, studied smaller-sized vehicles.
(e) Analyzing the suggested future work among the literature found that several studies have recommended evaluating more alternatives and covering further uncertainty in the analysis. For instance, Zheng et al. (2020) have pointed out in their future work that more uncertainty factors need to be integrated, such as the uncertainties related to the AHP method. Moreover, Onat et al. (2016) advocated enhancing more uncertainties, especially for those associated with temporal and spatial variations. Therefore, to illuminate this uncharted hiatus, this study covers more uncertainty with different models, particularly decision-makers and input parameters.

The rest of the paper is structured as follows: Section 3 details the LCSA, fuzzy MCDM, and CoCoSo methods; detailed results and discussion related to the LCSA, and ranking analysis are included in Section 4, which also contains suggestions for policy and practice. Finally, conclusions, recommendations, and future works are summarized.

2. Method

In this study, a hybrid life cycle sustainability assessment model is combined with novel multi-criteria decision-making techniques to select alternative-fuel bus technologies against specified evaluation criteria. Fig. 1. illustrate a simplified diagram of the methodology proposed in this study.

A multiregional input–output (MRIO)-based hybrid LCSA model is developed to analyze 13 macro-level sustainability

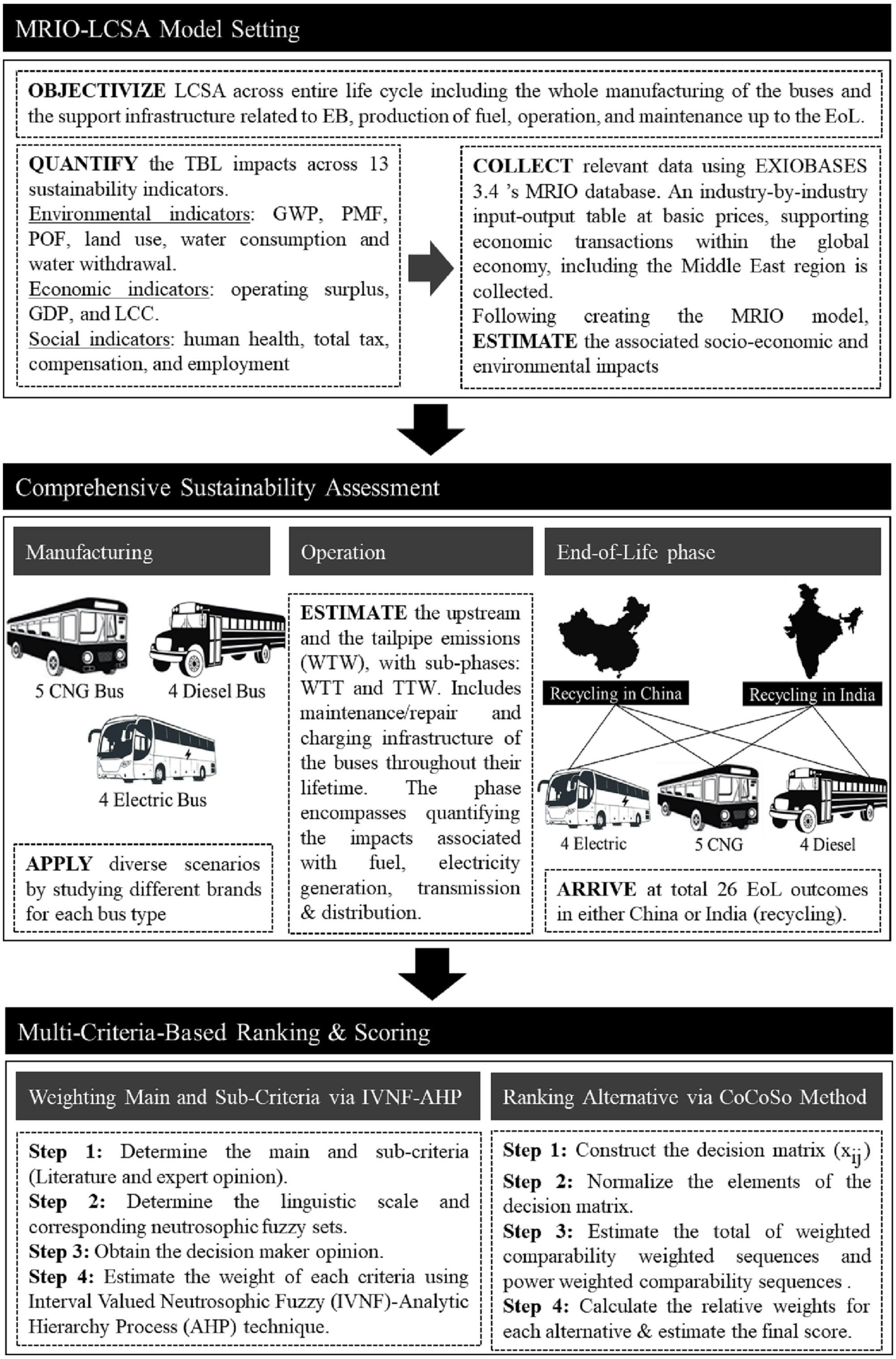

Fig. 1. Proposed research methodology.

(environmental, social, economic) indicators of alternative fuel bus technologies using a global MRIO database. The indicators are selected based on the decision maker's priority and data availability. Moreover, the chosen indicators are the major impact categories found in national policies and environmental agendas, such as GHG emissions, ecological land use, water consumption, GDP growth, etc. LCSA model is developed specifically to evaluate 3 bus technologies: CNG, diesel, and electric, all of which are prospective contenders for inclusion in a public city bus fleet in Qatar. A novel integrated MCDM model is then proposed to rank the alternatives according to their individual sustainability performance as determined by the hybrid LCSA model for both the global and local scenarios. Interval-Valued Neutrosophic Fuzzy-AHP is used to weight the main criteria and sub-criteria. The combined Compromise Solution (COCOSO) method is then used to rank a total of 26 alternatives.

2.1. Life cycle Sustainability Assessment

A comprehensive LCSA is required to understand the sustainability impacts of alternative bus technologies embedded in global supply chains. The MRIO-LCSA model proposed in this study quantifies the associated environmental, social, and economic impacts of

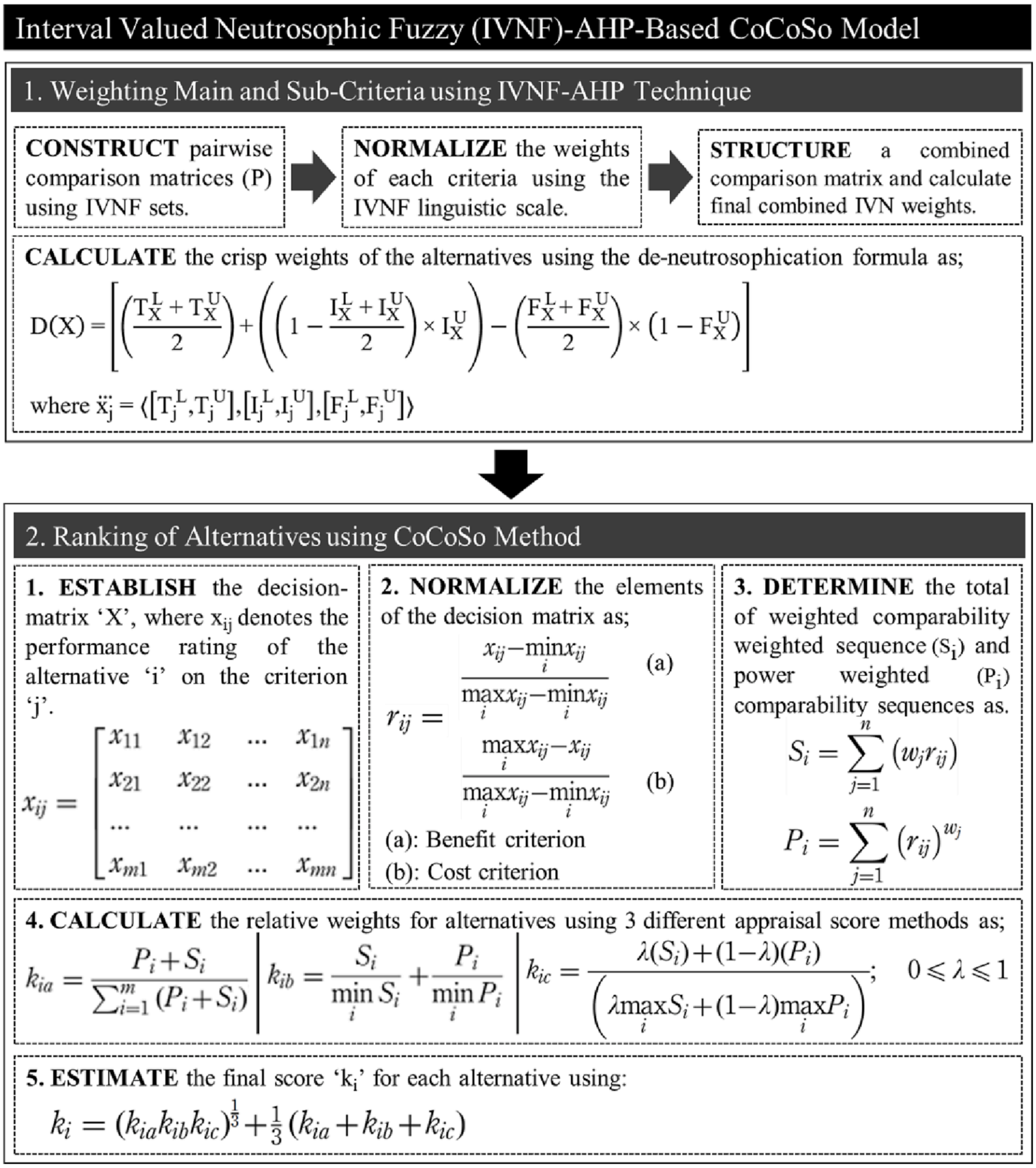

Fig. 2. Implementation steps for the IVNF-AHP-based CoCoSo model.

alternative fuel bus technologies under a single comprehensive framework. The study compares 3 different types of bus technologies namely; compressed natural gas (CNG), electric buses (EB), and diesel buses (DB). These three bus types are evaluated and compared based on 13 sustainability indicators, under the three aspects of sustainability, namely, environmental, social, and economic impacts. Firstly, the study considers the environmental aspects represented by global warming potential (GWP), photochemical ozone formation (POF), particulate matter formation (PMF), land use, water consumption, and water withdrawal. Secondly, the economic aspects represented by operating surplus, gross domestic product (GDP), and life cycle cost (LCC) are considered. Finally, four indicators that represent the social aspects: human health, total tax, compensation, and employment are taken to understand the associated impacts of the alternative bus technologies.

2.2. Scope of analysis

The system boundaries are outlined to evaluate three phases: manufacturing, operation, and End-of-Life (EOL). Quantifying the total impacts across the manufacturing phase includes both the impacts associated with electric bus battery manufacturing and the CNG tank production. Moreover, it covers the shipping and importing-to-Qatar impacts. The operating phase takes into account the effects caused by the generation of fuel and electricity, maintenance and repair, and the infrastructure for charging electric buses. The EoL phase evaluates the impact of recycling the selected 3 bus alternatives.

Furthermore, the manufacturing phase studies several brands for each type of bus; for the CNG buses, there are five brands imported from China, Turkey, Sweden, Poland, and India; for the EBs, there are four brands that are imported from China, Germany, Spain, and Sweden. Additionally, four DB brands are included in the analysis; a DB imported from both China and Poland, and 2 DBs imported from Turkey.

The manufacturing specifications of all the bus models considered in the study follow a certain standard such as 12 m (m) in length with an annual mileage of 146,000 km (km) and an average lifetime of 10 years. Moreover, our analysis assumes that all evaluated buses have the same occupancy rate. It is noteworthy that, all the sustainability impacts in this study are calculated and reported in kilograms per kilometer; it implies that the functional unit is 1 km of bus travel. The operation phase in this study includes both the tailpipe and the upstream emissions, collectively referred to as ''well-to-wheel'' (WTW). The WTW comprises two independent subphases: well-to-tank (WTT) and tank-to-wheels (TTW). In the MRIO-LCSA model, the WTT consists of three key components: first, inside Qatar fuel supply, representing the impacts of fuel (petroleum, CNG, electricity) production at power plants inside Qatar. The second key is inside Qatar sectors, representing the impacts of suppliers for fuel production inside Qatar, excluding the fuel supply. The third key component is the outside Qatar sectors, which contain the impacts of suppliers for fuel production outside Qatar.

However, the TTW indicates the direct impact or tailpipe emissions from fuel combustion during the operation phase of buses. The EoL phase in our study is assessing the benefits of the extracted materials from recycling all types of buses and evaluating the possible reduction in overall impacts. For this study, two scenarios for the recycling processes have been assumed; either all buses will go through recycling in China or India, which adds two more scenarios to the study analysis. Eventually, combining the possible scenarios from the manufacturing and EoL phases leaves us with twenty-six potential outcomes we evaluate in this study. Further information on the proposed MRIO-LCSA model, including mathematical formulae, may be found in the methods section of the Supplementary Information (SI) file.

2.3. Interval valued neutrosophic (IVN) fuzzy AHP-CoCoSo method proposal

In this study, the Neutrosophic AHP method is integrated with the CoCoSo approach to rank 26 alternatives under evaluation. The ranking model consists of two main stages: Stage 1 uses IVNF-AHP to assign weights to each main criterion and sub-criteria; Stage 2 uses the CoCoSo method to rank the alternatives. The schematics of the IVNF-AHP-CoCoSo method are presented in Fig. 2. Further, a comparative analysis is conducted in which the results from the NF-AHP & CoCoSo model are compared with the results obtained from the Spherical Fuzzy (SF)-AHP & CoCoSo model and the Pythogorean Fuzzy (PF)-AHP & CoCoSo model. Different weighting approaches are used amongst the three models (NF-AHP, PF-AHP, and SF-AHP); nevertheless, the CoCoSo methodology is employed as a ranking approach for all three models.

Stage 1: Weighting main and sub-criteria using the IVNF-AHP technique.

In this study, 3 different AHP methods are used individually to define the weights of each sustainability aspect (main criteria) and indicators (sub-criteria). The NF-AHP method is used in the main model of our study; however, the SF-AHP and PF-AHP methods are used for the comparative analysis. The methodology section in the SI file contains detailed instructions on how to apply the SF-AHP and PH-AHP. Nevertheless, the rest of this section explains the NF-AHP approach and its application procedures:

2.3.1. Neutrosophic sets (IVNF-AHP)

Neutrosophic sets were developed by Smarandache (1998) to solve the complex decision-making problems associated with uncertainties. One of the neutrosophic sets' significant advantages is the ability to declare accuracy, indeterminacy, and inaccuracy through assessing alternatives in MCDM (Karabašević et al., 2020). Moreover, the Interval-Valued Neutrosophic (IVN) sets have opened new horizons in MCDM to be utilized in several types of research, such as Commerce Development (Karabašević et al., 2020), and public transportation (Aboushaqrah et al., 2021). Several important definitions and operations related to the interval-valued neutrosophic sets are provided in the SI file. The steps of the IVNF-AHP method proposed by Bolturk and Kahraman, (2018) are applied in this study and presented as follows.

Step 1: Define the problem and hierarchically structure the goals, criteria, sub-criteria, and alternatives.

Step 2: Create the pairwise comparison matrices (P) using IVNF sets after gathering the experts' judgments. This study adopts the linguistic scale with its corresponding IVN sets as proposed by Bolturk & Kahraman (2018) (as in Table 2).

P_c matrix (Eq. (1)) represents the comparison of criteria for the goal.

$$P_c = \begin{bmatrix} \langle [T_{11}^L, T_{11}^U], [I_{11}^L, I_{11}^U], [F_{11}^L, F_{11}^U] \rangle & \cdots & \langle [T_{1n}^L, T_{1n}^U], [I_{1n}^L, I_{1n}^U], [F_{1n}^L, F_{1n}^U] \rangle \\ \vdots & \ddots & \vdots \\ \langle [T_{n1}^L, T_{n1}^U], [I_{n1}^L, I_{n1}^U], [F_{n1}^L, F_{n1}^U] \rangle & \cdots & \langle [T_{nn}^L, T_{nn}^U], [I_{nn}^L, I_{nn}^U], [F_{nn}^L, F_{nn}^U] \rangle \end{bmatrix} \quad (1)$$

P_A matrix (Eq. (2)) shows the comparison of alternatives to the selected set of criteria as:

$$P_A = \begin{bmatrix} \langle [T_{11}^L, T_{11}^U], [I_{11}^L, I_{11}^U], [F_{11}^L, F_{11}^U] \rangle & \cdots & \langle [T_{1m}^L, T_{1m}^U], [I_{1m}^L, I_{1m}^U], [F_{1m}^L, F_{1m}^U] \rangle \\ \vdots & \ddots & \vdots \\ \langle [T_{m1}^L, T_{m1}^U], [I_{m1}^L, I_{m1}^U], [F_{m1}^L, F_{m1}^U] \rangle & \cdots & \langle [T_{mm}^L, T_{mm}^U], [I_{mm}^L, I_{mm}^U], [F_{mm}^L, F_{mm}^U] \rangle \end{bmatrix} \quad (2)$$

The deneutrosophicated method proposed by Bolturk and Kahraman, (2018a) is used to check the consistency of both matrices P_c and P_A as in Eq. (3).

$$D(X) = \left[\left(\frac{T_X^L + T_X^U}{2} \right) + \left(\left(1 - \frac{I_X^L + I_X^U}{2} \right) \times I_X^U \right) - \left(\frac{F_X^L + F_X^U}{2} \right) \times \left(1 - F_X^U \right) \right] \quad (3)$$

Where. $x_j = \langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$

Step 3: Normalize the weights of each criteria using the IVNF linguistic scale. The steps concerning the IVNF-AHP based on the pairwise comparison matrix 'P_A' with respect to a specific criterion are presented as follows;

Step 3.1: Sum each column values of P_A matrix as in Eq. (4):

$$S_{ij} = \left\langle \left[\sum_{k=1}^m T_{kj}^L, \sum_{k=1}^m T_{kj}^U \right], \left[\sum_{k=1}^m I_{kj}^L, \sum_{k=1}^m I_{kj}^U \right], \left[\sum_{k=1}^m F_{kj}^L, \sum_{k=1}^m F_{kj}^U \right] \right\rangle \quad (4)$$

Step 3.2: Obtain the N_{kj} value by selecting the upper value for each parameter (T, I, F) and dividing each term in Eq. (4) by its appropriate element, leading to Eq. (5) as follows:

$$N_{kj} = \left\langle \left[\frac{T_{kj}^L}{\sum_{k=1}^m T_{kj}^U}, \frac{T_{kj}^U}{\sum_{k=1}^m T_{kj}^U} \right], \left[\frac{I_{kj}^L}{\sum_{k=1}^m I_{kj}^U}, \frac{I_{kj}^U}{\sum_{k=1}^m I_{kj}^U} \right], \left[\frac{F_{kj}^L}{\sum_{k=1}^m F_{kj}^U}, \frac{F_{kj}^U}{\sum_{k=1}^m F_{kj}^U} \right] \right\rangle \quad (5)$$

The resulting P_A matrix is presented in Eq. (6) as follows:

$$P_A = \begin{bmatrix} \left\langle \left[\frac{T_{11}^L}{\sum_{k=1}^m T_{kj}^U}, \frac{T_{11}^U}{\sum_{k=1}^m T_{kj}^U} \right], \left[\frac{I_{11}^L}{\sum_{k=1}^m I_{kj}^U}, \frac{I_{11}^U}{\sum_{k=1}^m I_{kj}^U} \right], \left[\frac{F_{11}^L}{\sum_{k=1}^m F_{kj}^U}, \frac{F_{11}^U}{\sum_{k=1}^m F_{kj}^U} \right] \right\rangle & \cdots & \left\langle \left[\frac{T_{1m}^L}{\sum_{k=1}^m T_{kj}^U}, \frac{T_{1m}^U}{\sum_{k=1}^m T_{kj}^U} \right], \left[\frac{I_{1m}^L}{\sum_{k=1}^m I_{kj}^U}, \frac{I_{1m}^U}{\sum_{k=1}^m I_{kj}^U} \right], \left[\frac{F_{1m}^L}{\sum_{k=1}^m F_{kj}^U}, \frac{F_{1m}^U}{\sum_{k=1}^m F_{kj}^U} \right] \right\rangle \\ \vdots & \ddots & \vdots \\ \left\langle \left[\frac{T_{m1}^L}{\sum_{k=1}^m T_{kj}^U}, \frac{T_{m1}^U}{\sum_{k=1}^m T_{kj}^U} \right], \left[\frac{I_{m1}^L}{\sum_{k=1}^m I_{kj}^U}, \frac{I_{m1}^U}{\sum_{k=1}^m I_{kj}^U} \right], \left[\frac{F_{m1}^L}{\sum_{k=1}^m F_{kj}^U}, \frac{F_{m1}^U}{\sum_{k=1}^m F_{kj}^U} \right] \right\rangle & \cdots & \left\langle \left[\frac{T_{mm}^L}{\sum_{k=1}^m T_{kj}^U}, \frac{T_{mm}^U}{\sum_{k=1}^m T_{kj}^U} \right], \left[\frac{I_{mm}^L}{\sum_{k=1}^m I_{kj}^U}, \frac{I_{mm}^U}{\sum_{k=1}^m I_{kj}^U} \right], \left[\frac{F_{mm}^L}{\sum_{k=1}^m F_{kj}^U}, \frac{F_{mm}^U}{\sum_{k=1}^m F_{kj}^U} \right] \right\rangle \end{bmatrix} \quad (6)$$

Step 3.3: Determine the neutrosophic priority vector for j^{th} alternatives by averaging each row, as in Eq. (7):

Table 2
Linguistic concepts and their neutrosophical equivalents.

	Linguistic term	Neutrosophic Sets (T,I,F)
1	"Equal importance"	"⟨[0.5,0,5],[0.5,0.5],[0.5,0.5]⟩"
2	"Weakly more importance"	"⟨[0.5,0.6],[0.35,0.45],[0.4,0.5]⟩"
3	"Moderate importance"	"⟨[0.55,0.65],[0.3,0.4],[0.35,0.45]⟩"
4	"Moderately more importance"	"⟨[0.6,0.7],[0.25,0.35],[0.3,0.4]⟩"
5	"Strong importance"	"⟨[0.65,0.75],[0.2,0.3],[0.25,0.35]⟩"
6	"Strongly more importance"	"⟨[0.7,0.8],[0.15,0.25],[0.2,0.3]⟩"
7	"Very strong importance"	"⟨[0.75,0.85],[0.1,0.2],[0.15,0.25]⟩"
8	"Very strongly more importance"	"⟨[0.8,0.9],[0.05,0.1],[0.1,0.2]⟩"
9	"Extreme importance"	"⟨[0.9,0.95],[0,0.05],[0.05,0.15]⟩"
10	"Extremely high importance"	"⟨[0.95,1],[0,0],[0,0.1]⟩"
11	"Absolutely more importance"	"⟨[1,1],[0,0],[0,0]⟩"

$$w_A = \begin{pmatrix} \left[\frac{T_{11}^L}{\sum_{k=1}^{m} T_{kj}^U}, \frac{T_{11}^U}{\sum_{k=1}^{m} T_{kj}^U}\right] \\ \left[\frac{I_{11}^L}{\sum_{k=1}^{m} I_{kj}^U}, \frac{I_{11}^U}{\sum_{k=1}^{m} I_{kj}^U}\right] \\ \left[\frac{F_{11}^L}{\sum_{k=1}^{m} F_{kj}^U}, \frac{F_{11}^U}{\sum_{k=1}^{m} F_{kj}^U}\right] \end{pmatrix} j = 1, 2, \cdots, m. \tag{7}$$

Step 3.4: Repeat the above steps for each criterion and obtain the neutrosophic priority weights for all the alternatives. Similarly, repeat the procedures to obtain the neutrosophic priority vector for all the criteria.

Step 4: Create a combined comparison matrix Ψ as in Eq. (8):

$$w_{c1} w_{cn} \Psi = \langle [T_{wc1}^L, T_{wc1}^U], [I_{wc1}^L, I_{WC1}^U], [F_{wc1}^L, F_{wc1}^U] \langle [T_{wc1}^L, T_{wc1}^U], [I_{wc1}^L, I_{11}^U], [F_{wc1}^L, F_{wc1}^U] \rangle$$

$$w_{A1} \langle [T_{wc1A1}^L, T_{wc1A1}^U], [I_{wc1A1}^L, I_{WC1A1}^U], [F_{wc1A1}^L, F_{wc1A1}^U] \rangle \cdots \langle [T_{wc1A1}^L, T_{wc1A1}^U], [I_{wc1A1}^L, I_{WC1A1}^U], [F_{wc1A1}^L, F_{wc1A1}^U] \rangle$$

$$w_{A2} \langle [2, T_{wc1A2}^U], [I_{wc1A2}^L, I_{WC1A2}^U], [F_{wc1A2}^L, F_{wc1A2}^U] \rangle \cdots \langle [T_{wc1A1}^L, T_{wc1A1}^U], [I_{wc1A1}^L, I_{WC1A1}^U], [F_{wc1A1}^L, F_{wc1A1}^U] \rangle$$

$$w_{Am} \langle [T_{wc1Am}^L, T_{wc1Am}^U], [I_{wc1Am}^L, I_{WC1Am}^U], [F_{wc1Am}^L, F_{wc1Am}^U] \rangle \cdots \langle [T_{wcAm}^L, T_{wcnAm}^U], [I_{wcnAm}^L, I_{WCnAm}^U], [F_{wcnAm}^L, F_{wcnAm}^U] \rangle$$

Step 5: Utilizing Eq. (9) to determine the alternatives' final combined interval-valued neutrosophic weights as follows:

$$\begin{aligned} A = & \langle [T_{wc1}^L, T_{wc1}^U], [I_{wc1}^L, I_{WC1}^U], [F_{wc1}^L, F_{wc1}^U] \rangle * \langle [T_{wc1A1}^L, T_{wc1A1}^U], [I_{wc1A1}^L, I_{WC1A1}^U], [F_{wc1A1}^L, F_{wc1A1}^U] \rangle \\ & + \langle [T_{wc1}^L, T_{wc1}^U], [I_{wc1}^L, I_{WC1}^U], [F_{wc1}^L, F_{wc1}^U] \rangle * \langle [T_{wc1Am}^L, T_{wc1Am}^U], [I_{wc1Am}^L, I_{WC1Am}^U], [F_{wc1Am}^L, F_{wc1Am}^U] \rangle \\ & + \cdots + \langle [T_{wc1}^L, T_{wc1}^U], [I_{wc1}^L, I_{11}^U], [F_{wc1}^L, F_{wc1}^U] \rangle * \langle [T_{wcAm}^L, T_{wcnAm}^U], [I_{wcnAm}^L, I_{WCnAm}^U], [F_{wcnAm}^L, F_{wcnAm}^U] \rangle \end{aligned} \tag{9}$$

Step 6: Find the crisp weights of the alternatives using the de-neutrosophication formula in Eq. (3) as given in Eq. (10):

$$A = (w_{A1}, w_{A2}, w_{A3}) \tag{10}$$

Stage 2: Ranking of alternatives using the CoCoSo approach.

Calculate the score for each alternative using the CoCoSo approach. The Combined Compromise Solution (CoCoSo) method is an innovative MCDM technique developed lately by (Yazdani et al., 2018). In comparison to Weighted Aggregated Sum Product Assessment (WASPAS), Simple Additive Weighting (SAW), and Exponential Weighted Product (EWP) techniques, the CoCoSo method yields more reliable results (Peng et al., 2020; Torkayesh et al., 2021). The CoCoSo technique consists of the following simple steps:

Step 1: Construct the decision matrix (x_{ij}) as given in Eq. (11):

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{nn} \end{bmatrix} \tag{11}$$

where x_{ij} shows the performance of alternative i for criterion j ($i \in \{1, 2, \cdots, m\} and j \in \{1, 2, \cdots, n\}$).

Step 2: Normalize the elements of the decision matrix using Eq. (12):

$$r_{ij} = \begin{cases} \dfrac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} & for benefit criterion \\ \dfrac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} & for cost criterion \end{cases} \tag{12}$$

Step 3: Estimate for each alternative, the total of the weighted comparability weighted sequences (S_i) and the power weighted comparability sequences (P_i) using Eq. (13) and Eq. (14) respectively as:

$$S_i = \sum_{j=1}^{n} w_j r_{ij} \tag{13}$$

$$P_i = \sum_{j=1}^{n} (r_{ij})^{w_j} \tag{14}$$

Step 4: Determine the relative weights of each option. The three separate aggregated appraisal score procedures used to determine the relative weights of alternatives are represented by Eqs. (15) - Eqs. (17):

$$k_{ia} = \frac{P_i + S_i}{\sum_{j=1}^{M} (P_i + S_i)} \tag{15}$$

$$k_{ib} = \frac{S_i}{\underset{i}{min} S_i} + \frac{P_i}{\underset{i}{min} P_i} \tag{16}$$

$$k_{ic} = \frac{(1-\lambda)P_i + \lambda S_i}{(1-\lambda)\underset{i}{min} P_i + \lambda \underset{i}{min} S_i}, 0 \le \lambda \le 1 \tag{17}$$

The arithmetic mean of the sums of WSM and WPM scores is expressed by Eq. (15). Eq. (16) expresses the total of WSM and WPM relative scores compared to the best. In contrast, Eq. (17) yields the balanced compromise of WSM and WPM model scores. In Eq. (17), λ is decided by decision-makers and varies from 0 to 1 (usually $\lambda = 0.5$).

Step 5: Estimate the final score 'k_i' for each alternative using Eq. (18) as:

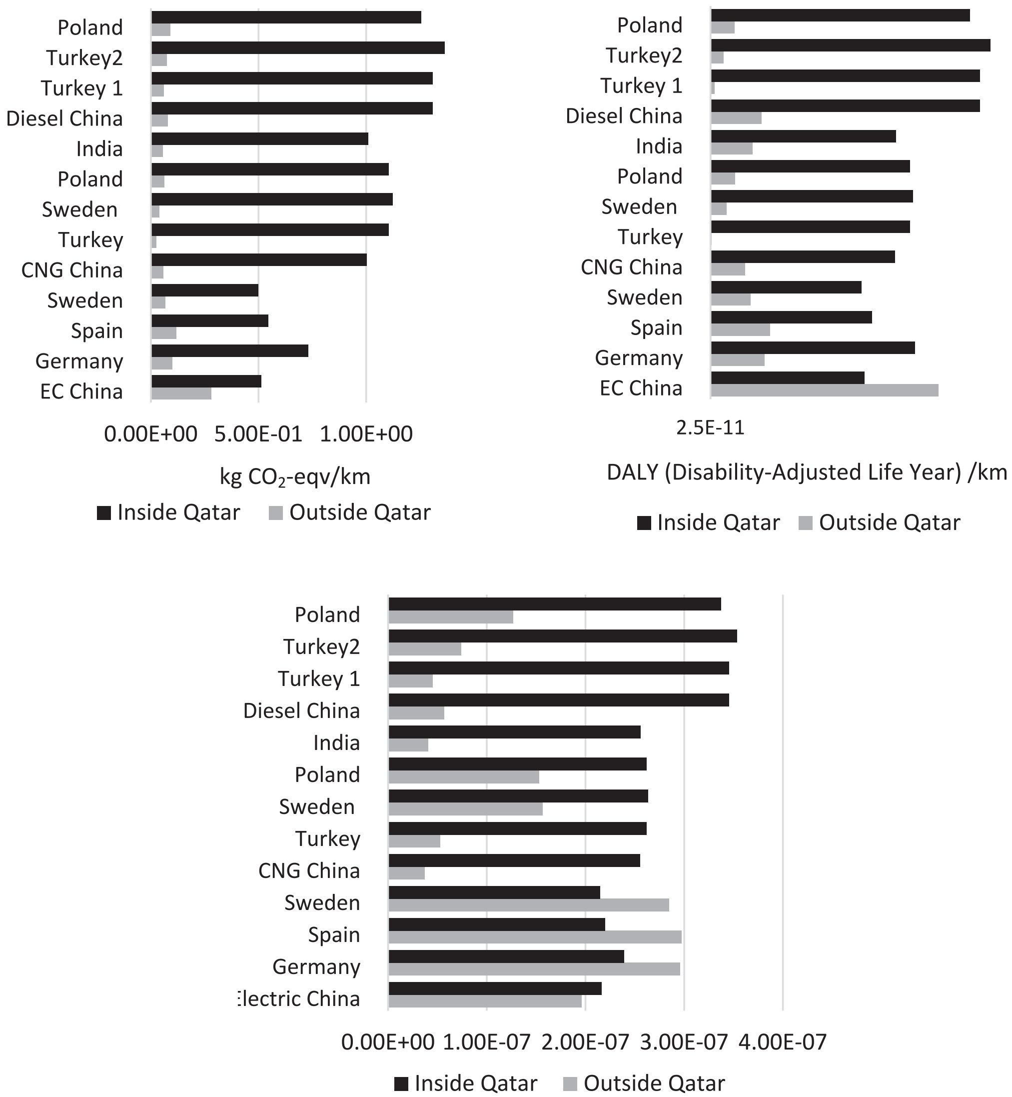

Fig. 3. (A) gwp (b) human health (c) gdp (inside/outside Qatar).

$$k_i = (k_{ia}k_{ib}k_{ic})^{1/3} + 1/3(k_{ia}+k_{ib}+k_{ic}) \tag{18}$$

The best alternative is decided to be the one with the highest final score.

3. Results

3.1. LCSA results

LCSA results present the distribution of the impacts both inside and outside the State of Qatar. Understanding the total impacts inside Qatar involves quantifying the associated impacts generated in place of the EB supporting infrastructure, maintenance & repair, TTW, and the WTT covering only the fuel supply and sectors within the State of Qatar. However, the analysis outside Qatar covers sectors from the WTT, manufacturing, and shipping outside Qatar. The environmental criteria cover seven indicators: GWP, PMF, POF, water consumption, land use, and water withdrawal. The overall results show that the EBs had a higher contribution than the DBs and the CNG buses since the environmental impacts of EBs were dominated by just four indicators: land use, PMF, water withdrawal, and water consumption. Moreover, the majority of the alternative environmental impacts occur inside the regional boundaries of Qatar.

Fig. 3a provides the results of the climate change impacts expressed in kg CO_2 equivalent, one of the environmental indicators. The results illustrate that diesel and CNG alternatives present higher total emissions per km travelled per bus when compared to the EBs. The environmental impacts of DBs and CNG buses mainly occur during the vehicle drive-cycle, due to the high direct tailpipe emissions (TTW). By contrast, the EBs hold zero tailpipe emissions. Instead, in the case of EBs, the supply chain of electricity generation causes most of the emissions. In other words, the environmental impacts of EBs during their operation depend on the power generation mix of the country in which the EBs operate.

The social criteria include 4 primary indicators (sub-criteria) namely: human health, compensation, tax, and employment. Like the environmental impacts, majority of the unfavourable social impacts happen inside Qatar's territorial boundaries. However, the EBs' employment, compensation, and tax benefits also implicate considerations of circumstance outside Qatar. Fig. 3b demonstrates that the highest human health impacts were from DBs; the source of these impacts were tailpipe emissions since the TTW form more than 60 % of its' impacts. The same applies to the CNG buses since the TTW form around 53 % of its human health impacts. Instead, the WTT impacts dominated the EBs' human health impacts because of electricity generation.

The operating surplus, GDP, and LCC all reflect the economic impact indicators under evaluation. According to the results of the LCSA, the DBs provided more significant economic benefits than the EBs and CNG buses in Qatar. Fig. 3c depicts the GDP growth associated with each bus choice, demonstrating that the DBs saw the highest GDP growth within the boundaries of Qatar. In contrast, the GDP advantages of EBs that occur outside the State of Qatar were the highest, when compared to the DBs and CNG buses. From the results of the social and economic impact, we can note that electrifying the fleet of buses does decrease human health impacts. On the other hand, it causes an overall reduction in the contribution to GDP.

Collectively, the geographic distribution results were manifested with different impacts of each bus alternative for the State of Qatar. For the EBs, most of the emission-related impacts happened inside Qatar; however, the benefit impacts such as employment, compensation, and GDP all occurred outside the State of Qatar. Nevertheless, environmental impacts related to the CNG buses inside Qatar were still fewer than the EBs. Moreover, the CNG buses achieved more social and economic benefits than the EBs. Compared to the DBs, the CNG buses had fewer economic impacts and similar social benefits. However, the environmental impact of the CNG buses inside Qatar is much less than the DBs, which would make CNG buses a more balanced alternative than the EBs and DBs. The detailed LCSA results for all the impacts related to the three aspects with their geographical distribution are given in the SI file (refer to Table S7 and Table S8).

3.2. IVN fuzzy AHP-CoCoSo

3.2.1. Stage 1: Determining the weights of main and sub-criteria

Step 1. The hierarchical structure of the sustainable bus selection problem is constructed as given in Fig. 4.

Step 2. The pairwise comparison matrices are based on a verbal assessment of three industry-academic specialists. After that, the verbal judgements are transformed to IVN sets using the 11-point significance scale shown in Table 2. Tables S11-S14 in SI include expert verbal judgements on the major and sub-criteria. Tables S15-S18 in SI exhibit the aggregated neutrosophic pairwise comparison matrix for main and sub-criteria.

Step 3. Using the specified interval-valued neutrosophic assessment scale, the normalized weights of each criteria are determined. Tables S19-S22 show the normalized weights calculated for the main and sub-criteria.

Step 4. Tables S23–S24 provide an estimation of the final combined IVN weights for the main and sub-criteria.

Step 5. To produce the crisp weights, the de-neutrosophication process is utilized. Table 3 shows the final weights.

Table 3 shows that the weights of each primary criterion for the selection problem are 0.36, 0.27, and 0.37 across the economic, social, and environmental aspects, respectively. The most important sub-criteria across the main-criteria economic, social, and environment were found to be; GDP (0.45), Human Health (0.46), and GWP (0.27), respectively. The 5 most important sub-criteria in terms of global weights are GDP (0.159), Human Health (0.128), Operating Surplus (0.116), GWP (0.099), and PMF (0.08).

3.2.2. Stage 2: The ranking of alternatives using the CoCoSo approach

Step 1: The decision matrix (x_{ij}) is defined as given in Table S26.

Step 2: The components of the decision matrix are normalized, and the results are presented in Table S27 and Table S28 (check the SI file).

Step 3. The total of the weighted comparability weighted sequences (S_i) is estimated for each choice outside and within the State of Qatar. Table S31 and Table S32 in the SI provide the power-weighted comparability sequences (P_i) for each alternative Outside and Inside the State, respectively.

Steps 4–5. All of the alternatives' relative weights are estimated.The final score for each alternative (k_i) is estimated accordingly, as shown in Table S33 and Table S34, presenting the relative weights and final scores for each alternative Outside and Inside Qatar respectively. However, Table 4 highlights the differences in ranking alternatives under the global and local scenarios.

The results are presented in two modalities, as shown in Fig. 5 and Fig. 6. The first modality is a global scenario that includes the complete impacts across the life cycle. The second modality reveals the local results that only highlight the impacts from the operation phase. Compared with the recycling scenario in India, Chinese recycling alternatives performed better from the perspective of global benefits. Indeed, the top ten options were occupied by the alternatives recycled in China.

From the ranked results, it is clear that when the EBs are recycled in India, the chances to be at the top of the ranking are non-existent. For example, the Swedish EB is the first option when recycled in China; however, it drops to the 17th option when recycled in India. On the other hand, compared to the EBs and the CNG buses, the DBs occupied the lowest ranking in both recycling scenarios. Considering only the local benefits, the CNG outperformed and outranked both the EBs and DBs, since the CNG buses occupied the top five places in the ranking results. The Chinese CNG buses are the best alternative that would achieve benefit for Qatar. However, the second Turkish DB (Turkey 2 in Fig. 6) occupied 13th place over the other bus alternatives.

To this end, the best alternative differs when we shift the perspective of the nature of the benefits from local to global. It also changes when we shift the recycling location. For instance, the EBs recycled in China achieve the best overall global benefits. On the other hand, from a local benefits perspective, the CNG buses will benefit most, since the five CNG alternatives occupied the top five ranking in two of the ranking methods.

3.3. Sensitivity analysis

Two different sensitivity analyses are performed in this section. Firstly, to validate the result of the proposed NF-AH & CoCoSo models, a sensitivity analysis is conducted by changing the threshold parameter (λ) in the process of the CoCoSo method. Fig. 7 and Fig. 8 show the effect of λ parameter on the performance scores of each alternative in the presented NF-AH & CoCoSo method for the

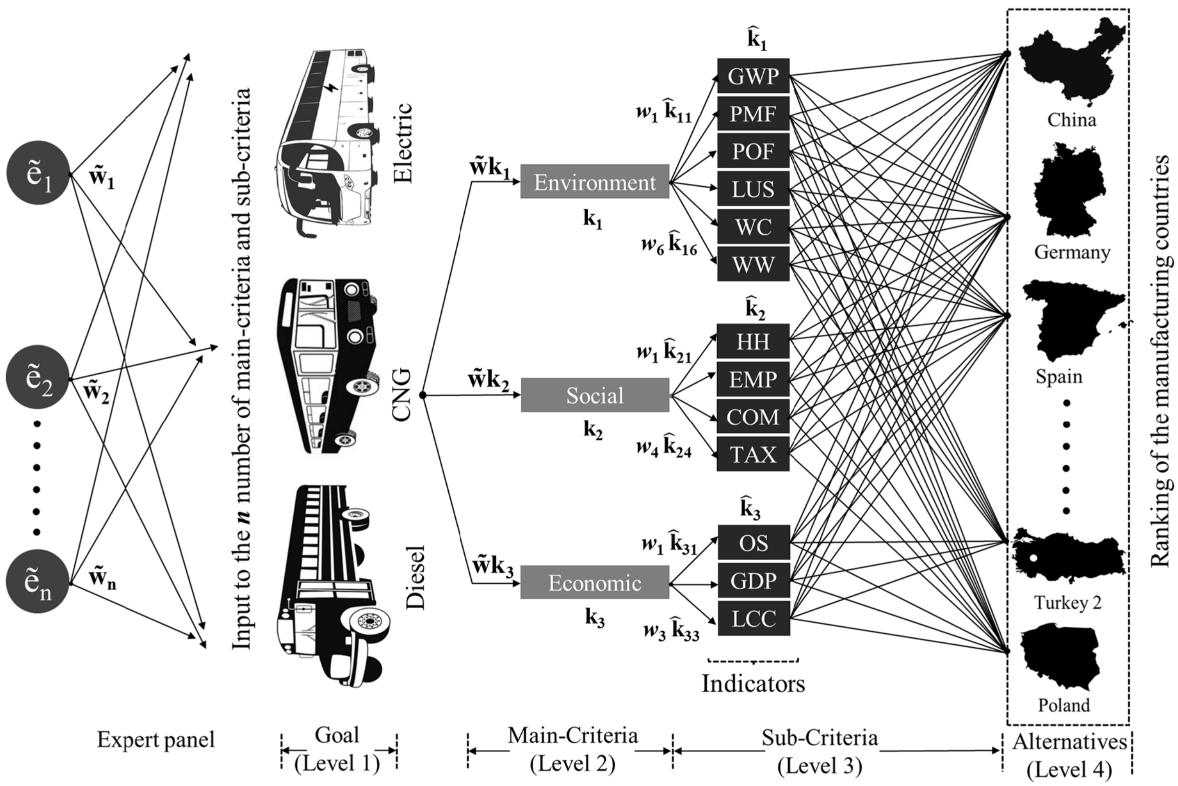

Fig. 4. The hierarchical structure of primary and sub-criteria.

Table 3
The neutrosophic fuzzy global and local weights of main and sub criteria.

Main Criteria	Weights	Sub Criteria	Code	Local weights	Global weights
Economic	0.36	Operating Surplus	OS	0.33	0.116
		Gross Domestic Product	GDP	0.45	0.159
		Life Cycle Cost	LCC	0.22	0.079
Social	0.27	Human Health	HH	0.46	0.128
		Employment	EMP	0.22	0.061
		Compensation	COM	0.20	0.057
		Taxation	TAX	0.12	0.035
Environmental	0.37	Global Warming Potential	GWP	0.27	0.099
		Particulate Matter Formation	PMF	0.22	0.080
		Photochemical Oxidant Formation	POF	0.17	0.062
		Land Use	LUS	0.05	0.018
		Water Withdrawal	WW	0.12	0.042
		Water Consumption	WC	0.18	0.064

Table 4
Comparative analysis for the criteria weights using SF-AHP, NF-AHP, PF-AHP, and IF-AHP.

Main-criteria	Main-criteria weights			Sub-criteria	Sub-criteria global weights					
	NF-AHP	SF-AHP	PF-AHP		NF-AHP		SF-AHP		PF-AHP	
					Local weight	Global weight	Local weight	Global weight	Local weight	Global weight
Economic	0.360	0.387	0.269	OS	0.329	0.116	0.326	0.126	0.450	0.121
				GDP	0.449	0.159	0.397	0.154	0.241	0.065
				LLC	0.223	0.079	0.277	0.107	0.309	0.083
Environmental	0.366	0.298	0.305	GWP	0.270	0.099	0.228	0.072	0.406	0.124
				PMF	0.220	0.080	0.204	0.064	0.127	0.039
				POF	0.169	0.062	0.183	0.058	0.156	0.047
				LUS	0.050	0.018	0.105	0.033	0.050	0.015
				WW	0.116	0.042	0.119	0.038	0.072	0.022
				WC	0.175	0.064	0.160	0.050	0.189	0.058
Social	0.276	0.315	0.426	HH	0.457	0.128	0.379	0.113	0.825	0.352
				EMP	0.218	0.061	0.225	0.067	0.065	0.028
				COM	0.202	0.057	0.228	0.068	0.063	0.027
				TAX	0.123	0.035	0.168	0.050	0.047	0.020

global and local weights respectively. For more details on the results of the sensitivity analysis, refer to Table S35 and Table S36 in the SI file. It is seen from Fig. 7 and Fig. 8 that the results of the presented NF-AHP & CoCoSo model are robust with different λ values for both the local and global scenarios.

3.4. Comparative analysis

Based on several fuzzy sets, comparative evaluations were conducted for AHP. This section compares the Neutrosophic fuzzy AHP method & CoCoSo technique with the Spherical fuzzy AHP method & CoCoSo and Pythagorean Fuzzy AHP method & CoCoSo methods to test the robustness and reliability of our model. The SI file includes all the detailed calculations related to the SF-AHP and PF-AHP methods. However, the following covers the weight and ranking comparison for the three proposed methods.

3.4.1. Weighting comparison

Table 4. presents the weights of each main criterion for the selected set of alternatives as; 0.387, 0.298, and 0.315 across the economic, environmental, and social criteria respectively. The most important sub-criteria for economic, social, and environmental factors are GDP (0.397), human health (0.379), and GWP (0.228), respectively. The top 5 most important sub-criteria in terms of global weights were found to be; GDP (0.154), operating surplus (0.126), LLC (0.107), and human health (0.113). The weights of the main criteria using PF-AHP were also estimated and found to be 0.269, 0.426, and 0.305 across the economic, environmental, and social criteria respectively. The most important sub-criteria for economic, environmental, and social factors are operating surplus (0.450), human health (0.825), and GWP (0.406), respectively. The top 5 most essential sub-criteria with regard to global weights using PF-AHP are human health (0.352), GWP (0.124), operating surplus (0.121), LLC (0.083), and GDP (0.065).

3.4.2. Ranking comparison

The ranks of each alternative under the 3 ranking models are presented in Table 5 and Table 6 for both outside and inside Qatar

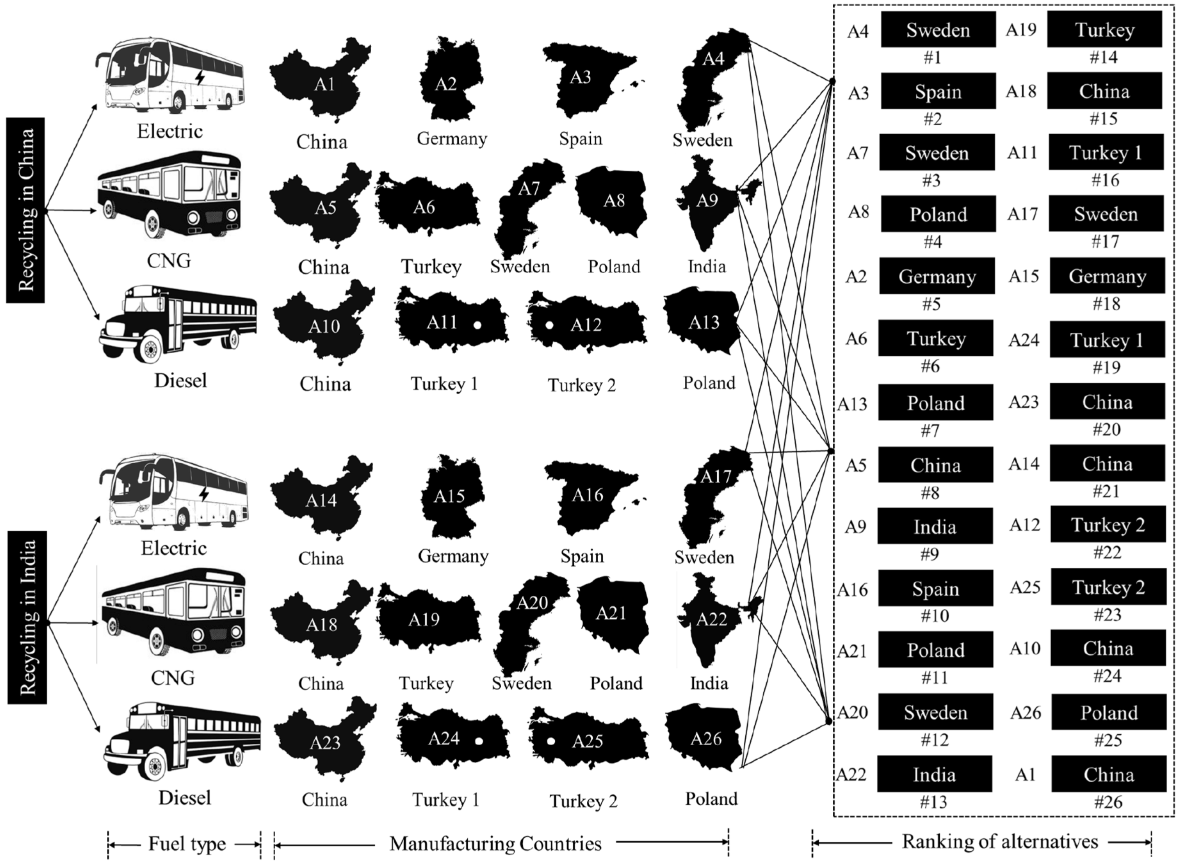

Fig. 5. The NF-AHP &CoCoSo ranking for the global scenario.

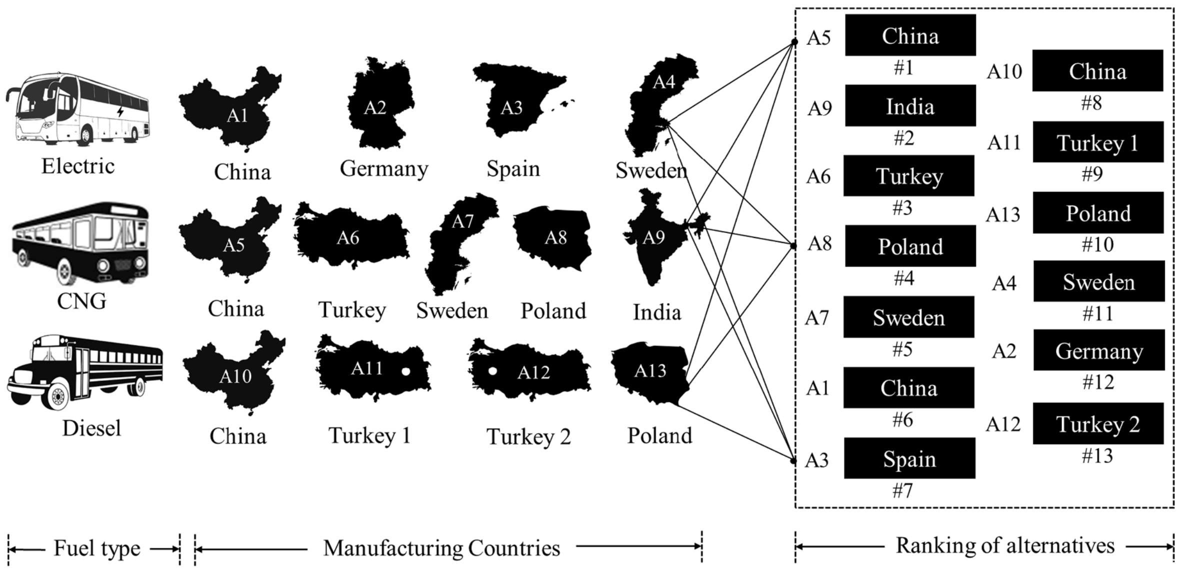

Fig. 6. The NF-AHP &CoCoSo ranking for the local scenario.

analysis, respectively. It is seen from the ranking results that, all 4 best alternatives are the same under the SF-AHP, PF-AHP, and NF-AHP approaches (see Table 5). The Swedish EB recycled in China is ranked the highest (k_i score = 2.03 under NF-AHP), making it the best-sought alternative among the other 26 alternatives concerning the 3 ranking models. The Spanish EB recycled in China is the

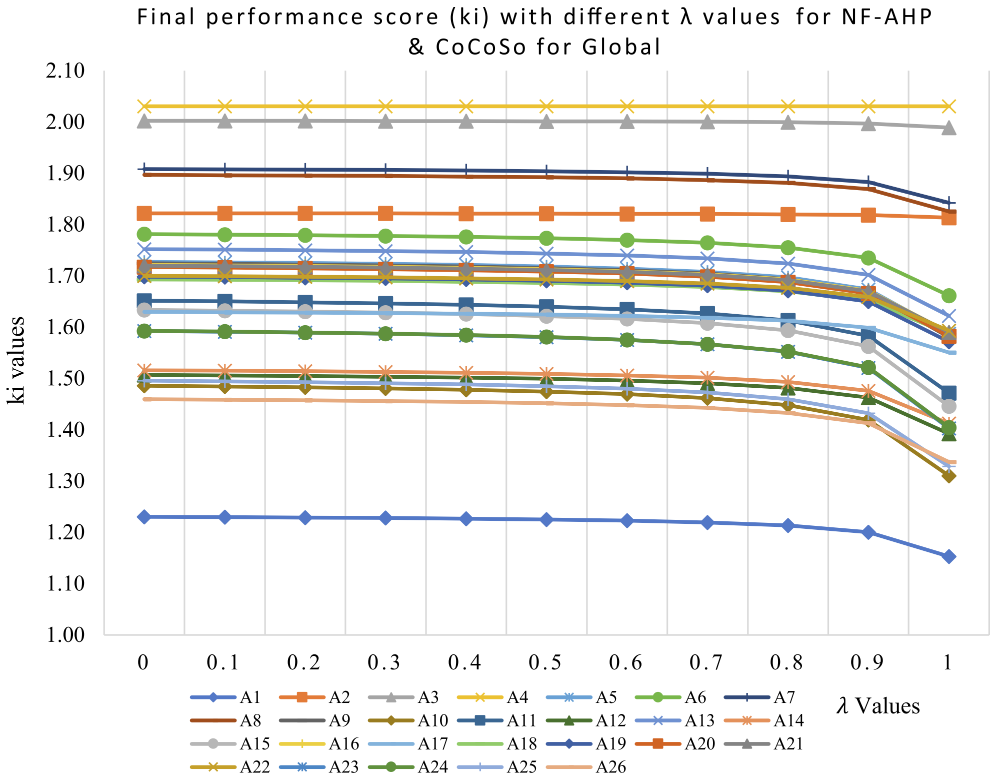

Fig. 7. Effect of changing the λ parameter on ranking of alternatives with NF-AHP & CoCoSo for global weights.

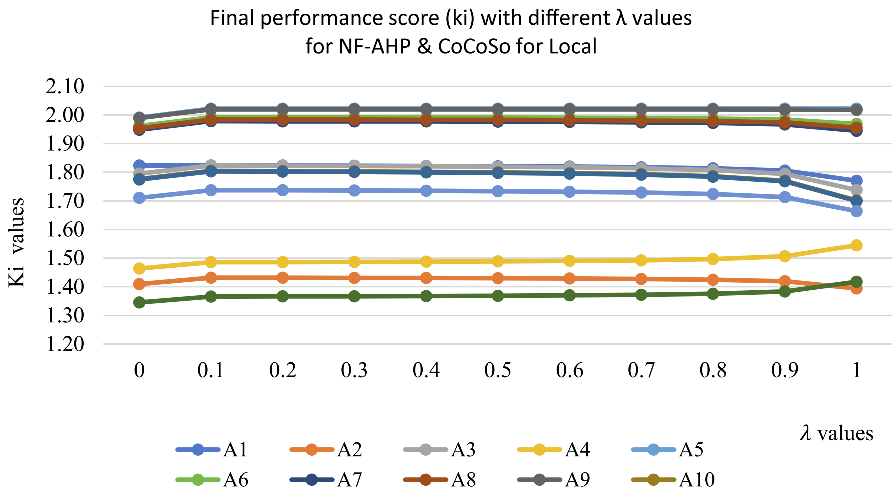

Fig. 8. Effect of changing the λ parameter on the ranking of alternatives with NF-AHP & CoCoSo for local weights.

second-best option, followed by the Swedish and Polish CNG buses, both recycled in China as the third and fourth-best alternatives. At the same time, the less preferred option among the 26 alternatives under study was the Chinese EB recycled in China across all the 3 ranking models.

Overall, the ranks slightly differ under the SF-AHP & CoCoSo method and the NF-AHP & CoCoSo method. However, there are dramatic differences between the NF-AHP and the PF-AHP method rankings, the fact being the global AHP method takes more uncertainties into account than the Pythagorean AHP method. The Swedish EB is ranked 1st when recycled in China under all the 3 ranking models. However, the rank drops for the Swedish EB when recycled in India. It falls all the way down to the 18th, 17th, and 10th places under the SF, NF, and PF sets, respectively. On the other hand, compared to the EBs, there is a slight difference in the CNG buses' ranking between the different ranking models. Moreover, the CNG outperformed and outranked the DBs with the recycling scenarios in all 3 ranking models.

As indicated in Table 6, the first two best alternatives are the same from the perspective of considering local benefits and for the different ranking methods. The Chinese CNG bus has the highest k_i score making it the best option over the 13 alternatives across the three different ranking models. As in Table 6, the Indian CNG bus is the second-best option and the Turkish CNG bus is the third-best option under the SF-AHP and NF-AHP model. However, under the PF-AHP rankings, the Chinese EB is the third-best option. While the least preferred options are the German EB followed by the Turkish DB-2 (Turkey 2 in Table 6), to occupy the 13th and the 12th places over the other bus alternatives across the 3 ranking models.

Overall, the local ranking of the alternatives in the SF-AHP & CoCoSo and the NF-AHP & CoCoSo methods are comparable since 8 of the 13 ranks are the same. However, some minor differences exist between the PF-AHP method and the other two ranking methods. The CNG buses occupied the top five options in both SF-AHP and NF-AHP models. Yet, in the PF-AHP model, the 3rd and 4th options are for the Chinese and Spanish EB, respectively. In the case of the EBs and DBs, the ranks differ when changing the ranking methods. For example, in the SF-AHP, the DBs had a higher ranking than the EBs since they occupied the sixth, seventh, and eighth positions. On the other hand, the EBs are at the bottom of the ranking, occupying positions nine through 12. Moreover, the DBs ranking was the lowest among other alternatives, with a slight difference between the NF and PF models. However, the EBs ranking improved in the NF and PF models compared with the SF ranking results since the EBs occupied the sixth and seventh places in the NF method and the third, fourth, and eighth in the PF method.

3.5. Policy and practice

Some policy and practice related discussions are presented as follows:

a) The geographical location of end-of-life bus recycling changed the overall life cycle sustainability performance of alternatives and therefore decision-makers should also consider the role of end-of-life management options when they select the most sustainable option during the procurement process.
b) Global life cycle sustainability assessment models are also critical to understanding the national and global impacts of alternative fuel bus technologies. Using a global MRIO analysis, a consumption-based life cycle social, economic, and environmental impacts can be quantified, and it will help the policymakers to see their net regional benefits of losses related to their alternative fuel procurement decisions. In this study, The EBs provided the most significant advantage to the global supply chain from the economic perspective.
c) Expert judgements should be incorporated into decision-making during the decision-making process, taking into account the role of changing priorities of sustainability criteria under the environmental, social, and economic pillars of the UN's Sustainable Development Goals.
d) Applying tax mechanisms, like a special excise tax rate on natural gas would enable transportation companies to utilize CNG buses and reduce operational expenses.
e) Policymakers should utilize the CNG buses as part of a comprehensive strategy to increase public transportation benefits and improve the infrastructure of public transportation in Qatar.
f) Subsidies for public transportation should be used to offset the cost of environmentally efficient buses such as CNG buses. The subsidies should be calculated based on potential reductions in toxic components and GHG emissions. This subsidy should be sufficient to cover the operating costs of CNG buses (Dyr et al., 2019).
g) The local government must increase the infrastructure investments, such as CNG filling stations, to accommodate the expanding fleet of buses on Qatar's roadways.

4. Conclusions and future work

This research provided a combination application of LCSA and different MCDM methods integrated with the CoCoSo approach to rank the sustainability performance of 13 different city bus alternatives based on 13 sustainability indicators concerning the transport sector in Qatar. The proposed approach aims to highlight the most viable city bus options that public transportation fleets could adopt to decarbonize the urban transit system. Moreover, it would assist policymakers in taking the necessary actions to support the most promising option. The findings of this study are quantified under two different scenarios: the first scenario considers the overall impacts, including the manufacturing, operation, and EoL phases, named as "global scenario" or "outside Qatar". The following points are highlighted, based on the results from the global scenario:

1. The environmental aspects revealed that CNG buses had the lowest PMF, POF, and water withdrawal levels compared to EBs and DBs. Moreover, the impacts on water consumption and land usage were such as the DBs but less than the EBs. Additionally, the GWP-related impacts were fewer than the DBs.
2. The EBs reaped the most benefits concerning social considerations due to their high employment and compensation levels across the worldwide supply chain. Their tax rate was also greater than that of the CNG buses. The EBs had a lower effect than DBs and were comparable to CNG buses when considering the impact on human health.
3. From the ranking results, the EBs recycled in China occupy the best two options among the 26 alternatives from the perspective of the global benefits: the Swedish and the Spanish buses.
4. The worst option among the 26 alternatives was the Chinese EB recycled in China in the three ranking models.

Table 5
Global Ranking of the Bus Alternatives.

				SF-AHP		NF-AHP		PF-AHP	
				k_i	Ranking	k_i	Ranking	k_i	Ranking
China	EB	China	A1	1.23	26	1.22	26	1.23	26
		Germany	A2	1.8	5	1.83	5	1.89	15
		Spain	A3	1.96	2	2	2	2.13	2
		Sweden	A4	1.99	1	2.03	1	2.2	1
	CNG	China	A5	1.66	9	1.7	8	1.93	13
		Turkey	A6	1.72	7	1.76	6	1.99	7
		Sweden	A7	1.87	3	1.9	3	2.04	3
		Poland	A8	1.86	4	1.89	4	2.04	4
		India	A9	1.67	8	1.7	9	1.91	14
	Diesel	China	A10	1.48	22	1.5	24	1.51	25
		Turkey 1	A11	1.63	14	1.66	16	1.75	19
		Turkey 2	A12	1.5	21	1.52	22	1.57	24
		Poland	A13	1.74	6	1.77	7	1.81	17
India	EB	China	A14	1.44	24	1.49	21	1.8	18
		Germany	A15	1.57	17	1.61	18	1.87	16
		Spain	A16	1.63	12	1.69	10	2.03	5
		Sweden	A17	1.55	18	1.61	17	1.97	10
	CNG	China	A18	1.61	16	1.67	15	1.98	8
		Turkey	A19	1.62	13	1.67	14	1.96	12
		Sweden	A20	1.64	11	1.69	12	1.96	11
		Poland	A21	1.64	10	1.7	11	1.97	9
		India	A22	1.62	15	1.67	13	1.99	6
	Diesel	China	A23	1.56	19	1.6	20	1.73	21
		Turkey 1	A24	1.56	20	1.6	19	1.73	20
		Turkey2	A25	1.48	23	1.5	23	1.61	22
		Poland	A26	1.43	25	1.46	25	1.59	23

Table 6
Local Ranking of the Bus Alternatives (Inside Qatar).

				SF-AHP		NF-AHP		PF-AHP	
				ki	ranking	ki	ranking	ki	ranking
Inside Qatar	EB	China	A1	1.77	10	1.77	6	2.15	3
		Germany	A2	1.43	12	1.43	12	1.57	12
		Spain	A3	1.77	9	1.78	7	2.11	4
		Sweden	A4	1.46	11	1.46	11	1.79	8
	CNG	China	A5	2.03	1	2.03	1	2.18	1
		Turkey	A6	2.01	3	2.01	3	2.1	5
		Sweden	A7	2	5	1.99	5	2.08	7
		Poland	A8	2	4	2	4	2.09	6
		India	A9	2.03	2	2.03	2	2.18	2
	Diesel	China	A10	1.91	6	1.9	8	1.75	9
		Turkey 1	A11	1.91	7	1.89	9	1.75	10
		Turkey 2	A12	1.47	13	1.45	13	1.32	13
		Poland	A13	1.83	8	1.81	10	1.7	11

On the other hand, the second scenario is only concerned with the operation phase; consequently, it is named "local scenario" or "inside Qatar". Based on the findings from the local scenario, it is essential to emphasize the following points:

1. Although CNG buses are found to have a high sustainability performance, it is important to note that these buses did not have the best performance in all environmental footprint categories. When compared to other options, they had a better air quality performance in some selected indicators such as PMF and POF". It is worth mentioning that CNG buses are favored in this analysis based on the selected MCDM methods, collected data, and weights obtained from the expert. However, the overall sustainability performance of bus alternatives can show differences in other countries depending on the expert weights and local data for emission and socioeconomic factors.
2. The employment, compensation, and tax benefits for CNG buses were higher than those for EBs and comparable to those for DBs within Qatar.
3. The CNG buses have the highest sustainability performance when social, economic, and environmental indicators are considered jointly in the MCDM model. However, it is important to note that Qatar targets a 25 % cut in greenhouse gas emissions by 2030 under the climate plan. The State of Qatar decelerated that 25 % of public buses will be electric by the beginning of 2023 and this favors the carbon footprint reduction goal. On the other hand, CNGs are also found to be sustainable options based on our MCDM

models. To this end, we recommend a balanced strategy for public bus procurement decisions that consider GHG and other sustainability targets, simultaneously. To this end, Qatar is working towards expanding the CNG network in the country to meet the growing demand for CNG, as public transport authorities are also looking to substitute diesel with less carbon-intensive CNG options.
4. The worst option is the second Turkish DB (Turkey 2).

The authors recommend considering more alternatives to EB technologies in the future based on the energy mix scenarios. Moreover, future research could examine implementing additional key indicators for a more comprehensive sustainability assessment of alternative bus types. The additional indicators would include safety, population density, fossil fuel reserves, health impacts of air pollution, average income, employment levels by income and gender group, as well as other considerations of social equity. Furthermore, future research should aim to quantify the error margins related to the MRIO model's outputs. To estimate the probability of a variety of outcomes, it is necessary to assess the sensitivity of the model system with respect to parameter uncertainty. Future research should additionally develop optimization analysis to estimate the ideal mix that forms Qatar's public city bus fleet by locating the percentage of each bus type. Thus, reallocating percentages of the types of buses making up Qatar's fleet would simply become easier with ongoing research devoted to this topic.

Moreover, future work can include different types of buses, such as fuel cell buses, since it is a viable technological alternative to fossil fuel-powered buses. From a methodological perspective, the authors recommend combining the IVNF-AHP with the "Possibility Degree (PD)" method for the objective scoring procedure in pairwise comparisons instead of the subjective scoring approach used in the study. Cosine similarity can be used with IVNF-AHP as well to handle the indeterminacy of information. In addition, the authors recommend performing a sensitivity analysis, which can improve decision-making by providing realistic assumptions about the future, including the uncertainties associated with the geopolitical relations that are associated with the various end-of-life scenarios.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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