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Approaches of assessing the alternative fuels sustainability in the transportation sector

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ABSTRACT

The rapid decline of fossil fuel sources, coupled with the increase in environmental and climate extremes, has been driving a trend towards finding alternative fuel and renewable energy sources. However, economic, environmental, and technical factors have made alternative fuel solutions possible to enter a bottleneck state. Therefore, it is necessary to assess alternative fuel sustainability in the transport sector to orient the development as well as to minimize their negative effects. Overview analyzing and discussing the environmental and economic life cycle impacts of alternative transport fuels is the aim of this study which also is in comparison with traditional fuels. Selected fuels in this study comprising diesel, petrol, liquefied petroleum gas, biodiesel, ethanol, hydrogen, fuel cell, and electricity. The life cycle assessment process based on suitable methodologies was utilized to conduct an assessment of sustainability for the aforementioned fuels. Furthermore, in the discussion, environmental and economic impact assessments of selected fuels were presented to highlight the role of fuels for the future of transportation.

KEYWORDS

alternative fuels; life cycle assessment; sustainability assessment; techno-economic analysis; transport.

INTRODUCTION

Recently, serious environmental impacts emergence as a challenge for the global transport sector since petroleum-based fuels is consumed for powering motorized vehicles principally results in greenhouse gas (GHG) and criteria pollutants [1]. Interestingly, the growth of alternative fuels is frequently related to sustainability of development, energy-efficient, efficiency, and conservation of the environment. Bio-diesel, compressed natural gas, liquefied propane, ethanol, hydrogen, fuel cell, and hybrid-electric among others are common alternative fuels that are available [2-4]. The development of new vehicle technologies is suggested to conduct life cycle analysis (LCA) for not only vehicle cycle impacts (such as vehicle production, manufacturing, and recycling) but the complete fuel cycle impacts also (consisting of the production of fuel, transport, and the driving phase with fuel consumption) [5]. Several selected studies were distinguished by the methodological approach. In the LCA studies, the consideration of the socio-economic impacts of transportation is compulsory because it symbolizes the quality of life, such as accessible ability, affordable ability, equity, time for travel, traffic jam, and uproar [6]. Based on economic input-output, hybrid life cycle analysis was carried out in the study of Yue et al. [7] which also assessed the potential for saving greenhouse gas emissions by using the vehicle-to-grid system (V2G), alongside the able emission effects as the battery is degraded [8].

Extended Range Electric Vehicles (EREVs) and Battery Electric Vehicles (BEVs) are the main focus in their work because mass-production of conventional hybrid vehicles has several limitations, for example, electric drive power is considerably lower as compared to mechanical power, the capacity of batteries is low (about 1-2 kWh) and connections to the grid is unavailable, in comparison with, EREVs, which is considered as the next generation for hybrid vehicles [9, 10]. The findings of this study indicated that the potential GHG emissions are saving for EREVs and BEVs from power production if the wear and tear of the battery from regulation services are negligible. Furthermore, it detected that the V2G system will not be efficient as degradation of battery increase [11]. Additionally, the study of Santoyo-Castelazo and Azapagic [12] highlighted the demand for the generic methodology for various energy systems, in which integrated sustainability can be analyzed on a life cycle basis for future scenarios. a decision-support framework was built up to analyze energy systems in terms of integrated sustainability, where aspects related to the environment, economy, and society are considered simultaneously, allowing the incorporation of a variety of preferences and decision-makers for sustainability criteria and point out options are the most sustainable. A life cycle approach is taken by the framework which integrates a range of sustainability indicators to analyze the sustainability of various electricity scenarios, applying multi-criteria decision analysis [13].

The significance of a system-based approach was highlighted by Onat et al. [14] for combining triple main points of sustainability to boost up the transition of the LCA approach into the LCSA framework. Their report obtained that the majority of the previous LCSA only paid attention to the life cycle inventories for product system in an isolated fashion and therefore, the linkages amongst the three bottom line influences for instance: environmental indicator, social indicator, and economic indicator related to sustainability have not yet been investigated by the prior researches. The recommendation in the study of Hoang, Tabatabaei, et al.[15] revealed that the road transport sector utilizes biofuels as an alternative fuel in internal combustion engine vehicles (ICEV) may solve the environmental and health concerns of fossil fuels. Additionally, biofuels form lower CO2 emissions than petroleum-based fuels, since thank photosynthesis, CO2 was fixed by them from the environment and the same amount was released in the combustion [16]. However, the first-generation biofuels have disadvantages in GHG emissions, biodiversity, land and water use, and may lead to water fouling [10, 17]. From this point of view, it is the next three generations of biofuels that are encouraged to use because they do not compete between food and fuel. As a result, the focal point of interest moves to algae as an alternative material for biofuel production [18-20].

The positive effects of biodiesel on air quality were studied in conventional diesel engines by Hoang and Pham [21]. Findings in the work of Hoang and Tran [22] showed that biofuel blends that have a low concentration of sulfur have the benefit to the quality of air without considerable damage for the air quality, an interesting example is the usage of ethanol and biodiesel blends may decline carbon monoxide emissions by 25% to 50%. Furthermore, 50% of particle emissions and 75% of hydrocarbons can be decreased by employing Bio-diesel blends [23]. On the other hand, the study observed an increment of nitrogen oxide emissions during biofuels production and usage (ethanol and biodiesel), the main reason is the formation of on-farm emissions by using the fertilizer [24]. Indeed, substantial environmental costs are related to corn-based ethanol while a sustainable option for biofuel is cellulosic ethanol. Similarly, obtained results of Darmayanti et al. revealed that applying switchgrass ethanol fuel as an alternative for gasoline help reduce GHG emissions, which can be explained that switchgrass agriculture uptake CO2 from the environment [25, 26].

Driving with the usage of E85 may lead to GHG emissions reductant by 65% per 1 km in contrast to gasoline. Additionally, ethanol produced by using lignocellulosic material has potentially notable advantages, especially information of GHG emissions [27-29]. Nevertheless, these strong points are dominated by negative impacts which comprise aspects of eutrophication, photochemical oxidation, and toxicity. Managing carefully switchgrass agriculture and ethanol production enhancements may be a good solution for minimizing these environmental concerns [30]. According to [31], the study addressed a prospective techno-economic and environmental assessment of the hydrogen production mix that could satisfy the hydrogen demand for road transport under alternative scenarios on the penetration of FCEV in Spain. Such a general road transport model has several interconnected elements, as shown in Figure 1.

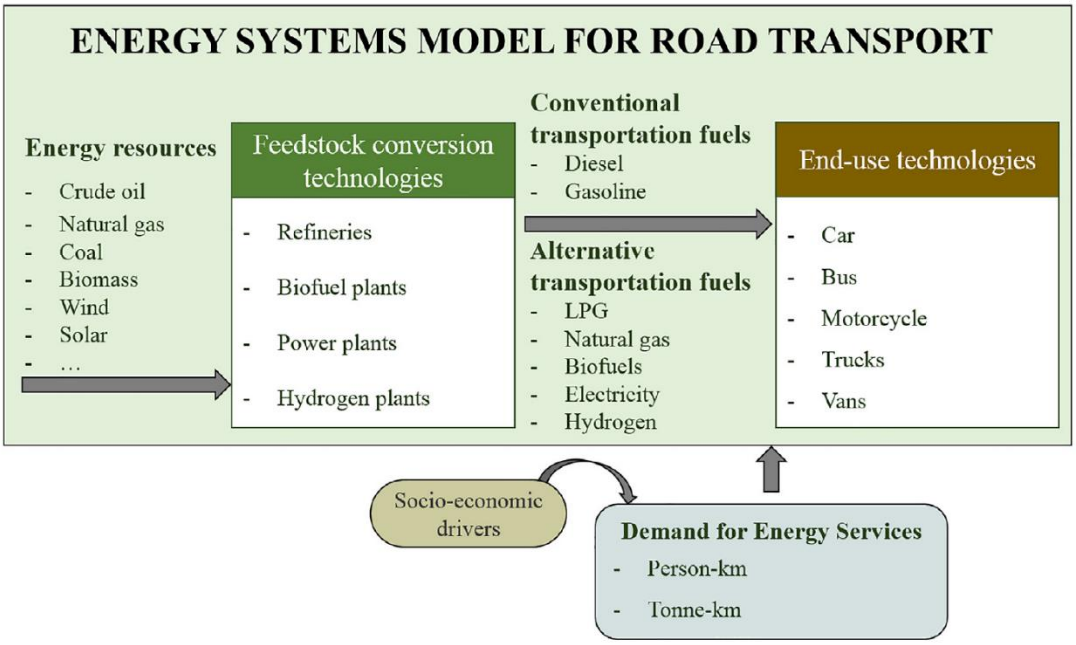

Figure 1. A framework of the general energy systems model for road transport [31]

A comparative life cycle impact analysis (LCIA) of Brazil sugarcane ethanol was carried out by White et al. [32] against biodiesel through various LCIA approaches to investigate impact categories, for example, particle emissions to the atmosphere, emissions to soil, emission to water, and land occupation. They stated that the environmental performance of ethanol is the worst in comparison with gasoline. The biodiesel production by rapeseed oil transesterification was investigated by González-García, García-Rey, and Hospido [33] who concentrated on the environmental profile related to the manufacturing life cycle (cradle-to-gate approach). The observed results indicated that even though dependence on fossil fuel, formation of GHG emissions, and depletion of the ozone layer can be decreased by using B100 made from rapeseed oil as an alternative for petroleum-based diesel [34], there is an increment in acidification and eutrophication of water [35], air and soil, photochemical smog and land occupation [36].

Furthermore, specific life cycle energy assessment of a country and greenhouse gas emissions exhausted from automotive fuels for India was studied by Gupta et al. 2016 [37] and Patil et al. [38] and they concluded that the best option belongs to split hybrid configuration which possibly to improve energy efficiency up to 10-60% [23], whereas, the lowest efficiency belongs to electricity which was 20%. The research of X. P. Nguyen [39] conducted LCA in the Vietnamese bus public transport sector and their results indicated a more balanced performance of the hybrid bus. The focus of all past researches is primarily greenhouse gas emissions with the addition of environmental impact analysis. Few types of research counting economic parameters besides environmental indicators to assess road transportation sustainability. The lack of comprehensive theory and calculation tools is one of the challenges that has limited the scope of the sustainability coefficient assessment of previous publications. This work aims to provide an overview of how to calculate environmental and economic sustainability criteria for fuels and propulsion systems in the transportation sector.

APPROACH TO CALCULATE SUSTAINABILITY

Objects

Figure 2 depicts the framework of the life cycle assessment for selected alternative fuels. The simultaneous application of Well-to-Wheel (WTW) [40] life cycle analysis and techno-economic analysis of the selected propulsion system technologies are used in this study. Fuel type and energy carrier types basing on electricity mix are described in Table 1, this work considers the integration of vehicle power-train technologies as well as different fuel types as follows: (1) Internal Combustion engine vehicle (ICEV) technology for Diesel, gasoline, biodiesel, LPG, and CNG fuel; (2) Flexi Fuel Vehicle (FFV) technology for ethanol fuel; (3) Fuel Cell Vehicle (FCV) for hydrogen fuel; and (4) Battery Electric Vehicle (BEV) for electricity fuel.

Table 1. The structure of energy sharing can be in 2 groups

Fuel Type	Energy CarrierType	% Share
Coal	Fossil	a1
Natural Gas		a2
Oil Fired Generation		a3
Hydro	Renewable	b1
Wind		b2
Solar		b3
Bioenergy		b4
Geothermal		b5
Total	100	100

Goal and scope

Based on the ISO 14040 standardized LCA procedure [41], the process simultaneously uses the Simapro software of PRe-Consulting Group to analyze the life cycle. The data is collected from two sources which are GREET model, life cycle inventory database Eco-Invent, developed by the Swiss center for life cycle inventories parallel with a variety of technical reports, reports of government, websites, sugar industry, and literature survey [42-45]. Recipe midpoint (H) and Recipe endpoint (H) methods are used to assess the effects of the Environmental life cycle which include: climate change, eutrophication of fresh water and marine, human health, formation of photochemical oxidant, formation of particulate matter, eco-toxicity of freshwater and marine, agricultural and urban land occupation, scarcity of water, depletion of metal and fossil.

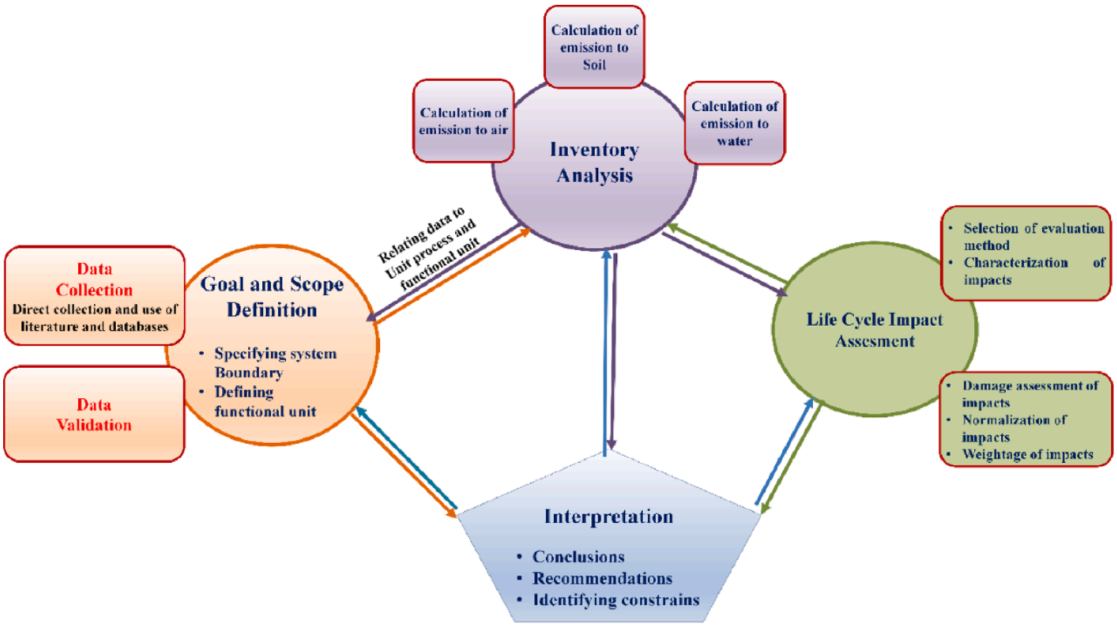

Figure 2. A framework of LCA for selected alternative fuels

Functional unit

“1 MJ of fuel input” represented as the functional unit (FU) in the process. Based on “1 MJ of fuel input”, the single score environmental impact assessment results can be calculated, which were also expressed in the functional unit “1 km of distance driven”. In addition, the functional unit “1 km distance driven” is used to assess the techno-economic influence [46, 47].

Life cycle boundary

The boundary of the system was classified to consist of the stages: extraction of material, processing, as well as production of fuel, and operation of vehicle phase. The classification of the life cycle analysis comprised two main components: (1) Well-to-Tank (WTT): involving influences of upstream, for example, extraction raw feedstock, treatment, manufacturing and delivery [48]and (2) Tank-to-Wheel (TTW) are direct effects, for example, emissions of the tailpipe and direct utilization of energy as the vehicles operate [37]. The estimation of the emissions considers three compartments: (1) emissions of atmospheric or airborne (consisting of greenhouse gas emissions and criteria air contaminants); (2) emissions to water (or, waterborne emissions); and (3) emissions to the soil which are in units of g/MJ, g/kJ and gg/MJ respectively [48, 49]. There are normally six emission types in the atmosphere: greenhouse gases (GHG) represented by CO2, and criteria pollute substances such as nitrogen oxides (NOx), particulate matter (PM2.5), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC's) and Sulphur dioxide (SO2) [49, 50]. The comparison of the life cycle emissions between conventional diesel transport fuel the alternative transport fuels (e.g. gasoline, biodiesel, ethanol, LPG, CNG, electricity, and hydrogen fuel) was conducted in this work. Furthermore, the contribution of selected fuel types was analyzed for understanding their environmental effect in various impact categories.

Life cycle inventory assessment

The inventory data of life cycle was collected by a data sources combination which includes (1) Ecoinvent 3.5 database published by the eco-invent center [51]; (2) the GREET Model [52]; (3) literature survey of recent peer-reviewed journals and reports of government and (4) online sources. Moreover, obtained data of the fuel economy rely on the criteria of most vehicles which have good fuel-efficient in the category of the selected vehicle. Vehicle fuel economy data for each fuel used are required. These can include vehicle type, fuel type, energy consumption, and fuel consumption. These data should be consulted from reliable sources such as from the manufacturer, from the vehicle registration and management agency, or a national data center. Due to the influence of the vehicle mass and their driving mode, there is a difference in conversion efficiencies of various vehicle power trains [53, 54]. Hence, it is necessary to investigate the impact of variations in the calorific value of the considered fuel types and efficiencies of vehicle power-train for comparison of selected fuels based on their functionality. Whereas the input data of the selected fuel types are specified in Simapro, the types of fuel were distinguished from their net calorific or lower heating values (MJ/kg) and efficiencies of the tank-to-wheel (TTW) which were obtained from current literature. The input data of fuel use these parameters to obtain unit energy (1 MJ) available to the vehicle drive train per unit energy (1 MJ) input to the vehicle [9, 55]. The Tank-to-Wheel (TTW) efficiency was defined in the study of Patil et al. [38] as the ratio between the amount of fuel energy available at the vehicle tank and the energy available at the wheel to drive the vehicle, which can be written as Equation (1).

$$\text{TTW efficiency} = \frac{\text{The energy of fuel available at the wheel}}{\text{The energy of fuel in the vehicle tank}} \tag{1}$$

Impact assessment

Two methodologies are named Recipe midpoint hierarchies (H) as well as Recipe endpoint [56]. Reporting characterization results is the role of Recipe mid-point while the single score results are reported by Recipe endpoint hierarchist (H) method which uses three endpoint indicators. Sleeswijk et al. [57] proposed Equation (2) for calculating the normalized results in order to compare impact category indicators to respective reference values for individual categories.

$$A_{e,s} = \sum_i \sum_x Q_{e,x,i} x M_{x,i,s} \tag{2}$$

Where,

Ae,s (e.g. in kg-eq./year) is the normalization factor for impact category e in reference system s,
Qe,x,i (e.g. in kg-eq/kg) is the normalization factor related to impact category e for substance x released to or extracted from environmental compartment I, and
Mx,i,s (e.g. in kg/year) is the release or extraction of substance x to or from compartment i in reference systems.

Environmental life cycle analysis

Recipe endpoint hierarchist (H) method is applied to convert the obtained assessment results of fuel cycle impact in previous stages into a single score [58]. Based on the mechanism of the environment, the single score modeling was developed to consist of multiple impacts which can harm human health and the environment [59]. The first units of a single score were milli-points per megajoule (mPt/MJ) which is complied with the functional unit “Per MJ of fuel input”. After that, this was converted according to the functional unit “Per km of distance traveled”. The single score results for assessing the environmental effect of 8 fuel types were expressed in the units of mPt/MJ and mPt/km. Then, the normalization of these environmental impact results was conducted concerning with diesel fuel for the comparative analysis before combining with the outputs of techno-economic analysis and the influence of the selected vehicle powertrain and fuel types on environment and economy were investigated simultaneously.

Techno-economic analysis

The techno-economic analysis was carried out completely for the selected incorporation of fuel types and vehicle powertrains to assess selected fuel and vehicle powertrain incorporations in term of the technology costs [60]. There are capital expenses and operating expenses in the economic analysis included. The techno-economic evaluation is able to be divided into two analyses: 1) Economic analysis of the capital expenses for the compatible combination of a selected vehicle powertrain and a specified fuel type, and 2) Economic analysis of the operating expenses for the selected vehicle and fuel integration [61-63]. The unit of economic costs were dollars ($) per distance driven ($/km). The yearly average distance traveled by a single vehicle and lifetime for owning a vehicle is given collected data [32, 47, 64]. Therefore, the whole distance of the vehicle during their lifetime. Additionally, the capital costs is expressed as the ratio of the individual vehicle technology cost and the total distance. In similarity, the costs of the fuel input were divided by distance traveled to calculate the operating costs of the vehicles in the units of $/km. Lastly, the total costs in $/km were obtained by normalizing the total costs in $ with respect to (w.r.t) diesel fuel [65].

Combining environmental life cycle analysis with techno-economic analysis

The combination of the environmental life cycle assessment results and the economic impact assessment results was carried out after normalization w.r.t types of diesel fuel. Each analysis type (the environmental and economic impact analysis) were assigned to account for 50% and after that, they are added together to achieve a single value for individual vehicle and fuel technology selection. The reference diesel fuel and vehicle technology are used in comparison with the results after this combination [66-68].

APPLICATION AND DISCUSSION

A general looking to WTT stage show that there were considerable criteria polluted emissions to air caused by biofuels. Indeed, the batteries production in the production phase of vehicle produced the emissions which attribute to the higher WTT GHG emissions of electric vehicles compared to other fuel types, symbolize a notable percentage of the environmental impacts in manufacturing of electric vehicle accounting to 10 to 75% of the all energy need for manufacturing and 10 to 70% of the manufacturing GHG emissions [69]. Dealing with the criteria pollutants in the WTT stage, CO and PM2.5 of ethanol were the highest while SO2 and NOx emissions rank the second following petrol and electric respectively. Furthermore, WTT NOx emissions obtained by electric vehicles are the highest among fuel types [48, 70]. On the other hand, considering the TTW stage, diesel created the highest GHG emissions followed by petrol. More interestingly, there were nearly no tailpipe emissions as using hydrogen and electricity which were the best performance in the TTW stage. Furthermore, related to vehicles which applied hydrogen fuel cell, the pathway of producing hydrogen affects heavily to the overall life cycle burdens [69].

There were considerable tail pipe emissions from the LPG along with CNG in TTW stage or when the vehicle operates. The study of Shahraeeni et al. [71] showed the higher emissions caused by CNG vehicles which is similar to the conclusion. A comparative life cycle assessment (LCA) was carried out in their work for light-duty commercial vehicles (LDCVs) and indicated that the requirement of CNG-powered LDCVs is 2% higher than the diesel-powered LDCVs as the overall life cycle is considered. Furthermore, their obtained result shows that the formation of SOx emission by the CNG-powered vehicle is reduced by 75% compared to that of the diesel-powered vehicle. Regarding to other criteria polluted substances to air (such as: VOCs, NOx, and CO), there was less emission produced by the CNG-powered LDCV at the stages of producing feedstock and fuel while it was opposite for the operation phase of vehicle, which could be explained by the higher energy demand of CNG-powered vehicle in comparison with diesel during the operation phase due to the energy density of the CNG fuel was lower than that of the diesel fuel [72-74].

The differences in GHG emissions were consistent with the results of Buchspies, Kaltschmitt, and Junginger [75] which obtained that the differences in a production environment are the main reason for the variations in GHG emissions. A good example was the bioethanol conversion process which required a large amount of energy, hence, the formation of GHG emissions by using fossil fuels such as coal for steam production and power generation was significantly higher than by usage of biomass. The selected material for producing ethanol might consequence in higher emissions from ethanol to the environment [76]. Generally, the findings of Pedrozo et al.[77], the performance of biodiesel and ethanol is not the best as the combination between WTT and TTW life cycle stages was considered. Their conclusion state that in comparison with diesel fuel, the performance of biodiesel fuels showed a slight reductant and obtain higher nitrogen oxides emissions, while there was no much change in the emissions of carbon monoxide, hydrocarbon, and smoke.

The data in the study by Jiao, Li, and Bai [78] indicated that ethanol produced the highest nitrates emissions to water, which is in agreement with the characterization results emphasizing ethanol as the highest effect fuel among the impact categories, for example, eutrophication of marine and depletion of water. The survival, metabolism, and growth of living organisms can be influenced by the increment of water bodies acidity caused by biodiesel production. The highest biochemical oxygen demand (BOD5) belongs to petrol with 1670 g/kJ while ethanol and electricity had the highest concentrations of nitrate and phosphate respectively [79]. The phosphates and nitrates concentration increased resulting in eutrophication. More remarkably, emissions of total dissolved solids (TDS) and total suspended solids (TSS) were the highest for LPG. Meanwhile, hydrogen FCV released the highest inorganic solids concentration to water [80].

The study by Bicer and Dincer [81] found that the toxic substance emissions like Cd are dominated mainly from the ethanol production phase, the production phase of hydrogen, As, Ba, Cr (III) dominate the formation of CU and V emissions, and the domination of Hg was detected in the petrol production processes, while it was popular to obtain Cr (VI), Co, Pb and Zn from the power generation process. Therefore, toxic substances emission represents soil quality was influence heavily by the production phases of petrol and power [82]. According to Bicer and Dincer [83], the complete ecosystems was impacted on a large scale by the release of the toxic substances emissions to the soil due to the groundwater absorb them or species likely took them and it was potential to harm crop plants, animals including humans as crop production use the polluted soils.

Prior researches of Vaughan, Faghri, and Li [84]and (Çankaya [85] discussed the highest capital costs of BEVs which was related to the reasons associate with technic, economic reasons, and reasons related to infrastructure, for instance, shortage of optimum public stations for refueling purpose. Especially interesting, according to (L. Lombardi et al. [86], advanced vehicle powertrains such as the technology of hydrogen fuel cell vehicle (FCV) and electric vehicles using the battery (BEVs) were predicted to be competitor along with achieving equivalence to the recent traditional vehicle technologies in term of overall life cycle costs and have significant contribution toward decarbonizing in the road traffic sector

CONCLUSIONS

This study conducted the assessment of the life cycles environmental and the techno-economic with the selected fuel types as well as powertrain systems of vehicle for the production of fuel and vehicle cost conditions. The process for assessing the environmental-economic-technical impacts of both fossil fuels and renewable fuels has been summarized. Based on the basic knowledge about the life cycle of fuels used for vehicles, it is possible to establish and evaluate the sustainability of promising alternative fuels in the future. Through discussions from published studies when applying the methods mentioned and analyzed in Section 2, it can be confirmed that: (1) In terms of the environment, the levels of impact on the environment are determined. arranged as follows: the lowest belongs to ethanol, followed by CNG, electricity, diesel, gasoline, LPG and the highest is FFV; (2) In terms of economy, total capital and operating costs of electric fuels are the highest, followed by ethanol, biodiesel, diesel, gasoline, CNG, hydrogen (fuel cell), and LPG respectively. Thus, modeling-based studies of sustainability have revealed that hydrogen fuel cell technology has the lowest combined economic-environmental impact, while that of FFV technology has the highest, followed by biodiesel, ethanol, electricity, LPG, gasoline, diesel and CNG.

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