UNIVERSIDADE DE LISBOA
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Potential of bioenergy in transportation systems from endogenous resources in Ecuador

" Documento Definitivo"

Doutoramento em Sistemas Sustentáveis de Energía

Danilo Arcentales Bastidas

Tese orientada por:
Professora Ph.D. Carla Alexandra Monteiro Da Silva
Professor Ph.D. Ángel Diego Ramírez Mosquera

Documento especialmente elaborado para a obtenção do grau de doutor

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Abstract

Climate change is a serious threat to sustainability. Anthropogenic climate change is due to the accumulation of greenhouse gases (GHG) in the atmosphere beyond natural levels. Globally, the transportation sector contributes to 14% of the overall GHG emissions; road transportation corresponds to two-thirds of this percentage. The road transportation sector in Ecuador is characterized by its primary use of fossil fuels as a source of energy. In 2016, this sector emitted 18.5 million tonnes of GHG, corresponding to 42% of the emissions of all sectors. Given this context, it is imperative to decarbonize road transportation by inserting alternative energy carriers and powertrain technologies. Electrification and use of biofuels on light-duty vehicles and mass transportation fleets are considered opportunities for GHG emissions mitigation and for improving local air quality. The electricity generation mix in Ecuador is mainly derived from hydropower, hence incurs relatively low GHG emissions along its life cycle. In this research, the insertion of electric and hybrid vehicles operated with alternative fuels in Ecuadorian road transportation is analyzed from an environmental perspective, using two well-known methods: Life cycle assessment (LCA) and well-to-wheels analysis (WTW). Results indicate that mitigation of GHG is possible when conventional buses used on bus rapid transit (BRT) systems are replaced by electric buses, considering an electricity generation mix of low and high hydropower. However, for a marginal electricity scenario, an inverse behavior is evidenced; the GHG emissions increased by 1 kilotonne for each 25% increase of electric bus penetration. On the other hand, if Ecuador decides to hybridize the public bus fleet, using ethanol as a fuel source, the country will need a production of approximately 1300 million liters of ethanol to satisfy the final energy demand. In terms of GHG emissions, there would be a considerable mitigation of CO_2 emissions (almost 80%) during the operational phase, when conventional fleet buses are replaced with plug-in hybrid buses. However, this is an enormous challenge for a country that only produces 50-60 million liters of ethanol per year. In terms of light-duty passenger vehicles, the environmental performance of a battery electric vehicle and ethanol-gasoline blend flex-fuel vehicle were analyzed by means of an attributional LCA for current and future scenarios. The results for current scenarios show that light-duty vehicles using ethanol-gasoline blends have higher environmental impacts than battery electric vehicles for global warming potential (GWP-130-180 g CO_2-eq/km for E5 (gasoline additivated with 5% of ethanol) and 42–176 g CO_2-eq/km for BEVs.), fossil depletion potential (FDP), marine eutrophization potential (MEUP), ozone depletion potential (ODP), particulate matter formation potential (PMFP), photochemical oxidant formation potential (POFP), and terrestrial

acidification potential (TAP) categories. In contrast, using the current electricity mix, the battery-electric vehicle has higher environmental impacts in freshwater eutrophization (FEP) and metal depletion (MDP) categories. In general, a battery electric vehicle has a better environmental performance than flex-fuel when in fact the electricity generated to charge such vehicles is highly renewable. The more fossil fuel electricity is used the flex-fuel vehicles will perform environmentally better. Nevertheless, E85 flex-fuel vehicles should not be discarded if the electricity generation for battery electric vehicles is not highly green (renewable or biobased). The Ecuadorian government needs policies that promote advanced transportation technologies, including alternative vehicles and energy carriers such as electricity or biofuels on transportation systems. Moreover, Ecuador should have policies and technical instruments to avoid charging electric vehicles with marginal fossil electricity.

Keywords: plug-in hybrid buses, life cycle perspective, well-to-wheels analysis, emission mitigation, environmental performance.

Resumo

As alterações climáticas constituem uma séria ameaça à sustentabilidade. As alterações climáticas antropogénicas são devidas à acumulação de gases com efeito de estufa (GEE) na atmosfera para além dos níveis naturais. Globalmente, o sector dos transportes contribui para 14% das emissões globais de gases com efeito de estufa, sendo que o transporte rodoviário corresponde a dois terços desta percentagem. O sector dos transportes rodoviários no Equador é caracterizado pela sua utilização principal de combustíveis fósseis como fonte de energia. Em 2016, este sector emitiu 18,5 milhões de toneladas de GEE, o que corresponde a 42% das emissões de todos os sectores. Dado este contexto, é imperativo descarbonizar o transporte rodoviário através da inserção de vectores de energia alternativos e de tecnologias de transmissão de energia. A electrificação e a utilização de biocombustíveis em veículos ligeiros e frotas de transporte de massas são consideradas uma oportunidade para a mitigação das emissões de GEE e a melhoria da qualidade do ar local. A mistura da produção de electricidade no Equador é maioritariamente derivada da energia hídrica, incorrendo assim em emissões relativamente baixas de gases com efeito de estufa ao longo do seu ciclo de vida. Nesta pesquisa, a inserção de veículos eléctricos e híbridos operados com combustíveis alternativos no transporte rodoviário equatoriano é analisada de uma perspectiva ambiental, usando dois métodos bem conhecidos: Avaliação do ciclo de vida (ACV) e análise well-to-wheels (WTW). Os resultados indicam que a mitigação dos GEE é possível quando os autocarros convencionais utilizados em sistemas de trânsito rápido (BRT) são substituídos por autocarros eléctricos, considerando uma mistura de produção de electricidade de baixa e alta energia hidroeléctrica. No entanto, para um cenário de electricidade marginal, esta diminuição não é retratada. Por outro lado, se o Equador decidir hibridizar a frota de autocarros públicos, utilizando etanol como fonte de combustível, o país precisará de uma produção de aproximadamente 1300 milhões de litros de etanol para satisfazer a procura final de energia. Em termos de emissões de GEE, haveria uma mitigação considerável das emissões de CO_2 (quase 80%) durante a fase operacional, quando os autocarros da frota convencional são substituídos por autocarros híbridos plug-in. No entanto, este é um enorme desafio para um país que produz apenas 50-60 milhões de litros de etanol por ano. Em termos de veículos ligeiros de passageiros, o desempenho ambiental de um veículo eléctrico a bateria e de um veículo flex-fuel de mistura etanol-gasolina foram analisados através de uma ACV atribucional para cenários actuais e futuros. Os resultados para os cenários actuais mostram que os veículos ligeiros que utilizam misturas etanol-gasolina têm impactos ambientais mais elevados do que os veículos eléctricos a bateria para o potencial de aquecimento global (GWP-130-180 g CO_2-eq/km para E5 e 42-

176 g CO_2-eq/km para BEVs.), potencial de esgotamento fóssil (FDP), potencial de eutrofização marinha (MEUP), potencial de esgotamento do ozono (ODP), potencial de formação de partículas (PMFP), potencial de formação de oxidantes fotoquímicos (POFP), e categorias de potencial de acidificação terrestre (TAP). Em contraste, utilizando a actual mistura de electricidade, o veículo eléctrico a bateria tem impactos ambientais mais elevados nas categorias de eutrofização de água doce (FEP) e de esgotamento de metais (MDP). Em geral, um veículo eléctrico a bateria tem um melhor desempenho ambiental do que o flex-fuel quando na realidade a electricidade gerada para carregar tais veículos é altamente renovável. Quanto mais electricidade de combustíveis fósseis for utilizada, os veículos flex-fuel terão um melhor desempenho ambiental. No entanto, os veículos flex-fuel E85 não devem ser descartados se a produção de electricidade não for altamente ecológica (renovável ou biobaseada). O governo equatoriano necessita de políticas que promovam tecnologias avançadas de transporte, incluindo veículos alternativos e portadores de energia, tais como electricidade ou biocombustíveis nos sistemas de transporte. Além disso, o Equador deveria ter políticas e instrumentos técnicos para evitar carregar os veículos eléctricos com electricidade fóssil marginal.

Palavras-chave: autocarros híbridos plug-in, perspectiva do ciclo de vida, análise do poço às rodas, mitigação de emissões, desempenho ambiental.

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Nomenclature and abbreviations

ANT	National Transit Agency (Agencia Nacional de Tránsito)
AR	Assessment report
ARCERNNR	Agency for Regulation and Control of Energy and Non-Renewable Natural Resources (Agencia de Regulación y Control de Energía y Recursos Naturales no Renovables)
ATM	Municipal Transit Authority (Agencia de Tránsito Municipal)
BEV	Battery electric vehicle
BRT	Bus rapid transit
CI	Compression ignition
CNG	Compressed natural gas
CH_4	Methane
C_6H_6	Benzene
CN	Cetane number
CO	Carbon monoxide
CO_2	Carbon dioxide
$CO_{2eq.}$	Carbon dioxide equivalent
CUTE	Comparative Urban Transport and Environment
E2012	Electricity mix average 2012
E5	5% ethanol content in gasoline
E15	15% ethanol content in gasoline
E85	85% ethanol content in gasoline
EA	Economic allocation
EC	Final energy consumption
EoL	End-of-life
EPB	Electric public bus
EEA	European Environment Agency
EEV	Enhanced Environmental friendly Vehicle
EPA	Environmental Protection Agency
EU	European Union
EV	Electric vehicle
FAO	Food and Agriculture Organization
FDP	Fossil depletion potential
FEP	Freshwater eutrophication potential
FFB	Fresh fruit bunches
FFV	Flex-fuel vehicle
FTP	Federal Test Procedure
FU	Functional unit
GHG	Greenhouse gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global warming potential

H_2	Hydrogen gas
HC	Hydrocarbons
HD	Heavy-duty
HDS	Hydrodesulphurization
HDT	Heavy-duty truck
HDV	Heavy-duty vehicle
HEV	Hybrid electric vehicle
HEV_{ED95}	Hybrid with compression ignition engine running on ethanol-based fuel for diesel engines
ICE	Internal combustion engine
ICEV	Internal combustion engine vehcile
ICEFFV	Internal combustion engine flex-fuel vehicle
IEA	International Energy Agency
IERAC	Ecuadorian Institute of Agrarian Reform and Colonization (Instituto Ecuatoriano de Reforma Agraria y Colonización)
INEC	National Institute of Statistics and Census (Instituto Nacional de Estadísticas y Censos
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal return rate
ISO	International Standards Organization (ISO)
ISO/TC	International Standards Organization/Technical Committee
LCA	Life cycle assessment
LDC	Light-duty cargo
LDV	Light-duty vehicle
LHV	Lower heating value
LPG	Liquefied petroleum gas
LUC	Land use change
MAGAP	Ministry for Agriculture, Livestock, Aquaculture and Fisheries (Ministerio de Agricultura, Ganadería, Acuacultura y Pesca)
MDP	Metal depletion potential
ME	Marginal electricity
MEER	Ministry of Electricity and Renewable Energies (Ministerio de Electricidad y Energías Renovables)
MEUP	Marine eutrophication potential
NH_3	Ammonia
NMHC	Nonmethane hydrocarbons
NO_x	Nitrogen Oxide
ODP	Ozone depletion potential
$PHEV_{flex}$	Plug-in hybrid with flex-fuel spark ignition engine
PLANEE	National Plan of Energy Efficiency (Plan Nacional de Eficiencia Energética)

$PM_{2.5}$	Particulate matter (2.5 um = diameter)
PMFP	Particulate matter formation potential
POFP	Photochemical oxidant formation potential
PT	Passenger transportation
RON	Research octane number
SA	System allocation
SI	Spark ignition
SNI	National Information System (Sistema Nacional de Información)
T	Temperature
TAP	Terrestrial acidification potential
TEA	Techno-economic assessment
TDPB	Traditional diesel public bus
TTW	Tank-to-wheels
UBEC	Union of Banana Exporting Countries
UC	Urea consumption
UK	United Kingdom
US	United States
WTT	Well-to-tank
WTW	Well-to-wheels
Wt	Weight
VOC	Volatile organic compounds
1G	First generation biofuel
2G	Second generation biofuel
3G	Third generation biofuel

List of units

°C	Celsius
cm	Centimeter
g/cm^3	Gram/cubic centimeter
g/t_{cane}	Gram/tonne of sugarcane
g/km	Gram/kilometer
g/l	Gram/liter
h	Hour
ha.	Hectares
kg/ha.	Kilogram/hectare
kJ/kg	Kilojoule/kilogram
kJ/MJ	Kilojoule/Megajoule
km/h	Kilometer/hour
km/y	Kilometer/year
kt	Kilotonne
kWh/km	Kilowatt-hour/kilometer
kWh/t_{cane}	Kilowatt-hour/tonne of sugarcane
l	Liter
l/km	Liter/kilometer
L_{diesel}/ha.	Liter of diesel/hectare
Mt	Megatonne
m^3/ha.	Cubic meter/hectare
MJ/kg	Megajoule/kilometer
ML	Million liter
MPa	MegaPascal
mm	Milimeter
ppm	Parts per million
t/ha	Tonne/hectare
t CO_2/kWh	Tonne of CO_2/kilowatt-hour
TWh	terawatt-hour

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1. Extended abstract

1. Extended Abstract

1.1 Introduction and objective

Climate change has been a major environmental concern since 1980 due to the accumulation of greenhouse gases (GHG) in the atmosphere beyond natural levels [1]. Evidence supports that worldwide GHG concentrations are increasing [2]–[4] despite implementing several mitigation policies. In 2010, global GHG emissions were recorded at 49.5 billion tonnes of carbon dioxide equivalent [3], a value reached faster than expected [5]. There is an urgent need to mitigate the effects of climate change, as it is a severe threat to sustainability. Climate scientists regularly state that human activities such as deforestation, agricultural practices, and fossil fuels burning are the primary causes of climate change [4], [6], [7].

Fossil fuels burning activity is commonly associated to transportation, building, electricity production and industrial sector. The transportation sector is considered as a key driver of GHG increase [8], non-renewable resource depletion and air quality degradation. Globally, transportation contributes to circa 14% of the total GHG emissions [3], which is associated with the combustion of petroleum-based fuels. The road transportation contributes almost two-thirds of the overall CO_2 emissions produced within this sector [9].

Greenhouse gases increase in the road transportation sector is primarily attributable to the amount of vehicles in circulation [10]–[13] as a result of the fast economic growth. Two decades ago, there were 600 million vehicles worldwide and in 2020, there are approximately 1.3 billion units [14]–[17]. Moreover, old fleet vehicles with delayed emission standards, i.e., less restrictive than European or Californian ones, also contribute to these emissions. In this context, being the fundamental driver of an Earth-wide temperature boost, human beings require cleaner technologies and should define a roadmap to decarbonize road transportation. The challenge is to change the current unsustainable transportation model without producing negative social and economic effects.

Several governments have implemented different strategies in their fight to mitigate GHG emissions in road transportation sector. An important player and old-fashioned strategy has been the use of bus rapid transit (BRT). The BRT is a public transport system designed to improve capacity and reliability in overcrowded cities. Due to the constant migration of people from rural to urban areas, the implementation of a BRT system has become extremely necessary in

several cities [18], [19], specifically in those with high population densities [20], [21]. The first wide-scale BRT concept started in Curitiba, Brazil, in 1974, where the initial idea was to build a rail-based metro system. The system's success inspired other cities; currently, there are almost 150 cities with BRT fleets. This system has ameliorated road public transportation services around the world and has mitigated GHG emissions due to the use of electricity or cleaner fuels on their buses. Some other governments have emphasized introducing hybrid and electric cars as new vehicle powertrain technologies aiming to promote more efficient transportation. The Enhanced Environmental friendly Vehicle (EEV) concept was introduced by the European Union (EU) to promote the use of the best available environmental technology for sensitive environments. The bus sector is being electrified and increasing its use of alternative fuels [22]–[27].

Alternative fuels are another solution for GHG mitigation because they are not derived from conventional sources like petroleum or coal. However, not all governments support these fuels and criticize the fact that its production compromises the food supply chain because some of them come from a food source (i.e., sugarcane). Moreover, land-use change and high dependence on fossil fuel resources due to outdated agricultural practices are critical remarks commonly mentioned by people with opposite thoughts [28]–[30]. These discrepancies have enabled the development of other advanced pathways to obtain 2nd and 3rd generation biofuels. The biomass source for 2nd generation includes food waste, organic waste, and wood. The 2nd generation biofuels are produced through biochemical and thermochemical processes by recovering lignocellulosic feedstock. Another advanced way of producing biofuels is based on improved biomass production by using engineered crops such as algae as the energy source (3rd generation). Aiming to determine which biofuel pathway is friendlier environmentally depending on the feedstock, it is fundamental to have an overall energy balance of production chains by applying a life cycle analysis (LCA).

Life cycle assessment (LCA) is a tool used to model the complex interaction between a product or service and the environment from which it was created until it is left for disposal. LCA studies originally started in the late 60s within the packaging industry, aiming to manage energy consumption. However, in the decade of 1990, this tool was formally accepted since many advances were accomplished in its methodology.

The transportation sector in Ecuador is highly energy intensive, with a sustained upward trend in the last decade. Within this sector, gasoline and diesel fuels are widely used, while the use of electricity or biofuels is still negligible. According to INEC (Spanish acronym for Instituto Nacional de Estadísticas y Censos; National Institute of Statistics and Census in English), the transportation sector emitted 18.5 million tonnes of GHG in 2016, which corresponds to 42% of the emissions of all sectors. The road transportation sector accounts for almost two-thirds of the overall consumption required for this sector. Ecuador's registered number of motorized road vehicles was 2.1 million in 2016 [31], reaching a motorization index of 126 cars per 1,000 inhabitants. The use of fossil fuels within this sector generates a negative impact not only in environmental terms but also in economic terms due to fuel imports to cover the entire demand. Moreover, the Ecuadorian government subsidized fuel prices. Between 2005 and 2018, Ecuador spent approximately $54,269 million in fuel subsidies, equivalent to 50% of gross domestic product (GDP) [32]. It is important to remark that Ecuador produced 483,000 barrels of petroleum and other liquids per day in 2020. In this context, any action or policy to mitigate fossil fuel dependence and its negative impacts would be justified.

Due to the accelerated urbanization in the three main cities of Ecuador (Guayaquil, Quito and Cuenca), the municipalities and local governments have been forced to implement several new transportation systems such as BRT and metro. For example, the Metrobus-Q is a high-capacity BRT system in Quito with three-line routes: Ecovía, Central Norte, and Trolleybus. The first two operate with diesel buses, and 74% of the third-line buses use electric energy technology. Moreover, Quito is also building an underground rail mass transit system, which will be in operation in the following years. In Guayaquil, the Metrovia BRT system was built in 2006 to control and regulate Guayaquil's urban mass transportation system. It consists of three-line routes that are planned to increase to seven in the coming years. Buses of Metrovia have exclusive lanes on one-way streets and are diesel-powered with premium diesel of less than 500 parts per million (ppm) sulfur. In Cuenca, the Tramway Cuatro Ríos is in the test phase and will start operation very soon.

The absence of contributions from renewable energy sources in the energy mix motivated the Ecuadorian government to start executing projects to change this situation, moving heavily to renewables [33]. By 2014, Ecuador had an installed capacity of 5,299 megawatts (MW), with a gas turbines-based capacity share of 18%, an internal combustion engine share of 27%, a hydro-based capacity of 42 %, and the remainder through biomass, solar and wind-based

capacity. The government forecasted that this capacity would be approximately 7,800 MW by 2018, with its main contribution coming from large-scale hydro. In 2017, the mix was 56.1% renewables and 43.9% non-renewables, with distribution losses of 12.1 %. In May 2017, Ecuador projected its National Plan of Energy Efficiency (PLANEE, for its acronym in Spanish), whose objective was to use electricity efficiently and to include the promotion of new technologies and alternative fuels in the transportation sector [34], [35].

Moreover, in 2010, the EcoPaís E5 Pilot Program (E5 = 5 % ethanol content in gasoline type Extra of 87 octane number-RON) started in Guayaquil and Durán. By 2015, this Program covered 86 percent of the demand for EcoPais E5 in the Guayas Province. For this purpose, Ecuadorian sugarcane and alcohol producers have produced 90 million liters (l) of ethanol; currently, the program covers more than 50% of the country. However, the agriculture sector does not give up on reaching an EcoPais fuel with 10% ethanol blend, as it was established on a government decree (#675). Other potential sources of ethanol have been explored by banana industry wastes [36]. It claims that Ecuador has the potential to produce an additional 118–266 l ethanol/ha yearly from this feedstock. Considering roughly 150,000 hectares (ha.), this would mean an extra 40 million liters of ethanol source a year.

Regarding biodiesel fuel, the Ecuadorian government began producing this biofuel from African palm in 2005. In 2013, the government enacted Executive Decree 1303, establishing that the biodiesel B5 blend would gradually increase until reaching B15. The latter represented a production of 480 million liters of biodiesel per year [37]. Afterwards, the National Fuel Trade Agency (ARCH) stated that only Ecopaís biofuel (5% ethanol blend) was available in the Ecuadorian market. Therefore, biodiesel should wait for more substantial incentives and marketing policies [38]. Meanwhile, the current use of biofuel processed from vegetable oil is destined for pilot projects such as Zero Fossil Fuels for Galapagos [37]. La Fabril is the only group in Ecuador producing biodiesel out of palm oil and jatropha. This group could process up to 50,000 hectares planted with African palm and jatropha. The actual production in 2016 was 16,259 tonnes/year, which represents 26.6% of its product market share. Its net cultivation productivity was 1 tonne of crude palm oil, which requires 5 t of fresh fruit bunches (FFB) [39]. The transesterification reaction mass flows are 845 kg of palm oil and 138 kg of anhydrous methyl alcohol, which are required to produce 891 kg of biodiesel and 92 kg of glycerin [40].

Giving this data we can say that 0.19 hectares are required to produce 1 ton of biodiesel, i.e. a factor of land use requirements of 0.19 ha/ton biodiesel.

To the best of our knowledge, several relevant studies have been published in the literature that focus on biofuels and electrification as potential ways to reduce GHG and air quality emissions, especially in developed countries. However, other countries, such as Ecuador, have not thoroughly investigated this topic. There is little research in Ecuador regarding possible pollutant mitigation achievements in the transportation sector. The primary motivation of this work is to evaluate the environmental impact that the implementation of alternative fuels and new power supply for vehicles, with the insertion of new powertrain technologies, could produce on the Ecuadorian road transportation systems. Acknowledging these concerns will help the Ecuadorian government create policies that could foster energy savings and sustainable development in the transportation sector.

The purpose of this thesis based on papers is to contribute positively to fostering sustainable road transportation systems in Ecuador through the insertion of alternative energy carriers and powertrain technologies for GHG emissions mitigation. For this case study, we focused primarily on electricity and ethanol as energy carriers for road transportation systems. Within biofuels, we have given priority to ethanol because it is the energy vector with the greatest application in road transportation systems in Ecuador when compared to biodiesel. In addition, biodiesel should wait for stronger incentives and marketing policies because the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources (ARCERNNR) stated that only Ecopaís biofuel (5% ethanol blend) was available in the Ecuadorian market. Moreover, diesel vehicles do not lead sales, which are traditionally led by gasoline combustion vehicles, with around 71.3% of the market share in Ecuador.

1.2 Methodology, target and research questions

Aiming to develop the present work and accomplish the general objective, we applied two well-known methods: Life cycle assessment (LCA) and well-to-wheels analysis (WTW).

1.2.1 Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is an environmental management tool used to model the complex interaction between a product or service and the environment, since it was created (raw materials) until it is left for disposal. LCA studies originally started in the late 60's within the

packaging industry, aiming to manage energy consumption. After this decade, several studies were developed considering raw materials and waste generation. However, it was in the decade of 1990 that this tool was formally accepted, since many advances were accomplished on its methodology [41]. In the same decade, a Technical Committee 207 (ISO/TC 207) from the International Standards Organization (ISO) was created, and the Life Cycle Analysis was regulated by the ISO norms 14040 and 14044.

There are two different types of LCA approaches that can be detailed: Attributional Life Cycle Assessment, which typically aims to attribute the impacts associated with the production and use of a product, using average and historical data; and the Consequential Life Cycle Assessment, which seeks to analyze the environmental impacts of a proposed change in a system under study, taking into account both consequences inside and outside the product life cycle [42].

1.2.1.1 Life cycle assessment framework

Based on the ISO 14040 and 14044 standards, the LCA methodology follows four main steps: definition of goal and scope, inventory analysis, impact assessment and interpretation.

1.2.1.1.1 Definition of goal and scope

This first step of the LCA study is to define the goal and the scope. In this step it is relevant to define the functional unit, the impacts of interest and the system boundaries. Moreover, the reason for executing the study has to be described in terms of the target audience and intended application. Fulfilling this objective ensures consistency in the study.

1.2.1.1.2 Inventory analysis

The next step is related to the data collection of inputs and outputs associated with a product or service. These data is referred to the functional unit previously settled. This stage is considered as the most intensive of the LCA study as it requires abundant information. For this step it is important to ellaborate a process flow chart with raw material, process stages, transportation requirements and uses; after this first step, data collection of inputs such as energy requirements is needed along with outputs such as emissions, waste flow and products.

1.2.1.1.3 Impact assessment

In this step the objective is to assess the potential significance of the impacts based on the results of the inventory analysis in a more meaningful basis. For example, the input and output flows are translated into environmental impacts such as global warming or resource depletion.

1.2.1.1.4 Interpretation

In this final step the idea is to clarify, quantify and evaluate the information that results from the inventory and/or the impact assessment stage, providing an easily understandable and complete LCA study in accordance with th goal and scope definition. At the end of this stage, with the established conclusions, is possible to achieve improvements in the process that results in a reduction of the environmental impacts.

1.2.2 Well-to-wheels analysis

The term well-to-wheels (WTW) refers to the entire process of energy flow and emissions estimation, from the mining of the energy source to its use in transportation and/or storage. A WTW analysis is composed of two stages: a well-to-tank (WTT) stage which accounts for feedstock extraction and fuel production until it reaches the pump service stations; and, a tank-to-wheel (TTW) stage which considers the operational phase. Consequently, WTW analysis is an application of LCA which is used to compare a wide range of automotive fuels and drivetrains/vehicles options from a global perspective. Compared to LCA, WTW does not take into account the energy and emissions involved in building facilities or end-of-life (EoL) stages.

The identified research questions are listed below supported by the targeted objective:

Target 1: Evaluation of different bus powertrain technologies

The Ecuadorian diesel-based bus fleet is analyzed with the insertion of new powertrain technologies such as hybrid and plug-in hybrid flex-fuel concepts. The influence on final energy consumption, air quality and 100 years global warming impact was assessed through a WTW approach.

Research question 1: How ethanol and bus electrification concepts will impact GHG and air pollutant emissions (NO_x, NH_3 and $PM_{2.5}$) in Ecuador?

Target 2: Life cycle assessment of Ecuadorian ethanol production as an energy carrier

The present study compiles a life cycle inventory for Ecuadorian sugarcane-derived ethanol production to quantify its environmental performance and identify the life cycle stages that cause significant impacts. A hybrid attributional and consequential life cycle analysis (LCA) approach has been followed. Economic allocation (EA) and system expansion (SE) were used to consider co-products in the milling and co-generation of electricity stages. The co-generation stage is analyzed in three different scenarios: (i) average mix displacement scenario, where the surplus electricity produced in the co-generation stage is displaced (reduced, replaced, or substituted as a result of a change in supply or demand for new (virgin) production of these determining products); (ii) marginal technology displacement scenario, where the marginal surplus electricity is displaced from the mix; and (iii) no displacement scenario.

Research question 2: What environmental impacts are generated by ethanol production through sugarcane in Ecuador?

Target 3: Comparative life cycle assessment of ethanol-gasoline blends and electricity as energy carriers for light-duty passenger transportation in Ecuador

Environmental performance comparison of light-duty passenger transportation in Ecuador with different energy carriers (ethanol-gasoline blends and electricity) through a life cycle analysis. Current, future, and single-resource scenarios are considered for BEVs and ICEFFVs. The functional unit assumed for the study was 1 km traveled.

Research question 3: What is environmentally superior in Ecuador as an energy carrier for light-duty passenger vehicles: ethanol-gasoline blends or electricity?

1.4 Findings and Results

Electrification and the use of biofuels on light-duty vehicles and mass transportation fleets are considered opportunities for GHG emissions mitigation and improving local air quality. Results indicate that mitigation of GHG is possible when conventional buses are replaced by plug-in hybrid electric buses. If Ecuador decides to hybridize the bus fleet with ED95, the country will need approximately 1,326 million liters of ethanol a year to satisfy the demand. If the option is to move forward with a $PHEV_{flex}$ fleet, the ethanol demand is much lower, 41–281 million liters per year. This is a significant challenge for a country that only produces 50-60 million liters of ethanol per year. Regarding air quality, the PHEV scenarios seem to be better than any other

scenario with zero local emissions. However, introducing ethanol could increase NH_3 particle precursors due to the SCR NO_x exhaust aftertreatment system.

Within biofuels as an alternative energy carrier for transportation systems, we have given priority to ethanol because of its greatest application in road transportation systems in Ecuador when compared to biodiesel. In addition, biodiesel still needs stronger incentives and marketing policies to increase its sales, which are traditionally led by gasoline combustion vehicles, with around 71.3% of the market share in Ecuador. The study linked to research question #2 compiles a life cycle inventory for Ecuadorian sugarcane-derived ethanol production to quantify its environmental performance and identify the life cycle stages that cause significant impacts. The global warming potential (GWP) impact was found to be 53.6 kg of carbon dioxide equivalent (kg $CO_{2eq.}$) per tonne of sugarcane produced. This latter is mainly due to the use of nitrogenous fertilizers and diesel, with 34% and 24% of the contribution, respectively. The GWP for 1 L of ethanol produced was reported as 0.60 kg $CO_{2eq.}$, where the distillation stage has the highest contribution with approximately 61% followed by the agricultural stage with 47%. The cogeneration stage reports a contribution of −8.4%. This latter negative contribution corresponds to the surplus electricity displacement. The Ecuadorian sugarcane and ethanol industries should focus on less polluting and sustainable processes (precision agriculture or avoiding pre-harvest burning activities) to reduce the environmental burdens. Companies should also apply industrial symbiosis and circular economy strategies to produce lesser environmental loads within the ethanol production chain.

In terms of light-duty passenger vehicles and linked to research question #3, the environmental performance of a battery electric vehicle and ethanol-gasoline blend flex-fuel vehicle were analyzed using an attributional LCA for current, future (2030, 2040, and 2050), and single resource electricity scenarios. The results for current scenarios show that light-duty vehicles using gasoline additivated with 5% of ethanol have higher environmental impacts than battery electric vehicles for global warming potential (GWP-130-180 g CO_2-eq/km for E5 and 42–176 g CO_2-eq/km for BEVs.), fossil depletion potential (FDP), marine eutrophization potential (MEUP), ozone depletion potential (ODP), particulate matter formation potential (PMFP), photochemical oxidant formation potential (POFP), and terrestrial acidification potential (TAP) categories. In contrast, using the current electricity mix, the battery-electric vehicle has higher environmental impacts in freshwater eutrophization (FEP) and metal depletion (MDP) categories

because of the discharge of mining waste in mineral extraction for the battery production and vehicle production processes. Regarding single resources electricity scenarios, the E85 scenario has less GWP than BEV scenarios when fossil fuel electricity is used to charge BEVs. Thus, E85 flex-fuel vehicles should not be discarded if the electricity generation is not highly green (renewable or biobased). The Ecuadorian government needs policies that promote advanced transportation technologies, including alternative vehicles and energy carriers such as electricity or biofuels on transportation systems.

1.5 Thesis Outline

This thesis has a paper-based-thesis structure composed of 8 chapters, including the extended abstract chapter, which refers to the motivation, problem statement, research questions, and applied methodology. Chapter 2 presents some basic aspects and generalities of biofuels as automotive fuel, especially ethanol and biodiesel. Secondly, this chapter presents an overview of sugarcane and ethanol production in Ecuador. Moreover, some general concepts regarding new alternative vehicle powertrain technologies are presented, as well as an overview of the main limitations of LCA methodology. Chapter 3 presents an overview of the sustainability of sugarcane for energy purposes especially in Brazil and Ecuador. Mitigation of greenhouse gas emissions through the shift from fossil fuels to electricity in the mass transportation system in Guayaquil is presented in Chapter 4. Chapter 5 presents an assessment of alternative vehicle powertrain technologies (plug-in hybrid vehicle) for public buses and bus rapid transit systems in Ecuador from a well-to-wheels perspective. Chapter 6 presents the environmental life cycle assessment of ethanol production in Ecuador. A comparison between ethanol (sugarcane-derived) –gasoline blends and electricity as energy carriers used on light-duty passenger vehicles is presented in Chapter 7. Finally, Chapter 8 includes the overall conclusions of this thesis, illustrates the key research findings, discusses the results based on research questions, and presents research limitations and suggestions for future research.

1.6 List of Published Articles

A list of published works linked with the targets/research questions is depicted in the following Table 1. 1:

Table 1. 1 Published Works linked with research questions.

Works Title	Status	Target/Research question number	Journal	DOI	Citations according to Scopus:
The Environmental Profile of Ethanol Derived from Sugarcane in Ecuador: A Life Cycle Assessment Including the Effect of Cogeneration of Electricity in a Sugar Industrial Complex	Published	2	Energies Journal Special Issue	10.3390/en15155421	1
Exploring the introduction of plug-in hybrid flex-fuel vehicles in Ecuador	Published	1	Energies Journal	10.3390/en12122244	5
Sustainability of sugarcane for energy purposes	Published	2	Sugarcane Biorefinery, Technology and Perspectives	10.1016/B978-0-12-814236-3.00005-6	2
Mitigation of greenhouse gas emissions through the shift from fossil fuels to electricity in the mass transport system in Guayaquil, Ecuador	Published	1	ASME IMECE Conference	10.1115/IMECE2018-87732	3
Environmental analysis of road transport: sugarcane ethanol-gasoline blend flex-fuel vs battery-electric vehicles (in revision)	Sent	3	Transportation Research Part D	NA	NA

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2. State of the Art

2. State of the art

2.1 Literature review

There is a concern regarding the atmosphere when we hear that road transportation is the predominant mode of transportation worldwide, as we know that motor vehicle emissions contribute to air contamination [43]. Pollution is one of the most worrisome problems due to its impacts on health and the economy [44]. Pollutants expelled in a mobile way are regulated under specific standards such as United States (U.S.) standards in America and Euro regulations in Europe to protect the environment and prevent human health hazards. There are several researches on engine design and after-treatment devices to control some pollutant emissions, such as selective catalytic reduction (SCR) and diesel particulate filters (DPF), which reduce NO_x and PM´s emissions, respectively [45]–[49]. Selective catalytic reduction is considered the best option to eliminate gases through a reduction reaction [50] but could lead to an increase in NH_3 emissions [51], [52]. Jung et al. (2019) analyzed the effect of emissions in a non-road diesel engine through the combination of a diesel oxidation catalyst (DOC) and a diesel particulate filter (DPF). Results show a consistent oxidation performance on CO and HC emissions. However, NO and NO_2 experienced undesirable oxidation [45]. Konstandopoulos et al. (2015) analyzed the influence of exhaust gas recirculation (EGR), SCR, and DPF technologies on diesel engine railcar emissions. Their results show that the combination of EGR+DPF has the potential to comply with particulate matter limits beyond stages IV and V. Moreover, SCR-based solutions can go beyond the stage IV NO_x limit by sizing up SCR devices [46]. Koebel et al. (2020) developed a general analysis of the use of urea on SCR devices for NO_x emissions mitigation on heavy-duty vehicles. The results indicate that more NH_3 emissions will be expelled if the exhaust gas resides shorter in the SCR device [48].

The massive use of fossil fuels, especially in vehicles, will boost GHG, particularly carbon dioxide (CO_2) emissions, which are significant contributors to these gases. For this reason, governments must quantify the energy consumption in the transportation sector and analyze the potential energy savings and GHG mitigation by implementing environmental strategies such as new powertrain technologies or new energy carriers for road transportation systems.

The trend in using biofuels on-road transportation systems strengthens the need to investigate the real-world impact of such fuel change on exhaust emissions. The effect of biofuels on exhaust emissions, mainly on light-duty passenger vehicles, has been studied by several researchers. Suarez-Bertoa *et* al. [53] analyzed this effect on a Euro 5a light-duty vehicle tested

with hydrous and anhydrous ethanol over the Worldwide Harmonized Light-Duty test cycle. Their results showed a reduction of NO_x emissions (30-55%) when a higher ethanol blend (E75-E85) was used but showed an increase in carbon monoxide, methane (CH_4), and carbonyls compared to lower ethanol blends (E5, E10, E15). Hubbard, Anderson, and Wallington also analyzed the influence of ethanol content on emissions and the fuel economy of a 2006-year Mercury Grand Marquis flexible fuel vehicle (FFV) [54]. The results displayed that ethanol, methane, and acetaldehyde emissions increased with increasing ethanol content. Also, NO_x emissions decreased by around 50% as the ethanol blend increased by up to 40%. However, there is no more decrease once the mixture reaches 50 or 80% (E50 or E80). Furthermore, Durbin et al. analyzed the effect of ethanol blends (0, 5.7, and 10 vol %) and volatility parameters on exhaust emissions for 12 vehicles certified with new emissions control technology [55]. Karavalakis et al. have also studied the impact of ethanol blends on regulated and unregulated emissions from light-duty vehicles and one flexible fuel vehicle (FFV) over a Federal Test Procedure (FTP) driving cycle [56]. CO emissions displayed a decrease with higher ethanol content for all vehicles. NO_x emissions results are varied, with increases in higher ethanol blends in some vehicles while other vehicles showed no significant decrease. The nonmethane hydrocarbon (NMHC) emissions showed a reduction in most of the vehicles with an increasing ethanol content. However, the FFV showed an increase with an ethanol blend of 85% (E85). Another study researched the effect of ethanol blended with gasoline on the performance of a spark ignition engine and their tailpipe emissions [57]. In terms of emissions, Hsieh et al. stated that there was a decrease in CO pollutants due to the increase in ethanol content. It was reported that NO_x emissions depended not on the ethanol content but on the engine's operating condition.

Although most of the studies analyzing the effect of ethanol content on tailpipe emissions have been implemented on light-duty vehicles, some have been assessed on heavy-duty vehicles and buses. For example, Mata et al. studied the effect of nitrous oxides and particle concentration emissions with an ethanol-diesel blend on bus fleets under different acceleration transitions and operating and different altitudes [58]. There was a reduction in particle concentration emissions when the ethanol-diesel blend was used compared to the low-sulfur diesel. However, nitrogen oxide (NO_x) emissions showed diverse results. The ethanol-diesel fuel blend reduced these emissions when the vehicle was operated at high altitudes but increased when the operation was at low altitudes. On the other hand, Gomez et al. developed a study that analyzed the effect of the ethanol-diesel blend on buses operated in different cities with different altitudes [59]. The

results displayed a decrease in NO_x and particulate matter emissions when buses with both fuels (diesel and ethanol-diesel blend) were tested at cities with altitudes.

A more novel and recent way to mitigate emissions in the transportation sector is by the insertion of new powertrain technologies such as hybrid or fully electric vehicles [24], [60]–[63]. Most of the studies have had a focus on light-duty passenger vehicles. Costa and Seixas analyzed the CO_2 emission mitigation by replacing gasoline-powered vehicles with 10 and 20% penetration of battery electric vehicles (BEV) in Sao Paulo [62]. They concluded that there was a considerable reduction of CO_2 emissions, around 11 megatonnes (Mt), when gasoline vehicles were replaced by electric vehicles. Hill et al. analyzed the role of electric vehicles in near-term mitigation pathways in the United Kingdom (UK) [63]. They think decarbonization strategies are extremely necessary to meet the UK's carbon budget and demonstrated that using electric vehicles has more environmental benefits than using an efficient internal combustion engine. Furthermore, Song et al. analyzed the potential reduction of GHG emissions in Macau by replacing light-duty gasoline and diesel vehicles with electric and hybrid technologies [64]. They used a well-to-wheels approach and found that even under the current electricity mix, a reduction in terms of GHG emissions can be achieved by inserting electric vehicles instead of conventional vehicles. Under an electricity mix of natural gas and solar energy used on these powertrain technologies, they concluded that there would be a reduction of 22 and 28% reduction in GHG emissions by 2030, respectively. On the other hand, Onat et al. found that electric vehicles (EVs) are not environmentally friendly when using the marginal electricity mix scenario in the United States [65]. Marginal electricity mix refers to the additional electricity demanded by the consumers that will come from the cheapest power plant that still has spare capacity at that time. Onat et al. accomplished a comparative study between conventional, electric and plug-in-hybrid vehicles through a carbon and energy footprint analysis over 50 states of the United States, using average and marginal electricity generation mixes. Moreover, the results showed that based on average electricity generation mix scenario, electric vehicles are less carbon-intensive in 24 states, and hybrid vehicles are more energy-efficient in 45 states. Faria et al. also analyzed the impact of three different electricity generation mix on electric vehicles by an economic and environmental life cycle assessment approach [66]. They developed a comparative study between internal combustion engine vehicles (ICEV) and electric vehicles represented by plug-in-hybrid and battery electric vehicles. Results showed that using renewable energy sources for the electricity generation does not always reflect low GHG emissions for electric vehicles due to the variability of these sources and due to the

different driving styles. A particularly aggressive driving style, with rapid accelerations and high speeds, immediately translates into a lower range per charge and, as a result, greater emissions owing to increased energy consumption. Moreover, electric vehicles resulted as the best option from an environmental and economic point of view.

Although the main focus on analyzing emissions mitigation through the insertion of new powertrain technologies has been put on light-duty passenger vehicles, within the last decade, several studies have strongly emphasized the use of hybrid and electric technologies in public buses [22]–[27], [67]. Scott Wayne et al. assessed the benefits of using alternative fuels such as compressed natural gas (CNG) and biodiesel and advanced technology such as diesel-electric hybrid and gasoline-electric hybrid in the United States transit bus fleet [68]. Their findings showed that diesel-electric hybrid buses were the most environmentally friendly scenario with the most significant CO_2 mitigation. A recent life cycle study in Macau's public transportation also analyzed the mitigation of GHG by promoting the use of the urban electric public bus. Song et al. concluded that electric public buses (EPB) pollute less than traditional diesel public buses (TDPB) only when natural gas and solar energy are considered in the electricity mixes [26]. It is noteworthy that Macau is a coal-intensive area of China. Thought should be given to Lajunen and Lipman research, wherein they supported that the pollutant emissions of electric buses are strongly related to electricity generation and not to the operational phase [69]. Moreover, they concluded that hybrid buses can slightly reduce emissions during the operational phase compared to diesel buses. On the other hand, fully electric vehicles can significantly reduce emissions by almost 75% compared to internal combustion engine vehicles. By contrast, Ribau et al. [70] and García Sanchez et al. [23] evidenced that the GHG emissions produced by diesel-based buses are mainly derived from the operational phase (TTW), 86% and 83%, respectively. Finally, a more recent study in Curitiba compared the benefits of emissions mitigation between a hybrid electric and plug-in-hybrid electric with a two-axle conventional bus [22]. Dennis Dreier et al. showed that advanced powertrain vehicles offer a more sustainable option, with higher decarbonization levels than conventional buses.

As noted above, several relevant studies published in the literature focus on biofuels and electrification as potential ways to reduce CO_2 and air quality emissions, especially in developed countries. Other countries, such as Ecuador, have not thoroughly investigated this topic. The primary motivation of this work is to evaluate the environmental impact that the

implementation of alternative fuels and new power supply for vehicles, with the insertion of new powertrain technologies, could have on the Ecuadorian road transportation systems.

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3. Sustainability of sugarcane for energy purposes

C. Silva (f.a.), R. Pacheco, D. Arcentales, F. Santos.
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3. Sustainability of sugarcane for energy purposes

3.1 Introduction

Pursuing fossil-free systems with minimum waste disposal covering food, energy, materials, and chemicals production is a significant driver for developing biorefineries where all these products could be produced simultaneously. The idea of having a dedicated unit to produce exclusively biofuels should be avoided, or its benefits over biorefinery should be proven. Economic and environmental aspects must be studied to select the most feasible biorefinery configuration. The former relates to a techno-economic assessment (TEA); the latter is usually tackled in a life cycle assessment (LCA) framework.

TEA and LCA studies are designed to address a specific question and contain different assumptions, data sources, and uncertainties. Therefore, it is not surprising that the results vary widely across the studies, and care must be taken to compare them directly. For example, a different geographical location/country will have different labor, insurance of equipment and materials costs, electricity and product prices, currencies, electricity generation mixes, transportation/distribution distances, and even different agriculture productivities induced by other climate/weather conditions. Additionally, different studies may refer to different chronologies (different reference dollars or euros) and different Intergovernmental Panel on Climate Change (IPCC) assessment report (AR) CO_{2eq} values. Table 3. 1 includes the 100-year time horizon global warming potentials (GWP) relative to CO_2. The AR5 values are the most recent, but AR2, AR3, and AR4 report values are also listed because they are sometimes used for inventory and reporting purposes.

Historically, sugarcane culture has been considered the main economic activity since the Brazilian colonial period, when slave labor was still used. Since then, with the rise in sugar consumption, the crop's economic importance has increased. At this time, sugarcane mills in Brazil produced only sugar. The Pró-Álcool program (1975) induced an increase in distilleries and sugarcane mills producing both sugar and ethanol in an integrated fashion. More recently, electricity production has also been a by-product of sugarcane mills, and therefore, the actual sugarcane mill is a biorefinery, producing food, electricity, and biofuel. Figure 3. 1 shows the historical evolution of sugarcane, ethanol, and electricity sold to the grid. The number of

registered flex-fuel cars also shows its link with ethanol availability and sugarcane industry growth.

From 2005 to 2014, co-generated electric energy dispatch increased from 1.1 to 19.4 terawatt-hours (TWh), and biomass became Brazil's third electric energy generation source, after hydro and fossil sources [71].

For example, in terms of sustainable assessment of the sugarcane mills, TEA and LCA could be used to determine the merit of a sugarcane biorefinery compared to the alternatives to produce ethanol and other co-products.

Table 3. 1 Differences in global warming potentials (GWP) for a 100-year time horizon, source Intergovernmental Panel on Climate Change (IPCC) assessment reports (ARs).

	Designation	Chemical formula	AR2-1996	AR4-2007	AR5-2013
Common among carbon footprint	Carbon dioxide	CO_2	1	1	1
	Methane	CH_4	21	25	28
	Nitrous oxide	N_2O	310	298	265

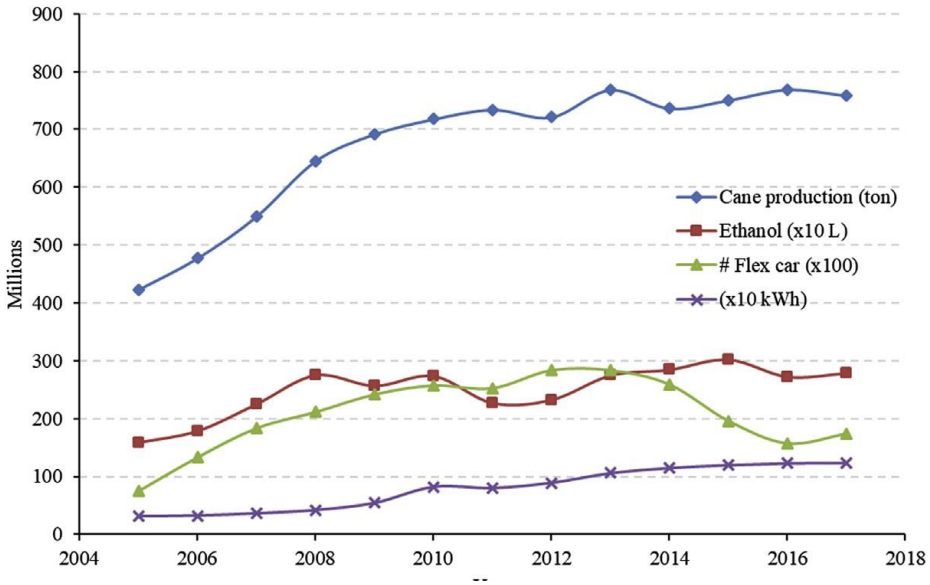

Figure 3. 1 Historical trends showing the increase in cane production, ethanol production, number of flex-fuel vehicles registered, and surplus electricity from bagasse in Brazil [362]–[365]

The following studies were reviewed from the literature to have Table 3. 2 inventory values, mainly from Brazil Center South region [71]–[74]. The quantification of wastes is stressed out because they can be further processed in the sugarcane biorefinery. Regarding straw and tips, studies recommend using about 50% of the total collected to maintain the field, control erosion, and keep moisture, temperature, and soil fertility. The remaining 50% is used for burning in boilers, producing electric energy. In addition, it is used to produce cellulosic ethanol, also known as second-generation (2G) ethanol. The sugarcane wastes from harvesting (straw) and juice extraction (bagasse) are produced in large quantities, about 280 million tonnes of bagasse and straw per year, and they are likely to increase shortly as new industrial plants are implemented. Currently, sugarcane residues are mostly burned to produce heat and electricity at the sugar mill. However, they could also be used as feedstocks for producing other high-value products in the context of the lignocellulosic biorefinery [75]. This would be a 2G biorefinery integrated with the first generation (1G), whose schematic is represented in Figure 3. 2.

The sugar mill could adopt other feedstocks besides sugarcane for year-round operation. Energy cane and sweet sorghum have different harvest times but can be processed for bioethanol using the same equipment [76].

The CO_2 intensity of electricity in Brazil is low due to the high percentage of renewables, 73 g CO_{2eq}/kWh carbon intensity [77]; electricity used in the processes, 14 kWh/tonnecane [72], is nowadays mainly suppressed by bagasse cogeneration and surplus electricity is sold to the grid, being a product of the biorefinery and no longer an input.

Land use change (LUC), when the natural landscape is transformed by human activity, and biogenic emissions of CO_2 as a result of sugar fermentation processes can also be considered when analyzing production processes [78]. The values of fossil energy consumption and CO_{2eq} emissions with no LUC, no biogenic emissions from fermentation, and credits to surplus electricity are from the literature: for the reference case [73], 2008 data for sugar production, fossil energy use 721 kJ/kg sugar and 234 g CO_{2eq}/kg sugar, respectively Table 3. 3.

Table 3. 2 Input—output inventory for 1G biorefinery from different sources in the literature. The uptake of CO_2 from sugarcane culture adopted is 653 kg CO_2 per tonne of sugarcane [79]

Stage	Inputs		Outputs	
Agriculture [74]	Nitrogen (N)	58.7 kg/ha/year	Sugarcane	**89 t/ha/year**
	Phosphate (P_2O_5)	20.63 kg/ha/year		
	Potassium (K_2O)	30.39 kg/ha/year		
	Limestone ($CaCO_3$)	400 kg/ha/year		
	Herbicide	5.00 kg/ha/year		
	Insecticide	2.00 kg/ha/year		
	Cropping practices	33.49 L_{diesel}/ha/year		
	Harvesting	49.09 L_{diesel}/ha/year		
	Water	140 m^3/ha/year		
Agriculture [73]	274 L_{diesel}/ha/year		Sugarcane	**86.7 t/ha/year**
	N	777 g/t_{cane}	Cane trash yield	**140 kg_{dry}/t_{cane}**
	P_2O_5	249 g/t_{cane}		
	K_2O	980 g/t_{cane}		
	$CaCO_3$	5183 g/t_{cane}		
	Herbicides	44 g/t_{cane}		
	Insecticides	3 g/t_{cane}		
Industrial [74]	Lime	1066.52 g/$t_{sugarcane}$	Bagasse	**0.27 tonne/t_{cane}**
	Phosphoric acid	23.28 g/$t_{sugarcane}$	Filtercake	**24 kg/t_{cane}**
	H_2SO_4	6.31 g/$L_{ethanol}$	Stillage	**14 L/$L_{ethanol}$**
	Lubricants	13.93 g/$t_{sugarcane}$	Ethanol	**85 L/$t_{sugarcane}$**
Industrial [73]	Lubricants	10.3 g/t_{cane}	Stillage	**11 L/L**
	Sulfur	156 g/bag	Filtercake	**31 kg/t_{cane}**
	Lime	880 g/t_{cane}	**Boiler cogeneration**	

Sulfuric acid fermentation	**7.4 g/L**	**Ash**	**2 kg/t_{cane}**
		Soot	**12 kg/t_{cane}**
		Bagasse	**0.264 tonne/t_{cane}**
		Ethanol	**86.7 L/$tonne_{cane}$**
		Electricity surplus	**10.7 kWh/t_{cane}**

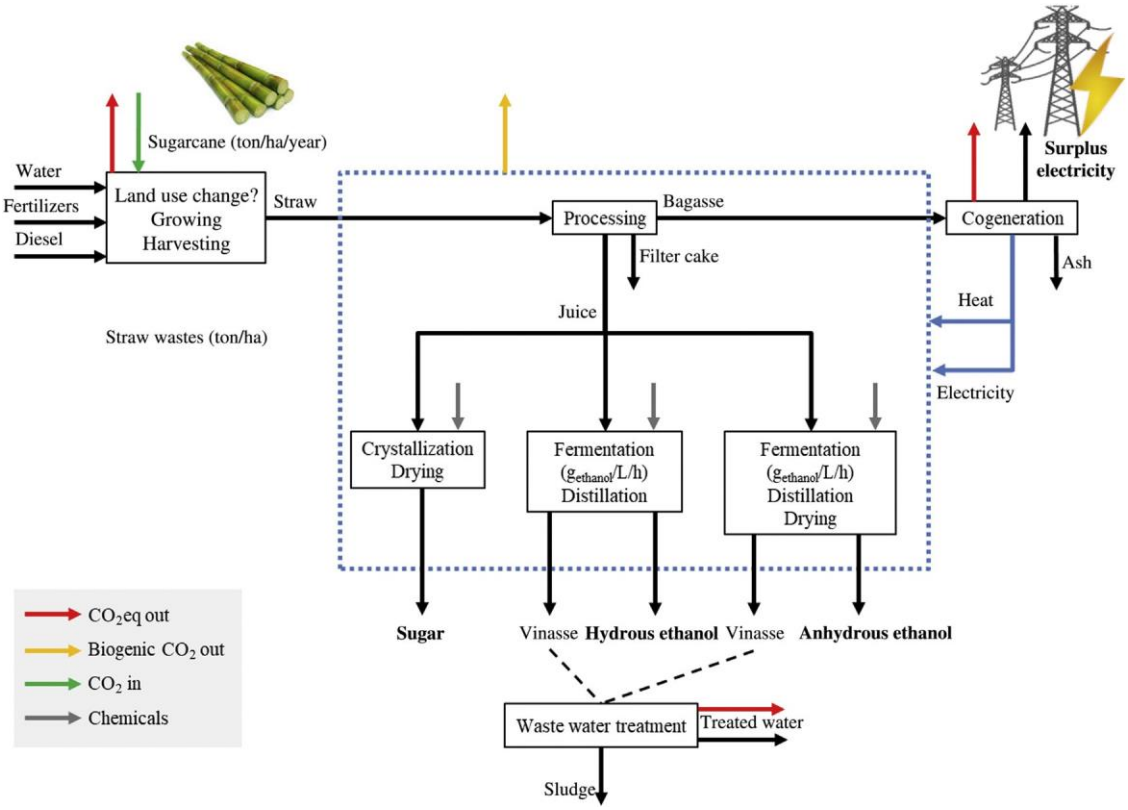

Figure 3. 2 Process material, emissions, and energy flow for a traditional sugarcane 1G biorefinery mill (can be used for sugarcane, energy cane, and sweet sorghum) [76]. A partition of 40% sugar, 39% hydrous ethanol, and 21% anhydrous ethanol is shown in [73].

Table 3. 3 Fossil energy consumption and CO_{2eq} emissions with no LUC, no biogenic emissions from fermentation, and credits to sur-plus electricity

Reference	Stage	Fossil energy	CO_2 eq emissions
Reference case [73]	Sugar production (2008)	721 kJ/kg sugar	234 g CO_2 eq/kg sugar
Reference case [73]	Ethanol life cycle	80 kJ/MJ	21.3 g CO_2 eq/MJ
[80]	Ethanol life cycle	202-238 MJ/MJethanol	24 g CO_2 eq/MJ
[72]	Agricultural and industrial (2005-2006)	-	417 g CO_2 eq/l for hydrous and 436 g CO_2 eq/l for anhydrous ethanol
[72]	Agricultural and industrial (2005-2006)*	-	19.8 g CO_2 eq/MJ for hydrous and 20.7 g CO_2 eq/MJ for anhydrous ethanol

*(density 0.785 kg/L, lower heating value 26.9 MJ/kg [81])

Other possible biorefineries could be projected to convert the process residues to 2G ethanol or even 3G ethanol further. Those virtual biorefineries are usually simulated using the AspenPlus software to get all virtual materials and energy flows [82]. These virtual inventories are then used in the LCA and TEA analysis. For example, a comparison of three biorefineries in terms of the internal return rate (IRR), a TEA metric [83]. Fifty percent of the straw waste (crop residues) was used in the soil. The other 50% was used in the cogeneration unit to produce extra electricity for the grid (biorefinery #1, Table 3. 4) and to produce ethanol from cellulose (biorefinery #2, Table 3. 4) and cellulose and hemicellulose (biorefinery #3, Table 3. 4). More specifically, 50% of sugarcane juice was used for sugar production and the other part of the juice, together with molasses, which is a by-product of vegetable origin obtained from the sugar manufacturing process, was used to produce ethanol. Furthermore, 50% of the sugarcane crop residues were hydrolyzed together with a surplus of bagasse (an amount that was not used to attend to the process heat and electricity demand) to produce 2G ethanol, and crop residues were used to participate into the energy supply of the process. No LCA global warming impact assessment was made, and only the value of CO_2 uptake 178 kg of carbon per 1000 kg of sugarcane stalks during the plant-growing phase is mentioned.

Table 3. 4 Techno-economic assessment (TEA) analysis, based on the internal return rate (IRR) metric of virtual biorefinery from sugarcane [80].

	Biorefinery #1 optimized 1G	Biorefinery #2 Integrated optimized 1G and 2G	Biorefinery #3 Future integrated optimized 1G and 2G
Ethanol yield L/tonne canne	89.3	110.7	131.5
Electricity surplus to the grid kWh/tonne cane	185.8	92.8	72.7
US$2009/L	0.288	0.317	0.253
IRR per year	16.9%	12.2%	18.4%

Gnansounou et al. (2015) used TEA and LCA metrics to select the best integrated sugarcane-based biorefineries [77]. They were integrated biorefineries producing 1G and 2G ethanol, sugar, molasses (for animal feed), and electricity in the context of Brazil. The metrics prospective economic performance (PEP) (for TEA) and climate change impact (CO_{2eq}) are used in a

reference system that produces gasoline (allowing a vehicle to move the same km), sugar, animal feed, and electricity, and in the integrated biorefineries. They concluded that integrated 1G2G biorefinery reduced 56%-59% of the CO_{2eq} emissions compared to the reference system and even got lower emissions than a dedicated 1G mill. The TEA metric showed that the 1G mill had higher economic performance, followed by the 1G2G with four main products: ethanol, sugar, electricity, and animal feed. This example compares a basket of products with other systems producing the same products, and, so, is not only a well-to-wheels study of the liquid fuel ethanol.

Another example in the literature considers sugarcane ethanol and palm oil biodiesel joint production in a biorefinery (joint sugarcane ethanol biodiesel—JSEB) whose products are ethanol, glycerin, kernel oil, cake, and electricity to the Brazilian grid. In this case, no sugar was produced [74]. The biodiesel that was internally produced was used to suppress the diesel fuel needs in managing soils, harvesting, and transportation. Based on the traditional system, life cycle CO2eq emissions of ethanol were 20.2 g/MJ, without LUC emissions. In comparison, CO_{2eq} emissions of ethanol produced by the JSEB were 15.6 g/MJ, a 23% reduction in life cycle emissions compared to the traditional system. This example shows a cradle-to-gate comparison of biorefinery systems. A cradle-to-gate analysis considers all the processes that occur before the stage at which a product is ready for use.

1G2G3G ethanol biorefinery integration systems, for example, exploring microalgae to consume the CO_2 released in subprocesses and used as raw material for ethanol production, is not yet fully explored [84] and could be a topic of future research. The only study found regarding algae use to collect the biogenic CO_2 from fermentation and produce biodiesel for all agriculture operations was in an ethanol distillery [85]. The authors showed a potential reduction of 10%-50% of CO_{2eq} emissions compared to a traditional Brazilian sugarcane ethanol distillery.

Despite this intense research in Brazil, other American countries will likely follow the Brazilian example. For instance, Ecuador's major sources of biomass are agricultural residues, animal manure, woody biomass, industrial effluents, and municipal solid wastes [86]. Ecuador’s agricultural production benefits from its geographic location and favorable weather conditions, having an average 12-hour day luminosity [87].

Biofuel production in Ecuador is poor compared to Brazil. Ecuadorian sugarcane production is mainly concentrated in the coastal region, close to Guayaquil (MAGAP), and it has been like that since the 1990's decade. For 2001, Ecuador counted a sugarcane-cultivated area of 69,085 ha. After four years, the total cultivated area increased to 135,000 ha. (75,000 ha. for sugar) of which solely 10,000 ha. were dedicated to ethanol production. For the same year, the Ecuadorian Ministry for Agriculture, Livestock, Aquaculture and Fisheries (MAGAP, acronym in Spanish) estimated that Ecuador had 675,932 ha. of suitable land for sugarcane production. A year later, by 2006, the total sugarcane cultivated area increased to 147,270 ha. This year, it was determined that almost 60% of the national sugarcane crops belonged to individual farmers, and the remaining 40% belonged to Valdez and San Carlos sugar companies [88]. In 2009, Ecuador had a daily capacity to produce 136,000 L of ethanol, resulting in an estimated production of 50 million liters per year [89]. The use of ethanol in fuels started in Guayaquil and Duran in 2010, where the Ecuadorian government launched a pilot program denominated Ecopaís fuel (E5), a blended gasoline type extra of 87 octane number with 5% ethanol processed through sugarcane production. Initially, the government aimed to increase the blend of gasoline with ethanol from 5% to 15% by 2016. For this reason, the government started promoting sugarcane production in small and large scale. After the introduction of Ecopaís, it was possible to observe a decrease in emissions of CO, NO_x, and HC [90]. Compared with the previous year (2011), Ecuador increased its sugarcane-cultivated area by 10%, having an installed capacity to distill around 185,000 L of alcohol per day. From that amount of liters, 20,000 L per day was used to produce ethanol [87]. Therefore, alcohol production was around 20.5 million liters in 2012, where 39% of the total was used for biofuel production [91]. The installed capacity by 2012 was 36 million liters of ethanol [87]. However, to reach the target of having blended gasoline with 15% (400 million liters of ethanol per year), it is required to sow larger sugarcane extensions and build new distilleries.

3.2 Flex-fuel vehicle technologies and well-to-wheels

When comparing the liquid fuel ethanol production system with gasoline refining to use in a flex-fuel vehicle, a WTW framework is used. For example, in Europe, the carbon footprint (as CO_{2eq}) of ethanol from sugarcane produced in Brazil does not account for LUC, nor biogenic CO_2 emissions. Table 3. 5 shows the well-to-tank (WTT) part of energy and CO_2 balance. From here, the "Primary energy input (1 + 1 $MJ_{expended}$)/MJ_{final})" is 3.09 MJ/MJ_{EtOH} and "total CO_2

emission 24.8 g CO_{2eq}/MJ_{EtOH}." The overall WTW using E5 to E85 blends are 26-37 MJ_{fossil}/100 km and 36-53 gCO_{2eq}/km, a reduction of more than 60% of the CO_2 equivalent emissions [92].

Table 3. 5 Brazilian sugarcane-to-ethanol for use in Europe. Excess bagasse used for electricity production. SCET1 pathway from [92] Edwards et al. (2013) with inventory data mostly from [72] Macedo et al. (2008). Intergovernmental Panel on Climate Change (IPCC)

Brazil's product to European context		Energy expended	GHG emissions g $CO_{2eq}/MJ_{ethanol}$			
Standard steps	Actual steps	$MJ/MJ_{ethanol}$	Total	as CO_2	as CH_4	as N_2O
Product and conditioning at source	Sugarcane cultivation + local transport	0.09	17.9	6.54	3.33	7.99
Transformation at source	Ethanol production	1.88	-1.4	-1.73	-0.06	0.36
	Of which credit for electricity from surplus bagasse	-0.06	-2.5	-2.37	-0.14	-0.03
Transportation to market	Ethanol long-distance transport	0.09	6.7	6.62	0.03	0.02
Transformation near market	NA					
Conditioning and distribution	Distribution	0.02	1.1	1.11	0.01	0.02
	Dispensing at the retail site	0.01	0.5	0.48	0.03	0.00
Total WTT		2.09	24.8			

WTT, well-to-tank

With the expanded greenhouse gases, regulated emissions, and energy use in transportation model (GREET), Wang et al. (2008) examined the WTW energy use and CO_{2eq} emissions of sugarcane-derived ethanol produced in Brazil and used to fuel light-duty vehicles in the United States [93]. The sugarcane-to-ethanol pathway evaluated in the GREET model comprises fertilizer production, sugarcane farming, sugarcane transportation, and sugarcane ethanol production in Brazil; ethanol transportation to United States (US) ports and then to US refueling stations; and ethanol use in E85 vehicles. Results for sugarcane ethanol were compared with those for petroleum gasoline. Their analysis showed that sugarcane ethanol can reduce CO_{2eq} by 78%. This value was recently updated to 40%-62% [94]. This mitigation can be associated with bagasse (sugarcane residue) being burned to generate electricity consumed in the sugar mills, and the surplus electricity is sent to the electricity interconnection network. [95].

Both European and United States advantages in using ethanol from sugarcane produced in Brazilian biorefineries were explored in conventional internal combustion engine vehicles, using 85% anhydrous ethanol blend with gasoline or hydrous ethanol 5%-10% blend with gasoline. Figure 3. 1 shows that flex-fuel technology could be another way to boost ethanol consumption and stimulate more efficient sugarcane from 1G2G3G biorefineries. With the future electrification of road vehicles, the plug-in hybrid flex-fuel technology could be the best choice regarding fuel flexibility (ethanol gasoline electricity), decarbonization, and use of endogenous resources [96].

Looking at the WTT part, for the same industrial emission burden, the higher the ethanol productivity, the better. Depending on the feedstock and fermentation conditions (e.g., temperature, agitation speed, and initial sugar concentration), ethanol productivity values can range from 0.13 to 6.55 $g_{ethanol}/L_{bioreactor\ medium/h}$. Engineered yeast strains can be used to increase ethanol production in industrial scenarios. Those may have an enhanced tolerance to ethanol concentration in the medium, pH fluctuations, temperature, osmotic stress, toxic inhibitors, and/or have the capacity to perform alcoholic fermentation of xylose (a pentose) in additionally to glucose (a hexose) obtaining a higher yield [97].

The industrial value of this productivity, which occurs in sugarcane mills, is not publicly known. If we try to estimate it to 1G mills, sugarcane juice density varies between 1,044.5 and 1,189.5 kg/m^3 [98], and from Table 3. 2, inventory for 1G mills, bagasse, and filter cake amount ~290 kg/1000 kg_{cane}. This means an availability of ~215 $L_{juice}/tonne_{cane}$. Taking the bioreactor

medium as 215 L and assuming 60-hour fermentation would mean a 1G productivity of ~5 $g_{ethanol}/L_{bioreactor\ medium/h}$. These are very rough claims and, of course, should be taken with caution. So, if this ethanol productivity was doubled utilizing engineered yeast and because results of the CO_{2eq} are expressed as per ethanol production, the doubled production would mean half the emission burden. The yeast's capability to process pentose will boost 2G ethanol production.

3.3 Conclusions

Integrated 1G2G biorefineries, processing food (sugar), ethanol (biofuel), heat, and electricity from bagasse (bioenergy for self-consumption) and surplus electricity to the Brazilian grid seems to be favorable from the point of view of techno-economic metrics and the global warming metric. Typically, integrated biorefineries show reductions in CO_{2eq} of 23%-60% compared to 1G optimized biorefineries. The engineered yeast strains used to increase ethanol productivity will improve the WTT values. The metric is expressed as MJ/ $MJ_{ethanol}$ and $gCO_{2eq}/MJ_{ethanol}$. For 1G mills, the latter is typically on the order of 20 g/MJ, without land use issues and disregarding biogenic emissions.

4. Mitigation of greenhouse gas emissions through the shift from fossil fuels to electricity in the mass transportation system in Guayaquil, Ecuador

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Abstract

Climate change is a serious threat to sustainability. Anthropogenic climate change is due to the accumulation of greenhouse gases (GHG) in the atmosphere beyond natural levels. Anthropogenic GHG emissions are primarily associated with carbon dioxide (CO_2) originated in the combustion of fossil fuels used for heat, power, and transportation. Globally, transportation contributes to 14% of the global GHG emissions.

The transportation sector is one of the main contributors to Ecuador's greenhouse gas emissions. In Guayaquil, the road mass transportation system comprises regular buses and the bus rapid transit (BRT) system. Electricity in Ecuador is mainly derived from hydropower, hence incurs relatively low GHG emissions along its life cycle. Therefore, transportation electrification has been seen as an opportunity to mitigate GHG emissions.

This study investigates the effect of partial replacement of the bus rapid system fleet. Feeders have been chosen as the replacement target in five different scenarios. The GREET Fleet Footprint Calculator tool calculates GHG emissions from diesel-based feeders. The GHG emissions associated with the electricity used for transportation are calculated using the life cycle inventory of Ecuador's electricity generation system. Three energy mix scenarios are used for this purpose. The 2012 mix had 61% hydropower; the mix had 85% hydropower, and the marginal electricity scenario was supposed to be the extreme case when the new electricity demand occurs during peak demand periods.

Results indicate that mitigation of GHG emissions is possible for almost all scenarios of percentage fleet replacement and all mix scenarios. Electric buses' efficiency and the carbon intensity of the electricity mix are critical for GHG mitigation.

4.1 Introduction

Climate change has been a primary environmental concern since 1980 [1]. Anthropogenic climate change is due to the accumulation of greenhouse gases (GHG) in the atmosphere beyond natural levels. Evidence supports that worldwide GHG concentrations are increasing [2]–[4] despite the implementation of several mitigation policies. In 2010, the global GHG emissions were recorded at 49.5 billion tonnes of $CO_{2eq.}$ [3], a value reached faster than expected [5]. There is an urgent need to mitigate the effects of climate change, as it is a severe threat to sustainability. Climate scientists regularly state that human activities are the primary

causes of climate change [4], [6], [7]. One of those human activities is transportation, which is considered a key driver of GHG increase [8]. Globally, transportation contributes to circa 14% of the total GHG emissions [3], associated with the combustion of petroleum-based fuels.

The increase in GHG emissions in the transportation sector is primarily attributable to the uncontrolled worldwide trade of vehicles [10], [11]. Two decades ago, there were 600 million vehicles worldwide; by 2020, it is expected to be 1.3 billion [14], [15]. Transportation is one of the main contributors to Ecuador's greenhouse gas emissions because of fossil fuel dependence. According to the National Institute of Statistics and Census (INEC), in 2015, the Ecuadorian transportation sector was associated with 46% of the country's total energy consumption. Consequently, this sector emitted 18.5 million tonnes of $CO_{2eq.}$ in the same year, corresponding to 42% of the total emissions. The main contributor to these emissions within the sector is the road transportation mode, which consumes almost 84% of the whole sector consumption [99]. The most demanded fuels for this mode are diesel and gasoline. Hence, the Ecuadorian government has attempted to minimize the environmental impact by using an ethanol blend and biodiesel in road vehicles [100]. In 2010, the government launched a pilot project plan in Guayaquil that marketed EcoPais fuel, an 87 octane (RON) gasoline - 5.0% ethanol blend [101], from which the ethanol component comes from sugarcane production. In addition, several studies have remarked that first-rate road public transportation can also be implemented to reduce private cars and alleviate GHG emissions due to cleaner fuels [102]–[105]. Furthermore, the implementation of a bus rapid transit system has become extremely necessary to improve public transport services in several cities [18], [19], specifically in those with high population densities [20], [21], such as Guayaquil.

It has also been estimated that GHG mitigation is possible by the introduction of hybrid or electric vehicles in the road vehicle fleet, with a particular focus on private cars [24], [60], [61]. Nevertheless, within the last decade, several studies have strongly emphasized the use of hybrid and electric technologies in public buses [22]–[27], [67]. Chester [61] compared the lifecycle energy and emissions footprints of passenger transportation in three-transit rich United States metropolitan centers (San Francisco, Chicago, and New York City) and concluded that automobiles contribute almost the total energy consumption and emissions in transportation in the studied regions. Scott Wayne et al. [68] assessed the benefits of using alternative fuels (clean diesel, stoichiometric compressed natural gas (CNG), and biodiesel) and advanced technology (diesel-electric hybrid and gasoline-electric hybrid) in the United States transit bus fleet. Their

findings showed that diesel-electric hybrid buses were the most environmentally friendly scenario with the most significant CO_2 mitigation.

A recent life cycle study in Macau's public transportation also analyzed the mitigation of GHG by promoting the use of the urban electric public bus [26]. Song et al. stated that electric public buses (EPB) pollute less than traditional diesel public buses (TDPB) only when natural gas and solar energy are considered in the electricity mixes. Thought should be given to Lajunen and Lipman [69] research, wherein they supported that the pollutant emissions of electric buses are strongly related to the generation of electricity (WTT) and not to the operational phase (TTW). By contrast, Ribau et al. [70] and García Sanchez et al. [23] evidenced that the pollutant emissions produced by diesel-based buses are mainly derived from the operational phase (TTW), 86% and 83%, respectively. Finally, a more recent study in Curitiba compared the benefits of emissions mitigation between a hybrid-electric and plug-in hybrid-electric with a two-axle conventional bus. Dennis Dreier et al. [22] showed that the advanced technologies offer a more sustainable option, with higher decarbonization levels than traditional buses.

Guayaquil is the largest city in Ecuador in terms of population (2.5 million people metropolis) and has approximately 310,000 registered vehicles [106]. Kennedy [102] pointed out that fully integrating all transportation modes requires a sustainable transportation system. In Guayaquil, public transportation is the most widely used mode of transportation, encompassing 83% of the different possible modes, followed by private transportation with 16% and non-motorized transportation with 1% [107]. These percentages can be interpreted as there is a public transportation system with quality service, but it is not the case. Hubenthal [108] said that for achieving a prime Ecuadorian public transportation system, the pertinent institutions must encourage its use and make progress in passenger's safety. To some extent, these goals have been achieved by the implementation of a bus rapid transit system in Guayaquil, giving better quality transportation to citizens. However, there is a pressing concern that we must address under environmental effects due to the rampant use of fossil fuels in transportation systems.

In Guayaquil, the mass transportation system comprises regular buses and the rapid bus system called Metrovia. The rapid bus system was implemented in 2006 to control and regulate Guayaquil's urban mass transportation system, seeking efficiency and quality of service. This bus rapid transit (BRT) system comprises 200 feeder buses with a capacity of 90 passengers and 205 articulated buses with a bus capacity of 160 passengers. Feeder buses are smaller than articulated buses, which transport passengers into short distances [109]. Buses of Metrovia have

exclusive lanes on one-way streets and are diesel-powered with premium diesel of less than 500 ppm sulfur.

The Ecuadorian energy demand is primarily provided by fossil hydrocarbons, which account for 79% of the total demand, followed by electricity, which accounts for 10% [110]. The National Plan for Good Living 2017-2021 states that Ecuador has doubled its electricity generation capacity with renewable energy in the last few years [111]. Electricity in Ecuador is mostly derived from hydropower, a renewable energy source, hence incurs relatively low GHG emissions along its life cycle. As the transportation sector is the major consumer of energy in Ecuador, electrification of transportation has been seen as an opportunity to mitigate GHG emissions and the use of renewable energy [101]. However, the consumption of electricity in transport is negligible in Ecuador. In 2014, thirty-five vehicles were registered as electric in the country [112], where a bus was used in just one.

To the best of our knowledge, there is no information regarding possible GHG mitigation achievements in Ecuador's mass transportation sector. Hence, in this study, the effect of partial replacement of the bus rapid system fleet in Guayaquil is investigated by modeling different scenarios of penetration of electric buses to estimate the GHG emissions mitigation potential. For this reason, a well-to-wheels (WTW) analysis was performed in this study. A WTW analysis for diesel comprises two stages: a well-to-tank (WTT) stage, which accounts for feedstock extraction and fuel production until it reaches the pump service stations, and a tank-to-wheel (TTW) stage, which considers the operational phase.

4.2 Methodology

4.2.1 GHG emissions from diesel-based BRT

Most road vehicles operate with gaseous and liquid fuels, which produce GHG (carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)) emissions, contributing to local air pollution [113]. Besides these emissions, other pollutants such as carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), sulfur dioxide (SO_2), and particulate matter (PM) are generated by the fuel combustion of mobile sources. A well-to-wheels (WTW) analysis was performed using the GREET Fleet Footprint Calculator tool for GHG emissions associated with the current BRT system at Guayaquil. Argonne National Laboratory developed this tool to assist United States metropolitan areas estimate GHG emissions of medium and heavy-duty vehicles [114]. Based on this, the TTW stage is assumed to be similar for Ecuador (Guayaquil)

conditions as it is considered a metropolitan area. Moreover, as was previously stated, the TTW stage contributes to 83-86% of the entire cycle. For this reason, the WTT stage is considered negligible in this case study.

The inputs needed for the GREET Fleet Footprint Calculator include the number of each type of vehicle, the vehicle mile traveled (VMT), and the fuel economy in miles per gasoline gallon equivalent. Based on this, a gasoline gallon equivalent equals 0.88 gallons of diesel #2, a low-sulfur diesel [115]. Metrovia buses operate with a premium diesel fuel of less than 500 ppm sulfur content. Due to diesel quality, the fleet uses Euro 3 engines [116]. The Metrovia is an urban BRT system. Therefore, the urban modal share percentage has been assumed to be 100%. The information on several indicators for the studied BRT system is presented in Table 4. 1. Feeders buses are low-capacity buses that travel short routes in the periphery. Articulated buses are high-capacity buses usually fitted with a joint that travel long distances.

Table 4. 1 BRT's Information [117] *for GHG emission calculation*

Type of bus	Feeders	Articulated
km/year	84,960	105,480
# of buses	200	205
Bus capacity	90	160
Driving share %	100% Urban	
Operational speed (km/h)	22.1	25.4
Emission control technology	Euro III	
Structural weight (t)	15	18
Fuel economy (km/gallon)	10	6

4.2.2 GHG emissions from the hypothetical electric feeders

A life cycle approach has been used to calculate the GHG emissions associated with electric vehicles. The life cycle inventory of electricity in Ecuador has been taken from [118]. In their study, Ramírez et al. included fossil fuel extraction, logistics, and refining in generating, transmitting, and distributing electricity. The study comprised information from 14 power plants, which accounted for 77% of electricity generation in 2012.

The Ecuadorian electricity mix has been changing since 2012 (Table 4. 2). Hydropower generation has increased from 61.2% in 2012 to 66.2% in 2016, and by the end of 2018, it is expected to be 79% of the total generation, due to the inclusion of several new hydropower plants [34]. Installed capacity in Ecuador will continue to grow along with the growing electricity demand. Hydropower is renewable electricity, and its GHG emissions are

considerably lower than those of thermal technologies. Therefore, electricity with a higher hydropower share usually incurs lower GHG emissions. This study takes two approaches regarding the electricity generation mix for the electric bus operation. One is the attributional approach, which considers the average mix, and the other is the consequential approach, which considers the marginal electricity generation technology. Marginal approaches in life cycle assessment are used when a change in the system is performed; in this case, transportation is a new demand, and therefore, it is considered to be covered by marginal technology. The marginal technology in Ecuador is thermal power derived from fuel oil. This study uses three electricity mixes: mix 2012, as an example of low hydropower for Ecuador; 85% hydro, as an example of high hydropower for Ecuador; and marginal electricity technology.

Table 4. 2 Technology shares of electricity generation in National Information System (SNI) by 2012 [118] *and 2016* [34].

Technology	2012	2016
Hydropower	61.2%	66.2%
Wind	--	0.3%
Solar	--	0.2%
Biogas	--	0.1%
Biomass thermal	1.5%	2.0%
Fossil thermal	35.6%	30.9%
Imports	1.2%	0.3%

Performance data from a manufacturer with a presence in Ecuador was used to quantify the GHG emissions associated with the electricity used in electric bus operations. Table 4. 3 shows the bus performance data.

Table 4. 3 Electric bus technical specifications [119]

Performance	Slope Start Capability	≤20%
	Autonomy	Sort1: 315km Sort2: 325km Sort3: 290km
	Approach/Departure Angle	8.5°/8.5°
Motor	Max. Power	150 kW×2
	Max. Torque	550 N·m×2
Battery	Capacity	324 kWh
Charger	Charging Type	80 kW
	Charging Time	3-4h

	Efficiency	90% [61], [68], [120], [121]
Bus Life	Operation Years	15 years

The charge efficiency of these electric buses is assumed to be 90% based on the literature. The GHG emissions associated with electric vehicles' operation consider the traveled distance, the bus efficiency, and the emission factor:

$$Emissions_{electricbus} = \sum(M_m \times Electric\ bus\ consumption \times EF) \quad (4.1)$$

Where:

M_m = average distance traveled by the electric bus (km)

Electric bus consumption (kWh/km). Two electric bus consumption are used, 1.29 and 1.75 kWh/km, as those are minimum and maximum values found in the literature (Table 4. 4).

EF = emission factor (t CO_2/kWh). Table 4. 5 reports the emission factors of the electricity mixes based on a life cycle assessment of the electricity network in Ecuador [118].

m = type of fuel or energy used by the vehicle (electricity)

Table 4. 4 Electric bus consumption

Electric bus consumption (kWh/km)	Reference
1.34	[122]
1.38	[27]
1.75	[27]
1.29	[119]

Table 4. 5 Emission factors for Ecuadorian electricity mixes [118]

Ecuadorian electricity mixes	EF (tCO_2-eq./kWh)
From 2012	0.4
85% hydro	0.1
Marginal	0.9

The BRT system comprises articulated buses and feeder buses with 160 and 90 passenger capacity [117]. The electric buses assessed in this study have a capacity of 80 passengers. Therefore, the feeders have been seen as adequate buses that can be replaced with electric buses. It has been assumed that one electric bus of 80 passengers is equivalent to one diesel-based bus. The feeder fleet comprises 200 buses; on average, each bus drove 84,960 km in 2016 [123].

Five replacement scenarios were modeled in Table 4. 6. Electricity demand to operate the electric fleets is presented in Table 4. 3.

Table 4. 6 Electric buses penetration scenarios

Penetration of Electric Buses	Number of diesel Feeder Buses	Number of electric Feeder Buses
0%	200	0
25%	150	50
50%	100	100
75%	50	150
100%	0	200

4.2.3 Total emissions

The emissions associated with the feeder's fleet each year are calculated by adding the emissions related to the diesel fleet with the emissions associated with the electric fleet:

$$Emission_{total} = Emission_{diesel} + Emission_{electric} \quad (4.2)$$

4.3 Results and Discussions

The GHG emissions from feeder buses considering different replacement scenarios at high and low electric bus consumption are presented in Figure 4. 1 and Figure 4. 2, respectively. In the current situation, where the entire fleet is diesel-based, the calculated GHG emissions are 22.2 kilo-tonnes (kt).

4.3.1 High electric bus consumption scenario

All electricity mix scenarios depict a linear decrease in GHG emissions as the share of electric-based buses increases. Approximately 3.021 kilotonnes of GHG emissions reduction would be attained if the entire fleet was replaced by electric buses, considering the marginal mix.

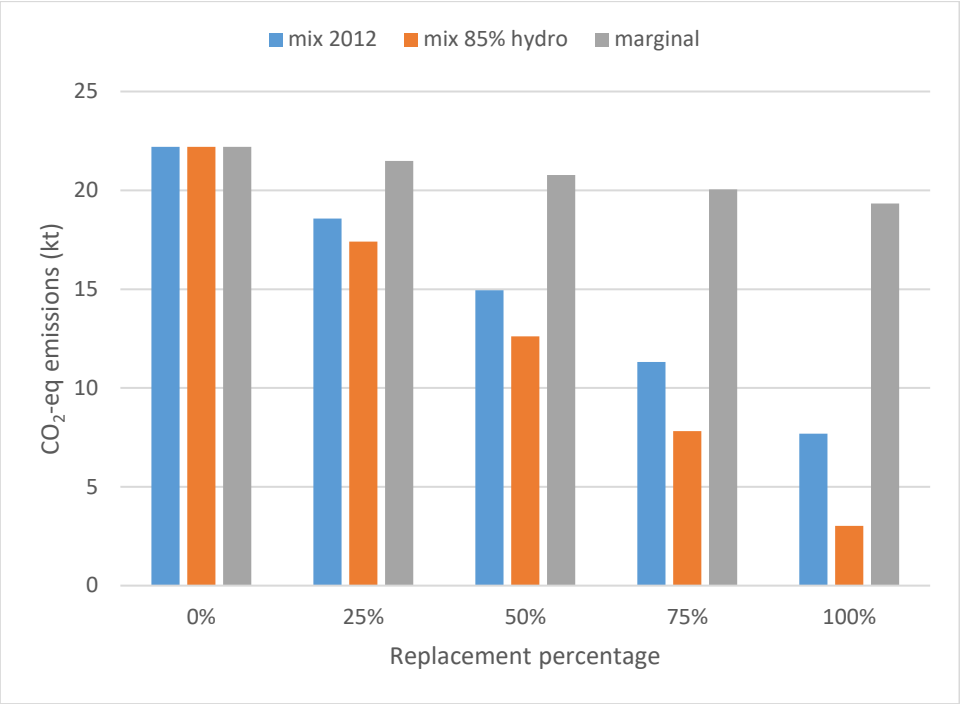

Figure 4. 1 CO_2 emissions results for feeder buses considering different scenarios at high electric bus consumption scenarios.

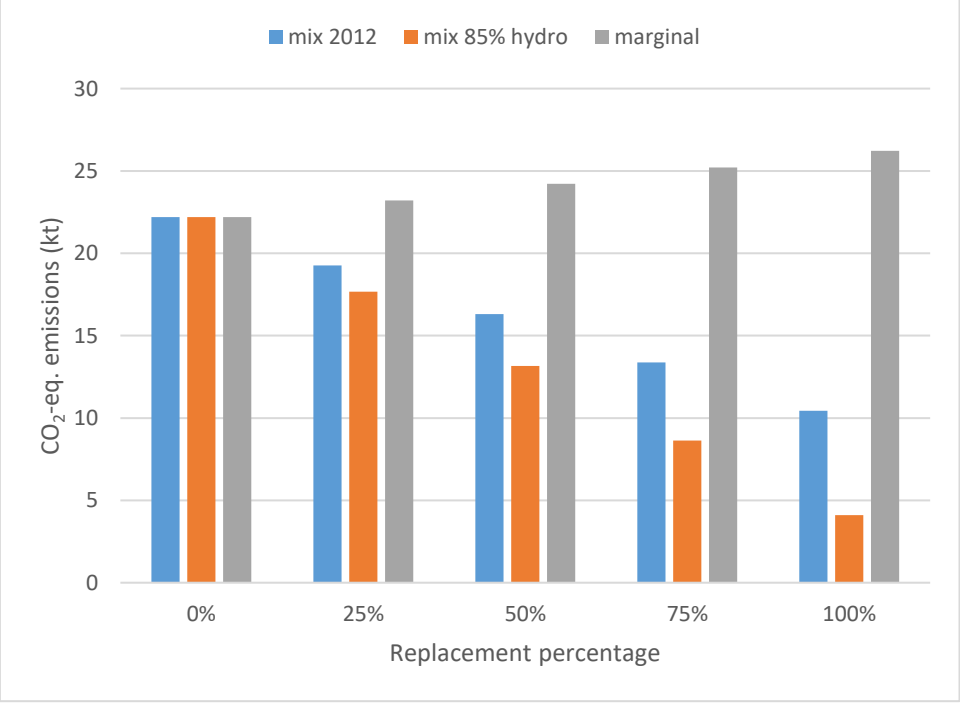

Figure 4. 2 CO_2 emissions results for feeder buses considering different low electric bus consumption scenarios.

Analyzing the electricity mix of 2012, GHG emissions from feeders decrease by virtually 3.6 kilotonnes for each scenario. This corresponds to an overall percentage decrease of 65.3% from the bus penetration scenario less electric to the bus penetration scenario for electric.

Similar behavior is observed for the electricity mix of 85% hydro. Greenhouse gas emissions associated with buses also present a decrease from each replacement scenario. From the current

situation to the extreme electric one, each scenario experiments with an average reduction of 4.8 kilotonnes, corresponding to an overall percentage decrease of 86%.

Notably, total GHG emissions from electric feeders using even marginal electricity are lower than the base case (scenario 0%). Marginal electricity in Ecuador is associated with fossil-based thermal power, most from internal combustion engines using fuel oil. This reduction in GHG emissions is related to the higher efficiency of internal combustion engine (ICE) power plants (above 45%) in comparison with automobile engines (typical range of 38-47%), which is due to the optimized operation conditions of stationary engines, at nominal values and constant engine speed.

4.3.2 Low electric bus consumption scenario

A similar linear trend decrease occurs for the low electric bus consumption case when the 2012 and 85% hydro mixes are considered. In contrast, the marginal electricity mix reflects an inverse behavior. Emissions increase by virtually one kilotonne for each 25% increase of electric bus penetration. This corresponds to an overall percentage increase of 18% from the least electric case to the extreme electric case.

Electric bus consumption is critical when assessing the potential mitigation of GHG emissions when a highly carbon-intensive electricity mix is used. A highly renewable electricity mix is essential to mitigate GHG from the shift from fossil-based buses to electric buses.

4.4 Conclusions

The main goal of this work was to study the mitigation of GHG through the replacement of fleet diesel buses with electric buses. Five different scenarios of percentage fleet replacement and three electricity mixes were considered for this study.

For the low electric bus consumption case and considering the three electricity mixes, the GHG emissions associated with the feeder's buses decreased when a higher share of electric buses was included in the fleet. Emissions could be reduced to 86% if the total fleet were replaced by electric buses when the 85% hydro mix was used.

The case of high electric bus consumption has similar trends to the lower consumption case when the 2012 electricity and 85% hydro mix are considered. Nevertheless, the marginal mix GHG increases as the electric bus share increases.

5. Exploring the Introduction of Plug-In Hybrid Flex-Fuel Vehicles in Ecuador

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D. Arcentales as a Ph.D. Student did the calculations and the writing.
C. Silva as supervisor guided the calculations and contributed to the writing.

Abstract

In Europe, diesel combustion is being restricted due to the impact of NO_x and $PM_{2.5}$ emissions on air quality. The bus sector is being electrified and is increasing its use of alternative fuels, such as natural gas (in spark ignition engines) and bioethanol (in compression ignition engines), to reduce such harmful emissions. Even if a diesel bus is equipped with selective catalytic reduction (SCR), its NO_x emissions are reduced, but it produces more NH_3 emissions that are $PM_{2.5}$ precursors. In developing countries, air quality is still barely monitored; however, the air quality issue is well-known and being addressed. Moreover, the Ecuadorian sugar cane industry is seeking ways to increase its ethanol production. This is the ideal framework for exploring a new technology and energy source in developing economies like Ecuador. This paper explores the impact of the Ecuadorian diesel bus fleet conversion to hybrid compression ignition ethanol (HEV-ED95), hybrid diesel, and plug-in hybrid flex-fuel using electricity and internal combustion engines ICE-E20 and ICE-El00. The impacts are measured regarding final energy consumption, criteria pollutant emissions (NH_3, NO_x, $PM_{2.5}$), and 100 years of global warming potential in a well-to-wheels framework. For the tank-to-wheels data, the method follows the typical values of conversion efficiency from final to useful energy (cross-checked with a micro-simulation model), the tier 2 European Environmental Agency approach combined with ethanol influence on compression ratio, lower heating value, criteria emissions taken from a literature review, and well-to-tank emission factors for electricity (10-58% thermal natural gas or coal powerplant contribution), for ethanol from banana industry wastes (ED95, E20 and El00), gasoline and diesel from US databases. A discussion on whether sugarcane biorefineries are

necessary is highlighted in the results. All input parameters have an uncertainty range between a minimum and a maximum, and a uniform distribution gives the probability for each.

5.1 Introduction

The transportation sector's contribution to crude oil depletion, climate change, and air quality degradation is worrisome. For example, according to the International Energy Agency (IEA), the transportation sector was accountable for 25% of greenhouse gas (GHG) emissions in 2016. According to the same source, it consumes 98% of crude oil-based fuels. Additionally, road transportation represents 40% of NO_x emissions and is the primary source of $PM_{2.5}$ in cities.

The focus on reducing NO_x emissions likely causes an increase in NH_3 slip aggravated by catalyst aging [52], [124]. Ammonia is an inorganic compound that can generate atmospheric ammonium aerosol salts in the presence of acid gases [125]. Knowledge of NH_3 tailpipe emissions is, therefore, essential.

The road transportation sector in Ecuador is characterized by its use of fossil fuels as the primary energy source. According to INEC (the Spanish acronym for Instituto Nacional de Estadísticas y Censos—National Institute of Statistics and Census in English), the transportation sector emitted 18.5 million tonnes of GHG, which corresponds to 42% of the emissions from all sectors [31]. Due to the accelerated urbanization in the main Ecuadorian cities, local governments have been forced to implement new transportation systems such as bus rapid transit (BRT). The most economical way to commute in Ecuador is by bus, the most used means of transportation. Counting regional, urban, public and international buses, there are approximately 23,400 buses, where 98% (23,056) correspond to diesel-based buses, and the other 2% (380) are gasoline-based buses, mainly used by schools. Recently, a bus line in Guayaquil purchased 20 electric buses for its daily operations, becoming the second South American city to have an electric bus fleet.

In 2010, the Eco País E5 Pilot Program (E5 = 5% ethanol content in gasoline type rated above 85 octane number) started in Guayaquil and Durán. Initially, the government aimed to increase the ethanol blend with gasoline from 5 to 15% by 2016. However, 400 million liters (l) of ethanol are needed per year to reach this target. The sugarcane cultivated area must add 66 thousand hectares to the existing 79 thousand hectares. By 2015, this program covered 86 % of the demand for extra fuel in the Guayas Province. Ecuadorian sugarcane and alcohol producers

were able to produce 80 million liters of ethanol. Ecuador's three major sugarcane companies produce most of this ethanol: Valdez with Codana, San Carlos with Soderal, and Coazucar with Producargo.

Banana industry wastes were explored as another potential source of ethanol [36], [126]. These studies claim that Ecuador has the potential to produce an additional 118–266 l ethanol/ha yearly from this feedstock. The roughly 150,000 ha in banana production would mean 40 million liters of ethanol annually.

Ecuador is also experiencing a change in electric power generation, moving heavily to renewables [33]. By 2014, Ecuador had an installed capacity of 5,299 MW, with a gas turbine-based capacity share of 18%, an internal combustion engine share of 27%, a hydro-based capacity of 42%, and the remainder from biomass, solar and wind-based capacity. The government forecasted that this capacity would be approximately 7,800 MW by 2018, with the main contribution coming from large-scale hydro. In 2017, the mix was 56.1% renewables and 43.9% non-renewables, with distribution losses of 12.1%.

By May 2017, Ecuador presented its National Plan of Energy Efficiency (PLANEE, for its acronym in Spanish), whose objective was to use electricity efficiently and to include the promotion of new technologies in the transportation sector [34], [35]. To the best of our knowledge, there is little information regarding possible pollutant mitigation achievements in the mass transportation sector in Ecuador.

This paper explores different bus concept options and their impacts on final energy consumption, air quality, and the impact of 100 years of global warming. The bus concepts are compression ignition running on diesel ($ICEV_{CI}$), hybrid with compression ignition engine running on diesel HEV_{diesel}, hybrid with compression ignition engine running on ethanol-based fuel for diesel engines (ED95) HEV_{ED95}, and a plug-in hybrid with flex-fuel spark ignition engine, running on ethanol E20 and E100 $PHEV_{flex}$.

The impacts are measured regarding final energy consumption, NO_x, $PM_{2.5}$ and NH_3 (converted to $PM_{2.5}$ equivalent), and $CO_{2eq.}$ through different replacement scenarios. NH_3 is already included in standards by imposing a limit of 10 ppm for SCR-equipped buses, and based on Equation (3) from Stelwagen and Ligterink [124], this would probably mean 46 mg/km NH_3 slip.

Ecuador follows European emission standards, so that we will stick with European emission models for the tank-to-wheels (TTW) data.

5.2 Material and Methods

This study compares the final energy consumption and local environmental impacts of six scenarios considering different fuels (diesel, ethanol blend, and electricity) and bus technologies (compression ignition, spark ignition, and plug-in hybrid flex-fuel). The scope of the study is the so-called well-to-wheels (WTW) analysis. It is divided into tank-to-wheels (TTW) according to the matrix of powertrains/fuels in Table 5. 1 and well-to-tank (WTT) according to Table 5. 2.

Table 5. 1 Matrix for TTW energy consumption and emissions calculations

	diesel	E20	E100	electricity
ICEV compression ignition (CI)	X			
HEV (CI)	X		x	
PHEV spark ignition (SI)		x	x	x

The general formulation for final energy consumption (TTW) of a fleet with several powertrain technologies and vehicle ages (equivalent to standard) is:

$$EC = \sum_y \sum_m \left(NV_{m,y,z} \times M_{m,y,z} \times FI_{m,y,z} LHV_m \rho_m\right) + \sum_y \left(NV_{y,z,electric} \times M_{y,electric} \times FI_{y,z,electric} * 3.6\right) \quad (5.1)$$

Where EC stands for the final energy consumption of the fleet (MJ/year); $M_{x,y,z}$ (km/year) is the average annual distance driven per vehicle of category *y*, standard *z*, and fuel *m*, excluding electric miles; $N_{m,y,z}$ is the number of vehicles of category *y*, standard *z*, and fuel *m*; $FI_{y,z,m}$ is the average fuel intensity of the vehicle (l/km or kWh/km); and LHV_m is the lower heating value of the liquid/gas fuel *m*.

The general model for emission, E_x, where *x* stands for each pollutant, NO_x, $PM_{2.5}$ or NH_3 is:

$$E_x = \sum_m \sum_y \sum_z \left(NV_{m,y,z} \times M_{m,y,z} \times EF_{x,m,y,z}\right) \quad (5.2)$$

Where, $EF_{x,y,z}$ (g/km), is the specific emission factor of pollutant *x*, for vehicle category *y*, emission standard *z*, and liquid fuel *m*; E_x is the emissions of pollutant *x*.

Ammonia is a colorless gas present in the atmosphere, which reacts with acid gases (H_2SO_4, HNO_3, etc.) to produce atmospheric ammonium aerosol salts and particles such as ammonium sulfate ($[NH_4]_2SO_4$), ammonium bisulfate (NH_4HSO_4), ammonium nitrate (NH_4NO_3), and ammonium chloride (NH_4Cl). Knowledge of NH_3 tailpipe emissions is therefore important. To convert NH_3 tailpipe emissions into $PM_{2.5}$ equivalent, the following chemical reactions will be considered:

$$2NH_{3(gas)} + H_2SO_4 \leftrightarrow (NH_4)_2SO_{4(particle)}$$

$$NH_{3(gas)} + HNO_{3(gas)} \leftrightarrow NH_4NO_{3(particle)} \qquad (5.3)$$

$$NH_{3(gas)} + HCl_{(gas)} \leftrightarrow NH_4Cl_{(particle)}$$

The mass-to-mass ratio of particle to NH_3 for these equations is 132.14/34.062, 80.043/17.031 and 53.491/17.031. An average factor of 3.91 is assumed for the $PM_{2.5}$ equivalent. Fuel consumption and emissions for new technologies will be compared with the baseline scenario to analyze their future insertion.

Our approach is based on real data from conventional bus fuel intensity, to which we then applied final to useful energy efficiencies to get our exploratory flex-fuel engine PHEV final ethanol and electricity consumption. This is a simplified approach and was "cross-checked" against the ADVISOR microsimulation model [127]–[129] for ICEV, HEV, and PHEV over a specific driving cycle (driving schedule). Figure 5. 1 presents the procedure schematic.

Table 5. 2 Matrix for WTT CO_2-eq. emission factors.

Energy Source	Min	Max
Diesel [130](g CO_{2eq}/MJ)	17.5 (621.1*)	23.5 (834.0*)
Gasoline [130] (g CO_{2eq}/MJ)	19.7 (654.4*)	26.3 (873.4*)
electricity (10% thermal based) g/kWh**	34.1 (natural gas)	102.4 (coal)
electricity (58% thermal based) g/kWh**	198.0 (natural gas)	593.9 (coal)
ethanol from banana waste [126] (g/MJ)	23.6 (540.2*)	23.6 (540.2*)

*g/L; using 794 kg/m^3 and LHV 28.8 MJ/kg for ethanol; 0.845 kg/L, with LHV of 42 MJ/kg for diesel; 0.755 kg/L and LHV of 44 MJ/kg for gasoline.

**10% and 58% thermal-based electricity were selected based on Ecuadorian conditions [118], [131].

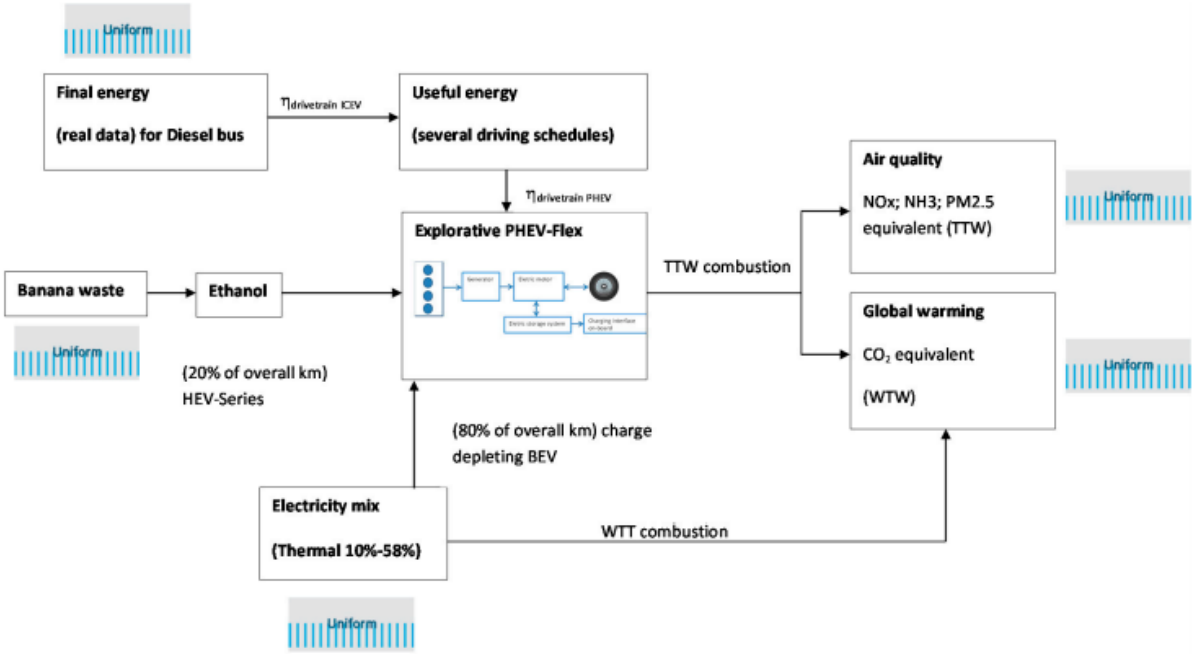

Figure 5. 1 Simplified model scheme for tank-to-wheels (TTW) air quality indicators and global warming impact well-to-wheels (WTW) evaluation/graphical abstract.

As a "cross-check" of the final to useful energy conversion efficiencies, the driving cycle was the World Harmonized Heavy Duty cycle (WHDC), with 40 km/h average speed, 20 km distance, and 12 stop-&-go situations.

5.2.1. Reference Scenario-100% ICEV Diesel Fleet

The inventory of the number of bus vehicles in Ecuador and the fuel used was obtained from the Transportation Statistics Yearbook published by the Instituto Nacional de Estadísticas y Censos (INEC) [31], The fuel consumption were estimated using a bottom-up approach and following the guidelines of the tier 2 methodology of the European Environmental Agency (EEA) (previous CORINAIR) [132].

The average annual distance was calculated using a 2016 database provided by the Ecuador Municipal Transit Authority of Guayaquil. The database presents odometer readings from several buses during inspection. Most buses have more than one inspection during the year; thus, they have two mileage records. Hence, subtracting two mileages recorded at different times divided by the time between both records gives us the average daily distance traveled.

The overall efficiency is a product of the powertrain components' efficiency. The efficiency of the diesel bus engine (ICEV buses, Figure 5. 2) was assumed to be 38–47% [133], [134], including heat losses, friction, pumping work, and auxiliaries like lights, power steering, brake

booster, and a sound system, etc. The transmission efficiency is typically 80–90% [135]. Therefore, we assume 26.6–37.6% for the diesel driveline (TTW efficiency) diesel density is 0.845 kg/L, with an LHV of 42 MJ/kg [81]. These values are to be "cross-checked" using microsimulation software. Diesel engine technology will be referred to as compression ignition (CI) and spark ignition (SI) engine technology.

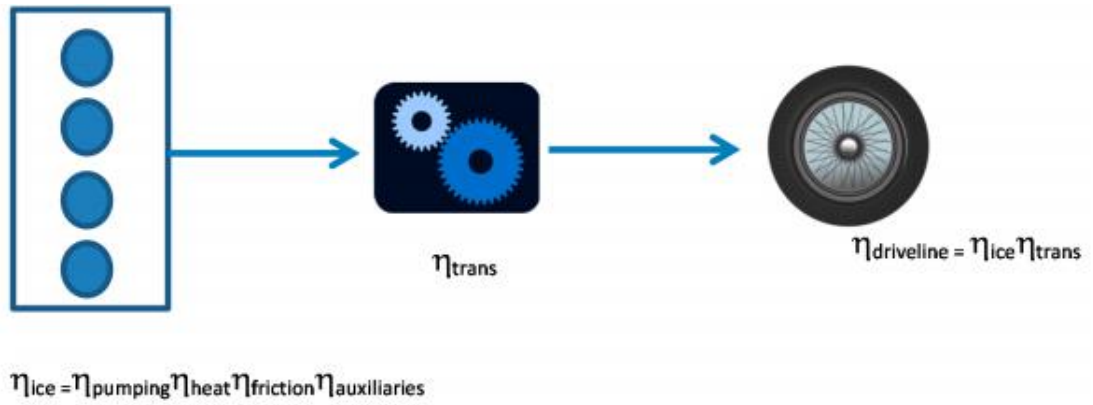

Figure 5. 2 Conventional compression ignition/spark ignition powertrain

5.2.2 Hypothetical Scenarios HEV with ED95

It is already possible to run a CI engine with ethanol using a higher compression ratio and additives. This HEV-ED95 runs on 95% ethanol and 5% additives to help self-ignition. Scania commercializes a bus with this technology. The OmniLink ethanol hybrid bus is based on a series of hybrid technologies (S-HEV) (Figure 5. 3 and Figure 5. 3).

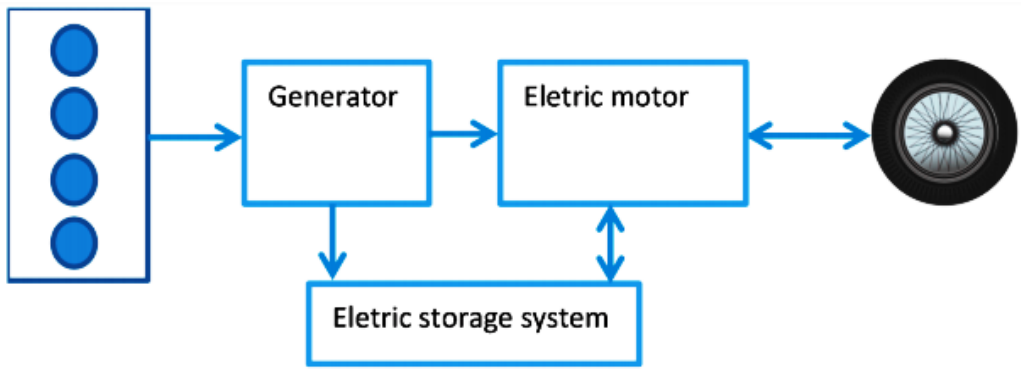

Figure 5. 3 HEV-ED95 hybrid powertrain

Table 5. 3 Technical specifications of Scania Omnilink HEV-ED95 bus

Electric Motor	Voith TFM Max 150 kW / max 2750 Nm
Energy Storage System	Maxwell supercapacitor 0.4 kWh
Passenger Capacity	114

Curb weight	16 tonnes
Engine	Max. output 270 hp (198 kW) Max. torque between 1250 Nm No. of cylinders 6 Displacement 9 dm3 Compression ratio 28:1

For real measurements, we only found a VTT Technical Research Centre of Finland Ltd. study where an HEV-ED95 bus was measured using a chassis dynamometer roller bench, recording 16.5 MJ/km for empty bus fuel consumption, 5.58 g/km for NO_x, and 0.037 g/km for PM [136]. This data is available through the LIPASTO traffic emissions database. Regarding TTW efficiency, according to this report, the real measured fuel consumption was 0.73 l/km.

5.2.3 Hypothetical Scenarios PHEV with E20 and E100

Passenger car manufacturers are already addressing the flex-fuel SI engine in a hybrid powertrain, e.g., Toyota presented an initial design of the first hybrid flexible-fuel vehicle (Hybrid FFV) in Sao Paulo, Brazil. The efficiency gains could be up to 6% with ethanol blends [137]. However, this technology is not yet available on buses. This is the reason our study is exploratory, and we do not have experimental data on this new hypothetical bus type. Due to ethanol's specific features, it cannot be used in standard diesel compression engines. Currently, the only engines suitable for ED95 are manufactured by Scania. Additionally, since the PHEV powertrain has several energy management strategies, the flex emission data must be estimated based on emission factors. Our reasoning is therefore supported by efficiency logic and available literature data.

Usually, the efficiency of a diesel engine is 30% higher than η_{ice} of SI engines [138]. Hence the TTW efficiency for the hypothetical flex-fuel driveline is ((26.6/1.3) * 1.06) – ((37.6/1.3) * 1.06); or 21.7-30.7%. The driveline efficiency ratio between SI and CI is near the 85% found in the literature [139].

The lower heating value of the blend is calculated by Equation 5.4, where "blend" stands for ethanol %, e.g., E20 would be 20%:

$$LHV_{blend} = (1 - blend/100) * LHV_{gasoline} + blend/100 * LHV_{ethanol} \quad (5.4)$$

The density follows the same procedure. Ethanol density is 794 kg/m^3 and LHV 28.8 MJ/kg [81]. Gasoline 755 kg/m^3 and 44 MJ/kg [81]. The effect ethanol blends have on CO_2 emissions is direct from combustion mass balance (assuming C_8H_{18} for gasoline); the equation is:

For the effect of ethanol blend on NO_x, NH_3, and $PM_{2.5}$ criteria, pollutant emissions were reviewed in the literature. Due to the lack of data for buses, the effect was taken from experimental

$$ECO_2\ [kg/kgfuel] = (1 - blend/100) \times 3.0877 + blend/100 \times 1.9130 = 0.0117 * blend + 3.0877 \quad (5.5)$$

studies on light-duty vehicles by Suarez-Bertoa et al., which indicate absolute emission factors for E5, E10, E15, E75, and E85 [53]. Hubbard, Anderson, and Wallington revealed relative differences between E0 and E10, E20, E30, E40, E55, and E80 [54]. Additionally, Table 5. 4 [140] includes several studies for finding E10 and E20 impacts on NO_x and $PM_{2.5}$ and shows an average impact of −11.8% and −17.1% for NO_x; and −6% and −36% for PM, respectively. From Table 5. 4, we assume E80 impacts to be the same as for E100, or −49% for NO_x and 153% for NH_3. In our study, we assume the correction factors, stated in Table 5. 5. The tendency for NH_3 to increase with ethanol blends and NO_x and $PM_{2.5}$ decrease is noteworthy.

Table 5. 4 Emission factors found in the literature for flex-fuel vehicles operation [53], [54].

	[53]			[54]		
	NO_x (mg/km) WLTP cy-cle	NH_3 (mg/km) WLTP cycle	$PM_{2.5}$ (mg/km) WLTP Cycle	NO_x (g/mile) FTP cycle	NH_3 (g/mile) FTP Cycle	$PM_{2.5}$ (g/mile) FTP cycle
E0	NA	NA	NA	0.0544	0.0353	NA
E5	62	6	NA	NA	NA	NA
E10	42	16	NA	0.0472	0.0408	NA
E15	51	14	NA	NA	NA	NA
E20	NA	NA	NA	0.0316	0.0638	NA
E30	NA	NA	NA	0.0245	0.0642	NA
E40	NA	NA	NA	0.0209	0.0705	NA
E55	NA	NA	NA	0.0293	0.0968	NA
E80	NA	NA	NA	0.0261	0.0896	NA

E85	19	26	NA	NA	NA	NA

Table 5. 5 NO_x, NH_3, and $PM_{2.5}$ assumed correction factors.

	NO_x	NH_3	$PM_{2.5}$
E10	-12%	+10 %	-6%
E20	-17%	+52 %	-36%
E80	-49%	+153 %	-36%
E100	-49%	+153 %	-36%

Criteria pollutants were obtained using Table 5. 5 correction factors applied to tier 2 emission factors for SI technology buses.

The new plug-in hybrid bus technology was based on the plug-in 7900 Electric Hybrid bus from Volvo (Table 5. 6 and Figure 5. 4). A SI engine replaced the internal combustion engine with the same rated power. Efficiency reasoning is used. In the literature [141]–[144]. The TTW efficiency varies, but typically, we may find 70–85% for a pure electric vehicle, BEV, depending on the driving cycle.

Table 5. 6 Technical specifications of plug-in 7900 Electric Hybrid bus from Volvo (PHEV).

Electric Motor	Max 160 kW / max 1200 Nm
Energy Storage System	Lithium-ion battery 76 kWh
Transmission	Volvo 2-speed automatic transmission
Charging System	Opportunity charging - conductive charging system - roof mounted. Fully automatic, fast charging. Fast charging time: up to six minutes.
Passenger Capacity	83
Curb weight	12 t
Engine Volvo D5K240 EU6	Max. output 240 hp (177 kW) Max. power at 2200 rpm Max. torque between 1200–1600 rpm 918 Nm No. of cylinders 4 Bore 110 mm Stroke 135 mm Displacement 5.1 dm3 Compression ratio 17.5:1 Oil-change volume, including oil filters, approx. 18.7 l

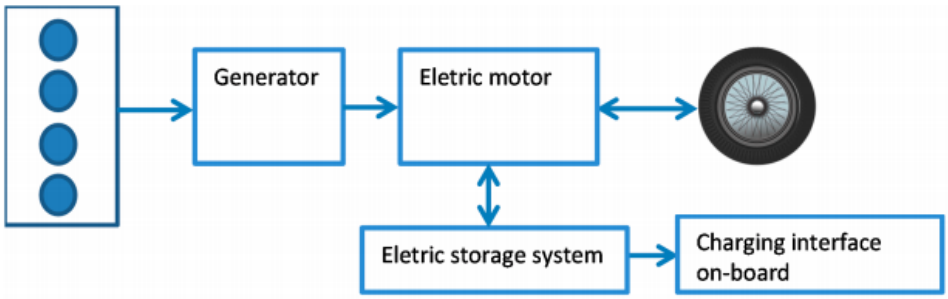

Figure 5. 4 PHEV flex fuel powertrain

According to the all-electric efficiency range assumed, 80% of the mileage is electric, and 20% flex-fuel, was assumed to have an efficiency of 70–85% for all-electric and 21.7–30.7% for flex-fuel. The 80% of the electric mileage is justified according to Renault Group [145]. We assume a charge-depleting energy management strategy, and 80% of km is like a pure electric vehicle, depleting the battery. At the same time, the internal combustion engine is switched-off. The remaining km are like a hybrid internal combustion engine vehicle. The range is necessary because we want to cover most possible real driving situations and not just a specific driving cycle. The overall inputs to Equations 5.1 and 5.2, such as fuel intensity and emissions factors, are given in Table 5. 7.

The uncertainty sources were identified: fuel consumption/drivetrain efficiencies and criteria emission factors. A maximum and minimum range in inputs were reflected in the model outcomes. CO_2 emissions as a function of fuel consumption had the same uncertainty levels. Regarding NH_3, the minimum $PM_{2.5}$ equivalency factor was 3.16, and the maximum was 4.70. This gave us a $PM_{2.5}$ equivalent range. For NO_x and $PM_{2.5}$, the literature reports usual uncertainties of 16% on average [146] without fuel correction and using the tier 3 approach from EEA. A tier 2 approach such as ours should have higher levels of uncertainty. Nevertheless, we stick to 16% to have a range of emissions. Uncertainty in the model input parameters is considered and reflected in the results by a uniform distribution (minimum and maximum range).

Table 5. 7 Inputs for fuel consumption and emissions calculations.

Technology y	Standard Z	Fuel m	M Annual mileage (km/y)	N Number of buses	FI l/km or kWh/km*	$EFNO_x$** (g/km)	$EFPM_{2.5}$ (g/km)	$EFNH_3$ (g/km)
conventional ICEV (compression ignition)	Euro III	diesel	78,767	23,056	FI_{diesel} =0.4-0.56 [147] 0.36 tier 2 0.46 VTT Capturing variations with the driving cycle	9.38	0.207	0.0029
conventional ICEV (compression ignition)	Euro V	diesel	78,767	23,056	FI_{diesel}	3.09	0.0462	0.011
HEV compression ignition	-	diesel	78,767	23,056	0.3-0.42 (less 25% than FIDiesel [148]	0.98 [149]	0.0231 less 50% than convencional ICEV [150]	0.0046 [149]
HEV compression ignition	Euro V, EEV	E95	78,767	23,056	0.73 [136]	5.58[136]	0.037[136]	NA***

ICEV (spark ignition) reference for applying [132](Table 5. 1)	-	-	-	-	-	2.5 (spark ignition EEV urban bus)[132]	0.005 (spark ignition EEV urban bus)	0.0019 (spark ignition heavy-duty vehicle)
PHEV	-	electricity	80% of 78,767	23,056	$\frac{FI_{diesel} * \rho_{diesel} * LHV_{diesel} * \eta_{driveline}\ Diesel}{3.6 * \eta_{driveline} Electric}$	0	0	0
PHEV	-	E20	20% of 78,767	23,056	$FI_{diesel} * \frac{\rho_{diesel} * LHV_{diesel} * \eta_{driveline}\ Diesel}{\rho E20 * LHVE20 * \eta_{driveline}\ E20}$	2.0	0.003	0.0029
PHEV	-	E100	20% of 78,767	23,056	$FI_{diesel} * \frac{\rho_{diesel} * LHV_{diesel} * \eta_{driveline}\ Diesel}{\rho E100 * LHVE100 * \eta_{driveline}\ E100}$	1.3	0.003	0.0029

* When electricity
**NO_2 equivalent
*** 10 ppm limit in Euro VI, equivalent to a minimum of 0.05 g/km assuming the stoichiometric combustion ratio of 9, a lambda of 18, typical for idle, and exhaust molar mass of 29 kg/kmol

5.3 Results

Runs of the ADVISOR microsimulation model [127]–[129] for one specific driving cycle with 12 stops were crosschecked with reviewed literature data on powertrain component efficiency (Figure 5. 5). The fuel converter (ICE) efficiency of a conventional diesel bus, an HEV and a PHEV (with charge depleting management strategy) buses are depicted, as well as their powertrain component efficiencies.

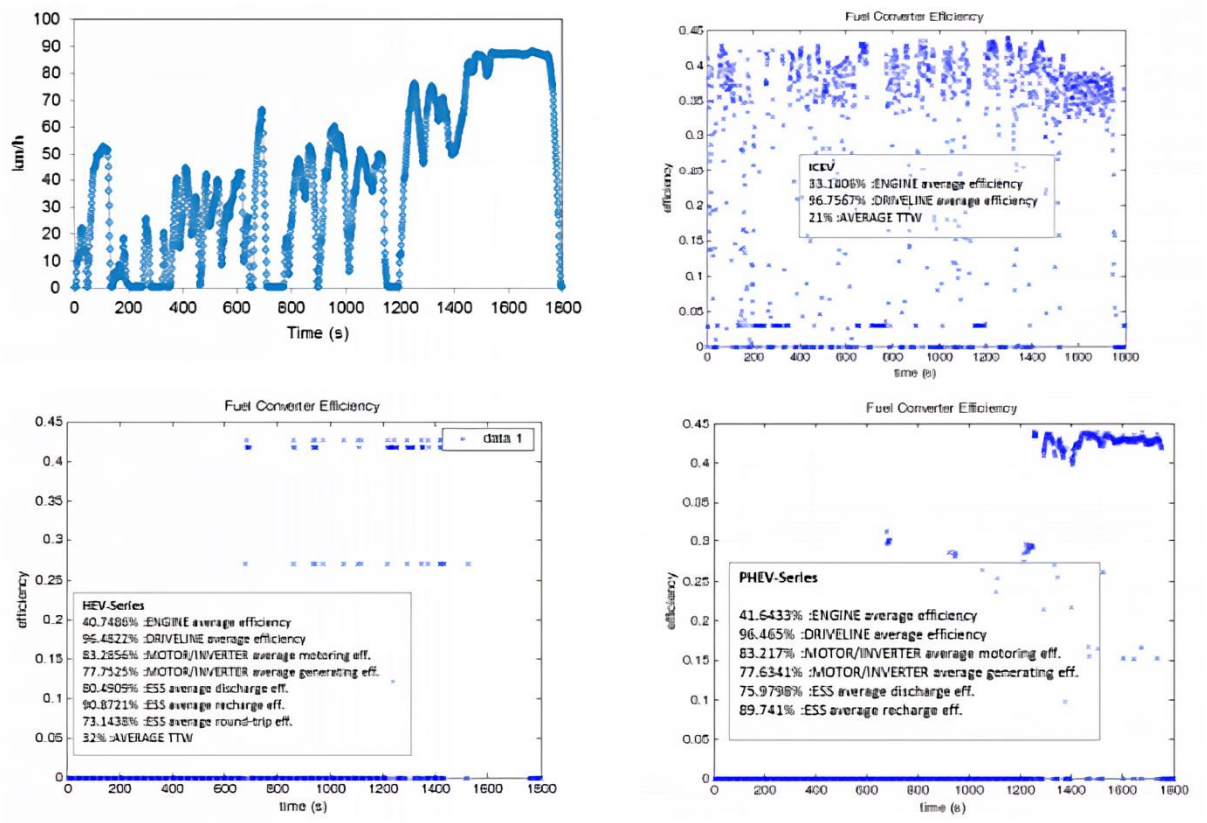

Figure 5. 5 ADVISOR model efficiencies for a specific driving cycle and PHEV energy management (average speed 40 km/h, distance 20 km, 12 stop-&-go situations). "Crosscheck" of efficiency assumptions

Figure 5. 5 shows that the efficiencies fall in the ranges reviewed, so we stick with our simplified approach for analyzing WTW. Considering the macro approach of fuel intensity and powertrain efficiency ratio seems suitable and intends to cover as many driving situations as possible. Considering this macro approach, the final energy consumption is depicted in Table 5. 8 for the reference and alternative scenarios.

Table 5. 8 Final energy consumption by source and per year, with uncertainty

	Electricity (GWh)	Diesel (ML*)	Gasoline (ML)	Ethanol (ML)
ICEVdiesel-Reference Euro III bus fleet	-	835 (654–1,017)	-	-
HEV_{diesel}	-	626 (490–763)	-	-
HEV_{ED95}	-			1325.72
$PHEV_{flexE20}$	2,215 (1,642–4,385)	-	164 (105–326)	41 (26–82)
$PHEV_{flexE100}$	2,215 (1,624–4,385)	-	-	281 (179–557)

*ML = million liters

So, if Ecuador decides to hybridize the bus fleet on ED_{95}, it will have to produce roughly 1,326 million liters of ethanol a year to satisfy the final energy demand. This means that the potential ethanol production from sugarcane (80 million liters a year) or banana industry waste (40 million liters a year) will not be enough. If the option is to move forward with a $PHEV_{flex}$ fleet, the ethanol demand is much lower, 41–281 million liters, which could not yet be met by banana industry waste. Ethanol production through the sugarcane industry could meet around 42% of the maximum ethanol production required for this case. The sugarcane industry must, in any case, provide most of the needed fuel.

Of course, the PHEV scenarios would be better in terms of air quality because it was assumed that 80% of the mileage is all-electric, with zero local emissions. Nevertheless, introducing ethanol could increase NH_3 particle precursors and if we look at the equivalent $PM_{2.5}$ in Table 5. 9, the hybrid ED_{95} fleet could be the worst-case scenario. The higher NH_3 emissions in HEV_{diesel} are due to the SCR NO_x exhaust aftertreatment system and the reduced $PM_{2.5}$ to the particle filters.

Table 5. 9 Criteria pollutants for the Ecuadorian bus fleet in t/year, with uncertainty.

	NO_2	$PM_{2.5}$	NH_3	$PM_{2.5}$ Equivalent
ICEV-Reference	17,034 (14,309–19,760)	375 (318–434)	5.3	396 (338–455)
HEV diesel	1,779 (1,495–2,065)	42 (35–49)	83.5	368 (364–376)
HEV_{ED95}	10,133 (8,512–11,755)	67 (78–95)	95.3	439 (429–450)
$PHEV_{E20}$	753 (633–874)	1.2 (1–1.3)	1.0	5.3 (5.1–5.4)
$PHEV_{E100}$	463 (389–537)	1.2 (1–1.3)	1.7	8.0 (7.8–8.2)

The TTW CO_2 emissions are part of a future study on a WTW approach and are depicted in Figure 5. 6. Biogenic CO_2 emissions of ethanol were set out in this analysis. Notably, there is considerable mitigation of TTW CO_2 emissions, around 78–80%, when conventional fleet buses are replaced with plug-in hybrid buses. Interestingly, the HEV_{ED95} has higher TTW CO_2 emissions due to the higher fuel consumption phenomena that overlap the lower CO_2 formation per liter of ethanol burned compared to diesel fuel (1.5 $kgCO_2$/L ethanol versus 2.7 $kgCO_2$/L diesel). The diesel-ethanol HEV-$_{ED95}$ technology energy consumption and CO_2 emissions were derived from the LIPASTO database on-road measurements and have no reported uncertainty.

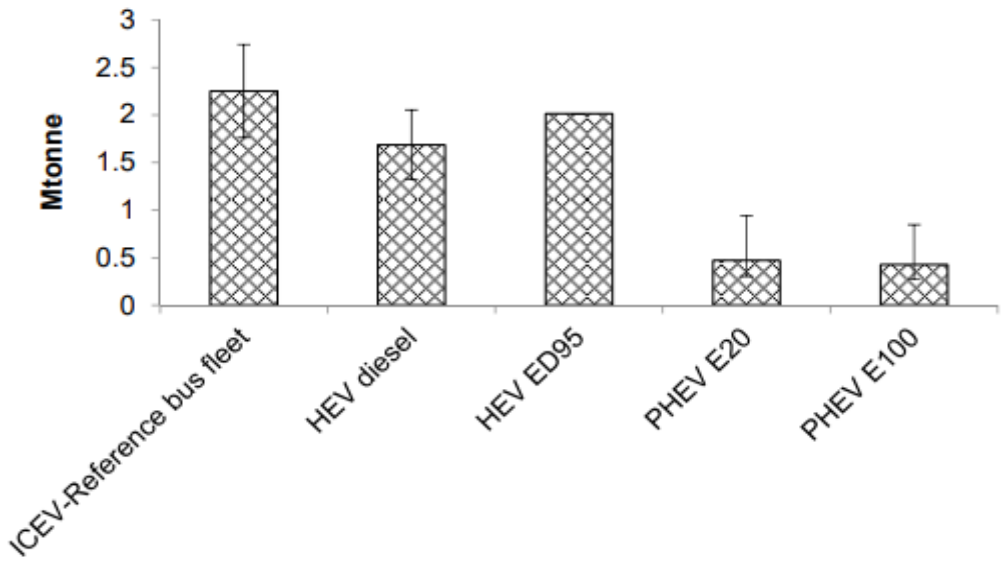

Figure 5. 6 TTW CO_2 emissions for the Ecuadorian bus fleet in millions t/year, with uncertainty (range based with uniform distribution).

Additionally, observing the WTW values in Figure 5. 7, electrification of the bus fleet has more positive impacts on air quality and global warming impact than moving to a bioeconomy bus fleet system. However, the flexibility of supplying a PHEV with three possible energy sources instead of just electricity is noteworthy. Finally, it is important to stress that biogenic CO_2 emissions of ethanol were also counted in this analysis.

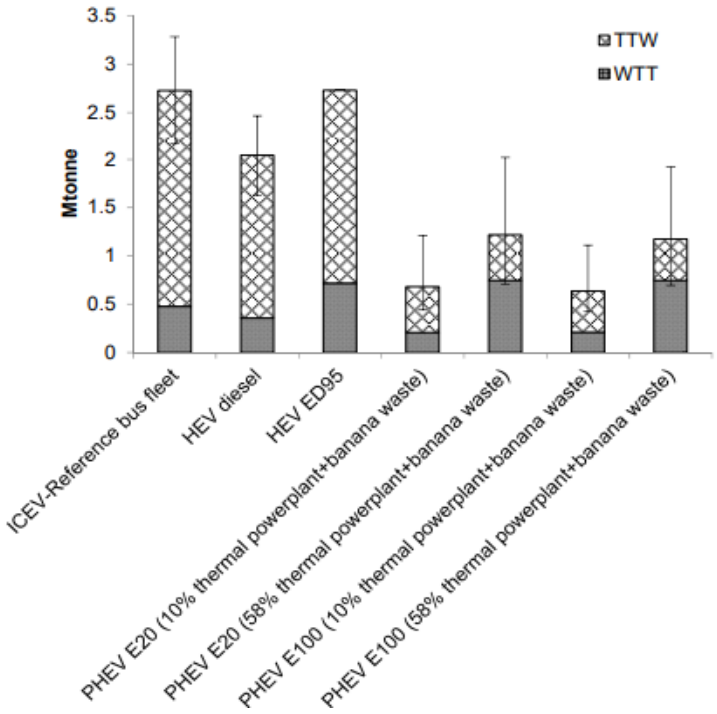

Figure 5. 7 WTW CO_2 emissions for Ecuadorian bus fleet in millions tonne/year, with uncertainty (range based with uniform distribution).

5.4 Discussion

These are preliminary results due to the limitations/constraints of the work. One main limitation is the lack of hybrid CI diesel and hybrid ED95 bus data in the EEA emission inventory guidebook [132]; therefore, the bus technologies are not compared using the same database. The ethanol effect on $PM_{2.5}$ in flex-fuel engines is also barely reported in the literature and should be explored experimentally. NH_3 emissions need more experimental data because they are particle precursors and are already limited in new European and American regulations to 10 ppm in exhaust gases. These values are barely seen in the reviewed literature. However, the uncertainty in the results could partially reflect these weaknesses and be taken as a preliminary result indicating whether Ecuador should pursue a bioeconomy.

In this context, the discussion on food vs. biofuels will be intensified. However, in a biorefinery context, Ecuador may continue producing sugar and its derivatives and producing ethanol through surplus bagasse. For example, Cavalett et al. [80] and Corrêa do Lago et al. [83] demonstrate the positive sugarcane conditions for the development of second-generation ethanol (non-food competitive), at least in the Brazilian context. Again, the flexibility of a vehicle running on three possible fuels is highlighted. Moving heavily to renewables in the future and having only 10% of electricity provided by thermal power plants (coal or natural gas) should be addressed.

5.5 Conclusions

As an explorative study, this paper shows some novel concepts regarding a new possible PHEV bus powertrain and a conversion factor for NH_3 emissions to $PM_{2.5}$ equivalent emissions. The simplified model using a range of fuel intensities and typical final to useful energy conversion efficiencies was crosschecked with a microsimulation model that allows the variation of efficiency data at various speeds and acceleration/deceleration rates.

The metrics calculated in this research were final energy consumption (by source), air quality-related pollutants, NO_x (as NO_2 equivalent), NH_3 and $PM_{2.5}$ equivalent, and 100-year global warming potential (as CO_{2eq}).

Suppose the diesel energy source is to be kept. In that case, hybrid technology is a good option for a replacement, reducing fuel consumption and TTW CO_2 emissions by 25% compared to the conventional ICEV technology. Still, despite the particle filters, it only reduces 7% of the $PM_{2.5}$ equivalent emissions.

Suppose an ethanol energy source is considered the future, and energy supply flexibility to the bus is a priority. In that case, plug-in hybrid flex-fuel vehicles are the best option to reduce emissions. However, Ecuador still needs more investment in ethanol production. The current capacity (considering ethanol production through sugarcane and banana waste) will not be enough to satisfy the demand, and it will be imperative to boost ethanol production through larger extensions of cultivated areas and sugarcane biorefineries. Increasing ethanol production through agricultural and forestry residues will also be essential. These new technologies will provide a 55–77% CO_{2eq} reduction in a heavy renewables penetration scenario, even if coal is used in the thermal powerplant. A future study on sugarcane biorefinery sustainability in Ecuador will bring the carbon footprint (well-to-wheels) benefits of such a PHEV flex-fuel bus system to the discussion.

6. The Environmental Profile of Ethanol Derived from Sugarcane in Ecuador: A Life Cycle Assessment Including the Effect of Cogeneration of Electricity in a Sugar Industrial Complex

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Abstract

The present study compiles a life cycle inventory for Ecuadorian sugarcane-derived ethanol production to quantify its environmental performance and identify the life cycle stages that cause major impacts. The scope of this study encompasses a cradle-to-gate analysis that includes agriculture, milling, distillation, and the co-generation of electricity. This assessment is modeled using the OpenLCA v1.10.3 software. Two functional units (FU) were established in this study: "1 tonne of sugarcane at the farm gate" for the agricultural stage and "1 L of ethanol at the plant gate". A hybrid attributional and consequential life cycle analysis (LCA) approach has been followed. Economic allocation (EA) and system expansion (SE) were used to consider co-products in the milling and co-generation of electricity stages. The co-generation stage is analyzed in three different scenarios: (i) average mix displacement scenario, where the surplus electricity produced in the co-generation stage is displaced; (ii) marginal technology displacement scenario, where the marginal surplus electricity is displaced from the mix and (iii) no displacement scenario. The global warming potential (GWP) impact at the farm gate level was reported as 53.6 kg of carbon dioxide equivalent (kg. $CO_{2eq.}$) per tonne of sugarcane produced. The two main contributors of the agricultural stage correspond to N_2O lixiviation and volatilization, with 34%, followed by the diesel used in agricultural machinery with 24%. The GWP for 1 L of ethanol produced was reported as 0.60 kg $CO_{2eq.}$ based on the average mix displacement scenario. No displacement scenario has a GWP impact of 0.84 kg CO_2/liter of ethanol The distillation stage has the highest contribution to GWP impact, with approximately 61%, followed by the agricultural stage, with 47%. The co-generation stage reports a contribution of −8.4% due to the displacement of surplus electricity. The scenarios where the system expansion method is applied have a lower GWP impact than those where no surplus electricity is displaced. Regarding terrestrial acidification potential impact, 0.01528 kg of $SO_{2eq.}$ was reported at the ethanol production level, especially due to the nitrogen and phosphorous content in the vinasse produced from the distillation process. The marine eutrophication impact for 1 L of ethanol produced was 0.00381 kg of $N_{eq.}$ due to the content of nitrogen contained in the vinasse and the use of nitrogenous fertilizers in the agricultural stage. Finally, sustainable and less polluting processes should be sought to create more eco-friendly Ecuadorian sugarcane and ethanol industries to reduce the environmental burdens. Companies should apply industrial symbiosis and circular economy strategies to produce lesser environmental loads within the ethanol

production chain. The sugarcane industrial sector should also promote surplus electricity production to gain credits.

Keywords: OpenLCA; system expansion; industrial symbiosis; bagasse; waste-to-energy; valorization; biofuel

6.1 Introduction

6.1.1 Worldwide Biofuels Context

There is rising awareness about the future mitigation of fossil resources [151]. There is a general scientific consensus that observed trends in global warming have been caused by the indiscriminate use of fossil fuels in human activities. The latter is threatening the global environment. For instance, more interest is beginning to be shown in the emergence of alternative sustainable energy sources [152].

Biofuels have been recognized as an alternative to reduce fossil fuel consumption and thus help decrease greenhouse gas (GHG) emissions [153]. In 2018, global biofuel production reached 153 billion liters, an increase of 7% compared to 2017 [154]. Biofuels account for approximately 3% of the global transportation sector [155]. The insertion of biofuels in worldwide transportation has been slowly dosed due to the potential risk of globally reducing food production by allocating more arable lands for energy crop production [156]–[159].

Although many countries have promoted and implemented biofuels to address energy security and a more environmentally friendly economy [160], [161], few scientists have suggested that biofuel development has been harmful to the environment, regardless of the country where it is produced [158]. The latter is justified because some crops can generate even more greenhouse gases than fossil fuels, depending on their production's feedstock and fuel processes [162]. Additionally, some emissions and environmental impacts are produced at other stages, as in the production of inputs used for crops and biofuels: pesticides, herbicides, and fertilizers for crop production; chemicals production for biofuel processing, and emissions produced from transport and distribution to the field and industrial plants for crops and biofuels processing [163]. On the other hand, it is also essential to consider the emissions that can be generated from land-use change, triggered by increased biofuel production. The main effects of land-use changes are that the carbon dioxide accumulated in its vegetation escapes into the atmosphere, altering the impact of global warming [164]. For instance, a more detailed analysis of the

environmental impacts of biofuels production is essential to have more solid evidence for policymakers to support biofuels development.

One of the main challenges regarding sustainability in the agricultural sector is to mitigate the dependence on non-renewable resources to reduce emissions [165], [166]. For instance, industrial symbiosis (IS) has gained strength lately in this sector. Several countries firmly apply industrial symbiosis due to its economic and environmental benefits. For example, nitrogen fertilizers are manufactured using non-renewable resources and are an essential outlet for fossil fuels [167]. Thus, industrial symbiosis enables these non-renewable inputs to be replaced through fertilizers sourced from organic waste such as vinasse and filter cake [168], [169]. Valorization of the lignin-rich stream from industrial-scale lignocellulosic ethanol [170], the aqueous phase reforming of glucose and xylose for hydrogen production [171], and the hydrogen production from sugar beet molasses through dark fermentation, photo-fermentation and gas upgrading [172] are other examples of industrial symbiosis in the sugar industry. Furthermore, agricultural sector companies have also been encouraged to cogenerate electricity by burning sugarcane bagasse in sugar industrial complexes [173], [174]. This approach allows companies to mitigate environmental impacts produced during the sugar production chain, and it also allows them to increase their product portfolios.

Biofuel production from agriculture or industrial wastes has been encouraged as an alternative renewable energy source. Bioethanol is the most common and worldwide developed biofuel, mainly in the American continent, which has a significant potential to replace gasoline as a vehicle fuel (E5 to E100) in light-duty vehicles or ED_{95} in heavy-duty vehicles (ED_{95} is a fuel grade containing up to 95% ethanol [96]. With light-duty vehicle electrification, it is still possible to use the ethanol in ED_{95} bus or goods transport and also SAF (Sustainable Aviation Fuel). The aviation sector also seeks biofuel penetration up to 50% in 2030 and 100% in 2050. The International Air Transportation Association (IATA), representing major global airlines, has committed to net-zero carbon emissions from global air transportation by 2050. The International Civil Aviation Organization (ICAO) under the CORSIA [175] scheme embraces ethanol as a possible feedstock sugarcane derived-ethanol, which is converted to drop-in fuel via dehydration, oligomerization, and hydrotreating. The agreed default core LCA value for sugarcane ethanol is 24.1 $gCO_{2eq.}/MJ$, while reference fossil jet fuel is 89 $gCO_{2eq.}/MJ$, accounting for transportation logistics and jet fuel burning in the airplane.

Traditionally, sugarcane has mainly been processed to obtain sugar for human consumption [174]. However, it has long been recognized as producing other products such as electricity, fuels, organic chemicals, and paper [176]. The recognition of sugarcane as a renewable energy source, biofuel, biomaterials, and food crops [177], [178] has produced a greater scientific interest in sugarcane products' life cycle environmental impacts.

Sugarcane biorefinery [179] for sugar, ethanol, heat, and electricity is the best configuration for circular economy and energy transition.

6.1.2 Life Cycle Assessment of Biofuels

The Life Cycle Assessment (LCA) is an environmental management tool to assess the burdens associated with a product or service during its entire life cycle [180]. The LCA has been broadly used to quantify the environmental burdens of different transportation biofuels to estimate the net effects of biofuel on several impact categories such as climate change, freshwater eutrophization, marine ecotoxicity, fossil resource scarcity, and water consumption [181]–[185]. Sydney et al. [182] analyzed the reduction in worldwide greenhouse gas emissions through cradle-to-grave life cycle assessments for corn, sugarcane, and beet ethanol, while Yan et al. [184] developed a comparative life cycle assessment analysis on ethanol produced from agave, corn, and sugarcane. Moreover, these assessments can be used to compare biofuels against conventional petroleum-derived fuels such as gasoline, diesel, and aviation fuels [186], [187]. Reviews of the environmental impacts of different biofuels are subject to significant biases associated with the methodology applied, making it difficult to compare the results rationally [188]. These biases derive from criteria modeling choices regarding system definition and boundaries, functional unit definition, reference systems, and co-product allocation methods [189]–[195]. Even so, some LCA studies differ in selecting life cycle impact assessment methods [196]–[201]. For instance, Elsayed et al. [194] developed a Well-to-Tank (WTT) LCA of different fuel options (gasoline, diesel, crude naphtha, compressed natural gas, methanol, Fischer-Tropsch naphtha, Fischer-Tropsch diesel, gaseous hydrogen, liquid hydrogen, and ethanol) through a system expansion and defined 1 Megajoule as the functional unit. On the other hand, Wallace et al. [190] and Macedo et al. [195] performed a Well-to-Wheels (WTW) LCA of ethanol fuel using a system expansion. Still, they differ in selecting the functional unit (1 km and 1 tonne of feedstock, respectively).

Raw Material and Conversion Technology Differences in Biofuels Reviews

Biofuels are classified into three groups: first-generation (1G), which are derived from edible plants grown; second-generation (2G), which are produced from non-edible crops; and third-

generation (3G), which are produced from algae and other microorganisms [202], depending on the raw material and the conversion technology [203]. 4G biofuel can also be considered if involving genetic engineering. Despite being an excellent substitute for gasoline, sugarcane and maize, used as raw materials to produce ethanol, constitute between 40% and 70% of the ethanol production costs [204], [205]. Moreover, first-generation (1G) ethanol production represents an ethical problem due to competition in land food and being water-intensive [206]–[208]. Nevertheless, many ethanol LCA studies focus on 1G bioethanol [93], [196], [198], [209]–[211]. On the other hand, cellulosic technology has been developed to convert 2G ethanol from lignocellulose biomass rather than sugar or starch [212]. Thus, the ethical conflict between food competition and energy demand is somehow reduced. However, one of the main reasons this conversion technology does not contribute worldwide in a considerable manner is the high production cost [213]. Some LCA studies of 2G bioethanol as a vehicle fuel have been conducted using bagasse, molasses, corn stover, and switchgrass as raw materials [196], [207], [214]–[219].

6.1.3. Biofuels in Ecuador

Ecuador possesses an abundant biomass potential from crops, including their residues and livestock activities residues from poultry, swine, and cattle [220]. Several conversion technologies can convert this biomass into biofuels or other energy carriers. Regarding biodiesel fuel, the Ecuadorian government began producing this biofuel from African palm in 2005. Concerning bioethanol fuel, its production started in 2010 with Ecopais gasoline.

6.1.3.1. Bioethanol in Ecuador

In Ecuador, ethanol comes basically from the sugarcane industry [37]. The Ecopaís Pilot Program (E5 = 5%v/v ethanol content in gasoline by volume type rated above 85 octane) started in Guayaquil and Durán. Initially, the government aimed to increase the ethanol blend with gasoline from 5% to 10% by 2016, focusing on the sugarcane expansion in coastal cities [221]. However, 400 million liters of ethanol are needed annually to reach this target, and the area of sugarcane crops should be extended by 500 km^2. It must be highlighted that around 79% of the industrial sugarcane crops are currently widespread in the Guayas Province [220]. The EcoPais fuel is sold in approximately 58% of the national territory [222]. This accomplishment was possible due to the expansion of the agricultural frontier and the investment of sugar mills to construct distillation plants for energy purposes. The three prominent sugar companies that produce most Ecuadorian ethanol are Valdez, San Carlos, and Coazucar.

6.1.4 Life Cycle Assessment of Energy Systems in Ecuador

Several LCA studies have been developed and applied to Ecuador's energy, transportation, and materials [37], [126], [230], [131], [223]–[229]. Ramirez et al. [131] analyzed the environmental sustainability of current (from 2012 to 2018) and forecasted electricity generation and supply scenarios using a life cycle approach. Briones et al. [224] presented a complete life cycle environmental performance of two hydropower schemes in Ecuador regarding electricity LCA studies. Moreover, Briones et al.[223], determined the net environmental performance of hydropower through a methodological approach that combines and balances two well-known environmental-ecological assessments: life cycle (LCA) and ecosystem services assessment (ESA). Ramirez et al. [229] examined the potential environmental impact of fossil-based electricity generation technologies used in Ecuador through ISO standards and CML 2000 methodology. Muñoz Mayorga et al. [230] developed a comparative life cycle assessment of electricity produced from jatropha oil (JO) in the Floreana Islands under three different systems. The analyzed systems include a blended system (BS) with 20% JO and 80% diesel, a reference system consisting of 100% diesel, and a jatropha system (JS) made up of JO. Parra et al. [228] explored the electricity produced in Galapagos from refined palm oil (RPO) produced in continental Ecuador and local waste cooking oil (WCO) using a comparative life cycle assessment methodological framework. Compared to refined palm oil, the results show better environmental performance in all the impact categories for the electricity produced from waste cooking oil. Ramirez et al. [226] quantified the change in the carbon footprint of the household cooking system from the current system based on liquefied petroleum gas to the proposed system based on electricity, using the LCA methodology.

Few LCA studies have focused on the environmental impacts of Ecuador's biofuel production, providing little knowledge and guidance for decision-makers in the country's energy sector [36], [37], [126]. Banana industry wastes have been explored as another potential source of ethanol in Ecuador [36], [126]. These studies claim that Ecuador can produce an additional 118–266 L of ethanol per hectare yearly from this feedstock. The latter represents an extra 40 million liters of ethanol per year. Noteworthy is that approximately 150,000 hectares are destined for banana production in Ecuador. On the other hand, Chiriboga et al. [37] determined the Energy Return on Investment (EROI) for bioethanol and biodiesel, including three raw materials for ethanol (sugarcane, corn, and forest residues) and four for biodiesel (African palm, pinion, bovine fat, and swine fat). The authors also developed an LCA for the mentioned biofuels. Despite these latter three LCA studies, the environmental profile of sugarcane-derived ethanol

has not been studied with a life cycle perspective. Regarding fossil gasoline and according to [231], [232], the GHG emissions for refinery activities were 5.46 $gCO_{2eq.}/MJ$.

From a life cycle perspective, there is currently no way to assess the environmental impact of using ethanol as an energy vector in Ecuadorian road transportation. There are also few studies on the environmental profile of sugarcane, the primary feedstock for producing ethanol in Ecuador.

The present study compiles a real-life cycle inventory for Ecuadorian sugarcane and sugarcane-derived ethanol production to quantify its environmental performance. This work considers the life cycle stages for 1G ethanol production: (i) agricultural, (ii) milling, (iii) distillation, and (iv) electricity co-generation stages to identify the critical processes that cause the major impacts. This study also aims to analyze the effect of electricity co-generation produced in the sugar industry complex on the environmental profile of ethanol.

6.2. Materials and Methods

The International Organisation for Standardisation (ISO) provides the LCA standards through the ISO 14040 and 14044 [233], [234]. LCA methodology consists of four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation.

6.2.1 Goal and Scope Definition

This study evaluates the environmental performance of sugarcane-derived ethanol production based on Ecuadorian conditions. The life cycle stages considered for this analysis are related to the agricultural, milling, distillation, and co-generation stages (Figure 6. 1). The production pathway of this study produces ethanol from sugarcane juice mixed with molasses obtained within the milling stage. This pathway produces sugar and vinasse through the milling and distillation stages. The inventory was gathered from a real Ecuadorian sugar mill company and an alcohol distillation plant. The national electricity mix is composed of 92% of hydropower generation and 7% of thermal power generation, with a $CO_{2eq.}$ intensity of 0.0115 kg $CO_{2eq.}/kWh$ and 3.3 kg $CO_{2eq.}/kWh$, respectively [131]. The remaining 1% corresponds to unconventional resource generation, such as wind and solar technologies.

It is worth mentioning that worldwide, there are different technologies and processes for converting sugarcane into ethanol and electricity, depending mainly on the agricultural practices of each country [73], [79], [207]. The two functional units (FU) used in this study are defined

as “1 tonne of sugarcane at the farm gate” for the agricultural stage and “1 L of ethanol at the plant gate”. The functional unit is a quantified description of the performance requirements that the product system fulfills. Moreover, the functional unit also serves as the reference basis for all environmental impact calculations and comparisons with other systems with the same function.

The scope of this study embraces all the activities for ethanol production, enabling a cradle-to-gate analysis. The whole system includes the extraction of raw materials within the agricultural stage and ends with the final product (ethanol) at the gate of the distillery plant. The resource consumption, materials (except building materials and capital equipment), and energy inputs used during sugarcane cultivation, transportation, milling, and final conversion are considered for this analysis. We have not considered the impact associated with the production of capital equipment nor the storage and transportation tasks after ethanol production.

Economic allocation (EA) and system expansion (SE) were used to take co-products into account in the milling and co-generation stages, respectively. The co-generation stage considers three different scenarios of system expansion presented in Table 6. 1. The system expansion method, also called displacement or substitution, was historically proposed to avoid allocation [235]. This method is a consequential approach that tends to represent the actual effects of generating multiple products from a pathway. The environmental burdens of producing the displaced products are credits that are then subtracted from the total environmental burdens of the production cycle.

Table 6. 1 System expansion scenarios for the co-generation stage.

Scenario	Description	Type of Generation Displaced
Average mix displacement	The surplus electricity generated in the co-generation stage is sold to the national electricity grid.	Average electricity mix
Marginal technology displacement	The surplus electricity generated in the co-generation stage is sold to the national electricity grid.	Internal combustion engine operating on fuel oil
No displacement	The effect of the surplus electricity generated is not considered.	Not applicable

The average mix displacement scenario is assumed to be more realistic compared with the marginal technology displacement scenario and the scenario without surplus electricity displacement. This latter is justified by the Organic Law of the Public Service of Electricity that

establishes that the Ecuadorian government, through the Electricity and Renewable Energy Ministry, may delegate, exceptionally, to private capital companies, the contribution to the electricity sector activities when it comes to projects that use non-conventional renewable energies such as biomass [236], [237].

6.2.2 Life Cycle Inventory

The life cycle inventory (LCI) stage is the methodology step that includes the compilation of an inventory of inputs and outputs of a product system. The LCI of the ethanol production system was obtained from different sources. The inventory was developed based on primary data from a sugar mill company concerning the agricultural and milling stages. For the distillation stage, the data was collected from an alcohol distillation company and supplemented with secondary data from peer-reviewed literature [238], [239]. Notably, these two companies are two of the largest in the Ecuadorian sugar and alcohol industries. The system description and inventory data are valid for sugarcane-based bioethanol in the coastal region of Ecuador and for the time framework 2017–2018.

The production of different co-products is a particular feature of the ethanol production chain. For this reason, allocation and system expansion are used to apportion the impacts generated by its production. The selection of the used method directly affects the results [196], [211]. This work considers the economic allocation primarily in the milling stage, at the centrifugation process, where some co-products (sugar and molasses) are generated.

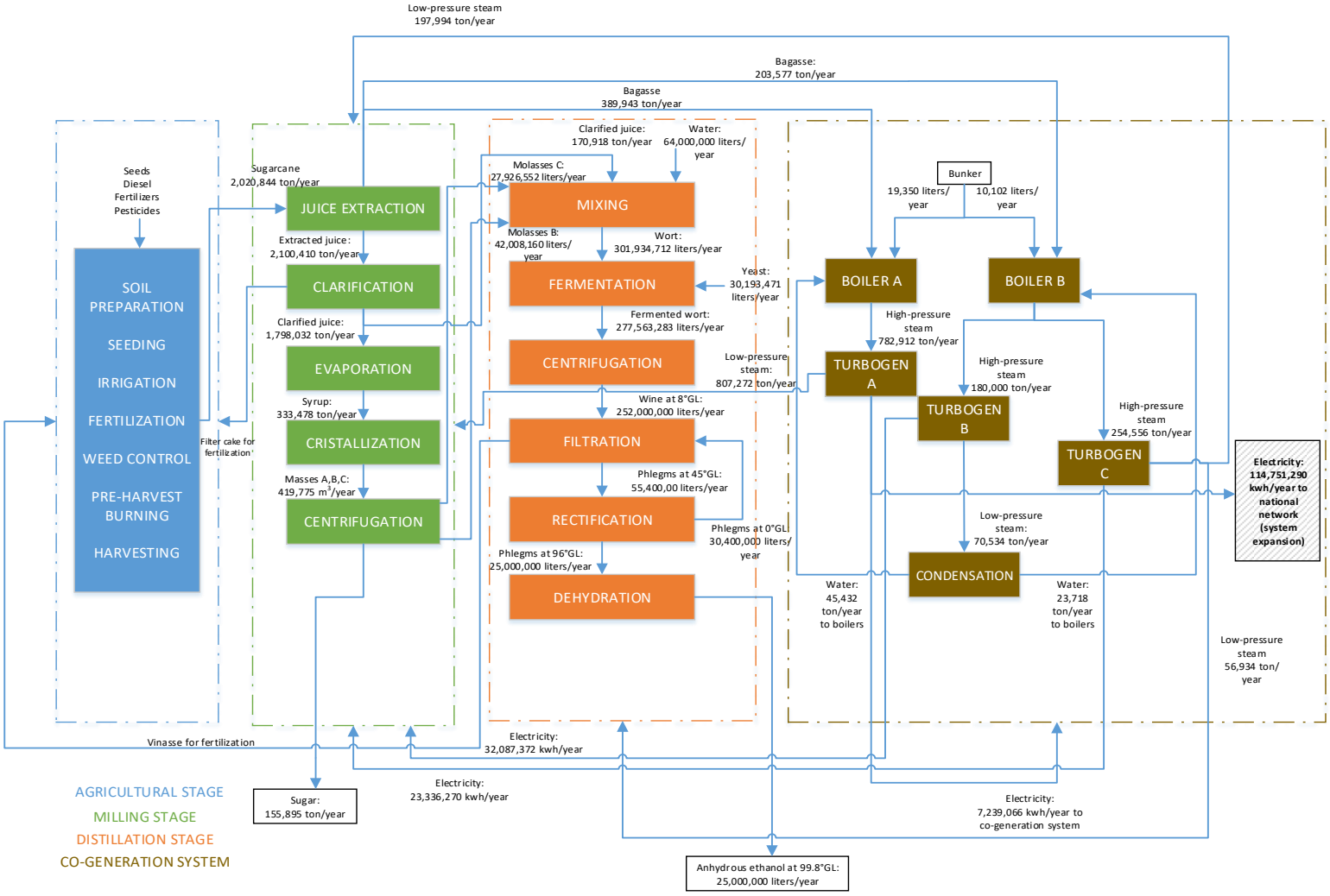

Figure 6. 1 Anhydrous ethanol life cycle system boundaries and main product flows quantification for the year 2018.

6.2.2.1. Agricultural Stage

The agricultural stage includes soil preparation, seeding, irrigation, fertilization, weed control, and harvest. Soil preparation includes leveling, clearing, and plowing with a ripper and a subsoiler. The soil needs to be prepared at least once every five years.

Like soil preparation, seeding is usually done once every five years, and the plowing phase can be performed by hand or machinery. For the irrigation phase, around 7 to 8 months is generally necessary using pivots, water cannons, or a gravity system. The fertilization, weed control, and harvesting processes are usually performed once per year, either by hand or by machinery. Generally, based on an Ecuadorian context, 100% of the sugarcane field is burned before each harvest process to perform the operations efficiently.

The agricultural stage inputs mainly include land, diesel, seeds, water, electricity, fertilizers, and agrochemicals (pesticides, herbicides, etc.). Among the outputs, the emissions generated in each process are primarily due to fossil fuel burning and fertilizers.

In cropland areas, only non-CO_2 emissions are considered since CO_2 emissions are balanced with the emissions that are captured by the annual plant re-growth [240]. Emissions of gases such as carbon monoxide (CO), methane (CH_4), nitrogen species (N_2O, NO_x), and non-methane volatile organic compounds (NMVOC), referred to as diesel combustion on agricultural machinery used for soil preparation, seeding, fertilization, weed control, harvesting, and agricultural residue burning, were considered [241]. For calculating non-CO_2 emissions due to the burning of agricultural residues, the emission factors suggested by the Intergovernmental Panel on Climate Change (IPCC) were applied [242]. Other emissions to soil and water were calculated using the Life Cycle Inventories of Swiss and European Agricultural Production Systems Report [238].

Direct and indirect emissions generated through the application of synthetic nitrogen fertilizers were calculated in this study. The amount of fertilizers annually used by the company (2018) was reported as 280 kg/ha for urea, diammonium phosphate as 20 kg/ha, and potassium muriate as 65 kg/ha. The total sugarcane cropped area of the mill in 2018 was 28,500 hectares (ha), resulting in 2,020,844 tonnes of sugarcane and a crop yield of 70.91 t/ha.

The inventory for the agricultural stage is shown in detail in Table S6. 1 in the Supplementary Material.

6.2.2.2 Milling Stage

The milling stage includes sugarcane milling, juice clarification, evaporation, crystallization, centrifugation, and drying to obtain sugar and molasses as the final products. The first sub-stage aims to obtain sugarcane juice. In sugarcane juice extraction, the bagasse can be obtained, separated, and sent to the boilers in the co-generation power plant to generate electricity and steam. The extracted juice can also be used to produce sugar and molasses through several processes (clarification, concentration, and crystallization). This extracted juice can also be directly diverted to a fermentation process to obtain ethanol.

The milling stage inputs mainly include water and some chemicals such as phosphoric acid, sulfur, lime, and calcium hydroxide at 9.40, 263.8, 1140.8, and 230.3 kg/1000 tonnes of sugarcane, respectively.

The final products are sugar and molasses (B and C) that can be used in the ethanol production phase (distillation stage). Based on the milling stage that produces more than one product, an economic allocation was used to fraction the flows of this process to the product system under study. For sugar product, a value of USD$33 for a sack of 50 kg was used for the allocation. Regarding molasses, values of USD$0.60 and USD$0.18 were used for molasses B and C, respectively.

The inventory for the milling stage is shown in detail in Table S6. 2 in the Supplementary Material.

6.2.2.3. Distillation Stage

Ethanol can be obtained directly from sugarcane juice or by mixing sugarcane juice with molasses (B and C) delivered during the milling process. The sugar and the remaining molasses from the milling stage are co-products that were not used in ethanol production. For this case, the wort obtained from the mixing process comes mainly from the sugarcane juice (71%), followed by molasses B (18%) and molasses C (11%). This latter proportion allows us to classify this ethanol as a first generation (1G). The molasses is mixed with sugarcane juice and fermented by yeast cultures. The yeast used for the fermentation process was 1020 kg/year. Urea is a nitrogen source for the yeast production [243]. Finally, after fermentation, the fermenter wash is pumped to the distillation unit, where the produced wine is distilled and rectified to obtain anhydrous ethanol at 99.8° of alcoholic grade. The inventory data for this stage was obtained directly from one distillation plant. The electricity consumption of the distillation plant

was 12,540,222 kW per the analyzed year. This distillation plant produced 25 million liters of ethanol in 2018. In 2021, the national ethanol production was planned to be 110 million liters [244]. Therefore, the studied plant contributes to Ecuadorian ethanol production and may account for approximately 20% of the national production.

The inventory for the distillation stage is shown in detail in Table S6. 3 in the Supplementary Material.

6.2.2.4. Co-generation Stage

Electricity and steam are produced via bagasse waste boiler. For the case study, approximately 593,000 tonnes of bagasse per year are burned in boilers with fuel oil to generate 1.21 million tonnes of high-pressure steam per year. Biogenic CO_2 emissions from combustion are considered neutral because they were captured during the annual sugarcane growth (belonging to the short-term carbon cycle). The high-pressure steam is then fed into a turbine coupled to a generator to produce electricity and low-pressure steam. This low-pressure steam is sent back to the milling stage for sugar production. This co-generation plant produced 177,414,000 kWh of electricity in 2018, of which 55,423,642 kWh was for internal consumption at the milling stage, 7,239,066 kWh for internal consumption at the co-generation plant for auxiliary equipment, and 114,751,290 kWh was sold to the national interconnection network. Approximately 12,540,222 kWh was purchased for electricity consumption in the distillation plant. It is noteworthy to mention that the electricity and steam production of this co-generation power plant is consistent with what was found in the literature [173], [174], [245], and its validation is shown in detail in the supplementary information. Moreover, the heat-to-power ratio and total co-generation plant efficiency results were validated with the ranges established in the literature [245]. The representativeness of electricity generation from sugarcane refineries to the Ecuadorian national mix is approximately 2.4% [246]. The co-generation power plants with sugarcane bagasse produce 136.4 MW from San Carlos S.A., Ecoelectric S.A., and Coazúcar S.A. companies [247].

The inventory for the co-generation stage is shown in detail in Table S6. 4 in the Supplementary Material.

6.2.3 Life Cycle Impact Assessment (LCIA)

This study's life cycle impact assessment (LCIA) was developed using the characterization factors in the ReCiPe midpoint v1.13 methodology from a hierarchical (H) perspective. This

assessment was modeled using the OpenLCA v1.10.3 software and Ecoinvent 3 APOS database, covering the emission-related impact categories shown in Table 6. 2. This study did not consider land-use change (LUC) impact because future agricultural expansion will likely come from non-virgin and low vegetation cover lands (non-tree land covers) [248], and do not significantly alter the carbon content in the soil neither the global warming potential impact. Moreover, Nagy et al. [249] stated that converting dry tropical forests to cropland due to agricultural expansion led to only minor changes in soil carbon dynamics. A study of carbon emissions from cropland expansion in the United States stated that, where biomass densities are small, the impact of land use change is thought to be a relatively minor contributor to emissions [250]. Notably, the Ecuadorian province with the highest potential for sugarcane production is Guayas, with 75% [220] located in the country's coastal zone.

Table 6. 2 Impact categories included in the LCA

Impact Category	Characterization Factor	Reference Unit
Climate change	climate change—GWP100	kg $CO_{2eq.}$
Freshwater eutrophication	freshwater eutrophication potential—FEP	kg $P_{eq.}$
Marine eutrophication	marine eutrophication potential—MEP	kg $N_{eq.}$
Abiotic depletion	metal depletion—MDP	kg $Fe_{eq.}$
Photo oxidant formation	photochemical oxidant formation potential—POFP	kg $NMVOC_{eq.}$
Particulate matter emissions	particulate matter formation potential—PMFP	kg $PM_{10eq.}$
Terrestrial acidification	terrestrial acidification potential—TAP100	kg $SO_{2eq.}$

6.2.4 Sensitivity Analysis

A sensitivity analysis was developed considering different sugarcane yields to study how productivity could influence the environmental profiles. Based on conversations with the staff from the companies where the data was obtained, the productivity indices of sugarcane have varied from year to year. 2018 the crop yield was approximately 71 t/ha (base case scenario). However, a more up-to-date yield is approximately 86 t/ha. These yields are within what has been found in the literature [251]–[256].

6.3 Results

6.3.1 Impact Assessment of Agricultural Stage

Table 6. 3 shows the environmental impacts analyzed at the sugarcane production level at the farm gate. The GWP impact for sugarcane production is 53.6 kg of carbon dioxide equivalent (kg. $CO_{2eq.}$) per tonne of sugarcane produced. This latter is mainly due to the use of nitrogenous

fertilizers such as urea that end up as ammonium and N_2O emissions because of a volatilization process [257]. Besides urea application, diesel is another input that primarily contributes to this environmental impact when one tonne of sugarcane is produced in the agricultural stage. Diesel is consumed in agricultural activities such as soil preparation, seeding, cultivation, irrigation, fertilization, and harvesting. Noteworthy is that CO_2 emissions produced from pre-harvest burning are balanced with the emissions that are captured by the annual plant re-growth [240].

Table 6. 3 Impact category indicator results in agricultural stage to produce sugarcane (FU = 1 tonne of sugarcane).

Impact Category	Unit	For 1 Tonne of Sugarcane
Global warming potential	kg $CO_{2eq.}$	53.6
Freshwater eutrophication potential	kg $P_{eq.}$	0.01539
Marine eutrophication potential	kg $N_{eq.}$	0.154
Metal depletion potential	kg $Fe_{eq.}$	1.195
Photochemical oxidant formation potential	kg $NMVOC_{eq.}$	0.847
Particulate matter formation potential	kg $PM_{10eq.}$	0.562
Terrestrial acidification potential	kg $SO_{2eq.}$	0.823

$CO_{2eq.}$: carbon dioxide equivalent; $P_{eq.}$: phosphorous equivalent; $N_{eq.}$: nitrogen equivalent; $Fe_{eq.}$: iron equivalent; $NMVOC_{eq.}$: non-methanol volatile organic compounds equivalent; $PM_{10eq.}$: particulate matter equivalent $SO_{2eq.}$: sulfur dioxide equivalent.

Contribution Analysis of Agricultural Stage for GWP, FEP, MEUP, MDP, POMFP, PMFP and TAP Impacts

Table 6. 4 shows the contribution analysis of the agricultural stage for GWP, FEP, MEUP, MDP, POMFP, PMFP, and TAP impacts. The main contributors of GWP impact in the agricultural stage correspond to N_2O lixiviation and volatilization with 33.5%, followed by the diesel used in agricultural machinery at 24.33%, the methane emissions due to pre-harvest burning at 11.55%, and the urea production at 11.34%.

The contribution analysis of the agricultural stage for MEP impact indicates that the application of fertilizers has the highest contribution, with 74.28%. The second most significant contributor to this impact corresponds to the ammonia emissions due to urea application, with 11.95%.

Regarding the FEP impact., the main contributor corresponds to the phosphorous emissions due to applying fertilizers at 64.87%, followed by the diesel burned in agricultural machinery at 12.14% and the market for urea production at 10.19%.

The MDP impact shows that the two main contributors correspond to the diesel burned in agricultural machinery at 59%, followed by transportation activities at 28%. Potassium sulfate, urea, and pesticide production show a low contribution to this impact, with 5.3%, 5.3%, and 1.4%, respectively.

The contribution analysis of agricultural stage for POFP impact evidence that the carbon monoxide and nitrogen oxides emissions due to pre-harvest burning have the highest contribution to this impact with 45.44% and 27.08%, respectively, followed by the diesel burned in agricultural machineries with 15.10%. Transportation activities and urea production show a low contribution to this impact, with 4.05% and 1.89%, respectively.

Regarding the PMFP impact, Table 6. 4 shows that the particulate emissions due to pre-harvest burning have the highest contribution with 64.01%, followed by the ammonia emissions due to urea application with 11.38%. Nitrogen oxides due to pre-harvest burning contribute to this impact of 8.97%.

The contribution analysis of the agricultural stage for TAP impact indicates that the ammonia emissions due to urea application are the main contributor to this impact at 60%, followed by the nitrogen oxide emissions due to pre-harvest burning at 16%. Urea production, transportation activities, and diammonium phosphate production show a low contribution to this impact, with 3%, 3%, and 2%, respectively.

Table 6. 4 Contribution analysis of agricultural stage for GWP, MEUP, FEP, MDP, POFP, PMFP, and TAP impacts.

Process	GWP	MEP	FEP	MDP	POFP	PMFP	TAP
N_2O lixiviation and volatilization	33.50%	-	-	-	-	-	-
Diesel burned in agricultural machinery	24.33%	3.11%	12.14%	59.4%	15.10%	8.27%	10%
CH_4 emissions due to pre-harvest burning	11.55%	-	-	-	-	-	-
Urea production	11.34%	2.30%	10.19%	5.1%	1.89%	1.65%	3%
Transportation	7.95%	-	6.23%	28.3%	4.05%	2.42%	3%
CO_2 emissions due to the application of nitrogenous fertilizers	5.39%	-	-	-	-	-	-
Others	5.94%	2.55%	2.34%	0.8%	1.64%	1.88%	2%
Nitrate emissions due to fertilizers	-	74.28%	-	-	-	-	-
Ammonia due to urea application	-	11.95%	-	-	-	11.38 %	60%
Nitrogen oxides due to pre-harvest burning	-	5.81%	-	-	27.08%	8.97%	16%
Phosphorus due to application of fertilizers	-	-	64.87%		-	-	-
Potassium sulfate production	-	-	1.62%	5.1%	-	-	-
Pesticide production	-	-	1.10%	1.4%	-	-	-

Triazine-compound production	-	-	1.49%	-	-	-	-
CO due to pre-harvest burning	-	-	-	-	45.44%	-	-
NMVOC emissions	-	-	-	-	4.25%	-	-
PM due to pre-harvest burning	-	-	-	-	-	64.01 %	-
SO_2 emissions	-	-	-	-	-	1.42%	5%
Diammonium phosphate production	-	-	-	-	-	-	2%

N_2O: nitrous oxide; CH_4: methane; CO_2: carbon dioxide; CO: carbon monoxide; NMVOC: non-methane volatile organic compounds; PM: particulate matter; SO_2: sulfur dioxide.

6.3.2 Impact Assessment of Ethanol Production

The results for the seven impact categories and the contribution analysis for each stage are shown in Table 6. 5. The results shown in this subsection consider the average mix displacement scenario, where the electricity produced in the co-generation power plant is displaced. The agricultural and distillation stages have the highest impacts in all categories.

The distillation stage has the highest contribution to GWP impact, with 0.369 kg CO_2 per liter of ethanol. Agriculture is the second system stage that most contribute to global warming potential impact (GWP), with 0.285 kg CO_2 per liter of ethanol, followed by the milling stage with 0.0013 kg CO_2 per liter of ethanol (Table 6. 5). The co-generation stage reports a value of -0.0505 kg CO_2 per liter of ethanols. The contribution of the distillation stage towards the GWP impact corresponds to approximately 61%, followed by the agricultural stage at 47%, the milling stage at 0.2%, and the co-generation stage at -8.4%. The considerable contribution of the distillation plant and the agricultural stage is mainly due to the emissions generated in the fermentation process and the urea and diesel used in field activities, respectively.

Freshwater eutrophication is measured in kilograms of phosphorous (kg of P) equivalents. The distillation and the agriculture stage have the most significant impact on this indicator, with 0.0001 kg of P per liter of ethanol and 0.0000928 kg of P per liter of ethanol, respectively (Table 6. 5). The latter corresponds to 34% for agricultural stage and 52% for distillation stage of the overall impact. These results are mainly due to the application of agrochemicals for sugarcane production and the high nitrogen and phosphorous content in the vinasse produced from the distillation column process.

Marine eutrophication is measured in kilograms of nitrogen (kg of N) equivalents. The ethanol life cycle shows that overall, 0.00381 kg of $N_{eq.}$ are generated for each liter of ethanol produced. As can be seen, the distillation stage becomes the most important contributor in this impact

category, with 0.00206 kg of $N_{eq.}$/liter of ethanol, followed by the agricultural stage with 0.0018 kg of $N_{eq.}$/liter of ethanol and by the milling stage with 0.00001 kg of $N_{eq.}$/liter of ethanol (Table 6. 5). The co-generation stage reports a value of -0.000064 kg of $N_{eq.}$/liter of ethanol. Similar to the impact mentioned above (FEP), the distillation stage's significant contribution (54%) is due to the high nitrogen content in the vinasse produced from the distillation column process. Notably, urea is used as a nitrogen source for yeast production. The contribution percentage of the agricultural stage to this impact is 47% overall. The latter is mainly due to the application of agrochemicals, such as nitrogenous fertilizers, for sugarcane production. The urea is a nitrogenous fertilizer that produces ammonium carbonate once it reacts with water, which then decomposes and releases NH_3.

The metal depletion impact category assesses the scarcity of abiotic mineral resources and metals in terms of kg of iron ($Fe_{eq.}$). Overall, 0.01557 kg $Fe_{eq.}$ per liter of ethanol is generated during the ethanol life cycle. Distillation is the system stage that most contribute to MDP impact, with 0.0078 kg $Fe_{eq.}$ per liter of ethanol, followed by the agricultural stage with 0.0068 kg $Fe_{eq.}$ per liter of ethanol, the milling stage with 0.00089 kg $Fe_{eq.}$ per liter of ethanol and the co-generation stage with −0.00000848 kg $Fe_{eq.}$ per liter of ethanol (Table 6. 5). This latter is mainly due to heavy metals incorporated through fertilizers and pesticides. The contribution percentage of the agricultural, milling, distillation, and co-generation stages to this impact are 44%, 5.7%, 50%, and −0.031 of the overall, respectively.

The photochemical oxidant formation potential impact is measured in an equivalent value of kilograms of non-metal volatile organic compounds (kg $NMVOC_{eq.}$). The results for the ethanol life cycle are shown in kg $NMVOC_{eq.}$/liter of ethanol. The distillation stage becomes the most important contributor in this impact category, with 0.012 kg $NMVOC_{eq.}$/liter of ethanol, followed by the agricultural stage with 0.0051 kg $NMVOC_{eq.}$/liter of ethanol and the milling stage with 0.0024 kg $NMVOC_{eq.}$/liter of ethanol (Table 6. 5). The distillation stage has the most outstanding contribution with 68%. The agricultural stage has the second highest contribution, with 28% due to inappropriate chemical pesticides containing methane and halocarbon compounds [151]. Using organic fertilizer helps reduce these pesticides that damage the environment [258]. The milling stage contributes to this impact with 12%. The co-generation stage contributes -9.9%.

The particulate matter formation potential is measured in terms of kg of $PM_{10eq.}$. The ethanol life cycle shows that overall, 0.01019 kg of $PM_{10eq.}$ are generated for each liter of ethanol produced. The distillation stage becomes the most important contributor in this impact category, with 0.0058 kg of $PM_{10eq.}$/liter of ethanol, followed by the agricultural stage with 0.0034 kg of $PM_{10eq.}$/liter of ethanol and the milling stage with 0.00083 kg of $PM_{10eq.}$/liter of ethanol (Table 6. 5). The contribution percentage of the agricultural, milling, and distillation stages to this impact are 33%, 8%, and 58% of the overall impact, respectively. The behavior of this environmental impact is mainly dominated by the emissions produced in the ethanol production chain, such as in the combustion of diesel in the agricultural stage, in bagasse burning to co-generate electricity and steam or in the fermentation process within the distillation stage.

Terrestrial acidification potential is measured in kilograms of sulfur dioxide (kg of SO_2) equivalents. The distillation and the agriculture stages have the most significant impact on this indicator, with 0.0098 kg of $SO_{2eq.}$ per liter of ethanol and 0.0049 kg of $SO_{2eq.}$ per liter of ethanol, respectively (Table 6. 5). The latter corresponds to 32% for the agricultural stage and 64% for the distillation stage of the overall impact. These results are mainly due to the application of agrochemicals for sugarcane production and the high nitrogen and phosphorous content in the vinasse produced from the distillation column process. The co-generation stage contributes -4.6% of the overall impact due to the displacement of electricity.

Table 6. 5 Impact categories in different stages to produce ethanol (FU = 1 L of ethanol).

Impact Category	Agricultural Stage		Milling Stage		Distillation Stage		Co-generation Stage		Total
	Impact Indicator Result	Contribution (%)	Impact Indicator Result	Contribution (%)	Impact Indicator Result	Contribution (%)	Impact Indicator Result	Contribution (%)	Impact Indicator Result
GWP (kg $CO_{2eq.}$)	0.28582	47.2	0.0013	0.2	0.369	60.9	−0.05059	−8.35	0.606
MDP (kg $Fe_{eq.}$)	0.00688	44.2	0.00089	5.7	0.0078	50.1	−0.0000048	−0.03	0.01557
MEUP (kg $N_{eq.}$)	0.0018	47.2	0.00001	0.3	0.00206459	54.2	−0.00006459	−1.70	0.00381
POFP (kg $NMVOC_{eq.}$)	0.00514	28	0.00249	13.6	0.01253	68.3	−0.00182	−9.92	0.01834
TAP (kg $SO_{2eq.}$)	0.00499	32.7	0.0012	7.9	0.0098	64.1	−0.00071	−4.65	0.01528
FEP (kg $P_{eq.}$)	0.0000928	34.4	0.0000372	13.8	0.00014	52	−0.00000031	−0.11	0.00027
PMFP (kg $PM_{10eq.}$)	0.00341	35.5	0.00083	8.1	0.00589	59	0.00006065	−0.60	0.01019

6.3.2.1. Marginal Technology Displacement and No Displacement Scenarios

Figure 6. 2 shows the environmental impacts for each scenario. The results obtained from each impact were normalized to a factor of 1 with the scenario "No displacement" impact scores. It is noteworthy that the scenario where the marginal electricity is displaced is the one that generates the lowest amount of environmental impacts. Fuel oil-based electricity is mainly displaced in this latter context. The most realistic scenario, the average mix displacement, occupies the second position regarding the environmental impacts generated, followed by the scenario where no surplus electricity displacement is considered. In the modelled system, ethanol has a better environmental performance, while the electricity that is displacing has a lower environmental performance.

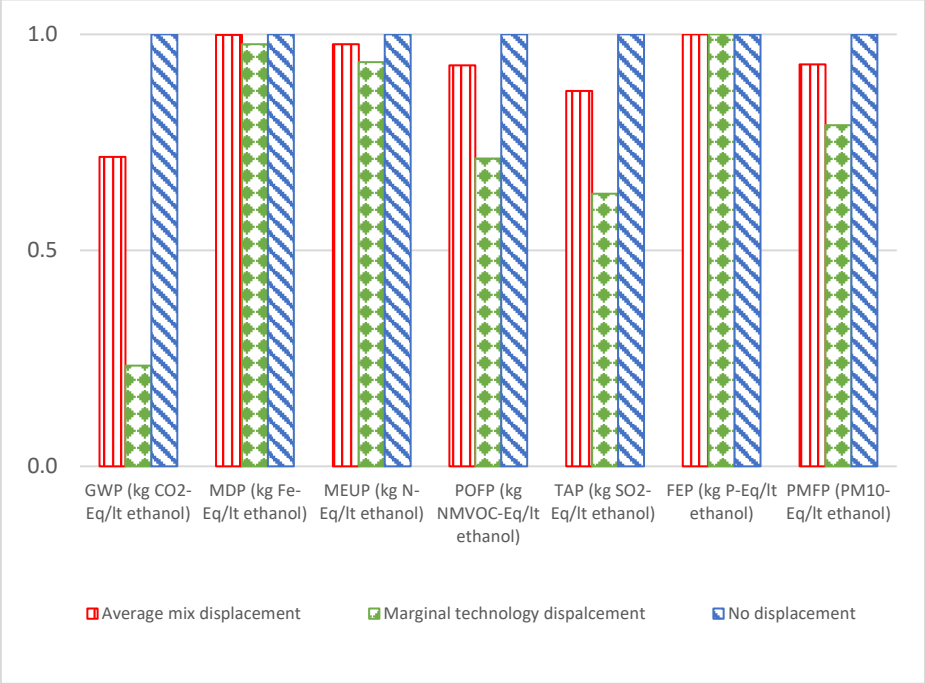

Figure 6. 2 Comparison of life cycle environmental impacts at cradle-to-plant-gate for the three system expansion scenarios: Average mix displacement, marginal technology displacement, and no displacement. The impact results were normalized to a factor of 1 according to the impact category result indicator of the scenario "No displacement."

6.3.3 Sensitivity Analysis

The parameter considered for this sensitivity analysis is the productivity index. The impact category that has caught more attention is the global warming potential to see how sensitive it is in response to crop yield variation. This analysis shows that the global warming potential impact has a variation of −14% when the sugarcane productivity increases to 86 t/ha (Figure 6. 3). The particulate matter formation potential impact also has a considerable decrease of 10% when the sugarcane yield increases from 71 to 86 t/ha.

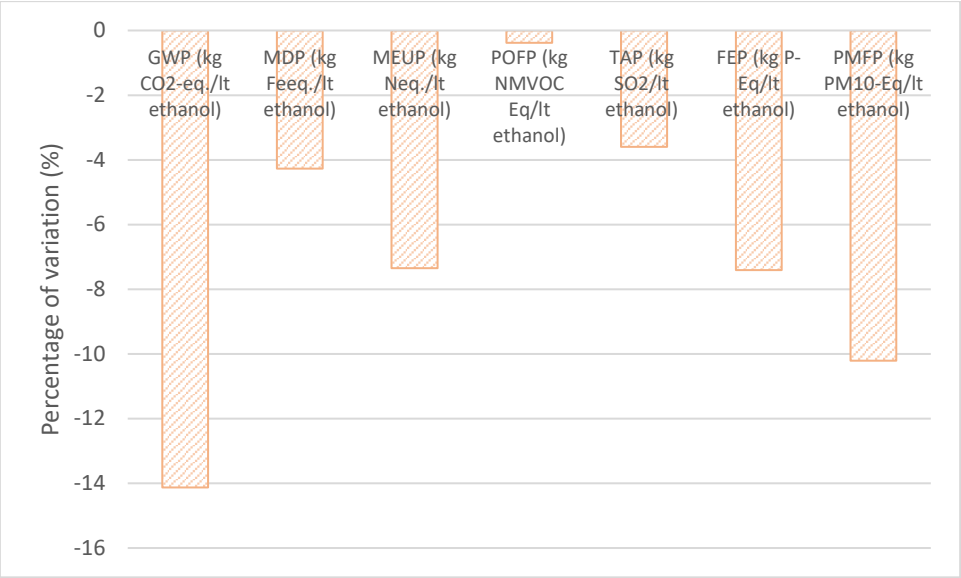

Figure 6. 3 Percentage of variation for each environmental impact indicator results through an increase of crop yield from 71 to 86 t/ha

6.4 Discussion

6.4.1 Comparison with Literature

The definition of system boundaries, functional units, allocation methods, technological conversion routes, and spatial and temporal variability differs widely among lifecycle analyses made of ethanol [160], [188], [259]. Furthermore, the sugarcane production system can be diversified with the different biorefinery configurations to obtain various products and by-products [208], [260]–[262]. Only GWP impact results were compared with existing literature, as this is the impact indicator result that can be found in almost every study. Moreover, climate change is currently the main sustainability thread.

6.4.1.1 Comparison with Literature at the Sugarcane Production Level, At-The-Farm-Gate.

Environmental impacts are sensitive to ethanol conversion efficiency, sugarcane yield, and percentage of cane trash burn [208]. Based on the literature review, Watanabe et al. [252] reported a sugarcane yield of 82 tonnes per hectare (t/ha) for Brazil, compared to an average sugarcane yield of 78.15 t/ha for Indonesia [160]. On the other hand, Silalertruksa et al. [251] reported an average sugarcane yield of 75 t/ha for Thailand. The sugarcane yield of this study is lower than the compared articles and achieved a value of 70.9 t/ha in 2018 (Table 6. 6). The GWP impact from sugarcane production was reported as 53.6 kg of carbon dioxide equivalent (kg. $CO_{2eq.}$) per sugarcane tonne. The main contributors of GWP impact at this level correspond to N_2O lixiviation and volatilization, diesel used in agricultural machinery and urea production. Similar results of contribution analysis were stated by Tsiropoulos et al. [253], indicating that the GWP

impact at the farm gate is mainly affected by the N_2O emissions from oxidation of nitrogen in nitrogenous fertilizers and by the emissions generated from their production.

The GWP impact of the study from India and Brazil shows a lower value than the value reported in this study for sugarcane production with 45 and 36 kg. $CO_{2eq.}$/tonne of sugarcane, respectively [253]. This higher GWP impact in this study is mainly due to the greater amount of nitrogen and potassium fertilizers (3.95 kg/t and 0.92 kg/t, respectively) that are applied compared to the other studies (0.78–2.69 kg/t and 0.82–0.9 kg/t respectively) [253].

A recent publication from Hiloidhari et al. [254] reported a carbon footprint of 58.59 kg $CO_{2eq.}$/t of sugarcane associated with the cultivation, transport, and processing stages (Table 6. 6).

Table 6. 6 GWP impact results at three different levels compared with literature.

Ref.	Country	Yield	$CO_{2-eq.}$			System Boundaries	Allocation	Bioethanol Generation
		(t/ha)	kg $CO_{2-eq.}$/tc	kg $CO_{2-eq.}$/ts	kg $CO_{2-eq.}$/Liter of Ethanol			
This study	Ecuador	70.9	53.6	568	0.60	agricultural, milling, distillation, and co-generation stages	Economic	1G
[72] a	Brazil	87.1	-	-	0.44	sugarcane production; processing; ethanol production	NA	1G
[72] b	Brazil	87.1	-	-	0.35	sugarcane production; processing; ethanol production	NA	1G
[73]	Brazil	86.7	-	234	0.45	sugarcane production; harvesting; transportation; processing; ethanol production; distribution	Economic, physical, and energy-based	1G
[253]	India	59.2	45	-	0.09–0.64 c	sugarcane production; sugarcane processing to sugar; sugarcane processing to ethanol	Economic	2G
[92]	Brazil	-	-	-	0.35	sugarcane production + local transport; ethanol production (without surplus energy credits)	NA	NA
[251]	Thailand	75	38	350	0.39	sugarcane cultivation and harvesting, transportation; sugar milling, steam, and power generation from bagasse; molasses ethanol production, raw material production, and by-product utilization.	Economic allocation	2G
[254]	India	70	58.59	401	0.295	sugarcane cultivation, co-generation, and ethanol production	Economic, mass, and energy allocation	2G
[160]	Indonesia	78.1	49	-	0.61	sugarcane harvesting, milling, ethanol production, and transport	Economic	2G

a Scenario Brazil 2005, b Scenario Brazil 2020, c in kg CO_2/kg of ethanol, tc: tonne of sugarcane, ts: tonne of sugar.

6.4.1.2 Comparison with Literature at the Ethanol Production Level at the Plant Gate

This study develops an environmental profile of ethanol produced through sugarcane in Ecuador, evaluating the effect of using bagasse to cogenerate electricity. The GWP impact generated

at the ethanol production level is 0.60 kg. $CO_{2eq.}$/liter of ethanol based on Ecuadorian conditions and based on the average mix displacement scenario (Table 6. 6). This value falls within the range found in the literature 0.07–0.61 kg $CO_{2eq.}$/liter [72], [73], [160], [251], [253], [254].

Tsiropoulos et al. [253] obtained a range of greenhouse gas emissions between 0.07–0.50 kg $CO_{2eq.}$/liter of ethanol in India for a high (surplus electricity accounted) and a low-system (no surplus electricity is accounted) performance, respectively. The low-system performance case of this latter study (0.50 kg $CO_{2eq.}$/liter of ethanol) has a lower carbon footprint than the average mix displacement scenario of our study (0.60 kg $CO_{2eq.}$/liter of ethanol). The ethanol from the latter study causes lower GHG emissions mainly because it is produced exclusively from molasses (2G), a by-product of sugar production. Moreover, the functional unit in the study by Tsiropoulos et al. [253] was defined as 1 kg of hydrous ethanol, compared to our study of 1 L of anhydrous ethanol. Nevertheless, for comparative purposes, the hydrous ethanol for our base scenario (average mix displacement) shows a GWP impact of 0.57 kg. $CO_{2eq.}$/liter of ethanol. The impact assessment was also developed using Impact 2002+ methodology, while this study used ReCiPe.

Compared to our study, Khatiwada et al. [160] reported a similar value of GWP (0.61 kg $CO_{2eq.}$/liter of ethanol) for ethanol production in Indonesia. The main difference between this latter study and our analysis is that the ethanol was produced with cane molasses pre-treated to obtain a concentrated juice before fermentation. The authors also performed a sensitivity analysis of various parameters to evaluate energy and GHG balances in different allocation ratios. Similar to our study, the sensitivity analysis shows that the GHG emissions are highly sensitive to sugarcane yield. Pacheco et al. [263] reviewed that ethanol production can generate 0.35–0.40 kg $CO_{2eq.}$/liter of 1G ethanol through sugarcane feedstock in Brazil. On the other hand, Watanabe et al. [252] reported three different values of GWP impact based on three different biorefinery configurations: 0.447, 0.319, and 0.27 kg $CO_{2eq.}$/liter of ethanol for 1G-base, 1G-optimized, and integrated 1G2G ethanol biorefinery. Comparing our study with the 1G-optimized scenario, which represents a modern autonomous distillery for first-generation ethanol production and electricity co-generation, there is a difference of 0.30 kg $CO_{2eq.}$/liter of ethanol. This difference could be related to the higher sugarcane yield (82 t/ha) of the study from Watanabe et al. [252] and also due to the sugarcane straw fraction recovered (50%) for energy generation in the cogeneration system.

Silalertruksa et al. [251] reported a GWP impact of 0.39 kg $CO_{2eq.}$/liter of molasses-derived ethanol in Thailand, considering a base sugarcane biorefinery that includes conventional sugarcane farming, sugar milling, molasses ethanol production, and electricity generation. The lower GWP impact of this latter study compared with our study could be attributed to the higher sugarcane productivity (76 t/ha versus 71 t/ha) and the difference in sugar prices for the economic allocation (USD$27 versus USD$33 for a sack of 50 kg).

Finally, Hiloidhari et al. [254] assessed the life cycle energy, carbon, and water footprint of sugarcane-based sugar, ethanol, and electricity in India. The GWP impact for ethanol production was reported as 0.29 kg. $CO_{2eq.}$/liter of ethanol. The lower GWP impact for this latter study compared to ours could be attributed to the fact that the ethanol in India is mainly produced from molasses (2G).

Regarding the system expansion applied in the co-generation stage, the marginal technology displacement and the no displacement scenarios report a GWP impact of 0.19 kg. $CO_{2eq.}$/liter of ethanol and 0.84 kg $CO_{2eq.}$/liter of ethanol, respectively. The average mix displacement scenario was 0.60 kg $CO_{2eq.}$/liter of ethanol. The difference between the average and the marginal technology displacement scenarios is due to the credits of the Ecuadorian system, depending on what electricity is displaced. This difference is by a factor of 3.15. This factor is similar to what was reported by Tsiropoulos et al. [253], who compared an optimistic and a conservative surplus electricity system expansion scenario and estimated a difference factor of 3 [253]. Comparative results found in the literature indicate that the scenarios where system expansion is applied led to lower impact values compared to the scenario where no surplus electricity is displaced [174], [253], [264]. Notably, the carbon footprint of ethanol in systems that include co-generation depends on the mix or type of electricity displaced.

Considering the contribution analysis, results of the GWP impact at the plant gate indicate that the sugarcane agricultural stage and the distillation stage have the highest contribution within the complete ethanol production chain, with approximately 47% and 61%, respectively. These results are aligned with Cavalett et al. [79] and Amores et al. [151] results, which concluded that the agricultural stage is one of the most intensive stages in terms of GHG emissions, with 70% and a range of 58–63%, respectively. Amores et al., 2013 [151] state that GWP impact is mainly affected by fossil fuel utilization in agricultural machinery. Gabisa et al. [243] also reported that sugarcane farming is the most significant contributor to GWP impact, with a range

contribution of 58.2–75%. In contrast, a study on molasses ethanol production in Indonesia showed that agriculture contributes 38% to the GWP impact, releasing the other 62% of the contribution to the industrial stages where the sugarcane is processed and then converted into ethanol [265].

6.4.2 Recommendations

The pilot program called Ecopais (95% extra gasoline with 5% anhydrous ethanol), which started in Guayaquil in 2010, sought to reduce environmental emissions and oil derivative imports. The program has had positive environmental and social aspects. Nevertheless, the Ecuadorian sugarcane and ethanol industry should implement more efficient processes in its production chain to have the least possible environmental impact. Companies should apply industrial symbiosis and circular economy to foster eco-innovation, create and share mutually profitable transactions, and improve industries' business and technical processes. Moreover, the bagasse should be used for electricity generation instead of industrial waste.

Another recommendation should be focused on precision agriculture, specifically in using fertilizers. There are opportunities to reduce the amount of fertilizers used in agriculture by implementing industrial symbiosis and circular economy strategies. Moreover, sugarcane growers must coherently fertilize their agricultural fields to achieve precision in farming, guarantee greater sustainability, and maximize crop yield [255], [256]. Another recommendation should be related to looking for other agronomic alternatives to improve crop yield.

Aiming to achieve a higher percentage of ethanol in the mixture is necessary to invest in a more significant agricultural sugarcane expansion. Moreover, new technologies and conversion routes of biomass to explore the environmental benefits of other biofuels (2G and 3G) should be promoted. The integration of 1G and 2G technologies could reduce the GHG emissions of ethanol production by a factor of 1.4 compared to 1G technology [252].

6.4.3 Future Research Needs

Climate change's impact on the weather (rain events, temperatures) and alterations in sugarcane crop yield would be advisable to prospect the future security of the ethanol supply based on this crop. For example, if the sugarcane productivity drops to the Indian values (Table 6. 6) of 59.2 tonne/ha (a 16% decrease), our system's CO2eq emissions per FU would increase by 19%, maintaining all the other conditions. Droughts increase due to climate change, contextualizing the need to assess the water balance of the system. Water consumption can be categorized into

blue, green, and gray. A water balance in terms of blue water entering the system and water vapor leaving the system to the atmosphere will be interesting to determine.

Improved yeast used in fermentation to increase ethanol production may positively impact the systems; for example, an increase in ethanol yield of 20% for the same conditions.

6.5 Conclusions

Biofuels have been recognized as an alternative transportation fuel to reduce the consumption of fossil fuels. Nevertheless, a detailed life cycle assessment is necessary to support its development. The environmental profile of ethanol derived from sugarcane was analyzed through a life cycle perspective, including the effect of electricity co-generation in a sugar industrial complex. This analysis considered four stages: agricultural, milling, distillation, and co-generation. The present study also compiles a life cycle inventory for ethanol-derived sugar cane production in Ecuador.

The GWP impact generated at the farm gate level was reported as 53.6 kg of $CO_{2eq.}$ per sugarcane due to N_2O volatilization and diesel application in agricultural machinery.

Considering the ethanol production level, the GWP impact was reported as 0.60 kg. $CO_{2eq.}$/liter of ethanol. The contribution analysis shows that the agricultural and ethanol distillation stages contribute the highest GWP impact within the complete ethanol production chain. Credits were received for displacing surplus electricity produced in the co-generation stage.

The terrestrial acidification potential impact was 0.01528 kg of $SO_{2eq.}$ at the ethanol production level due to the vinasse's high nitrogen and phosphorous content. The marine eutrophization potential was calculated as 0.00381 kg of $N_{eq.}$ per 1 L of ethanol due to the high nitrogen content in the vinasse and to the use of nitrogenous fertilizers in the agricultural stage.

The electricity demand covered by the industrial sugarcane sector reduces the demand for electricity generation by the power sector, and the ethanol life cycle is credited depending on whether it displaces average or marginal electricity. Three different scenarios were proposed in the co-generation stage: (i) average mix displacement scenario where the surplus electricity produced in the co-generation stage is displaced; (ii) marginal technology displacement scenario where the marginal surplus electricity is displaced from the mix; and (iii) no displacement scenario. The marginal technology displacement and the no displacement scenarios report a GWP impact of 0.19 kg. $CO_{2eq.}$/liter of ethanol and 0.84 kg $CO_{2eq.}$/liter of ethanol, respectively.

Ethanol has a better environmental performance whereas the electricity that is displacing it has a lower environmental performance.

The average mix displacement scenario reported a GWP impact of 0.60 kg $CO_{2eq.}$/liter of ethanol. Scenarios, where system expansion is applied led to lower impact values compared to the scenario where no surplus electricity is displaced [264]. This latter shows the importance for the sugarcane industrial sector to increase its co-generation capacity to embrace its electricity demand.

To have environmentally friendlier sugarcane and ethanol industries, sustainable and less polluting processes should be sought to reduce the environmental burdens. Companies should apply industrial symbiosis and circular economy strategies to produce lesser environmental loads within the ethanol production chain. To guarantee greater sustainability, sugarcane growers must optimize synthetic fertilizer application by implementing precision agriculture.

Finally, Ecuador has mainly developed 1G ethanol derived from sugarcane through fermentation and distillation. There is a limited implementation of conversion processes of other feedstocks into ethanol in Ecuador, relegating the development of 2G and 3G biofuels. Therefore, future research should be focused on these biofuels.

This study contributes to the sustainability assessment of biofuel production, including the effect of electricity cogeneration from a sugar industry complex. Moreover, it allows the assessment of road transportation based on ethanol or ethanol and gasoline blends as fuels in Ecuador from a life cycle perspective.

Supplementary Information

S6.1 Life cycle inventory

S6.1.1 Agricultural stage

Table S6. 1 Compilation of Inputs and outputs for the agricultural stage per FU = 1 tonne of sugarcane

Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
2,4-dichlorophenol	0.06	kg	Product flow	Ecoinvent [98] market for 2,4-dichlorophenol | APOS, U - GLO
atrazine	0.0587	kg	Product flow	Ecoinvent [98] atrazine production | APOS, U - RoW
diammonium phosphate	0.282	kg	Product flow	Ecoinvent [98] market for diammonium phosphate | APOS, U - RER
diesel, burned in agricultural machinery	107.24	MJ	Product flow	Ecoinvent [98] diesel, burned in agricultural machinery | APOS, U - GLO
dinitroaniline-compound	0.049	kg	Product flow	Ecoinvent [98]market for dinitroaniline-compound | APOS, U - GLO
filter cake, from sugarcane juice filtration	0.36	kg	Product flow	(This study) Sugarcane juice Clarification process – EC
pesticide, unspecified	0.035	kg	Product flow	Ecoinvent [98] market for pesticide, unspecified | APOS, U - GLO
potassium sulfate	0.916	kg	Product flow	Ecoinvent [98] market for potassium sulfate | APOS, U - RoW
triazine-compound, unspecified	0.0877	kg	Product flow	Ecoinvent [98] triazine-compound production, unspecified | APOS, U - RoW
Urea	3.94	kg	Product flow	Ecoinvent [98] market for urea | APOS, U - RO
vinasse, from fermentation of sugarcane	1.21	kg	Product flow	(This study) From filtration process at distillery - EC
Water, river	25.38	m3	Elementary flow	-
Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Ammonia	0.2	kg	Elementary flow	-
Cadmium	2.75E-05	kg	Elementary flow	-
Carbon dioxide, fossil	2.8958	kg	Elementary flow	-

Carbon monoxide, from soil or biomass stock	8.4336	kg	Elementary flow	-
Chromium	0.00445	kg	Elementary flow	-
Copper	0.00243	kg	Elementary flow	-
Dinitrogen monoxide	0.06021	kg	Elementary flow	-
Lead	7.10E-04	kg	Elementary flow	-
Mercury	2.00E-06	kg	Elementary flow	-
Methane, from soil or biomass stock	0.2475	kg	Elementary flow	-
Nickel	0.00145	kg	Elementary flow	-
Nitrate	0.497	kg	Elementary flow	-
Nitrogen oxides	0.2292	kg	Elementary flow	-
NMVOC, non-methane volatile organic compounds, unspecified origin	0.036	kg	Elementary flow	-
Particulates, < 2.5 um	0.36	kg	Elementary flow	-
Phosphorus	0.00998	kg	Elementary flow	-
sugarcane	1	t	Product flow	-
Sulfur dioxide	0.04	kg	Elementary flow	-
Zinc	0.00218	kg	Elementary flow	-

S6.1.2 Milling stage

Table S6. 2 Compilation of inputs and outputs of processes in the milling stage of ethanol production, each process is normalized with a basis on its unit flow.

Juice extraction process Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Sugarcane	0.96	t	Product	(This study) Sugarcane San Carlos from the agricultural stage
Water, river	5.44	m3	Elementary flow	-
Electricity, high voltage	12.5	kWh	Product	From electricity co-generation stage

Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Bagasse from sugarcane	0.28	t	Waste	-
Mixed juice	1	t	Product	-
wastewater, average	6.03	m3	Waste	Ecoinvent [98] market for wastewater, average | wastewater, average | APOS, U - RoW

Juice clarification process

Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Mixed juice	1.07	t	Product	(This study) From the juice extraction process
Lime	0.00117	t	Product	Ecoinvent [98]market for lime | lime | APOS, U - RoW
lime, hydrated, packed	0.00023	t	Product	Ecoinvent [98]lime production, hydrated, packed | APOS, U - CH
Low-pressure steam	19.31	kWh	Product	(This study) From electricity co-generation power plant process
phosphoric acid, industrial grade	9.65E-06	t	Product	Ecoinvent [98] phosphoric acid, industrial grade, without water| APOS, U - GLO
Polyacrylamide	0.0000259	t	Product	Ecoinvent [98]market for polyacrylamide | polyacrylamide | APOS, U - GLO
Sulfur	2.70E-04	t	Product	Ecoinvent [98] market for sulfur | sulfur | APOS, U - GLO
Electricity, high voltage	2.72	kWh	Product	From electricity co-generation stage

Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
filter cake, from sugarcane juice filtration	0.027	t	Product	
Clarified juice	1	t	Product	-

Evaporation process

Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Clarified juice	5.39	t	Product	(This study) From juice clarification process
Low-pressure steam	2166.5	kWh	Product	(This study) From electricity co-generation process
neutralising agent, sodium hydroxide-equivalent	1.17E-05	t	Product	Ecoinvent [98] market for a neutralising agent, sodium hydroxide-equivalent | APOS, U - GLO

sodium hydroxide, without water	0.00153	t	Product	Ecoinvent [98] market for sodium hydroxide, without water, in 50% solution state| APOS, U - GLO
Electricity, high voltage	16.07	kWh	Product	From electricity co-generation stage
		Outputs		
Flow	Amount	Unit	Flow type	Life cycle inventory source
Sugarcane juice syrup	1	t	Product	-

Crystallization process

Inputs

Flow	Amount	Unit	Flow type	Life cycle inventory source
alkylbenzene sulfonate, linear, petrochemical	2.64E-06	t	Product	Ecoinvent [98] market for alkylbenzene sulfonate, linear, petrochemical | APOS, U - GLO
alkylbenzene sulfonate, linear, petrochemical	1.91E-06	t	Product	Ecoinvent [98] market for alkylbenzene sulfonate, linear, petrochemical| APOS, U - GLO
Sugarcane juice syrup	0.794	t	Product	(This study) From evaporation process
Electricity, high voltage	12.77	kWh	Product	From electricity co-generation stage
sodium perborate, tetrahydrate, powder	5.24E-06	t	Product	Ecoinvent [98] sodium perborate production, tetrahydrate, powder | APOS, S - RER
		Outputs		
Flow	Amount	Unit	Flow type	Life cycle inventory source
Masses A,B,C	1	m3	Product	-

Centrifugation process

Inputs

Flow	Amount	Unit	Flow type	Life cycle inventory source
Masses A,B,C	2.69	m3	Product	(This study) From cristallization process
Electricity, high voltage	68.79	kWh	Product	From electricity co-generation stage
		Outputs		
Flow	Amount	Unit	Flow type	Life cycle inventory source
Sugar	1	t	Product	
Molasses B	0.38	t	Product	
Molasses C	0.26	t	Product	

S6.1.3 Distillation stage

Table S6. 3 Compilation of inputs and outputs of processes in the distillation stage of ethanol production; each process is normalized with a basis on its unit flow.

Wort preparation process				
Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Clarified sugarcane juice	6.20E-04	t	Product	(This study) From juice clarification
Molasses B	2.10E-04	t	Product	(Thi study) From milling stage centrifugation
Molasses C	1.40E-04	t	Product	(This study) From milling stage centrifugation
Water, well, in ground	0.23	l	Elementary flow	-
Electricity, high voltage	0.00563	kWh	Product	From electricity co-generation stage
Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Wort (24-30° Brix)	1	l	Product	-

Fermentation process				
Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
fodder yeast	0.108	kg		Ecoinvent [98] market for fodder yeast | fodder yeast | APOS, U - GLO
Wort (24-30° Brix)	1.088	l	Product	(This study) From wort preparation
Electricity, high voltage	0.024	kWh	Product	From electricity co-generation stage
Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Fermented wort	1	l	Product	

Carbon dioxide	0.011	kg	Elementary flow	-
wastewater, average	0.01	l	Waste	Ecoinvent [98] market for wastewater, average | wastewater, average | APOS, U - RoW

Centrifugation process

Inputs

Flow	Amount	Unit	Flow type	Life cycle inventory source
Electricity, high voltage	0.046	kWh	Product	From electricity co-generation stage
Fermented wort	1.11	l	Product	(This study) From fermentation process

Outputs

Flow	Amount	Unit	Flow type	Life cycle inventory source
Juice wine (8-10°GL)	1	l	Product	-
fodder yeast	0.08	kg	Flow waste	Ecoinvent [98] market for fodder yeast | fodder yeast | APOS, U - GLO

Filtration process

Inputs

Flow	Amount	Unit	Flow type	Life cycle inventory source
Low-pressure steam	0.88	kWh	Product	(This study) From electricity co-generation process
Juice wine (8-10°GL)	4.55	l	Product	(This study) From centrifugation at distillery
Phelgms (0°GL)	0.10	l	Product	(This study) From rectification at distillery
Electricity, high voltage	0.070	kWh	Product	From electricity co-generation stage

Outputs

Flow	Amount	Unit	Flow type	Life cycle inventory source
Phelgms (45°GL)	1	l	Product	-
vinasse, from fermentation of sugarcane	5.32	kg	Product	-

Rectification process

Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Phelgms (45°GL)	2.21	l	Product	(This study) From filtration process

Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Phelgms (96°GL)	1	l	Product	-
Phelgms (0°GL)	1.21	l	Product	-

Adsorption process

Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
cyclohexane	9.80E-04	kg	Product	Ecoinvent [98] market for cyclohexane | cyclohexane | APOS, U - GLO
Phelgms (96°GL)	1	l	Product	(This study) From rectification process

Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Anhydrous ethanol	1	l	Product	-

S6.1.4 Co-generation stage

Table S6. 4 Compilation of inputs and outputs inventory for the co-generation stage per FU = 1 kWh of electricity

Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Heavy fuel oil	0.00017	kg	Product flow	Ecoinvent [98] market for heavy fuel oil| APOS, U - GLO
Bagasse from sugarcane	0.0035	t	Waste	
Water completely softened	0.00041	kg	Product flow	Ecoinvent [98] market for water, completely softened| APOS, U - GLO

Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Ash, from combustion of bagasse	0.00029	t		-

Low pressure steam	4.75	kWh	Product	-
Electricity, high voltage	1	kWh	Product	-
Carbon monoxide	5.146E-07	t	Elementary flow	-
Nitrogen oxides	5.23E-06	kg	Elementary flow	-
Particulates, < 2.5 um	6.39E-07	kg	Elementary flow	-

S6.2 Co-generation stage validation

The electricity yield in the co-generation plant of this study was 1.076 GJ/tonne of bagasse. Regarding steam, the yield was 4.86 GJ/tonne of bagasse. The steam yield in energy units, GJ/tonne of bagasse, was calculated by multiplying the saturated steam enthalpy in kJ/kg by the steam yield in kg/tonne of bagasse. Two articles with comparable information have been found in the literature, one for a sugar industrial complex in Brazil [23] and another in Australia [24]. The results of electricity and steam efficiency generation obtained from this study are in the same order of magnitude as those studies (Table S6. 5). However, the heat-to-power ratio and the cogeneration efficiency obtained in this study differ from what is found in both references. Despite this, these parameters are similar to the ranges stated by Birru et al. [104]: heat-to-power ratio (4-14.3) and total energy efficiency ranges (84-92%) for back-pressure steam turbines.

Table S6. 5 Comparison of heat-to-power ratio and co-generation efficiency of this study with literature

Reference	Bagasse type	LHV (GJ/t of bagasse)	Electricity (GJ/t of bagasse)	Steam (GJ/t of bagasse)	Steam + electricity (GJ/t of bagasse)	Cogeneration efficiency	Heat to power ratio
This study	Wet	7.74	1.08	4.86	5.94	76.72	4.51
Renouf et al. [23]	Wet		1.44	0.91	2.35	30.35	0.63
Guerra et al. [24]	NA		1.54	0.35	1.89	24.46	0.23

*50-51% moisture

7. Environmental analysis of road transport: sugarcane ethanol-gasoline blend flex-fuel vs battery-electric vehicles

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D. Arcentales as a Ph.D. Student did the conceptualization, methodology, investigation, writing, and visualization.

A. Ramirez, as supervisor, guided the conceptualization, the methodology, and the review and editing of the original draft.

C. Silva, as supervisor, guided the conceptualization and review and edit the original draft.

Abstract
Decarbonizing the passenger car transportation sector is mandatory. Nevertheless, other environmental impact categories should also be tackled. This research compares the life cycle environmental performance of passenger car transportation in Ecuador with energy carriers: first-generation ethanol-gasoline blends and electricity. The current battery electric vehicle (BEV) scenario utilizes electricity from the 2018 national mix, composed of 17% fossil and 83% renewable sources. Regarding the flex-fuel vehicle, the current scenario refers to the mixture percentage of ethanol-gasoline E5 (gasoline additivated with 5% of ethanol). The functional unit is defined as 1 km. The global warming potential (GWP) results are between 130-180 g $CO_{2\text{-eq}}$/km for E5 and 42–176 g $CO_{2\text{-eq}}$/km for BEVs. For future scenarios, the GWP ranges are 250-270 g $CO_{2\text{-eq}}$/km for E15 scenarios and 80-130 g $CO_{2\text{-eq}}$/km for E85 scenarios. E85 scenario has less GWP than BEV scenarios when fossil fuel electricity is used to charge them.

Keywords: renewables, transport, decarbonization, first-generation ethanol, carbon footprint, life cycle assessment

7.1 Introduction

On a global scale, energy consumption is considered the largest source of greenhouse gas (GHG) emissions from daily human activities [266]. About two-thirds of worldwide GHG emissions are related to burning fossil resources from human activities such as heating, electricity generation, transportation, and industry [267]. Fossil fuels comprise about 80% of worldwide primary energy demand [268]. Since the Industrial Revolution's early days, energy consumption produced through fossil fuels has constantly been growing [269]. The energy model that this society has prioritized is based on the extraction and consumption of these resources. However, the world economy and the development of this planet cannot continue to depend on these fossil resources. The dependence on these resources would rampantly accelerate global warming [270] and trigger serious problems such as rising sea levels, soil desertification, extreme weather events, and floods [270]–[272].

The transportation sector consumed approximately 31,310 terawatt-hours (TWh) of final energy in 2015 [273], one of the leading energy consumers worldwide. From an environmental perspective, transportation is the sector of the economy of many nations where

GHG emissions have constant growth [274]–[276]. The emissions of harmful gases produced in the transportation sector represent a latent threat to human health and its environment due to the variety of negative impacts they can generate, such as acidification, eutrophication, global warming, loss of biodiversity, and metal depletion [277]. According to Mohsin et al. [278], the transportation sector represented about 23% of global carbon dioxide emissions in 2016. These emissions could increase due to the vehicle fleet's growth, which will double by 2050 [279]. Most worldwide light-passenger cars use internal combustion engines that run on fossil fuels [280]. Nevertheless, France, Norway, the Netherlands, and the United Kingdom recently announced prohibitions on gasoline-powered vehicle sales in the foreseeable future [281], [282]. Moreover, the European Parliament proposed through Regulation 2019/631 that only zero-emissions vehicles will be allowed by 2035 [283]. The use of biofuels in internal combustion engine flex-fuel vehicles (ICEFFV), hydrogen in fuel-cell electric vehicles, and electricity in battery electric vehicles (BEVs) are being promoted as cleaner options to alleviate the environmental implications of the automotive industry [284]–[286]. However, charging stations with a reliable energy source must be readily available in metropolitan areas for these two technologies [287].

The Life Cycle Assessment (LCA) is a widely exploited tool to assess the environmental performance of a product, process, or service all around its life cycle. LCA standards are supplied by the International Organization for Standardisation (ISO) under the ISO 14040 and 14044 standards [234]. The application of this methodology has been frequent in transportation analysis studies. The initial LCA studies on transportation systems started in the 1970s [288]. For the environmental evaluation of transport, an LCA study usually includes (i) the fuel life cycle that refers to the fuel extraction, production, processing, distribution, and operation known as Well-to-Wheels (WTW); (ii) the vehicle life cycle, which relates to the vehicle manufacture, maintenance, and end-of-life (EoL). Table S1 from the Supporting Information presents peer-reviewed publications concerning the use of LCA in passenger car transportation options.

Due to overall carbon neutrality, biofuels continue to provide significant prospects for further emission reductions from the transportation sector [289], for the short-term and the long-term, even under extensive and fast vehicle fleet electrification [286]. There are

three biofuels: first-generation biofuels are derived from edible crops; second-generation biofuels come from cellulosic biomass sources; third-generation biofuels are related to algal biomass feedstock [290]. Ecuador has plenty of biomass resources [220], [291], and its first-generation ethanol is mainly produced through sugarcane crops. Notably, the environmental profile of sugarcane-derived ethanol is sensitive to the cane yield, the price of molasses, and the electricity co-generation through bagasse [160], [292]. Hence, it would be thought-inspiring to perform an LCA of ICEFFVs, including some of these parameters that influence the environmental performance of ethanol.

On the other hand, transportation electrification has been an opportunity to mitigate GHG emissions and stop dependence on fossil fuels. Several studies have utilized LCA tools to analyze GHG emission reduction through BEV insertion [293]–[297].

The BEVs and ICEFFVs are frequently studied independently, although their mitigation potentials are inextricably linked [286]. Future mitigation scenarios suggest that the amount of biofuels required for the transportation sector will be heavily influenced by the extent and rate of BEV implementation [298], [299]. LCA studies for passenger vehicles with different powertrains have been mainly performed in European countries, Australia, China, Brazil, Canada, and the United States of America [65], [288], [308], [309], [300]–[307]. Latin American countries apart from Brazil have not been investigated. LCA studies for energy systems in Ecuador have been performed for electricity [131], [223], [224], [228]–[230], [310], biodiesel [37] and ethanol [36], [37], [126], [292]. However, Ecuador's transportation sector has never been studied from a life cycle perspective. Transportation is the sector with the highest consumption in the country, with a helpful energy balance of 14001 GWh [311].

The present work compares the environmental performance of two different vehicle powertrains (battery electric vehicles - BEV and internal combustion engine flex-fuel vehicles - ICEFFV) and their respective energy carrier (electricity and different ethanol-gasoline blends) through a life cycle assessment in Ecuador. Current and future electricity mixes based on projections are considered for BEVs. Different blends of first-generation ethanol-gasoline flex-fuel vehicles are evaluated for internal combustion engine vehicles.

7.2 Materials and Methods

7.2.1 Scope

Table 7. 1 shows the technical characteristics of the fuel consumption and powertrain of the two analyzed vehicles. The two vehicles were selected for comparison based on their similar mass and power ratios. The flex-fuel vehicle has a mass of 1561 kg and an engine power of 132 kW; the battery electric vehicle has a mass of 1544 kg and an engine power of 112 kW.

Table 7. 1 Fuel consumption and powertrain technical specifications for the analyzed vehicles

Powertrain	Blends	Fuel consumption (l/km)[a]	Energy consumption (kWh/km)[b]	Powertrain technical characteristics
ICEFFV	E5	0.099	0.612	Spark ignition combustion type, Euro 5a emission standard, 132 kW of power engine, and 1596 cm3 of engine displacement.
	E15	0.093	0.57	
	E85	0.102	0.63	
BEV	n.a.	n.a.	0.14[c]	200 km per charge, 35 kWh capacity, 3.7 V cell nominal voltage.[c]

[a] Fuel consumption was obtained from [53]
[b] For ICEFFV energy consumption, the ethanol energy content used was 22.6 MJ/l.
[c] Powertrain technical characteristics and energy consumption for BEV were obtained from BEV [65], [312]. Includes charging

This study's breadth represents a cradle-to-grave strategy, considering the Well-To-Wheels (WTW) analysis and the vehicle life cycle, including the battery life cycle in the case of BEV. Figure 7. 1 shows the system boundaries of the BEVs. Figure 7. 2 shows the system boundaries of the ICEFFV. Table 7. 2 depicts the proposed scenarios for the two analyzed powertrains with their respective vector/energy carrier description. The analysis considers current, future, comparative, and single-resource electricity scenarios. For current scenarios, battery electric vehicles are evaluated using the Ecuadorian electricity mix of 2018; the ethanol-gasoline blend flex-fuel vehicles (E5) are assessed, including the effect of the type of electricity mix displacement: average (avg), marginal (mgl), and no displacement (no disp.) based on Arcentales et al. [313]. This latter study developed a system expansion for the surplus electricity produced in sugar mills, displacing the electricity produced in the national network. This is justified by the fact that the environmental burdens of displaced products are also expelled from the system

[41], [314]–[316]. For future scenarios, battery electric vehicles are analyzed using future electricity mixes (S1, S2, and S3 for 2030, 2040, and 2050) based on projections developed by the National Institute of Energy Efficiency and Renewable Energy [131], [317], and the ethanol-gasoline blend flex-fuel vehicles (E15 and E85) are performed considering the effect of the type of electricity generation displacement. It is noteworthy that, for this latter ethanol-gasoline blend flex-fuel scenarios (E15 and E85), in addition to shifting the average and marginal energy mix [292], scenarios were developed where energy mixes are shifted based on future projections [131], [317].

Moreover, vehicle efficiency improvements were assumed for future scenarios. For comparative purposes, the analysis considers a scenario using an inventory for ethanol production on a modern distillery plant in Brazil (E5 BR, E15 BR, and E85 BR). Another justification for using an inventory of ethanol produced in Brazil is that this inventory uses ‘’allocation at the point of substitution’’ as the allocation method, so we can be sure to compare everything aligned to this method. It is essential to point out that two different sugarcane yields (71 t/ha and 86 t/ha) are also considered for comparative purposes to analyze the effect of the environmental profile of the ethanol-gasoline blend flex-fuel vehicle by changing one of the variants that are sensitive to this energy vector. Finally, for the single resource electricity scenarios, three electricity mixes are evaluated on the BEV to analyze possible scenarios if the electricity mix is 100% hydro or 100% from non-renewable sources such as natural gas (NG) or fuel oil (FO). The 100% FO-ICE (fuel oil – internal combustion engine) mix scenario is modeled since it is the current marginal mix.

On the other hand, the 100% NG-CC (natural gas – combined cycle) mix scenario is also considered. According to the literature review, 100% NG-CC plant could be installed more regularly in the coming years and become the new marginal mix [318]–[320]. The

objective of these single-resource electricity scenarios is to establish the general trends regarding which resources to use for electricity generation: ethanol from biomass, hydropower, or two fossil fuels (current marginal and future marginal). It is noteworthy that, for ICEFFVs, CO_2 emissions data during the vehicle use phase are considered by Suárez-Bertoa et al. [53]. The sugarcane growth is assumed to compensate for biogenic CO_2 emissions due to the ethanol burning in ICEFFVs.

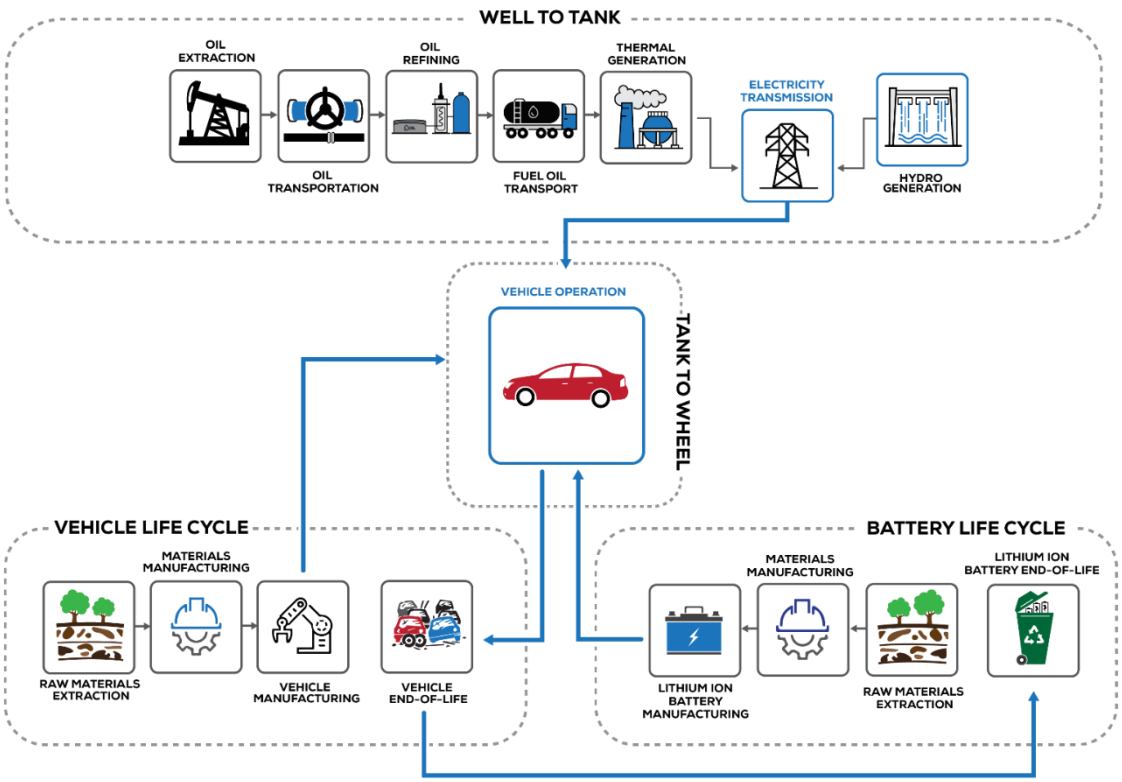


Figure 7. 1 General scheme of the system boundaries of the battery electric vehicle

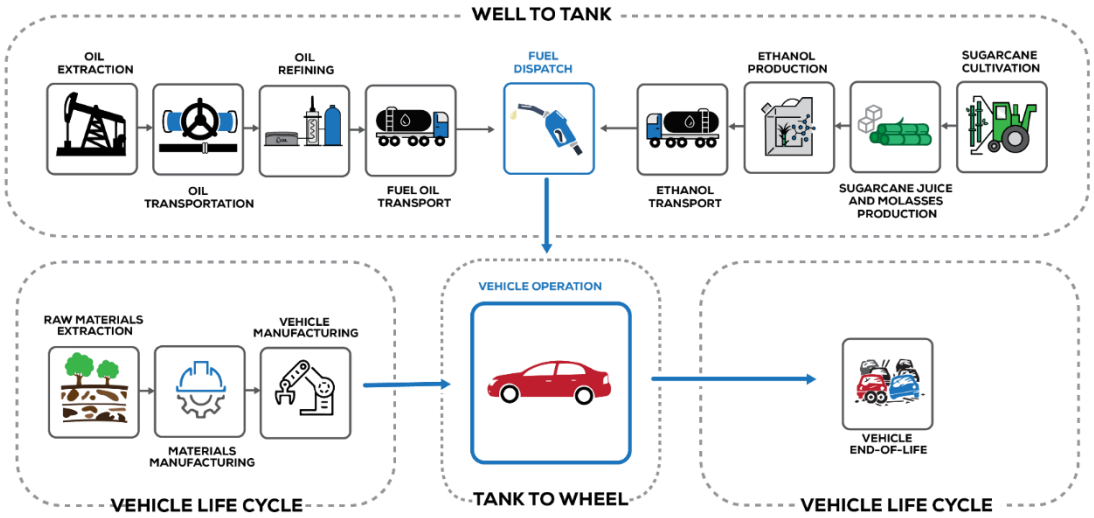


Figure 7. 2 General scheme of the system boundaries of internal combustion engine flex-fuel vehicles.

Table 7. 2 Proposed scenarios for the two analyzed powertrains with their respective energy carrier

Scenarios	Powertrain	Vector/carrier description	Ethanol-Gasoline blend	Ethanol data source	Sugarcane yield	Electricity mix*	Renewable - fossil share of electricity mix
BEV mix 2018	BEV	Electricity	n.a.	n.a.	n.a.	2018	83% - 17%
BEV S1-2030	BEV	Electricity	n.a.	n.a.	n.a.	S1-2030	65% - 35%
BEV S2-2030	BEV	Electricity	n.a.	n.a.	n.a.	S2-2030	75% - 25%
BEV S3-2030	BEV	Electricity	n.a.	n.a.	n.a.	S3-2030	76% - 24%
BEV S1-2040	BEV	Electricity	n.a.	n.a.	n.a.	S1-2040	66% - 34%
BEV S2-2040	BEV	Electricity	n.a.	n.a.	n.a.	S2-2040	65% - 35%
BEV S3-2040	BEV	Electricity	n.a.	n.a.	n.a.	S3-2040	66% - 34%
BEV S1-2050	BEV	Electricity	n.a.	n.a.	n.a.	S1-2050	46% - 54%
BEV S2-2050	BEV	Electricity	n.a.	n.a.	n.a.	S2-2050	47% - 53%
BEV S3-2050	BEV	Electricity	n.a.	n.a.	n.a.	S3-2050	62% - 38%
BEV 100% Hydro	BEV	Electricity	n.a.	n.a.	n.a.	100% hydropower	100% - 0%
BEV 100% FO-ICE	BEV	Electricity	n.a.	n.a.	n.a.	100% FO-ICE	0% - 100%
BEV 100% NG-CC	BEV	Electricity	n.a.	n.a.	n.a.	100% NG-CC	0% - 100%
E5 (avg) EC CO_2 (71 t/ha)	ICEFFVs	Ethanol-gasoline blend.	5% ethanol-95% gasoline	[313]	71 t/ha	2018 average	83% - 17%
E5 (avg) EC CO_2 (86 t/ha)	ICEFFVs	Ethanol-gasoline blend	5% ethanol-95% gasoline	[313]	86 t/ha	2018 average	83% - 17%
E5 (mgl) EC CO_2	ICEFFVs	Ethanol-gasoline blend	5% ethanol-95% gasoline	[313]	71 t/ha	2018 marginal	83% - 17%
E5 (no disp.) EC CO_2	ICEFFVs	Ethanol-gasoline blend	5% ethanol-95% gasoline	[313]	71 t/ha	No displacement	n.a.
E5 (avg) EC CO_2	ICEFFVs	Ethanol-gasoline blend	5% ethanol-95% gasoline	[313]	71 t/ha	2018 average	83% - 17%
E5 BR CO_2	ICEFFVs	Ethanol-gasoline blend	5% ethanol-95% gasoline	[321]	n.a.	n.a.	n.a.
E15 (avg) EC CO_2	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	2018 average	83% - 17%

E15 (mgl) EC CO_2	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	2018 marginal	83% - 17%
E15 (no disp.) EC CO_2	ICEFFVs	Ethanol-gasoline blend	5% ethanol-85% gasoline	[313]	71 t/ha	No displacement	n.a.
E15 EC CO_2 (S1-2030 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S1-2030	65% - 35%
E15 EC CO_2 (S2-2030 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S2-2030	75% - 25%
E15 EC CO_2 (S3-2030 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S3-2030	76% - 24%
E15 EC CO_2 (S1-2040 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S1-2040	66% - 34%
E15 EC CO_2 (S2-2040 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S2-2040	65% - 35%
E15 EC CO_2 (S3-2040 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S3-2040	66% - 34%
E15 EC CO_2 (S1-2050 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S1-2050	46% - 54%
E15 EC CO_2 (S2-2050 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S2-2050	47% - 53%
E15 EC CO_2 (S3-2050 disp.)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	S3-2050	62% - 38%
E15 EC CO_2 (avg)	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[313]	71 t/ha	2018 average	83% - 17%
E15 BR CO_2	ICEFFVs	Ethanol-gasoline blend	15% ethanol-85% gasoline	[321]	n.a.	n.a.	n.a.
E85 EC CO_2 (avg)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	2018 average	83% - 17%
E85 EC CO_2 (mgl)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	2018 marginal	83% - 17%
E85 EC CO_2 (no disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	No displacement	n.a.
E85 EC CO_2 (S1-2030 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S1-2030	65% - 35%
E85 EC CO_2 (S2-2030 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S2-2030	75% - 25%

E85 EC CO_2 (S3-2030 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S3-2030	76% - 24%
E85 EC CO_2 (S1-2040 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S1-2040	66% - 34%
E85 EC CO_2 (S2-2040 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S2-2040	65% - 35%
E85 EC CO_2 (S3-2040 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S3-2040	66% - 34%
E85 EC CO_2 (S1-2050 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S1-2050	46% - 54%
E85 EC CO_2 (S2-2050 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S2-2050	47% - 53%
E85 EC CO_2 (S3-2050 disp.)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	S3-2050	62% - 38%
E85 EC CO_2 (avg)	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[313]	71 t/ha	2018 average	83% - 17%
							n.a.
E85 BR CO2	ICEFFVs	Ethanol-gasoline blend	85% ethanol-15% gasoline	[321]	n.a.	n.a.	

*For BEVs, the electricity mix column refers to the electricity used for battery charging. For ICEFFVs, as the carbon footprint of ethanol systems that include co-generation depends on the mix or type of electricity displaced, this column refers to the environmental burdens of the displaced products that are also displaced. In almost all ICEFFV scenarios, the effect of surplus electricity co-generation is considered. Average, marginal, and no displacement mix scenarios for the co-generation plant are based on [292]. S1-2030, S1-2040, S1-2050, S2-2030, S2-2040, S2-2050, S3-2030, S3-2040, and S3-2050 electricity mixes are based on projections developed by the National Institute of Energy Efficiency and Renewable Energy [131], [317]. BEV: Battery electric vehicle; ICEFFVs: internal combustion engine flex-fuel vehicles; FO-ICE: fuel oil internal combustion engine; NG-CC: natural gas combustion engine; avg: average, mgl: marginal; no disp.: no displacement; n.a.: not applicable

The functional unit (FU) is a quantifiable unit of a product, service, or process performance that allows for comparison among comparable studies [233], [322], [323]. The functional unit for this study was defined as ‘’1 km traveled, considering the minimum energy consumption found in the literature for each vehicle powertrain and a lifetime of 150,000 km.’’. The minimum energy consumption for BEVs and ICEFFVs was 0.14 kWh/km [65], [66] and 0.106 l/km [53], respectively. Battery replacement was not considered in this study based on a recent study that concludes that batteries still satisfy the driver's daily travel requirements long after they have reached their commercial lifespan [324]. Moreover, the battery lifespan is estimated as 15 years based on [325].

A sensitivity analysis, shown in the Supporting Information (Figure S1), presents two different vehicle lifetimes (150,000 km and 230,000 km) and assumes two different energy consumptions (maximum and minimum). Most of the studies reviewed in the literature have a vehicle lifetime of 150,000 km [326]–[328]. The lifetime of 230,000 km is justified based on a study from Girardi et al. [329], who established that mileage lifetime for an e-Golf Volkswagen. The maximum energy consumptions found for BEVs and ICEFFVs were 0.24 kWh/km [300], [330] and 0.12 l/km [53], respectively.

7.2.2 Life cycle inventory (LCI) data sources

7.2.2.1 Energy carriers inventories

Table 7. 3 shows the inventory data sources for each energy carrier. The system model used for this study was the allocation method. The allocation method considered for this study was the ‘’Allocation at the point of substitution’’ (APOS). However, for ethanol production, a system expansion was developed for electricity co-generation to represent a change in the system. This latter information can be evidenced by Arcentales et al. [313].

7.2.2.2 Vehicle cradle-to-grave inventories

Table 7. 4 shows the vehicle life cycle inventory data sources for each relevant process (from cradle to grave)

7.2.2.3 Vehicle use

For the analysis of the environmental impact during the operation phase, it is essential to consider the emissions produced per kilometer traveled, the fuel or energy consumption of the vehicle, and the vehicle lifetime for the maintenance aspects. The fuel consumption and emission factors for E5, E15, and E85 ethanol-gasoline blend flex-fuel vehicles were obtained from Suárez-Bertoa et al. [53].

The battery electric vehicle's operation phase is associated with a number of charge-discharge cycles directly proportional to the vehicle traveled distance [288]. BEV has zero tailpipe emissions, but the electrical power source may negatively impact the environment.

Table 7. 3 Data sources for energy carriers' life cycle inventories

Energy carrier	System boundaries	References	Comments
Electricity*	Resource extraction, electricity generation, transport, infrastructure, and supply.	[131], [229], [317]	Future energy mixes are based on Espinoza et al. [317]
Ethanol	Sugarcane cultivation, sugarcane milling, electricity co-generation, and ethanol distillation.	[292]	The effect of electricity generation displacement was considered based on projections of future electricity mixes.
Gasoline**	The regional oil derivatives market, transportation, and distribution.	[321]	From the Colombian petrol inventory "market for petrol, unleaded | APOS, U – CO" and adapted to the Ecuadorian context based on the percentage of fuel imports [331]

*The dataset for natural gas–combined cycle (NG-CC) electricity generation was obtained from Mexico
**The original dataset was based on surveys mainly for Germany and Switzerland

Table 7. 4 Data sources for each vehicle life cycle inventories

Process description	System boundaries	References	Comments

Internal combustion engine flex-fuel vehicle manufacturing and end-of-life	Vehicle production, infrastructure, transport, maintenance, and dismantling.	[321]	From the inventory, "Passenger car production petrol/natural gas." This vehicle is compatible with an Ecuadorian sedan passenger vehicle [332].
BEV manufacturing	Vehicle production without battery, infrastructure, transport, and dismantling.	[321]	
Lithium-ion battery manufacturing*	Battery manufacturing (includes mining) and transport	[333] [312]	Nickel-manganese-cobalt battery (NMC). Most of the information for NMC Li-ion battery production was obtained from Accardo et al. [312]. Injection molding value data used for non-cell materials production was obtained from Majeau-Bettez et al. [333].
Lithium-ion battery end-of-life	Battery recycling and transport	[321]	This dataset represents a 50-50 mix of the two different technologies for the treatment of Li-Ion batteries: pyrometallurgical and hydrometallurgical.

*The lithium-ion battery is assumed to be produced in China. This assumption relies on China being the global market leader for NMC cathodes.

Regarding the energy consumption of BEV, a minimum value was selected based on peer-reviewed publications that also analyze compact passenger cars [288], [300], [330], [334]–[338]. The minimum energy consumption found was 0.14 kWh/km [66].

7.2.3 Life cycle impact assessment (LCIA)

OpenLCA v1.10.3 was used to quantify the environmental performance in the evaluated scenarios [339]. The quantification of the environmental impacts was based on the ReCiPe midpoint methodology from a hierarchical (H) perspective. Nine midpoint impact indicators were used to analyze the scenarios and are defined in Table 7. 5. The selected impacts are relevant for the road transportation sector: ozone depletion, global warming, eutrophication, particulate matter formation, photochemical oxidant formation, and terrestrial acidification, which are a consequence of atmospheric emissions [340], [341]; metal depletion due to battery electric vehicles and fossil fuel depletion due to over-extraction of fossil resources.

Table 7. 5 Midpoint impact indicators selected with their brief definition

Midpoint impact indicator	Definition*
Global warming potential (GWP)	Cumulative radiative over a specified time horizon results from greenhouse gas emissions.
Fossil depletion potential (FDP)	Over-extraction of all fossil resources.
Freshwater eutrophication potential (FEP)	Freshwater quality degradation.
Marine eutrophication potential (MEUP)	Marine water quality degradation due to nutrient enrichment.
Metal depletion potential (MDP)	Scarcity of mineral resources and metals.
Ozone depletion potential (ODP)	Reduction in the density of the stratospheric ozone layer.
Particulate matter formation potential (PMFP)	Atmospheric pollutants of primary and secondary particulate matter precursors.
Photochemical oxidant formation potential (POFP)	Quantifies the photochemical reactions of volatile organic compounds causing adverse effects on human health.
Terrestrial acidification potential (TAP)	This impact measures the increase in the acidity of soil due to atmospheric pollutants such as SO2 and NOx.

*Impact categories definition were obtained from [342], [343]

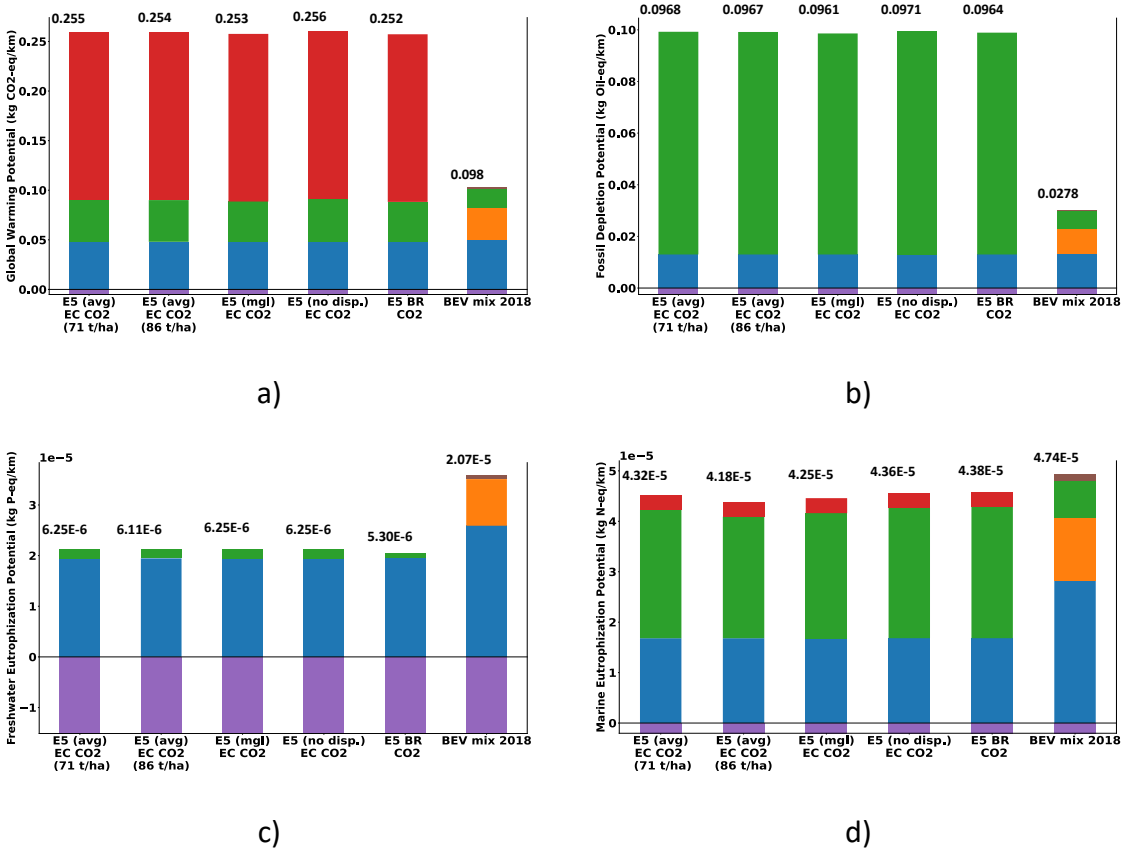
7.3 Results and Discussions

The environmental impact results are given for the two vehicle powertrains (1) for current scenarios, (2) for future scenarios (2030, 2040, and 2050), and (3) for single resource electricity scenarios through a comparison with current scenarios.

7.3.1 Environmental impacts for current scenarios

LCIA results for current scenarios are analyzed for various vehicle life cycle phases: i) vehicle production, ii) battery production, iii) energy carrier production, iv) vehicle use, v) vehicle end-of-life, and vi) battery end-of-life. The vehicle and battery end-of-life includes recycling all the reusable materials such as metal and plastic parts. Figure 7. 3 illustrates the environmental impact results of the two powertrain systems based on current frameworks. The scenario with the lowest GWP impact is the BEV mix 2018 with 0.098 kg CO_2 eq./km, followed by E5 BR CO_2 with 0.252 kg CO_2 eq./km (Figure 7. 3a). The scenario with the highest GWP impact is the E5 (no disp.) EC CO_2 with 0.256 kg CO_2 eq./km, followed by E5 (avg) EC CO_2 (71 t/ha) with 0.255 kg CO_2 eq./km, E5 (avg) EC CO_2 (86 t/ha) with 0.254 kg CO_2 eq./km and E5 (mgl) EC CO_2 with 0.253 kg CO_2 eq./km. These results show that the GWP impact caused by ICEFFVs depends on the electricity co-generation displacement and the sugarcane productivity index to a lesser

extent. Electricity co-generation displacement means that the surplus electricity produced in sugar mills displaces electricity produced in the national network. Therefore, the environmental burdens of the network electricity are also displaced. When no surplus electricity is considered (no displacement) in ICEFFVs, the GWP is higher because there are no avoided environmental burdens from displaced products. When surplus electricity is considered (average or marginal) in ICEFFVs, the marginal electricity mix displacement scenario shows a lower GWP than the average electricity mix displacement scenario. This latter is justified by the marginal electricity mix generating higher environmental burdens that are then avoided.



a) b)

c) d)

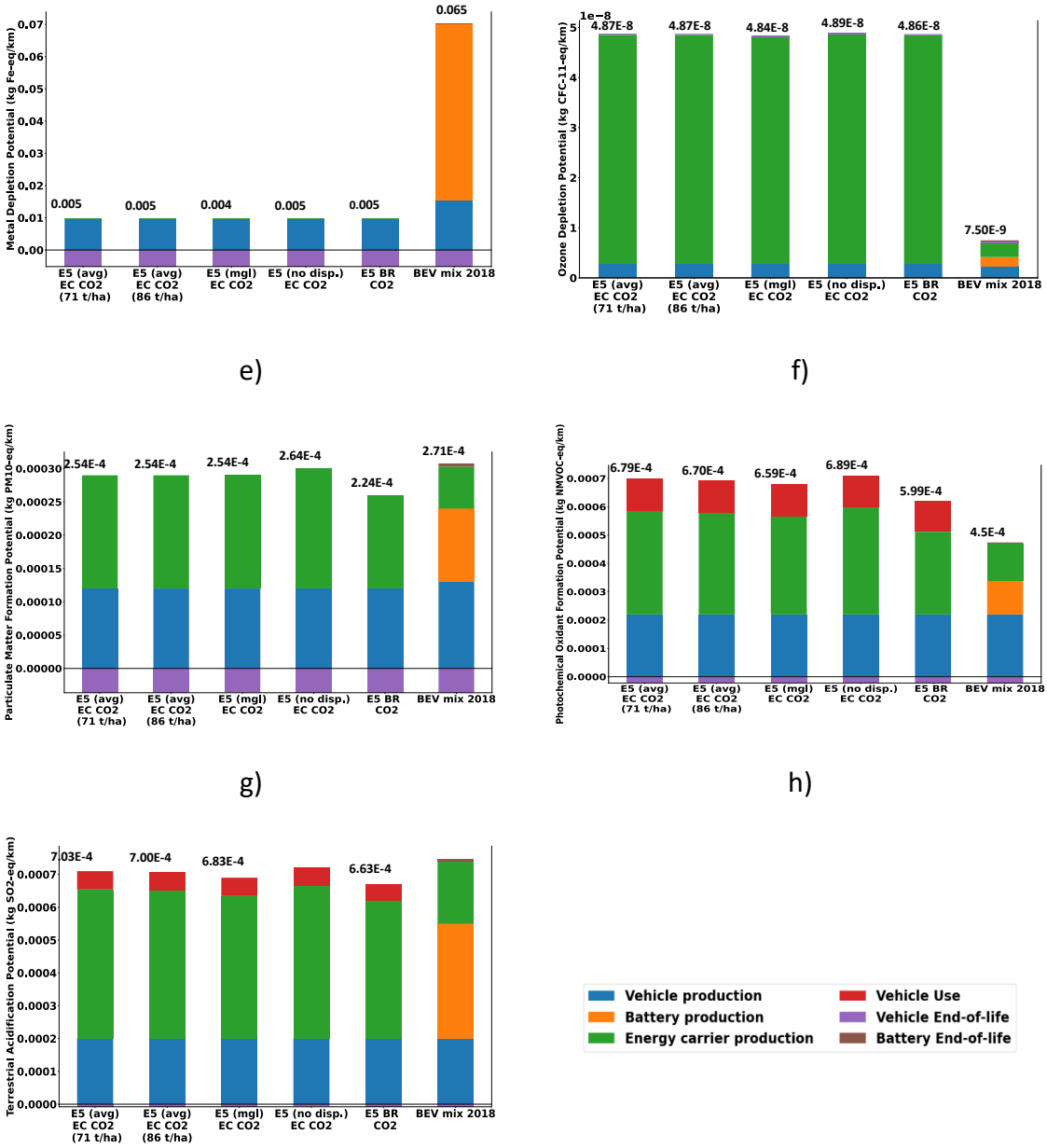


Figure 7. 3 Environmental impact results for the analyzed vehicles based on current scenarios: a) global warming potential; b) fossil depletion potential; c) freshwater eutrophization; d) marine eutrophization; e) metal depletion potential; f) ozone depletion potential; g) particulate matter formation potential; h) photochemical oxidant formation potential and i) terrestrial acidification potential.

In terms of overall contribution by stages for the BEV, vehicle manufacturing has the highest contribution with 51% of the GWP impact, followed by battery production with 32%, energy carrier production with 20%, battery end-of-life with 1.5%, and vehicle end-of-life with -5% due to recycling credits. The vehicle end-of-life includes reusing and recycling all the resources and recovery materials such as metal and plastic parts. This latter provokes resources and energy savings. Thus, the avoided pollutant emissions cause

environmental benefits, and vehicle end-of-life values are negative in some environmental impact categories. On the other hand, the vehicle use phase on an ethanol-gasoline blend flex-fuel vehicle contributes 68% of the GWP life cycle, followed by the vehicle manufacturing process with 18% and energy carrier production with 16%. The vehicle end-of-life has a negative GWP contribution of -2% but is favorable to the environment due to materials recovery. Energy carrier production contributes considerably to the GWP life cycle impact, mainly due to higher diesel consumption and agrochemical use in agricultural activities.

The results obtained for the potential impact of fossil depletion (measured in kg of oil equivalent) have similarities to the GWP impact because both are directly proportional to fossil fuel consumption. The scenario with the lowest FDP impact is taken by BEV mix 2018 with 0.0278 kg oil-eq./km (Figure 7. 3b). From a contribution perspective, vehicle manufacturing contributes 48% of the overall FDP impact, followed by battery production and energy carrier production with 35% and 24%, respectively. On the other hand, the energy carrier production phase on an ethanol-gasoline blend flex-fuel vehicle contributes 89% of the FDP life cycle. In comparative terms, based on the actual mix, the BEV using the 2018 electricity mix is more ecological with 0.0278 kg oil-eq./km than the best baseline E5 (mgl) EC CO_2 scenario with 0.0961 kg oil-eq./km.

The potential impact of freshwater eutrophication is measured in kg of phosphorous (P) equivalents. The best environmental scenario is the E5 BR CO_2 with 5.30 E-06 kg P-eq./km, followed by the E5 (avg) EC CO_2 (86 t/ha) with 6.10 E-06 kg P-eq./km, the E5 (mgl) EC CO_2 with 6.24 E-06 kg P-eq./km, the E5 (avg) EC CO_2 (71 t/ha) with 6.2512 E-06 kg P-eq./km, the E5 (no disp.) EC CO_2 with 6.254 E-06 kg P-eq./km and the BEV mix 2018 scenario with 2.07 E-05 kg P-eq./km (Figure 7. 3c). From a contribution level, vehicle manufacturing has 84% of the overall FEP impact, followed by energy carrier

production with 15%. Electric vehicles significantly contribute to this impact because of the discharge of mining waste in mineral extraction for battery production and vehicle production processes.

For the marine eutrophication potential impact (expressed in kg nitrogen equivalent), the E5 (avg) EC CO_2 (86 t/ha) scenario is the most environmentally friendly option with 4.19 E-05 kg N-eq./km (Figure 7. 3d). All other flex-fuel vehicle scenarios have a similar MEUP impact in a range of 4.26 E-05 kg N-eq./km to 4.39 E-05 kg N-eq./km for E5 (mgl) EC CO_2 and E5 BR CO_2 respectively. On average, the energy carrier production on an ethanol-gasoline vehicle contributes 60% of the MEUP life cycle, followed by vehicle manufacturing with 38%. On the other hand, the vehicle's end-of-life has a negative MEUP contribution of -5 % due to recycling credits. The battery electric vehicle has an impact of 4.74 E-05 kg N-eq./km. Based on comparative terms, the E5 flex-fuel vehicle has a lower environmental impact than the BEV mix 2018 in most of the analyzed scenarios.

Regarding the metal depletion potential (MDP) impact, the E5 BR CO_2 scenario shows the best environmental result with 0.004567 kg Fe-eq./km, followed by the E5 (avg) EC CO_2 (86 t/ha) and the E5 (avg) EC CO_2 (71 t/ha) with 0.0045979 kg Fe-eq./km (Figure 7. 3e). Based on contribution terms, vehicle production has 98% of the overall impact, and the other 2% corresponds to energy carrier production. The BEV mix 2018 scenario shows the worst environmental result with 0.065 kg Fe-eq./km. It is essential to mention that battery manufacturing has the highest impact contribution, with 78% and vehicle production has 21% of the overall life cycle impact. In comparative terms, BEVs show a higher impact contribution than ethanol-gasoline vehicles due to the metals used for battery manufacturing.

The potential impact of ozone depletion is measured in an equivalent value of trichlorofluoromethane (CFC-11 eq.). The best environmental scenario refers to BEV mix 2018 with 7.50 E-09 kg CFC-11-eq./km). For life cycle stages analysis, on average, energy carrier production has the highest contribution with 38%, followed by vehicle and battery manufacturing with 29% and 25%, respectively (Figure 7. 3f). Regarding ethanol-gasoline vehicles, the worst environmental scenario is the E5 (no disp.) EC CO_2 vehicle, which accounts for 4.89 E-08 kg CFC-11-eq/km. The E5 (mgl) EC CO_2 scenario reported the lowest value with 4.841 E-08 kg CFC-11-eq./km. Most ODP emissions are generated during the energy carrier production on ethanol-gasoline blend flex-fuel vehicles, with almost 94% contribution on average. These emissions are present in ethanol production by applying fertilizers, pesticides, and herbicides.

The E5 BR CO_2 shows the best environmental profile for the particulate matter formation potential impact with 0.00022 kg PM10-eq/km, followed by the other flex-fuel vehicles with 0.00025 kg PM10-eq/km and the BEV mix 2018 scenario with a value of 0.00027 kg PM_{10}-eq/km (Figure 7. 3g). Regarding life cycle stage contribution for battery electric vehicles, the most significant contribution is vehicle manufacturing, with 48%, followed by battery manufacturing, with 40% on average. Vehicle manufacturing has the highest contribution, mainly due to processing components for gliders and powertrains. Electricity generation also substantially participates 23% in the overall impact. On the other hand, for flex-fuel vehicles, the energy carrier production has 65% of the overall PMFP impact on average, followed by vehicle production with 50%. The vehicle's end-of-life has a negative contribution of -15 % due to materials recovery. In comparative terms, electric vehicle scenarios seem more environmentally friendly than ethanol-gasoline blend flex-fuel vehicles, except for flex-fuel vehicles using ethanol produced in Brazil.

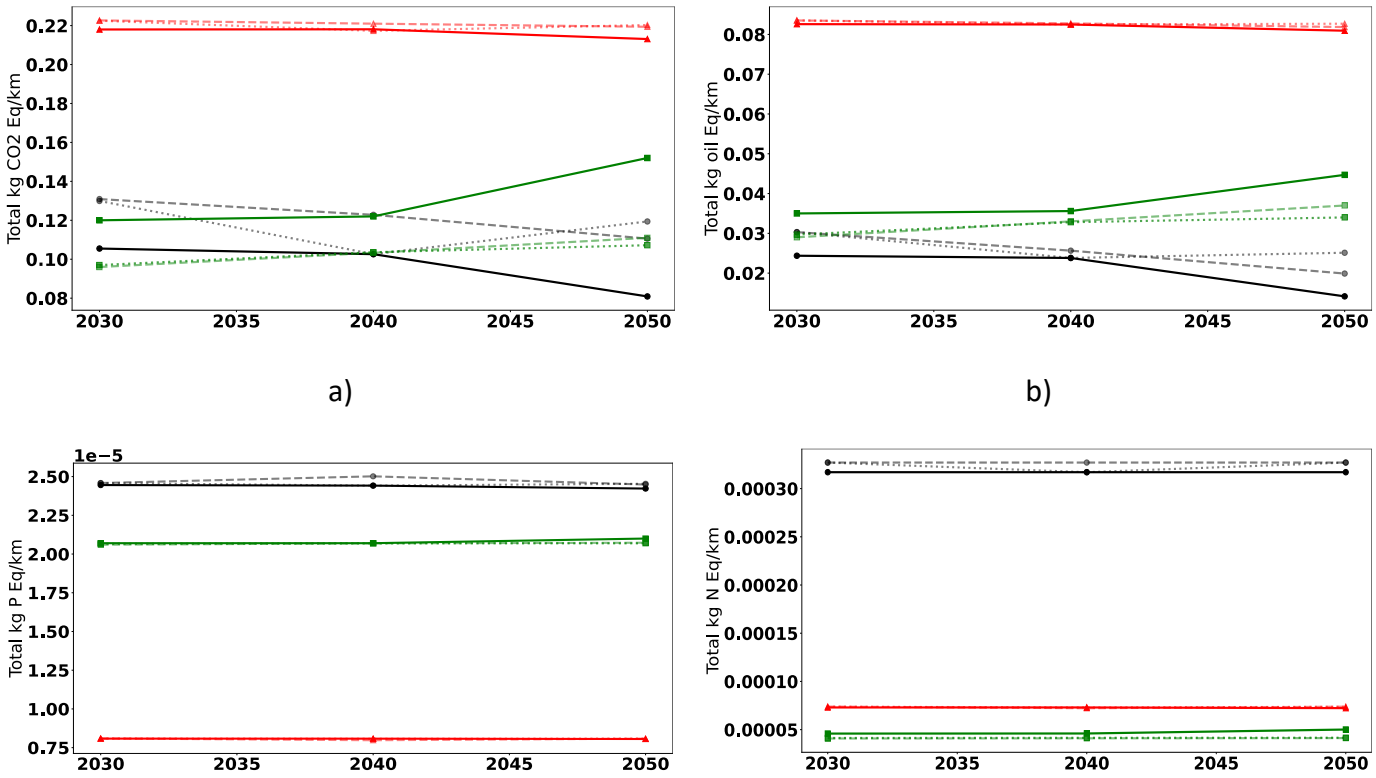
The photochemical oxidant formation potential (POFP) is measured in kilograms of NMVOC-eq./km. Figure 7. 3h shows that the scenario BEV mix 2018 presents the best environmental result for the POFP impact category (0.00045 kg NMVOC-eq./km). Regarding average contribution, vehicle production has 49% of the overall POFP impact, followed by energy carrier production with 29% and battery production with 27%. The high environmental impact of battery production results from metal mining activities and electronic parts manufacturing. The vehicle's end-of-life has a negative contribution of -5 % based on plastics and metals recovery. In terms of ethanol-gasoline blend flex-fuel vehicles, the worst environmental scenario is represented by the E5 (no disp.) EC CO_2 with 0.00069 kg NMVOC-eq./km, followed by the E5 (avg) EC CO_2 (71 t/ha) with 0.00068 kg NMVOC-eq./km. Based on the average contribution per stage on ethanol-gasoline vehicles, the energy carrier production shows a higher input on POFP overall impact with 53%, followed by vehicle manufacturing with 34% and vehicle use with 17%. Comparing BEVs with ethanol-gasoline vehicles, the BEV results in a better-promising technology to reduce ground-level ozone precursors.

Regarding the impact of terrestrial acidification potential (TAP), the BEV mix 2018 scenario reports a value of 0.0007 kg SO_2-eq./km (Figure 7. 3i). On average, the life cycle of the battery production was responsible for a significant portion of the TAP impact due to the large consumption of metals and plastics. Battery production contributes overall with 47%, followed by vehicle production with 27%, energy carrier production with 25%, and battery end-of-lie with 1%. Vehicle end-of-life has a negative contribution of -1%. According to ethanol-gasoline blend flex-fuel vehicles, the scenario with the highest TAP impact is represented by the E5 (no disp.) EC CO_2 with 0.00071 kg SO_2-eq./km. Energy carrier production contributes to this impact category with 64%, followed by vehicle

production with 30% and vehicle use with 7%. On the other hand, vehicle end-of-life has a negligible positive environmental impact of -1 %.

7.3.2 Environmental impacts for future scenarios

Figure 7. 4 illustrates the environmental impact results of the two powertrain systems based on future frameworks. The scenario with the lowest GWP impact is the E85 (S12050 displacement) EC CO_2-A with 0.0809 kg CO_2 eq./km followed by the E85 (S12040 displacement) with 0.103 kg CO_2 eq./km (Figure 7. 4a). These latter results suggest that when ethanol percentage is high on an ethanol-gasoline blend flex-fuel vehicle, the GWP impact is low. This is mainly due to the overall carbon neutrality of sugarcane production. Moreover, the effect of electricity cogeneration displacement on ethanol production evidences that ICEFFVs have a lower environmental burden when the electricity being displaced has a higher environmental impact [292].



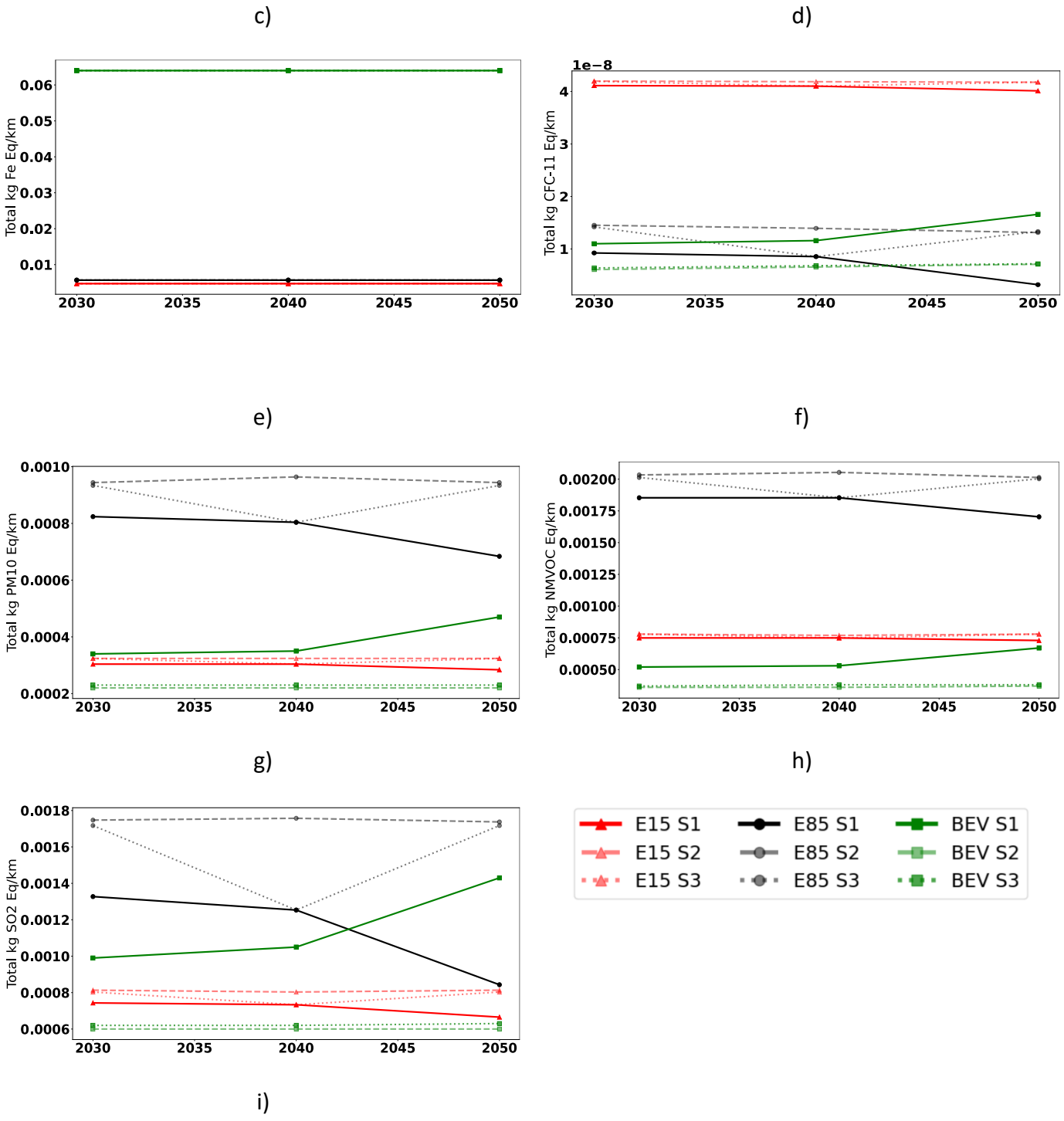


Figure 7. 4 Environmental impact results for the analyzed vehicles based on future scenarios: a) global warming potential; b) fossil depletion potential; c) freshwater eutrophization; d) marine eutrophization; e) metal depletion potential; f) ozone depletion potential; g) particulate matter formation potential; h) photochemical oxidant formation potential and i) terrestrial acidification potential.

Considering BEV scenarios, the lowest GWP impact is shown by the BEV using the mix S3-2030 with 0.093 kg CO_2 eq./km, followed by the BEV using the mix S2-2030 with 0.097 kg CO_2 eq./km. The BEV represents the worst environmental scenario using the

mix S1-2050 with 0.15 kg CO_2 eq./km. Regarding the E15 flex-fuel vehicles, the E15 (S2-2030 displacement) EC CO_2 scenario shows the highest GWP impact with 0.223 kg CO_2 eq./km, followed by E15 (S3-2030 displacement) EC CO_2 with 0.220 kg CO_2 eq./km. Based on a comparison between BEV and ethanol-gasoline blend flex-fuel vehicles, the E85 (S1-2050 displacement) scenario is environmentally friendlier than BEV scenarios solely when the electricity mix is used as an energy carrier on BEVs still depends on fossil resources such as S1 and S2 for 2050.

The best environmental option for the fossil depletion potential (FDP) impact is the E85 (S1-2050 displacement) EC CO_2 scenario with 0.014 kg oil-eq./km, followed by the E85 (S1-2040 displacement) EC CO_2 scenario with 0.023 kg oil-eq./km, as shown in Figure 7. 4b. The BEVs scenarios report values between 0.029 – 0.044 kg oil-eq./km. The worst environmental options are E15 scenarios (values between 0.0809 – 0.0835 kg oil-eq./km). The E85 scenarios look environmentally friendlier than any BEVs, mainly due to the fossil dependence on electricity mixes (S1, S2, and S3) used for BEV charging.

For the freshwater eutrophication potential (FEP), Figure 7. 4c shows that the best environmental profile is attributed to the scenarios with 15% ethanol-85% gasoline blend with FEP values ranging between 7.98 E-06 – 8.09 E-06 kg P-eq./km. The BEV scenarios have FEP values ranging between 2.07 E-05 and 2.10 E-05 kg P-eq./km. The worst environmental option refers to the scenarios powered by ethanol 85% - gasoline 15% blend with values ranging between 2.42 E-05 – 2.50 E-05 kg P-eq./km. It is essential to highlight that E85 vehicles significantly contribute to this impact due to the application of agrochemicals in agriculture activities such as the fertilization stage.

The marine eutrophication potential (MEUP) is shown in Figure 7. 4d. The BEVs scenarios are the best environmental options with MEUP values ranging between 4.08 E-

05 to 5.01 E-05 kg N-eq./km. The E15 scenarios report MEUP values between 7.23 E-05 to 7.39 E-05 kg N-eq./km. The worst environmental performance is attributed to the scenarios with higher ethanol content, with values ranging from 3.17 E-04 to 3.27 E-04 kg N-eq./km. Similar to the impact analyzed above, the increase of agrochemical application in agricultural activities due to expansion is sensitive to this impact.

For the metal depletion potential (MDP), the best environmental profile is attributed to the E15 scenarios with 0.0047 kg Fe-eq./km compared to the E85 scenarios with a value of 0.0056 kg Fe-eq./km, as shown in Figure 7. 4e. The worst environmental profile is assigned to the BEVs scenarios with 0.064 kg Fe-eq./km. This latter is justified due to the metals used for battery manufacturing in BEVs.

Regarding the ozone depletion potential (ODP), the scenarios with the lowest environmental profile are the E85 flex-fuel vehicles with values ranging between 3.20 E-09 kg CFC-11-eq./km from the E85 (S1-2050 disp.) EC CO_2 scenario, to 9.25 E-09 kg CFC-11-eq./km from the E85 (S1-2030 disp.) EC CO_2 scenario. Considering BEV scenarios, which have ODP results between E15 and E85 flex-fuel vehicles, the BEV's lowest ODP impact is shown by the mix S2-2030 with 6.08 E-09 kg CFC-11-eq./km followed by the BEV using the mix S3-2030 with 6.39 E-09 kg CFC-11-eq./km. The highest ODP impact is shown by the E15 (S2-2030 disp.) EC CO_2 scenario with 4.20 E-08 kg CFC-11-eq./km (Figure 7. 4f). Similar to the GWP impact, these results suggest that the ODP impact decreases when ethanol percentage increases on an ethanol-gasoline blend flex-fuel vehicle.

For the particulate matter formation potential (PMFP), the best environmental scenarios refer to the BEVs using S3-2030 and S3-2050 mixes with 0.00020 and 0.00023 kg PM_{10}-eq./km, respectively (Figure 7. 4g). E15 scenarios are less environmentally friendly than

BEV scenarios except for the BEV using S1-2050 electricity mix with 0.00042 kg PM_{10}-eq./km. This latter is justified due to the electricity mix's fossil dependence for that year's projection. The worst environmental profile is attributed to the E85 scenarios, with values ranging from 0.00068 to 0.00094 kg PM_{10}-eq./km.

Considering the photochemical oxidant formation (POFP), the best environmental option is attributed to BEV scenarios with values ranging from 0.00036 to 0.00067 kg NMVOC-eq./km, as shown in Figure 7. 4h. The E15 scenarios report values ranging from 0.00073 to 0.00078 kg NMVOC-eq./km. The worst environmental profile is attributed to the E85 scenarios, with values ranging from 0.0017 to 0.0020 kg NMVOC-eq./km. These latter results suggest that increasing the ethanol percentage is not a good option for this impact category.

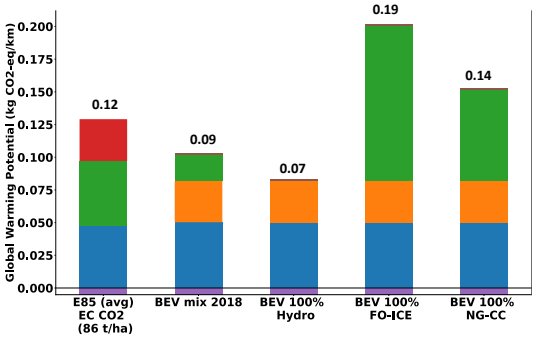
For the terrestrial acidification potential (TAP), the lowest TAP burden is referred to the BEV scenarios with values ranging from 0.0006 to 0.0014 kg SO_2-eq./km (Figure 7. 4i). The E15 scenarios have a lower environmental profile than the E85 scenarios, with TAP values ranging from 0.00067 to 0.00081 kg SO_2-eq./km. The worst environmental performance is attributed to the E85 scenarios with TAP values ranging from 0.00084 kg SO_2-eq./km for E85 (S1-2050 displacement) EC CO_2 to 0.00176 kg SO_2-eq./km for E85 (S2-2040 displacement) EC CO_2. These results suggest that the increase in ethanol percentage would reflect a higher soil acidity. This is mainly due to fertilizers used for sugarcane production.

7.3.3 Environmental impacts for single resource electricity scenarios

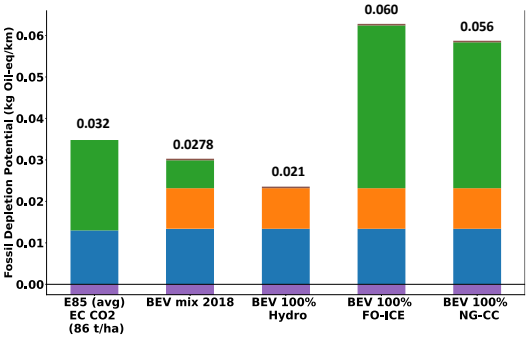
The environmental impact results of five scenarios: E85 (avg) EC CO_2 (86 t/ha), BEV mix 2018, BEV 100% Hydro, BEV 100% FO-ICE, and BEV 100% NG-CC are shown in Figure 7. 5. The BEV scenario's lowest GWP impact is depicted using 100% hydroelectricity with 0.078 kg CO_2-eq./km, followed by the BEV mix 2018 scenario with

0.098 kg CO_2-eq./km (Figure 7. 5a). The E85 (avg) EC CO_2 (86 t/ha) scenario has a lower burden (0.124 kg CO_2-eq./km) than BEV using electricity 100% fossil (NG-CC and FO-ICE). These latter results suggest that BEVs are more environmentally friendly when the electricity used for charging is primarily renewable. If the electricity used to charge BEVs is fossil, ICEFFVs with higher ethanol contribution have better environmental performance. This latter is supported by the fact that the energy vector used by BEVs includes a carbon-intensive resource; the ethanol system can displace the environmental burdens produced by the highly fossil fuel electricity mix. Regarding overall contribution by stage for E85 scenario, energy carrier production has the highest contribution to GWP impact with 38%, followed by vehicle production with 37% and vehicle use with 29%. Vehicle end-of-life has a contribution of -4% due to materials recovery. For the BEV 100% hydro scenario, vehicle production has the highest contribution at 64%, followed by battery production at 40% and energy carrier production at a negligible contribution of 0.08% due to hydroelectricity.

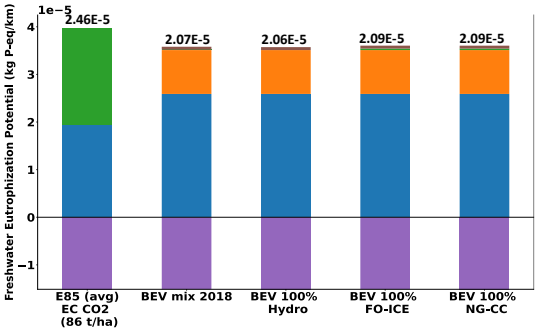
The fossil depletion potential shows a similar environmental performance to global warming potential (Figure 7. 5b). Regarding the FEP and MEUP impacts, the BEV using 100% hydroelectricity scenario has the lowest environmental impacts with 2.06 E-05 kg P-eq./km and 3.99 E-05 kg N-eq./km, respectively. The E85 scenario has higher burdens than any BEV scenario, with 2.46 E-05 kg P-eq./km and 3.17 E-04 kg N-eq./km, respectively (Figure 7. 5c and Figure 7. 5d). These results are justified by the agrochemicals application in agriculture activities, being sensitive to these impacts.


Global Warming Potential (kg CO2-eq/km)
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
0.12
0.09
0.07
0.19
0.14
E85 (avg) EC CO2 (86 t/ha)
BEV mix 2018
BEV 100% Hydro
BEV 100% FO-ICE
BEV 100% NG-CC

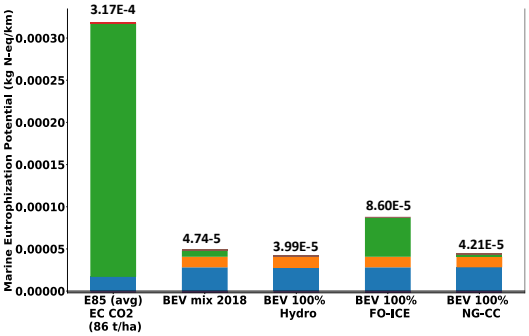
a)


Fossil Depletion Potential (kg Oil-eq/km)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.032
0.0278
0.021
0.060
0.056
E85 (avg) EC CO2 (86 t/ha)
BEV mix 2018
BEV 100% Hydro
BEV 100% FO-ICE
BEV 100% NG-CC

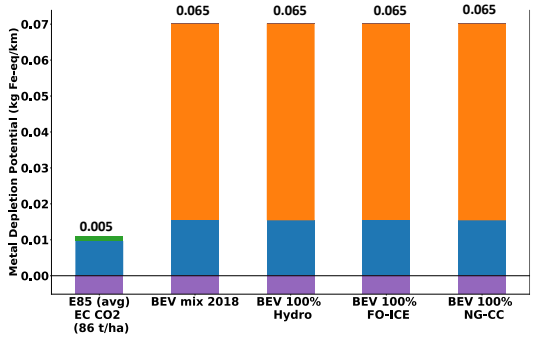
b)


Freshwater Eutrophization Potential (kg P-eq/km)
1e−5
4
3
2
1
0
−1
2.46E-5
2.07E-5
2.06E-5
2.09E-5
2.09E-5
E85 (avg) EC CO2 (86 t/ha)
BEV mix 2018
BEV 100% Hydro
BEV 100% FO-ICE
BEV 100% NG-CC

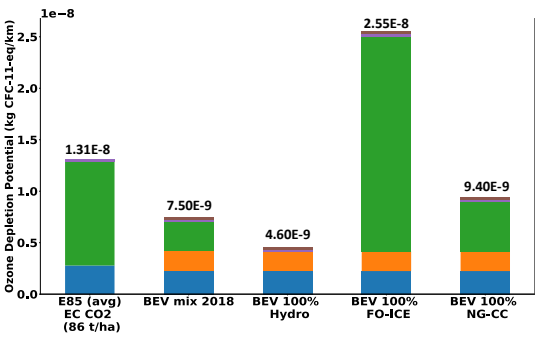
c)


Marine Eutrophization Potential (kg N-eq/km)
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
3.17E-4
4.74-5
3.99E-5
8.60E-5
4.21E-5
E85 (avg) EC CO2 (86 t/ha)
BEV mix 2018
BEV 100% Hydro
BEV 100% FO-ICE
BEV 100% NG-CC

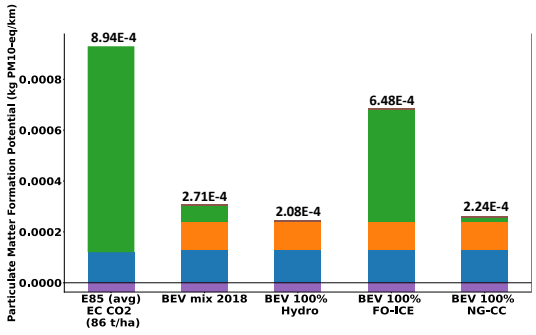
d)


Metal Depletion Potential (kg Fe-eq/km)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.005
0.065
0.065
0.065
0.065
E85 (avg) EC CO2 (86 t/ha)
BEV mix 2018
BEV 100% Hydro
BEV 100% FO-ICE
BEV 100% NG-CC

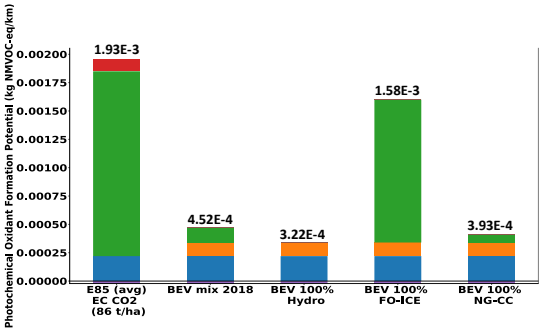
e)


Ozone Depletion Potential (kg CFC-11-eq/km)
1e−8
2.5
2.0
1.5
1.0
0.5
0.0
1.31E-8
7.50E-9
4.60E-9
2.55E-8
9.40E-9
E85 (avg) EC CO2 (86 t/ha)
BEV mix 2018
BEV 100% Hydro
BEV 100% FO-ICE
BEV 100% NG-CC

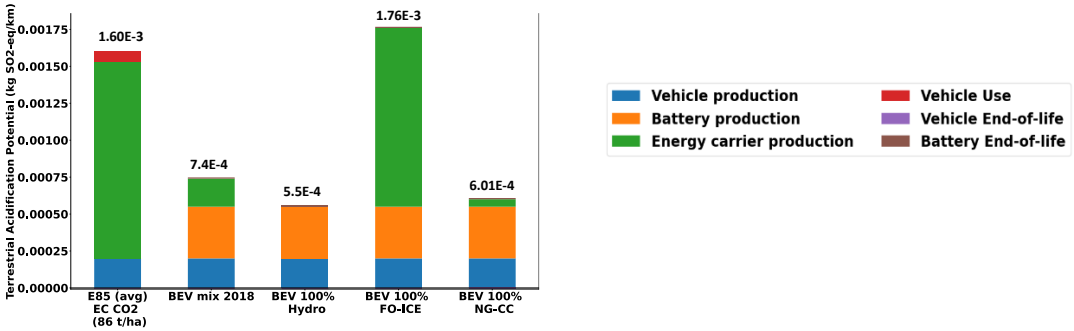
f)


Particulate Matter Formation Potential (kg PM10-eq/km)
0.0008
0.0006
0.0004
0.0002
0.0000
8.94E-4
2.71E-4
2.08E-4
6.48E-4
2.24E-4
E85 (avg) EC CO2 (86 t/ha)
BEV mix 2018
BEV 100% Hydro
BEV 100% FO-ICE
BEV 100% NG-CC

g)


Photochemical Oxidant Formation Potential (kg NMVOC-eq/km)
0.00200
0.00175
0.00150
0.00125
0.00100
0.00075
0.00050
0.00025
0.00000
1.93E-3
4.52E-4
3.22E-4
1.58E-3
3.93E-4
E85 (avg) EC CO2 (86 t/ha)
BEV mix 2018
BEV 100% Hydro
BEV 100% FO-ICE
BEV 100% NG-CC

h)



i)

Figure 7. 5 Environmental impact results for single resources electricity scenarios: a) global warming potential; b) fossil depletion potential; c) freshwater eutrophication; d) marine eutrophication; e) metal depletion potential; f) ozone depletion potential; g) particulate matter formation potential; h) photochemical oxidant formation potential and i) terrestrial acidification potential

The E85 scenario reports the lowest value for the metal depletion potential with 0.0057 kg Fe-eq./km (Figure 7. 5e). The BEVs have higher burdens than the E85 scenario with a value of 0.065 kg Fe-eq./km. This latter result is justified based on the materials used for battery manufacturing. For any BEV scenario, the highest contribution is attributed to battery production, followed by vehicle production with 24%.

The ozone depletion potential (ODP) impact shows that the best environmental profile is depicted by the BEV 100% hydro scenario with 4.60 E-09 kg CFC-11-eq./km, followed by the BEV mix 2018 scenario with 7.50 E-09 kg CFC-11-eq./km, the BEV 100% NG-CC scenario with 9.40 E-09 kg CFC-11-eq./km and the E85 scenario with 1.31 E-08 kg CFC-11-eq./km (Figure 7. 5f). The worst environmental performance is attributed to the BEV 100% FO-ICE with 2.55 E-08 kg CFC-11-eq./km.

Regarding the particulate matter potential and the photochemical oxidant formation potential impacts, the BEV 100% hydro scenario has the lowest environmental burdens with 0.00020 kg PM_{10}-eq./km and 0.00032 kg NMVOC-eq./km, respectively, followed by the BEV 100% NG-CC scenario with 0.00022 kg PM_{10}-eq./km and 0.00039 kg NMVOC-eq./km, the BEV mix 2018 scenario with 0.00027 kg PM_{10}-eq./km and 0.00045

kg NMVOC-eq./km and the BEV 100% FO-ICE scenario with 0.00064 kg PM_{10}-eq./km and 0.00158 kg NMVOC-eq./km (Figure 7. 5g and Figure 7. 5h). The E85 scenario has the worst environmental performance with 0.00089 kg PM_{10}-eq./km for PMFP and 0.00193 kg NMVOC-eq./km for POFP. These results suggest that PM emissions would increase if the electricity is mainly generated through thermal power plants.

The terrestrial acidification potential (TAP) impact shows that the BEV represents the best environmental scenario mix of 100% hydro and BEV mix of 100% NG-CC with 0.00055 and 0.0006 kg SO_2-eq./km, respectively, followed by the BEV mix 2018 scenario with 0.0007 kg SO_2-eq./km (Figure 7. 5i). The E85 and BEV 100% FO-ICE scenarios are the worst environmental options, with 0.00150 and 0.0017 kg SO_2-eq./km, respectively.

7..3.4 Comparison of results with literature

Aiming to compare the results obtained with the literature, studies with the same functional unit, "1 km," were chosen. However, it should be mentioned that LCA results compared with literature always differ due to different system boundary definitions, spatial and temporal variability, and different inventories, databases, or software used for the analysis. Moreover, LCA studies between BEV and ethanol-gasoline blend flex-fuel vehicles usually diverge due to parameter variability in all life-cycle stages. For instance, in the vehicle production stage, technical specifications, such as the weight, vary between one vehicle and another. Furthermore, several cathode chemistries can be applied when analyzing the battery production stage, affecting the environmental impact categories. The electricity generation or fuel production processes vary between countries or regions, influencing the environmental impact.

The most widely analyzed impact category from peer-reviewed literature is global warming potential. Thus, only GWP impact results were compared with the literature, as climate change is currently the main sustainability thread. Table 7. 6 shows peer-reviewed

studies tabulated with country information, functional unit, vehicle lifetime, and the well-to-wheel emissions from each study. The reported GWP ranges for E5 flex-fuel vehicles and BEV using the 2018 mix are 0.252-0.256 kg CO_2-eq/km and 0.095 kg CO_2-eq/km, respectively. Our GWP results for current scenarios (E5 and BEV mix 2018) agree with most of the literature reviewed: 0.05-0.81 kg CO_2 eq./km for E0, 0.13–0.18 kg CO_2 eq./km for E5 and 0.042–0.1764 kg CO_2 eq./km for BEVs. It is important to remark that for reviewed studies that analyze internal combustion engines fueled 100% with gasoline, we assumed these cases to be similar and comparable to the E5 ethanol-gasoline blend flex-fuel vehicle used in this work since it has a negligible mixture of ethanol.

Table 7. 6 Review of life-cycle assessment studies of ICEFFVs and BEVs, showing the well-to-wheel (WTW) GHG emissions in each study.

Source	Geographical relevance	Functional unit	Lifetime (km or years)	Ethanol-gasoline blend for flex-fuel vehicle	GHG emissions for BEV (kg CO_2-eq./km)	GHG emissions for ICEV (kg CO_2-eq./km)
This study	Ecuador	1 km	150,000 km	E5, E15, E85	BEV (2018): 0.095; BEV S3: 0.094-0.104; BEV (Hydropower): 0.075; BEV (NG-CC): 0.14;	E5: 0.252-0.256; E15: 0.217-0.223; E85: 0.08-0.13
[344]	United States	1 km	12 years	E10	0.042 -0.076	E10: 0.168-0.174
[301]	Spain	1 km	150,000 km	E0 (100% gasoline)	0.05	0.185
[345]	Australia	1 km	10.23 years	E0, E65	0.17	E0: 0.25; E65: 0.15
[288]	Brazil	1 km	160,000 km	E25, E100	0.149	E25: 0.29; E100: 0.097
[346]	European Union	1 km	200,000 km	E5, E85	0.139	E5: 0.131-0.18; E85: 0.115-0.13
[338]	Italy	1 km	150,000 km	E0 (100% gasoline)	0.1764	E0: 0.308
[302]	Canada	1 km	150,000 km	E0 (100% gasoline)	0.16	E0: 0.27
[347]	Norway	1 km	200,000 km	E0 (100% gasoline)	0.61 - 1	0.81

GHG: Greenhouse gases; BEV: battery electric vehicle; ICEV: internal combustion engine vehicle; NG-CC: natural gas - combined cycle

Girardi et al. [338] reported a value of 0.308 kg CO_2-eq./km for ICEV petrol and 0.1764 kg CO_2-eq./km for BEV; Bicer&Dincer [302] reported a value of 0.27 kg CO_2-eq./km

for ICEV petrol and 0.160 kg CO_2-eq./km for BEV; Puig-Samper Naranjo et al. [301] reported a value of 0.260 kg CO_2-eq./km for ICEV petrol and 0.134 kg CO_2-eq./km for BEV; and, Hoque et al. [345] indicated a GWP impact of 0.25 kg CO_2-eq./km for gasoline vehicle and 0.131-0.18 kg CO_2-eq./km for BEV. Although our results are within what the literature reports, it is essential to mention that the GWP impact of the two energy carriers depends on the country-specific electricity grid considered.

For future scenarios (E15, E85), the reported GWP range is 0.217-0.223 kg CO_2 eq./km for E15 scenarios and 0.08-0.13 kg CO_2 eq./km for E85 scenarios. For BEV mix S3, GWP ranges are between 0.094 and 0.104 kg CO_2 eq./km. Our best environmental GWP performance is attributed to the hypothetical BEV 100% hydro scenario with 0.075 kg CO_2-eq./km. These GWP results are within the range reported in the literature: 0.168-0.174 kg CO_2 eq./km for E10, 0.29 kg CO_2 eq./km for E25, 0.115-0.13 kg CO_2 eq./km for E85 and 0.097 kg CO_2 eq./km for E100. De Souza et al. [288] reported a value of 0.29 kg CO_2-eq/km for E25 vehicles and 0.149 kg CO_2-eq/km for BEV. These latter authors also analyzed a vehicle fueled with 100% ethanol, and they concluded that the lower the percentage of ethanol in the mixture, the greater the GWP impact; therefore, the BEV is more beneficial for the environment.

In contrast, Petrauskiené et al. [305] and Andersson & Borjesson [346] agree that even with a low or no percentage of ethanol in the fuel mix, the petrol ICEV has a lesser GWP impact than BEV. Petrauskiené et al. [305] reported a value of 0.105 kg CO_2-eq./km compared to 0.142 kg CO_2-eq./km for BEV based on a study developed in Lithuania. However, based on an electric vehicle scenario with a forecasting 2050 generation mix, the BEV looks better environmentally than a gasoline-powered one with 0.0708 kg CO_2-eq./km. Andersson & Borjesson [346] concluded in their work that renewable fuels are

found to have a more significant potential to reduce the life-cycle greenhouse gas emissions than a low-carbon electricity mix.

7.3.5 Policy recommendations

Based on the analysis of results, most BEV scenarios, especially those using highly green electricity (i.e., BEV 100% hydro), perform better than vehicles with ethanol (E85) in all impact categories except for MDP. Nevertheless, E85 scenarios against fossil-based electricity BEV scenarios have a lower environmental burden in the GWP, FDP, MDP, and ODP categories. The greater use of these vehicles should be motivated and encouraged with public policies and municipal ordinances. As a first aspect to consider, Ecuador should have policies and technical instruments to avoid charging electric vehicles with marginal fossil electricity. The electricity used for electric vehicle charging must be generated from highly renewable sources. Suppose this electricity used for electric vehicle charging is not highly green. In that case, the flex-fuel vehicle is an option to be considered to minimize the environmental impacts produced by the passenger car road transportation sector.

Although BEV scenarios look better than ethanol-gasoline blend flex-fuel scenarios in most environmental impacts evaluated, it is imperative to consider different options in road transportation systems. This latter consideration is evident when high-efficiency E85 scenarios analyzed in this study show similar results to BEVs on FDP and GWP impacts. Thus, based on the Ecuadorian context, the use of ethanol in transportation systems should not be neglected. A more extensive agricultural sugarcane growth is required to get a higher proportion of ethanol in the ethanol-gasoline blend. However, Ecuadorian sugarcane farmers must implement good practices in field activities, such as precision agriculture [255], [256], to obtain a much higher sugarcane yield while reducing the environmental burden. Ecuadorian sugarcane and alcohol producers can produce 80

million liters of ethanol per year [96], although this might lead to a ‘’food vs fuel’’ conflict [348], [349]. Additionally, private sugar companies should invest in developing innovative biomass conversion technologies and pathways to investigate the ecological advantages of second and third-generation biofuels used in transportation systems [350], [351]. With second-generation (2G) ethanol, better environmental performance would be possible because it is a by-product and has no burden of previous processing and agriculture.

Although this study does not consider an analysis of public transportation, it is essential to note that riding public transportation generates, on average, lower emissions than car passenger vehicles [352]–[355]. The Ecuadorian government should improve mass public transport systems' safety, comfort, and leisure time to achieve other tasks while traveling to encourage its use while reducing private vehicle use [356]–[359].

7.3.6 Limitations

One imitation regarding energy carriers is referred to the gasoline production. An Ecoinvent database was selected for gasoline production in Colombia but adapted to the Ecuadorian context. It is important to mention that this is considered a minor limitation since the Colombian context should not be very different from the Ecuadorian context concerning gasoline production. A similar situation was experienced with the vehicle production stage, in which an Ecoinvent database was chosen for inventory purposes. Another limitation is related to the vehicle's operation stage. The combustion gases of ethanol-gasoline vehicles were obtained from a study that does not correspond to the Ecuadorian context. It is expected that gas emissions from flex-fuel vehicles will be lower in the future since it is a prospective study, and indeed, the vehicle’s engines will be more efficient.

A limitation concerning lithium-ion batteries is related to the recycling processes since they are poorly developed. Moreover, it is assumed that lithium-ion batteries are exported to comply with their recycling process since local or regional management is not possible in the near future. Notably, this panorama generates uncertainty worldwide and not solely in Ecuador. Thus, globalization in automobile battery life-cycle, especially in end-of-life processes, is a future challenge for LCA practitioners [308], [360].

7.4 Conclusions

The environmental performance of a battery electric vehicle and ethanol-gasoline blend flex-fuel vehicle were analyzed by means of an attributional LCA. Overall, based on current scenarios, seven out of nine environmental impacts (GWP, FDP, MEUP, PMFP, ODP, POFP, and TAP) evidence a better performance on a battery electric vehicle than an internal combustion engine vehicle supplied with different ethanol-gasoline blends. In contrast, two out of nine environmental impacts (MDP and FEP) show better environmental performance on a flex-fuel vehicle supplied with different ethanol-gasoline blends than a battery-electric vehicle in a baseline framework. The GWP impact results for current scenarios are 130-180 g CO_2-eq/km for E5 and 42–176 g CO_2-eq/km for BEVs. Vehicle production contributes 18% to flex-fuel and 53% to battery electric vehicles to this impact. When metal depletion potential (MDP) is analyzed, the environmental impact is mainly driven by the battery production stage due to the metals used for this purpose (the main reason is cobalt production, which is used in cathode manufacturing).

E85 flex-fuel vehicles are an excellent option for tackling climate change. For instance, the E85 (S1-2050 displacement) scenario is more environmentally friendly than BEV scenarios when the electricity mix used to charge BEVs still depends on fossil resources such as S1 and S2. Regarding the single-resource electricity scenarios, a battery electric

vehicle has a better environmental performance than flex-fuel when the electricity generated to charge such vehicles is highly renewable. When the electricity used to charge BEVs is fossil, the flex-fuel vehicles with high ethanol contribution will perform better environmentally. The BEV 100% hydro scenario has the best environmental profile for all impact categories except for MDP. The fossil fuel-based electricity scenarios have the worst environmental profile in the GWP, FDP, and MDP categories. In general, battery electric vehicles have a better environmental performance when the electricity used to charge such vehicles is highly renewable. Nevertheless, E85 flex-fuel vehicles should not be discarded if the electricity generation is not highly green (renewable or biobased). From a greenhouse gas mitigation perspective, the resource is more important than the energy carrier and powertrain, especially when the resource is low in carbon emissions (hydraulic or biomass).

The results of GWP are statistically sensitive concerning vehicle energy consumption and vehicle lifetime parameters. The lower the lifetime assumed, the greater the GWP impact of the scenario.

The Ecuadorian government should implement policies and technical instruments to avoid charging electric vehicles with marginal fossil electricity. Moreover, future research should be focused on analyzing what would happen with flex-fuel vehicles using second-generation (2G) ethanol since this study focuses on first-generation (1G) ethanol. Finally, freight transportation should be analyzed since it was determined that trucks are the vehicles that produce the most significant amount of polluting gases in Ecuador [361].

Supplementary information

S7.1 Literature review: Life cycle analysis of private transportation

Table S7. 1 summarizes peer-reviewed publications concerning the use of LCA in passenger car transportation options. The table is divided into the country/region covered by the study, goal of the assessment, functional unit, powertrains technology, energy carrier (blends of x% ethanol with gasoline Ex, gasoline, diesel, hydrogen, etc.), system boundaries, and environmental impact categories.

Table S7. 1 Summary of peer-reviewed publications of life cycle analysis of private transportation based on different powertrains and resources.

Reference	Country/Region	Goal	Functional unit	Powertrains (energy carrier)	System boundaries	Environmental impacts
De Souza et al. (2018) [288]	Brazil	Compare the environmental performances of different vehicle alternatives based on Brazilian conditions based on an attributional life cycle perspective.	1 km	ICEV (fueled with gasoline, with a mixture of ethanol (E25) and ethanol, and with ethanol), PHEV (fueled with gasoline), and BEV	Fuel production, electricity generation, vehicle and battery manufacturing, vehicle use phase and vehicle maintenance, vehicle and battery end-of-life.	Ozone depletion potential, abiotic depletion potential, fossil depletion potential, global warming potential, human toxicity potential, photochemical oxidant potential, acidification potential and eutrophication potential.
Karaaslan et al. (2017) [300]	United States	Cradle-to-grave environmental impacts of five sport utility vehicles (SUVs) powered with different fuel options (gasoline, diesel, plug-in hybrid, hydrogen fuel cell-powered, and plug-in electric battery).	200,000 miles	ICEV (fueled with gasoline and diesel), PHEV (fueled with gasoline), FCEV (hydrogen), BEV	Vehicle and battery manufacturing, hydrogen fuel cell manufacturing, vehicle use phase and vehicle maintenance, vehicle and battery end of life.	Energy consumption, GHG emissions, and water withdrawal

Puig-Samper Naranjo et al. (2021) [301]	Spain	This study estimates and compares present and future life cycle environmental burdens of different powertrain alternatives in Spain.	1 km	ICEV (fueled with gasoline and diesel), HEV (fueled with gasoline), and BEV.	Raw materials extraction and transformation, vehicle manufacturing, vehicle operation, vehicle use phase, vehicle end of life.	Global warming potential, ozone depletion potential, Ionizing radiation potential, Particulate Matter Formation Potential, Photochemical Oxidant Formation Potential – Ecosystems, Photochemical Oxidant formation Potential - Humans, Terrestrial acidification potential, Freshwater Eutrophication Potential, Human Toxicity Potential - cancer, Human Toxicity Potential – non-cancer, Terrestrial Ecotoxicity potential, Freshwater Ecotoxicity Potential, Marine Ecotoxicity Potential, Agricultural Land Occupation Potential, Water Consumption Potential, Surplus Ore Potential, Fossil fuel potential
Bicer et al. (2018) [302]	Canada	Perform an environmental impact assessment of three vehicles using different energy carriers through a process-based life cycle assessment methodology.	1 km	BEV, PHEV, ICEV (fueled with gasoline, diesel, liquefied petroleum gas, compressed natural gas, hydrogen, ammonia, methanol (90%), and gasoline (10%))	Vehicle operation, manufacturing, maintenance, and disposal.	Human toxicity potential, global warming potential, acidification potential, eutrophication potential, ozone depletion potential, and Terrestrial ecotoxicity potential.
Bauer et al. (2015) [303]	Switzerland	Provide a comparative LCA of current and future mid-sized European passenger vehicles based on a novel integrated vehicle simulation framework to	1 km	ICEV (fueled with gasoline, diesel, and natural gas), HEV (fueled with gasoline), BEV, and FCV	Energy carrier production, equipment life cycle, vehicle operation.	Particulate Matter Formation Potential, Photochemical oxidant formation, Human Toxicity potential, Terrestrial Acidification Potential

		consider future technological development.				
Onat et al. (2015) [65]	United States	Perform a state-based comparative carbon and energy footprint analysis among different powertrain alternatives. Several temporal and spatial variations were considered for this analysis, such as electricity generation mix, regional driving patterns, and vehicle and battery technological advances.	1 km	ICEV, BEV, PHEV, HEV.	Material extraction, processing, production, vehicle operation phase, and end of life.	Energy consumption and carbon footprint
Tagliaferri et al. (2016) [304]	European Union	Perform an attributional lifecycle analysis with a consequential approach to future BEV and HEV and compare them with a diesel-based conventional vehicle.	1 km	ICEV (fueled with diesel), HEV (fueled with diesel 30% and 60%), PHEV, and BEV.	Manufacturing, use, and disposal phases	Global warming potential, human toxicity potential, abiotic depletion potential, fossil depletion potential, acidification potential, eutrophication potential, ozone depletion potential, photochemical oxidant potential, freshwater ecotoxicity potential, marine ecotoxicity potential, terrestrial ecotoxicity potential.
Petrauskien et al. (2019) [305]	Lithuania	Evaluate and compare the environmental impacts between electric and conventional vehicles	1 km	ICEV (fueled with petrol and diesel), BEV	Fuel cycle, equipment life cycle, vehicle operation	Climate change, Ionizing radiation potential, human toxicity potential, fossil depletion potential, metal depletion potential.
Ternel et al. (2021) [306]	France	Compare GHG emissions of current and future mid-range passenger cars considering both the vehicle and the fuel life cycle.	1 km	ICEV, HEV, PHEV, BEV.	Fuel/energy supply, fuel/energy use, vehicle life cycle.	Greenhouse gases emissions
Liu et al (2022) [309]	China	Quantify and compare the GHG emissions of different powertrain vehicles in a life cycle perspective for current and future integrated scenarios.	1 km	GICEV, EV, PHEV, EREV and BEV	Manufacturing, assembly, repairing, recycling, and their supporting facilities.	Energy consumption and greenhouse gas emissions
Koroma et al (2022) [308]	European Union	Evaluate the environmental performance of BEV and refurbished EV batteries by combining changes in the charging	1 European B-segment BEV	BEV	Vehicle and LIB production, vehicle use, end-of-life, Li-ion battery refurbishment, manufacture of avoided LIBs.	Global warming potential, mineral resource scarcity, fine particulate matter formation, human non-carcinogenic toxicity, human carcinogenic toxicity, stratospheric ozone

		electricity mix over time, and battery efficiency fades.				depletion, ionizing radiation, ozone formation, acidification, eutrophication, ecotoxicity, land use, fossil resource scarcity, and water consumption
Sisani et al (2022) [307]	Italy	Assess environmental and human health impacts due to direct and indirect emissions generated by passenger vehicles with emission standards not lower than Euro 6.	1 km	PHEV, HEV (fueled with gasoline), ICEVg, ICEVd, BEV	Raw materials extraction and transformation, vehicle manufacturing, operation, and maintenance.	Global warming, photochemical ozone formation, particulate matter, freshwater eutrophication, acidification, freshwater eco-toxicity, resource depletion, human toxicity non-cancer, human toxicity cancer.

Powertrains.- BEV: Battery electric vehicle, ICEV: Internal combustion engine vehicle, ICEVg: internal combustion engine fueled with gasoline, ICEVd: internal combustion engine fueled with diesel, PHEV: Plug-in hybrid electric vehicle, LIB: Lithium-ion batteries, HEV: Hybrid electric vehicle, GICEV: gasoline internal combustion engine vehicle, EREV: Extended range electric vehicle, EV: electric vehicle, BEV: battery electric vehicle, FCV: Fuel cell vehicle, HFCV: Hybrid fuel cell vehicle. Environmental impacts.- CC: Climate Change, GWP: Global Warming Potential, ADP: Abiotic depletion potential, ODP: Ozone Depletion Potential, IRP: Ionizing Radiation Potential, PMFP: Particulate Matter Formation Potential, EOFP: Photochemical Oxidant Formation Potential - Ecosystems, HOFP: Photochemical Oxidant formation Potential - Humans, TAP: Terrestrial Acidification Potential, MEUP: Marine Eutrophication, FEP: Freshwater Eutrophication Potential, HTTP: Human toxicity potential, HTPc: Human Toxicity Potential - cancer, HTPnc: Human Toxicity Potential – non cancer, TEP: Terrestrial ecotoxicity potential, TETP: Terrestrial Ecotoxicity Potential, FETP: Freshwater Ecotoxicity Potential, METP: Marine Ecotoxicity Potential, LOP: Agricultural Land Occupation Potential, WCP: Water Consumption Potential, SOP: Surplus Ore Potential, FFP: Fossil Fuel Potential, ACP: Acidification potential, ETP: Eutrophication potential, HTTP: Human Toxicity Potential, PMF: Particulate Matter Formation, POF: Photochemical Oxidant Formation, FDP: Fossil Fuel Depletion Potential, POP: Photochemical oxidant potential, MDP: Metal depletion potential, MRS: mineral resource scarcity, FPMF: fine particulate matter formation, HnCT: human non-carcinogenic toxicity and human carcinogenic toxicity (HCT).

S7.2 Sensitivity analysis

A sensitivity analysis was conducted to determine the effect in the GWP impact category by (i) changing the energy consumption of the analyzed powertrains, maximum and minimum, and (ii) changing the vehicle lifetime to 150,000 km or 230,000 km. All the other parameters are kept unchanged. The sensitivity analysis is conducted solely for some BEVs and E85 scenarios using ethanol produced in Ecuador (sugarcane yield 71 t/ha, (D. Arcentales et al., 2022). Overall, 20 scenarios were evaluated for sensitiveness, 16 for BEVs, and 4 for ethanol-gasoline blend flex-fuel vehicles. The following observations were noted:

(i) When hydroelectricity is taken as an energy carrier, the GWP is not sensitive to the vehicle energy consumption (0.0000435 kg CO_2-eq/km higher when maximum energy consumption is assumed, which is not statistically significant). However, the lifetime variation is more sensitive to this impact. The GWP impact is 0.030 kg CO_2-eq/km higher (60% higher) when a shorter lifetime (150,000 km) is assumed (Figure S7. 1).

(ii) When fuel-oil-based electricity is used for BEVs, there is greater sensitivity in the variation of vehicle energy consumption with a difference of 0.085 kg CO_2-eq/km between maximum and minimum energy consumption (65% variation in energy consumption reflects 31% variation in results). Regarding vehicle lifetime, the variation is approximately 0.030 kg CO_2-eq/km, being higher for a lifetime of 150,000 km (Figure S7. 1).

(iii) Regarding an electric vehicle using electricity produced 100% by natural gas, the vehicle energy consumption variation shows the most heightened sensitivity with 0.050 kg CO_2-eq/km of difference. On the other hand, the vehicle lifetime parameter indicates a higher impact contribution of 0.030 kg CO_2-eq/km when a shorter lifetime is used (Figure S7. 1).

(iv) For the BEV mix 2018, the vehicle lifetime is more sensitive to this impact because it has a 0.030 kg CO_2-eq/km difference in contrast to the vehicle energy consumption parameter that has a difference of 0.014 kg CO_2-eq/km between maximum and minimum values (Figure S7. 1).

(v) When ethanol from Ecuador is used as a fuel source for ethanol-gasoline vehicles (E85), the GWP impact is more sensitive for vehicle lifetime parameters with a difference of 0.015 kg CO_2-eq/km between maximum and minimum lifetime. In contrast, the vehicle energy consumption parameter has a difference of 0.0008 kg CO_2-eq/km (Figure S7. 1), which is not statistically significant.

(vi) For comparison purposes, when GWP is evaluated, vehicles with low energy consumption using ethanol-gasoline blends (E85) have lower environmental impacts than some BEVs (Figure S7. 1).

After this GWP sensitivity analysis concerning vehicle energy consumption and vehicle lifetime, we can determine that the results differ from the baseline scenarios by 10-12% for the E85 (avg) EC CO_2-A (71 t/ha) scenarios and by 14-31% for the BEV scenarios. Finally, it should be noted that GWP results will be affected by changes in energy consumption and lifetime. The lower the lifetime, the greater the GWP impact of the scenario. Likewise, the higher the energy consumption, the greater the GWP impact of the vehicle. Concerning the contribution analysis results, no significant variations are seen through this analysis.

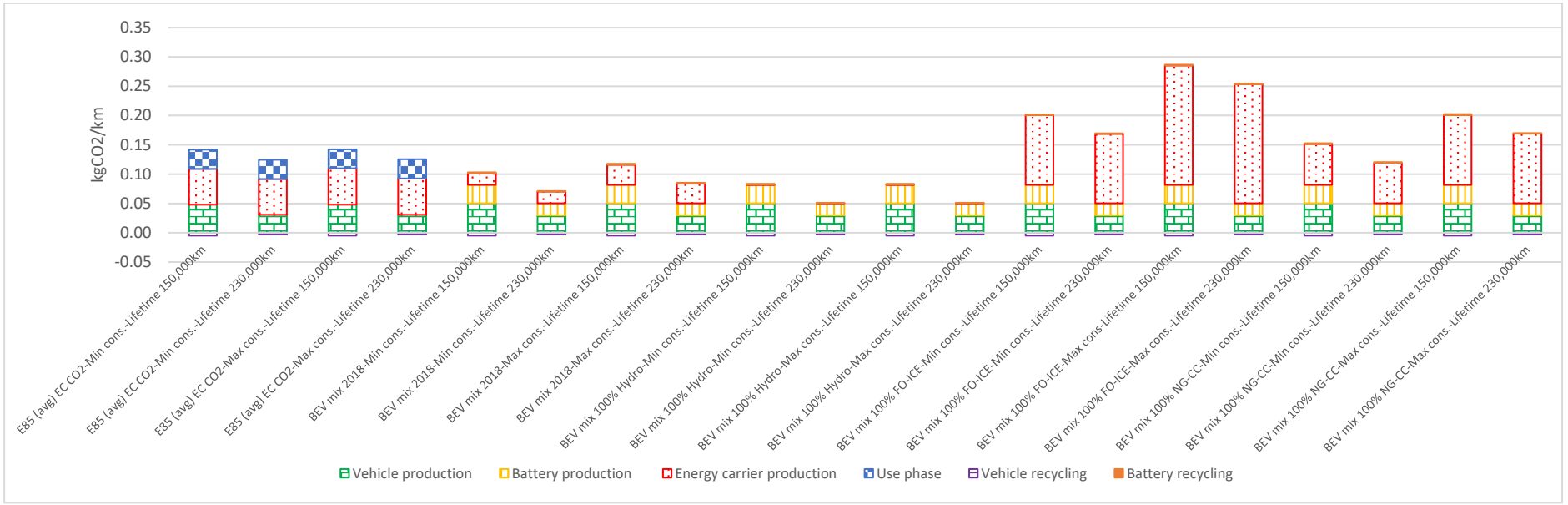


Figure S7. 1 GWP impact results for the sensitivity analysis of the analyzed scenarios

8. Overall conclusions, limitations and future work

8.1 Overall conclusions

The transportation sector is considered a key driver of GHG increase, non-renewable resource depletion, and air quality degradation. The increase in greenhouse gas emissions in the road transportation sector is primarily attributable to the uncontrolled worldwide trade of vehicles due to fast economic growth. Several countries and cities have implemented different strategies in their fight to mitigate GHG emissions in the road transportation sector. An old-fashioned strategy has been the use of bus rapid transit (BRT). Some other countries have emphasized the hybridization or electrification of the transportation sector, aiming to mitigate GHG emissions. Alternative fuels are another solution for GHG mitigation because they are not derived from conventional sources like petroleum or coal. Expectations on biofuels are high because they can also impulse the agriculture sector, besides decarbonizing the transportation sector. However, not all governments support these fuels and criticize the fact that their production compromises the food supply chain because they come from a food source.

The transportation sector in Ecuador is highly energy intensive, with a sustained upward trend in the last decade. Within this sector, gasoline and diesel fuels are widely used, while the use of electricity or biofuels is marginal. There is little research in Ecuador regarding possible pollutant mitigation achievements in the transportation sector. Acknowledging these concerns will help the Ecuadorian government create policies or strategies that could foster energy savings and sustainable development in the transportation sector.

This work explores the insertion of alternative energy carriers and powertrain technologies from a life cycle environmental perspective in Ecuadorian road transportation, specifically light-duty passengers and buses. The research process was based on the following steps:

- Assessment of different bus powertrain technologies in Ecuador through a well-to-wheels perspective;

- Life cycle assessment of Ecuadorian sugarcane and ethanol production in order to evaluate the environmental performance of ethanol as an energy carrier for sustainable transportation;

- Comparative environmental analysis on light-duty passenger vehicles between ethanol-gasoline blends and electricity.

The following research questions were developed and answered:

Research question 1: How will Ecuador's ethanol and bus electrification concepts impact GHG and air pollutant emissions (NO_x, NH_3 and $PM_{2.5}$)?

The Ecuadorian diesel-based bus fleet was analyzed with new powertrain technologies such as hybrid and plug-in hybrid flex-fuel concepts. The influence on final energy consumption, air quality and 100 years global warming impact was assessed through a WTW approach.

Suppose the diesel energy source is to be kept. In that case, hybrid technology is a good option for a replacement, reducing fuel consumption and TTW CO_2 emissions by 25%, but, despite the particle filters, only reducing 7% the $PM_{2.5}$ equivalent emissions. If an ethanol energy source is seen as the future, and energy supply flexibility to the bus is a priority, the best option to reduce emissions will be the plug-in hybrid flex-fuel vehicles. These new technologies will provide a 55–77% CO_{2eq}. reduction, even if coal is used in thermal power plants, on a heavy renewables penetration scenario. However, Ecuador still needs more investment in ethanol production. The current ethanol capacity (50-60 million liters of ethanol per year) will not be enough to satisfy the demand.

Research question 2: What environmental impacts are generated by ethanol production through sugarcane in Ecuador?

Sugarcane and ethanol production are assessed from a life cycle perspective. Data was collected from the two biggest mills in Ecuador. The global warming potential (GWP) impact was found to be 53.6 kg of carbon dioxide equivalent (kg. $CO_{2eq.}$) per tonne of sugarcane produced due to fertilizers application and diesel used in agricultural machinery. The GWP for 1 L of ethanol produced was reported as 0.60 kg $CO_{2eq.}$, where the distillation stage has the highest contribution, with approximately 61%. Regarding the freshwater eutrophication potential, the distillation and the agriculture stage have the most significant impact, with 0.0001 kg of P per liter of ethanol and 0.0000928 kg of P per liter of ethanol, respectively. The latter corresponds to 34% for the agricultural stage and 52% for the distillation stage of the overall impact. These results are mainly due to the application of agrochemicals for sugarcane production and the high nitrogen and phosphorous content in the vinasse produced from the distillation column process.

Ecuadorian sugarcane and ethanol industries should apply industrial symbiosis and circular economy strategies to produce lesser environmental loads within the ethanol production chain.

Research question 3: What is environmentally superior in Ecuador as an energy carrier for light-duty passenger vehicles: ethanol-gasoline blends or electricity?

Decarbonizing the private transportation sector depends mainly on the energy carrier chosen as the power source used by the vehicle. Through a life cycle analysis, this study aims to compare the environmental performance of light-duty passenger vehicles in Ecuador with different energy carriers (ethanol-gasoline blends and electricity). The results show that current scenarios using ethanol-gasoline blends have higher environmental impacts than battery electric vehicles

for GWP (130-180 g CO_2-eq/km for E5 and 42–176 g CO_2-eq/km for BEVs.), FDP, MEUP, ODP, PMFP, POFP, and TAP categories. In contrast, using the current electricity mix, the battery-electric vehicle has higher environmental impacts in the FEP and MDP categories. Finally, E85 flex-fuel vehicles should not be discarded if the electricity generation is not highly green (renewable or biobased).

8.2 Research limitations

One primary limitation/constraint of this work is the lack of powertrain information, such as hybrid CI diesel and hybrid ED95 bus data in the EEA emission inventory guidebook. Moreover, the ethanol effect on $PM_{2.5}$ emissions in flex-fuel engines is taken from the literature and should be explored experimentally.

A limitation regarding energy carriers is referred to the gasoline production information that was obtained from an Ecoinvent database but adapted to the Ecuadorian context. Another limitation is related to the emissions produced during the vehicle operation stage. The combustion gases of ethanol-gasoline vehicles were obtained experimentally from a study that does not correspond to the Ecuadorian context but to the Spanish driving conditions.

Finally, a limitation concerning lithium-ion batteries is related to the recycling process information since they are poorly developed. Notably, this panorama generates uncertainty worldwide and not solely in Ecuador. Thus, globalization in the automobile battery life cycle, especially in end-of-life processes, is a future challenge for LCA practitioners [308], [360].

8.3 Guidelines for further research

The research developed in this work found several possibilities for future research. A life cycle assessment on second-generation ethanol (i.e. from agriculture waste) and other second and

third-generation biofuels in Ecuador could be achieved in the future. This would not compromise the food supply chain, which is a critical limitation of first-generation biofuels. Moreover, a comparative life cycle assessment between conventional light-duty vehicles and other new alternative biofuels used in light-duty vehicles, such as biodiesel and hydrogen could be developed.

A very innovative work would be a life cycle analysis of the oil produced in Ecuador. It is a study that has not been carried out in this context. Moreover, gathering the information for this type of work is an interesting challenge. It would also be innovative to analyze strategies for the mid and long-term scenarios with the insertion of new BRT and mass transportation systems in the main cities of Ecuador.

The inclusion of LCA studies for Ecuadorian freight transportation would also be interesting. Most of the studies focus solely on passenger transportation, not this type of heavy-duty vehicle.

Finally, it would be worthy to include social and economic aspects in Ecuador's LCA of transportation energy carriers. Usually, these aspects are not included.

References

[1] E. Wolff *et al.*, “Climate Change Evidence & Causes,” *Natl. Acedemy Sci.*, p. 36, 2014.

[2] N. Oreskes, “The scientific consensus on climate change: How do we know we’re not wrong?,” in *Climate Modelling: Philosophical and Conceptual Issues*, 2018.

[3] Intergovernmental Panel on Climate Change, “Climate Change 2014: Synthesis Report - Summary Chapter for Policymakers,” 2014.

[4] T. R. Karl and K. E. Trenberth, “Modern Global Climate Change,” *Science*. 2003.

[5] R. Garnaut, *The Garnaut Climate Change Review*. 2008.

[6] J. S. Levine, “Global Climate Change,” in *Global Climate Change and Freshwater Ecosystems*, New York, NY: Springer New York, 1992, pp. 1–25.

[7] C. Rosenzweig, W. Solecki, and R. Slosberg, “Mitigating New York City’s heat island with urban forestry, living roofs, and light surfaces,” *86th AMS Annu. Meet.*, 2006.

[8] D. A. Hensher, “Climate change, enhanced greenhouse gas emissions and passenger transport - What can we do to make a difference?,” *Transp. Res. Part D Transp. Environ.*, vol. 13, no. 2, pp. 95–111, 2008.

[9] OECD/ITF, “The Cost and Efficiency of Reducing Transport GHG Emissions — Preliminary Findings,” *Transport*, 2009.

[10] C. Monsalve, “Controlling Greenhouse Gas Emissions Generated by the Transport Sector in ECA : Policy Options.,” no. February, p. 64, 2013.

[11] N. Rivers and R. Wigle, “REDUCING GREENHOUSE GAS EMISSIONS IN TRANSPORT: ALL IN ONE BASKET?,” *Sch. Public Policy Publ.*, 2018.

[12] M. Vinicio, R. Moncayo, M. A. Caraballo Núñez, O. Hilarion´alvarez, H. Hilarion´alvarez Hernández, and S. Vivanco Pinta, “Emisión de dióxido de carbono de vehículos automotores en la ciudad deLoja, Ecuador,” *Cedamaz*, vol. 08, pp. 23–29, 2018.

[13] INECC, “Los vehículos automotores como fuentes de emisión,” *Inecc*, 2006.

[14] D. Sperling and E. Clausen, “The developing world’s motorization challenge,” *Issues Sci. Technol.*, vol. 19, no. 1, p. 59, 2002.

[15] D. Sperling and D. Gordon, “Two Billion Cars: Transforming a Culture,” *TR news*, vol. 259, pp. 3–9, 2008.

[16] R. Mohr, D; Muller, N; Krieg, A; Gao, P; Kaas, H W; Krieger, A; Hensley, “The road to 2020 and beyond: What’s driving the global automotive industry?,” *McKinsey Co.*, 2013.

[17] J. Voelcker, “1.2 Billion Vehicles On World’s Roads Now, 2 Billion By 2035: Report,” *Green Car Reports*, 2015.

[18] P. Sayeg and D. Bray, “Estimating changes in emissions from bus rapid transit: Making best use of transport sector experience,” *Wiley Interdiscip. Rev. Energy Environ.*, vol. 1, no. 3, pp. 308–316, 2012.

[19] DDPP, “Deep Decarbonization Pathways,” *SDSN - IDDRI.*, 2015.

[20] M. KII and S. HANAOKA, “Comparison of Sustainability Between Private and Public Transport Considering Urban Structure,” *IATSS Res.*, vol. 27, no. 2, pp. 6–15, 2003.

[21] G. Cooney, T. R. Hawkins, and J. Marriott, “Life cycle assessment of diesel and electric public transportation buses,” *J. Ind. Ecol.*, vol. 17, no. 5, pp. 689–699, 2013.

[22] D. Dreier, S. Silveira, D. Khatiwada, K. V. O. Fonseca, R. Nieweglowski, and R. Schepanski, “Well-to-Wheel analysis of fossil energy use and greenhouse gas emissions for conventional, hybrid-electric and plug-in hybrid-electric city buses in the BRT system in Curitiba, Brazil,” *Transp. Res. Part D Transp. Environ.*, vol. 58, no. December 2017, pp. 122–138, 2018.

[23] J. A. García Sánchez, J. M. López Martínez, J. Lumbreras Martín, M. N. Flores Holgado, and H. Aguilar Morales, “Impact of Spanish electricity mix, over the period 2008-2030, on the Life Cycle energy consumption and GHG emissions of Electric, Hybrid Diesel-Electric, Fuel Cell Hybrid and Diesel Bus of the Madrid Transportation System,” *Energy Convers. Manag.*, vol. 74, pp. 332–343, 2013.

[24] M. G. Haddad, C. J. Mansour, and C. Afif, “Future Trends and Mitigation Options for Energy Consumption and Greenhouse Gas Emissions in a Developing Country of the Middle East Region: a Case Study of Lebanon’s Road Transport Sector,” *Environ. Model. Assess.*, 2017.

[25] X. Ou, X. Zhang, and S. Chang, “Alternative fuel buses currently in use in China: Life-cycle fossil energy use, GHG emissions and policy recommendations,” *Energy Policy*, vol. 38, no. 1, pp. 406–418, 2010.

[26] Q. Song *et al.*, “Could urban electric public bus really reduce the GHG emissions: A case study in Macau?,” *J. Clean. Prod.*, vol. 172, pp. 2133–2142, 2018.

[27] B. Zhou *et al.*, “Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions,” *Energy*, vol. 96, pp. 603–613, 2016.

[28] E. Johnson, “Goodbye to carbon neutral: Getting biomass footprints right,” *Environ. Impact Assess. Rev.*, 2009.

[29] T. W. Patzek, “Thermodynamics of the corn-ethanol biofuel cycle,” *Critical Reviews in Plant Sciences*. 2004.

[30] D. Pimentel and T. W. Patzek, “Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower,” in *Food, Energy, and Society, Third Edition*, 2007.

[31] INEC, “Anuario de Transporte 2015,” *Inf. Anu.*, p. 46, 2015.

[32] Diario El Universo, “Gasto en subsidios equivale al 50 % del PIB y a toda la deuda de Ecuador,” 2019.

[33] M. A. Ponce-Jara, M. Castro, M. R. Pelaez-Samaniego, J. L. Espinoza-Abad, and E. Ruiz, “Electricity sector in Ecuador: An overview of the 2007–2017 decade,” *Energy Policy*, vol. 113, 2018.

[34] MEER, “Plan Nacional De Eficiencia Energética - PLANEE (Versión 2016–2035),” 2017.

[35] J. E. A. M.R.Y. Peláez Samaniego, *Eficiencia energética y ahorro de energía en el Ecuador*. Cuenca: Universidad Cuenca, 2015.

[36] S. Graefe *et al.*, “Energy and carbon footprints of ethanol production using banana and cooking banana discard: A case study from Costa Rica and Ecuador,” *Biomass and Bioenergy*, vol. 35, no. 7, 2011.

[37] G. Chiriboga, A. De La Rosa, C. Molina, S. Velarde, and G. Carvajal C, “Energy Return on Investment (EROI) and Life Cycle Analysis (LCA) of biofuels in Ecuador,” *Heliyon*, vol. 6, no. 6, 2020.

[38] Martínez Olaya Hernán Eduardo, “Análisis Del Uso De Biocombustibles En Ecuador Periodo 2010-2017,” 2018.

[39] H. Stichnothe and F. Schuchardt, “Life cycle assessment of two palm oil production systems,” *Biomass and Bioenergy*, vol. 35, no. 9, pp. 3976–3984, 2011.

[40] A. G. Queiroz, L. França, and M. X. Ponte, “The life cycle assessment of biodiesel from palm oil (‘ dendê’) in the Amazon,” *Biomass and Bioenergy*, vol. 36, pp. 50–59, 2012.

[41] J. Guinée, “Handbook on life cycle assessment - Operational guide to the ISO

standards," *International Journal of Life Cycle Assessment*. 2001.

[42] M. A. Curran, "Life-Cycle Assessment," in *Encyclopedia of Ecology, Five-Volume Set*, 2008.

[43] J. Lelieveld, J. S. Evans, M. Fnais, D. Giannadaki, and A. Pozzer, "The contribution of outdoor air pollution sources to premature mortality on a global scale," *Nature*, vol. 525, no. 7569, pp. 367–371, 2015.

[44] A. Bin Baghini, Mojtaba; Ismail, "Bus Rapid Transit (BRT) System Impacts to Environmental Quality," no. February, 2014.

[45] Y. Jung, Y. D. Pyo, J. Jang, G. C. Kim, C. P. Cho, and C. Yang, "NO, NO2 and N2O emissions over a SCR using DOC and DPF systems with Pt reduction," *Chem. Eng. J.*, 2019.

[46] A. G. Konstandopoulos, M. Kostoglou, C. Beatrice, G. Di Blasio, A. Imren, and I. Denbratt, "Impact of Combination of EGR, SCR, and DPF Technologies for the Low-Emission Rail Diesel Engines," *Emiss. Control Sci. Technol.*, 2015.

[47] P. Bera and M. S. Hegde, "Recent advances in auto exhaust catalysis," *J. Indian Inst. Sci.*, vol. 90, p. 26, 2010.

[48] M. Koebel, M. Elsener, and M. Kleemann, "Urea-SCR: a promising technique to reduce NOx emissions from automotive diesel engines," *Catal. Today*, vol. 59, no. 3, pp. 335–345, 2000.

[49] J. H. Baik *et al.*, "Control of NOxemissions from diesel engine by selective catalytic reduction (SCR) with urea," *Top. Catal.*, vol. 30, no. 1, pp. 37–41, 2004.

[50] A. M. Leman, J. Afiqah, F. Dafit, R. Fakhrurrazi, and Z. Supaat, "Advanced Catalytic Converter in Gasoline Enginer Emission Control : A Review," vol. 02020, pp. 1–6, 2017.

[51] M. L. M. de Oliveira, C. M. Silva, R. Moreno-Tost, T. L. Farias, A. Jiménez-López, and E. Rodríguez-Castellón, "A study of copper-exchanged mordenite natural and ZSM-5 zeolites as SCR–NOx catalysts for diesel road vehicles: Simulation by neural networks approach," *Appl. Catal. B Environ.*, vol. 88, no. 3–4, pp. 420–429, May 2009.

[52] M. L. M. Oliveira, C. M. Silva, R. Moreno-Tost, T. L. Farias, A. Jiménez-López, and E. Rodríguez-Castellón, "Modelling of NOx emission factors from heavy and light-duty vehicles equipped with advanced aftertreatment systems," *Energy Convers. Manag.*, vol. 52, no. 8–9, pp. 2945–2951, Aug. 2011.

[53] R. Suarez-Bertoa, A. A. Zardini, H. Keuken, and C. Astorga, "Impact of ethanol containing gasoline blends on emissions from a flex-fuel vehicle tested over the

Worldwide Harmonized Light duty Test Cycle (WLTC)," *Fuel*, vol. 143, pp. 173–182, Mar. 2015.

[54] C. P. Hubbard, J. E. Anderson, and T. J. Wallington, "Ethanol and air quality: Influence of fuel ethanol content on emissions and fuel economy of flexible fuel vehicles," *Environ. Sci. Technol.*, 2014.

[55] T. D. Durbin, J. W. Miller, T. Younglove, T. Huai, and K. Cocker, "Effects of fuel ethanol content and volatility on regulated and unregulated exhaust emissions for the latest technology gasoline vehicles," *Environ. Sci. Technol.*, 2007.

[56] G. Karavalakis, T. D. Durbin, M. Shrivastava, Z. Zheng, M. Villela, and H. Jung, "Impacts of ethanol fuel level on emissions of regulated and unregulated pollutants from a fleet of gasoline light-duty vehicles," *Fuel*, 2012.

[57] W. D. Hsieh, R. H. Chen, T. L. Wu, and T. H. Lin, "Engine performance and pollutant emission of an SI engine using ethanol-gasoline blended fuels," *Atmos. Environ.*, 2002.

[58] C. Mata, A. Gómez, and O. Armas, "The influence of ethanol-diesel blend on pollutant emissions from different bus fleets under acceleration transitions," *Fuel*, 2017.

[59] A. Gómez, C. Mata, and O. Armas, "Effect of ethanol-diesel fuel blend on diesel engine emissions produced by different bus fleets," *J. Energy Eng.*, 2016.

[60] V. Guayanlema, S. Espinoza, A. D. Ramirez, and A. Núñez, "Trends and mitigation options of greenhouse gas emissions from the road transport sector in Ecuador," 2014, pp. 933–941.

[61] M. V. Chester, A. Horvath, and S. Madanat, "Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions," *Atmos. Environ.*, vol. 44, no. 8, pp. 1071–1079, 2010.

[62] E. Costa and J. Seixas, "Contribution of electric cars to the mitigation of CO2 emissions in the city of Sao Paulo," in *2014 IEEE Vehicle Power and Propulsion Conference, VPPC 2014*, 2014.

[63] G. Hill, O. Heidrich, F. Creutzig, and P. Blythe, "The role of electric vehicles in near-term mitigation pathways and achieving the UK's carbon budget," *Appl. Energy*, 2019.

[64] Q. Song, Y. Wu, J. Li, Z. Wang, D. Yu, and H. Duan, "Well-to-wheel GHG emissions and mitigation potential from light-duty vehicles in Macau," *Int. J. Life Cycle Assess.*, 2018.

[65] N. C. Onat, M. Kucukvar, and O. Tatari, "Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States," *Appl. Energy*, vol. 150, pp. 36–49, Jul. 2015.

[66] R. Faria, P. Marques, P. Moura, F. Freire, J. Delgado, and A. T. De Almeida, “Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles,” *Renew. Sustain. Energy Rev.*, vol. 24, pp. 271–287, Aug. 2013.

[67] S. G. Wirasingha, N. Schofield, and A. Emadi, “Feasibility analysis of converting a Chicago Transit Authority (CTA) transit bus to a plug-in hybrid electric vehicle,” *2008 IEEE Veh. Power Propuls. Conf. VPPC 2008*, 2008.

[68] S. W. Wayne, J. A. Sandoval, and N. N. Clark, “Emissions benefits from alternative fuels and advanced technology in the U.S. transit bus fleet,” *Energy Environ.*, vol. 20, no. 4, pp. 497–515, 2009.

[69] A. Lajunen and T. Lipman, “Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses,” *Energy*, vol. 106, pp. 329–342, 2016.

[70] J. P. Ribau, C. M. Silva, and J. M. C. Sousa, “Efficiency, cost and life cycle CO2optimization of fuel cell hybrid and plug-in hybrid urban buses,” *Appl. Energy*, vol. 129, pp. 320–335, 2014.

[71] Paulo Sergio Vasconcelos and Lucio Guido Tapia Carpio, “Bagasse, Straws, Tips and Vinasse: From Sugarcane Waste to a Clean and Renewable Bioenergy Source,” *Int. J. Adv. Soc. Sci. Humanit. - IJASSH*, 2017.

[72] I. C. Macedo, J. E. A. Seabra, and J. E. A. R. Silva, “Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020,” *Biomass and Bioenergy*, vol. 32, no. 7, 2008.

[73] J. E. A. Seabra, I. C. Macedo, H. L. Chum, C. E. Faroni, and C. A. Sarto, “Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use,” *Biofuels, Bioprod. Biorefining*, vol. 5, no. 5, 2011.

[74] S. P. Souza, M. T. de Ávila, and S. Pacca, “Life cycle assessment of sugarcane ethanol and palm oil biodiesel joint production,” *Biomass and Bioenergy*, 2012.

[75] J. C. del Río, G. Marques, A. G. Lino, C. F. Lima, J. L. Colodette, and A. Gutiérrez, “Lipophilic phytochemicals from sugarcane bagasse and straw,” *Ind. Crops Prod.*, 2015.

[76] M. Kim and D. F. Day, “Composition of sugar cane, energy cane, and sweet sorghum suitable for ethanol production at Louisiana sugar mills,” *J. Ind. Microbiol. Biotechnol.*, 2011.

[77] E. Gnansounou, P. Vaskan, and E. R. Pachón, “Comparative techno-economic assessment and LCA of selected integrated sugarcane-based biorefineries,” *Bioresour.*

Technol., vol. 196, 2015.

[78] S. M. Paixão, L. Alves, R. Pacheco, and C. M. Silva, "Evaluation of Jerusalem artichoke as a sustainable energy crop to bioethanol: energy and CO2eq emissions modeling for an industrial scenario," *Energy*, 2018.

[79] O. Cavalett *et al.*, "Environmental and economic assessment of sugarcane first generation biorefineries in Brazil," *Clean Technol. Environ. Policy*, vol. 14, no. 3, pp. 399–410, 2012.

[80] O. Cavalett, M. F. Chagas, J. E. A. Seabra, and A. Bonomi, "Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods," *Int. J. Life Cycle Assess.*, vol. 18, no. 3, pp. 647–658, 2013.

[81] J. B. Heywood, *INTERNAL COMBUSTION ENGINE*, vol. 21. 1988.

[82] A. Bonomi *et al.*, "The Virtual Sugarcane Biorefinery (VSB)," 2011.

[83] A. Corrêa do Lago, A. Bonomi, O. Cavalett, M. Pereira da Cunha, and M. A. Pinheiro Lima, "Sugarcane as a carbon source: The Brazilian case," *Biomass and Bioenergy*, vol. 46, pp. 5–12, 2012.

[84] A. C. R. Teixeira, J. R. Sodré, L. L. N. Guarieiro, E. D. Vieira, F. F. de Medeiros, and C. T. Alves, "A Review on Second and Third Generation Bioethanol Production," in *25th SAE BRASIL International Congress and Display*, 2016.

[85] S. P. Souza, A. R. Gopal, and J. E. A. Seabra, "Life cycle assessment of biofuels from an integrated Brazilian algae-sugarcane biorefinery," *Energy*, vol. 81, pp. 373–381, 2015.

[86] S. Zafar and C. S. Decker, "DEVELOPMENT OF BIOMASS ENERGY SYSTEMS IN ECUADOR What is Biomass ?," no. May, 2009.

[87] E. Purdy and H. Vega, "Ecuador Biofuels Annual Ecuador Biofuel Industry , Bioethanol , Biodiesel , Production , Forecast 2012," 2012.

[88] J. D. MORALES ENRÍQUEZ, "LA INDUSTRIA DE LOS BIOCOMBUSTIBLES EN ECUADOR: el estado de situación," p. 137, 2010.

[89] J. M. Domínguez, "Are Biofuels Socially Accepted in Guayaquil ?," pp. 18–24, 2012.

[90] V. Paredes, *Estado del desarrollo de biocombustibles en el Ecuador*. Guayaquil, 2015, p. 26.

[91] Grupo Spurrier, "Biocombustibles," Quito, 2013.

[92] R. Edwards *et al.*, "Well-to-Wheels analysis of future automotive fuels and powertrains in the European context Report," *Jt. Res. Cent. EU Ispra, Italy*, vol. 4, pp. 1–62, 2013.

[93] M. Wang, M. Wu, H. Huo, and J. Liu, "Life-cycle energy use and greenhouse gas

emission implications of Brazilian sugarcane ethanol simulated with the GREET model," *Int. Sugar J.*, vol. 110, no. 1317, pp. 1–15, 2008.

[94] M. Wang, J. Han, J. B. Dunn, H. Cai, and A. Elgowainy, "Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use," *Effic. Sustain. Biofuel Prod. Environ. Land-Use Res.*, pp. 249–280, 2015.

[95] M. Wang, M. Wu, H. Huo, and J. Liu, "Life-cycle energy use and greenhouse gas emission implications of Brazilian sugarcane ethanol simulated with the GREET model," *Int. Sugar J.*, vol. 110, no. 1317, 2008.

[96] D. Arcentales and C. Silva, "Exploring the introduction of plug-in hybrid flex-fuel vehicles in Ecuador," *Energies*, vol. 12, no. 11, p. 2244, 2019.

[97] S. H. Mohd Azhar *et al.*, "Yeasts in sustainable bioethanol production: A review," *Biochemistry and Biophysics Reports*. 2017.

[98] Z. Astolfi-Filho, L. A. Minim, J. Telis-Romero, V. P. R. Minim, and V. R. N. Telis, "Thermophysical properties of industrial sugar cane juices for the production of bioethanol," *J. Chem. Eng. Data*, 2010.

[99] Sustainable Energy for All and World Bank, "Rapid Assessment Gap Analysis: Honduras," pp. 1–45, 2013.

[100] A. Mosquera, "Policies and strategies for changing the energy matrix in Ecuador," 2008.

[101] IRENA, "Renewable Energy Policy Brief Ecuador," no. June, p. 10, 2015.

[102] C. A. Kennedy, "A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area," *Transportation (Amst).*, vol. 29, no. 4, pp. 459–493, 2002.

[103] N. Laffel, "Promoting Public Transportation for Sustainable Development," pp. 1–25, 2006.

[104] P. W. G. Newman, "Sustainability and cities: Extending the metabolism model," *Landsc. Urban Plan.*, vol. 44, no. 4, pp. 219–226, 1999.

[105] T. SATIENNAM, A. FUKUDA, and R. OSHIMA, "a Study on the Introduction of Bus Rapid Transit System in Asian Developing Cities," *IATSS Res.*, vol. 30, no. 2, pp. 59–69, 2006.

[106] City Hall Statistics, "Vehículos matriculados Guayaquil." Municipio de Guayaquil, Guayaquil, p. 1, 2016.

[107] BRT+ Centre of Excellence and EMBARQ, "Global BRT Data," *Version 3.34*, 2018. .

[108] A. Hubenthal, "Evaluación del sector transporte en Ecuador con miras a plantear

medidas de mitigación al Cambio Climático," *United Nations Dev. Program.*, vol. 20, pp. 1–24, 2010.

[109] World Resources Institute, "Modernizing Public Transportation," *Transport*, pp. 1–44, 2010.

[110] CONELEC, "Plan Maestro de Electrificación 2013-2022," 2013.

[111] SENPLADES, "Plan Nacional de Desarrollo 2017-2021," *Senplades*, pp. 1–148, 2017.

[112] INEC, "Anuario de Estadísticas de Transportes 2014," *Anual*, pp. 1–198, 2014.

[113] L. Q. Maurice, L. Hockstad, N. Hohne, J. Hupe, D. S. Lee, and K. Rypdal, "Mobile Combustion," *IPCC Guidel. Natl. Greenh. Gas Invent.*, pp. 1–78, 2006.

[114] A. Burnham, "User Guide for GREET Fleet Footprint Calculator." U.S. Department of Energy. Argonne Laboratory, p. 9, 2012.

[115] C. & S. Gable, "Gasoline Gallon Equivalent (GGE)," 2017. .

[116] El Expreso, "La Metrovía solicita mejorar el diésel local," Guayaquil, p. 1, 2017.

[117] Federico Von Buchwald de Janon, *Movilidad Urbana de Guayaquil*. Guayaquil: Universidad Católica Santiago de Guayaquil, 2014.

[118] A. D. Ramirez, B. Rivela, A. J. Boero, and A. M. Melendres, "Life cycle assessment of the electricity network in Ecuador," 2015, pp. 1–9.

[119] BYD, "China Buses Organization," 2018. .

[120] P. Bubna, D. Brunner, J. J. Gangloff, S. G. Advani, and A. K. Prasad, "Analysis, operation and maintenance of a fuel cell/battery series-hybrid bus for urban transit applications," *J. Power Sources*, vol. 195, no. 12, pp. 3939–3949, 2010.

[121] M. O. Keefe, "Thermal Management of PHEV / EV Charging Systems," 2010.

[122] R. Prohaska, K. Kelly, and L. Eudy, "Fast Charge Battery Electric Transit Bus In-Use Fleet Evaluation," 2016.

[123] F. Metrovía, "Metrovia," 2016. .

[124] U. Stelwagen and N. Ligterink, "NH3 emission factors for road transport," Ultrecht, 2015.

[125] B. H. Baek, J. A. Koziel, and V. P. Aneja, "A preliminary review of gas-to-particle conversion monitoring and modelling efforts in the USA," *Int. J. Glob. Environ. Issues*, 2015.

[126] A. B. Guerrero and E. Muñoz, "Life cycle assessment of second generation ethanol derived from banana agricultural waste: Environmental impacts and energy balance," *J. Clean. Prod.*, vol. 174, 2018.

[127] J. P. Ribau, J. M. C. Sousa, and C. M. Silva, "Plug-In Hybrid Vehicle Powertrain

Design Optimization: Energy Consumption and Cost BT - Proceedings of the FISITA 2012 World Automotive Congress," 2013, pp. 595–613.

[128] C. M. Silva, T. L. Farias, H. C. Frey, and N. M. Rouphail, "Evaluation of numerical models for simulation of real-world hot-stabilized fuel consumption and emissions of gasoline light-duty vehicles," *Transp. Res. Part D Transp. Environ.*, vol. 11, no. 5, pp. 377–385, 2006.

[129] T. Markel *et al.*, "ADVISOR: a systems analysis tool for advanced vehicle modeling," *J. Power Sources*, vol. 110, no. 2, pp. 255–266, 2002.

[130] G. Cooney, M. Jamieson, J. Marriott, J. Bergerson, A. Brandt, and T. J. Skone, "Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models," *Environ. Sci. Technol.*, vol. 51, no. 2, pp. 977–987, Jan. 2017.

[131] A. D. Ramirez, A. Boero, B. Rivela, A. M. Melendres, S. Espinoza, and D. A. Salas, "Life cycle methods to analyze the environmental sustainability of electricity generation in Ecuador: Is decarbonization the right path?," *Renew. Sustain. Energy Rev.*, vol. 134, 2020.

[132] C. Kouridis *et al.*, "EMEP/EEA air pollutant emission inventory guidebook," 2018.

[133] T. Kogo, Y. Hamamura, K. Nakatani, T. Toda, A. Kawaguchi, and A. Shoji, "High Efficiency Diesel Engine with Low Heat Loss Combustion Concept - Toyota ' s Inline 4-Cylinder," *SAE Int.*, 2016.

[134] A. Thiruvengadam, S. Pradhan, P. Thiruvengadam, M. Besch, D. Carder, and O. Delgado, "Heavy-Duty Vehicle Diesel Engine Efficiency Evaluation and Energy Audit," *Center for Alternative Fuels, Engines & Emissions: West Virginia University Final Report*, 2014. .

[135] J. Zheng, C. Song, Q. Peng, and Z. Wang, "Experimental study on transmission efficiency of hybrid electric bus transmission with synthetic box assembly," in *2012 Asia-Pacific Power and Energy Engineering Conference*, 2012, pp. 1–5.

[136] N. O. Nylund, J. Laurikko, P. Laine, J. Suominen, and M. P. A. Anttonen, "Benchmarking heavy-duty ethanol vehicles against diesel and CNG vehicles," *Biomass Convers. Biorefinery*, 2013.

[137] T. G. Leone *et al.*, "The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine E ffi ciency," *Environ. Sci. Technol.*, vol. 49, pp. 10778–10789, 2015.

[138] K. D. Edwards, R. M. Wagner, T. E. Briggs, and T. J. Theiss, "Defining Engine

Efficiency Limits," *17th DEER Conf.*, 2011.

[139] R. Wang, Y. Wu, W. Ke, S. Zhang, B. Zhou, and J. Hao, "Can propulsion and fuel diversity for the bus fleet achieve the win – win strategy of energy conservation and environmental protection ?," *Appl. Energy*, vol. 147, pp. 92–103, 2015.

[140] S. Mueller, S. Unnasch, B. Keesom, S. Mohan, and L. Goyal, "The Impact of Higher Ethanol Blend Levels on Vehicle Emissions in Five Global Cities," 2018.

[141] C. Silva, M. Ross, and T. Farias, "Analysis and simulation of 'low-cost' strategies to reduce fuel consumption and emissions in conventional gasoline light-duty vehicles," *Energy Convers. Manag.*, vol. 50, no. 2, pp. 215–222, Feb. 2009.

[142] S. Eaves and J. Eaves, "A cost comparison of fuel-cell and battery electric vehicles," *J. Power Sources*, 2004.

[143] H. C. Righolt and F. G. Rieck, "Energy chain and efficiency in urban traffic for ICE and EV," in *2013 World Electric Vehicle Symposium and Exhibition, EVS 2014*, 2014.

[144] J. Kappel and B. V. Mathiesen, "Screening of tank-to-wheel efficiencies for CNG, DME and methanolethanol fuel blends in road transport," 2013.

[145] R. Group, "The range of hybrid cars," 2020. [Online]. Available: https://www.renaultgroup.com/en/news-on-air/news/the-range-of-hybrid-cars/. [Accessed: 22-Nov-2022].

[146] C. Kouridis, D. Gkatzoflias, I. Kioutsioukis, L. Ntziachristos, C. Pastorello, and P. Dilara, "Uncertainty estimates and guidance for road transport emission calculations," 2010.

[147] M. J. Bradley, "Bus Technology & Alternative Fuels Demonstration Project," Manchester, 2006.

[148] S. Zhang *et al.*, "Real-world fuel consumption and CO2 emissions of urban public buses in Beijing," *Appl. Energy*, vol. 113, no. 0, pp. 1645–1655, Jan. 2014.

[149] C. Keramydas *et al.*, "Real-World Measurement of Hybrid Buses' Fuel Consumption and Pollutant Emissions in a Metropolitan Urban Road Network," *Energies*, vol. 11, no. 10, p. 2569, Sep. 2018.

[150] S. L. Hallmark, B. Wang, and R. Sperry, "Comparison of on-road emissions for hybrid and regular transit buses," *J. Air Waste Manage. Assoc.*, vol. 63, no. 10, pp. 1212–1220, Oct. 2013.

[151] M. J. Amores, F. D. Mele, L. Jiménez, and F. Castells, "Life cycle assessment of fuel ethanol from sugarcane in Argentina," *Int. J. Life Cycle Assess.*, vol. 18, no. 7, pp. 1344–1357, 2013.

[152] C. C. Lisboa, K. Butterbach-Bahl, M. Mauder, and R. Kiese, “Bioethanol production from sugarcane and emissions of greenhouse gases - known and unknowns,” *GCB Bioenergy*, vol. 3, no. 4, pp. 277–292, 2011.

[153] K. Hanaki and J. Portugal-Pereira, “The Effect of Biofuel Production on Greenhouse Gas Emission Reductions,” in *Biofuels and Sustainability*, M. Takeuchi, K., Shiroyama, H., Saito, O., Matsuura, Ed. Springer, Tokyo, 2018, pp. 53–71.

[154] REN21 Secretariat, “MARKET AND INDUSTRY TRENDS,” 2019. [Online]. Available: https://www.ren21.net/gsr-2019/chapters/chapter_03/chapter_03/. [Accessed: 30-Nov-2021].

[155] B. P. Company, “British Petroleum Statistical Review of World Energy,” London, United Kingdom, 2014.

[156] T. D. et al. Fargione J, Hill J, “Biofuels: effects in landand fire – response.,” *Science (80-.).*, vol. 321, no. 5886, pp. 199–200, 2008.

[157] D. P. Ho, H. H. Ngo, and W. Guo, “A mini review on renewable sources for biofuel,” *Bioresour. Technol.*, vol. 169, pp. 742–749, 2014.

[158] B. D. Solomon, “Biofuels and sustainability,” in *Ecological Economics Reviews*, vol. 1185, Ann. N. Y. Acad. Sci, 2010, pp. 119–134.

[159] R. W. Kates *et al.*, “Sustainability Science,” *Science (80-.).*, vol. 292, no. 5517, pp. 641–642, 2001.

[160] D. Khatiwada, B. K. Venkata, S. Silveira, and F. X. Johnson, “Energy and GHG balances of ethanol production from cane molasses in Indonesia,” *Appl. Energy*, vol. 164, pp. 756–768, 2016.

[161] R. Luque *et al.*, “Biofuels: A technological perspective,” *Energy Environ. Sci.*, vol. 1, no. 5, pp. 542–564, 2008.

[162] R. Ahorsu, F. Medina, and M. Constantí, “Significance and challenges of biomass as a suitable feedstock for bioenergy and biochemical production: A review,” *Energies*, vol. 11, no. 12, p. 3366, 2018.

[163] Food and Agriculture Organization of the United Nations (FAO), “Biofuels: prospects risks and opportunities,” in *The State of Food and Agriculture*, Rome, Italy: FAO, 2008, pp. 1–97.

[164] M. Lange, “The GHG balance of biofuels taking into account land use change,” *Energy Policy*, vol. 39, no. 5, pp. 2373–2385, 2011.

[165] S. Harchaoui and P. Chatzimpiros, “Energy, Nitrogen, and Farm Surplus Transitions in Agriculture from Historical Data Modeling. France, 1882–2013.,” *J. Ind. Ecol.*, vol. 23,

no. 2, pp. 412–425, 2019.

[166] Sutton MA *et al.*, “Our Nutrient World: The challenge to produce more food and energy with less pollution,” Centre for Ecology and Hydrology: Edinburgh, Scotland, 2013.

[167] P. G. Levi and J. M. Cullen, “Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products,” *Environ. Sci. Technol.*, vol. 52, no. 4, pp. 1725–1734, 2018.

[168] J. T. Trimmer and J. S. Guest, “Recirculation of human-derived nutrients from cities to agriculture across six continents,” *Nat. Sustain.*, vol. 1, no. 8, pp. 427–435, 2018.

[169] K. Koppelmäki, J. Helenius, and R. P. O. Schulte, “Nested circularity in food systems: A Nordic case study on connecting biomass, nutrient and energy flows from field scale to continent,” *Resour. Conserv. Recycl.*, vol. 164, no. 105218, p. 105218, 2021.

[170] E. Miliotti, S. Dell’Orco, G. Lotti, A. M. Rizzo, L. Rosi, and D. Chiaramonti, “Lignocellulosic ethanol biorefinery: Valorization of lignin-rich stream through hydrothermal liquefaction,” *Energies*, vol. 12, no. 723, p. 723, 2019.

[171] G. Pipitone, G. Zoppi, A. Frattini, S. Bocchini, R. Pirone, and S. Bensaid, “Aqueous phase reforming of sugar-based biorefinery streams: from the simplicity of model compounds to the complexity of real feeds,” *Catal. Today*, vol. 345, pp. 267–279, 2020.

[172] K. Urbaniec and R. Grabarczyk, “Hydrogen production from sugar beet molasses - A techno-economic study,” *J. Clean. Prod.*, vol. 65, pp. 324–329, 2014.

[173] J. P. M. Guerra, J. R. Coleta, L. C. M. Arruda, G. A. Silva, and L. Kulay, “Comparative analysis of electricity cogeneration scenarios in sugarcane production by LCA,” *Int. J. Life Cycle Assess.*, vol. 19, no. 4, pp. 814–825, 2014.

[174] M. Anne Renouf, R. J. Pagan, and M. K. Wegener, “Life cycle assessment of Australian sugarcane products with a focus on cane processing,” *Int. J. Life Cycle Assess.*, vol. 16, no. 2, pp. 125–137, 2011.

[175] CORSIA, “ICAO. CORSIA supporting document: CORSIA Eligible Fuels – Life Cycle Assessment Methodology,” 2019.

[176] J. M. PATURAU, *By-products of the cane sugar industry - an introduction to their industrial utilization.*, 3rd ed., vol. 3. 1989.

[177] S. A. Miller, A. E. Landis, and T. L. Theis, “Environmental trade-offs of biobased production,” *Environ. Sci. Technol.*, vol. 41, no. 15, pp. 5176–5182, 2007.

[178] H. von Blottnitz and M. A. Curran, “A review of assessments conducted on bio-ethanol

as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective," *J. Clean. Prod.*, vol. 15, pp. 607–619, 2007.

[179] C. Silva, R. Pacheco, D. Arcentales, and F. Santos, *Sustainability of sugarcane for energy purposes*. Academic Press, 2019.

[180] I. V. Muralikrishna and V. Manickam, "Environmental Management Life Cycle Assessment," *Environ. Manage.*, vol. 1, no. 2, pp. 57–75, 2017.

[181] J. Hill, "Life Cycle Analysis of Biofuels," in *Encyclopedia of Biodiversity: Second Edition*, Elsevier Inc., 2013, pp. 627–630.

[182] E. B. Sydney *et al.*, "Current analysis and future perspective of reduction in worldwide greenhouse gases emissions by using first and second generation bioethanol in the transportation sector," *Bioresour. Technol. Reports*, vol. 7, 2019.

[183] H. L. Chum, E. Warner, J. E. A. Seabra, and I. C. Macedo, "A comparison of commercial ethanol production systems from Brazilian sugarcane and US corn," *Biofuels, Bioprod. Biorefining*, vol. 8, no. 2, 2014.

[184] X. Yan, K. R. Corbin, R. A. Burton, and D. K. Y. Tan, "Agave: A promising feedstock for biofuels in the water-energy-food-environment (WEFE) nexus," *J. Clean. Prod.*, vol. 261, 2020.

[185] L. G. Pereira, O. Cavalett, A. Bonomi, Y. Zhang, E. Warner, and H. L. Chum, "Comparison of biofuel life-cycle GHG emissions assessment tools: The case studies of ethanol produced from sugarcane, corn, and wheat," *Renewable and Sustainable Energy Reviews*, vol. 110. 2019.

[186] R. W. Stratton, H. M. Wong, and J. I. Hileman, "Quantifying variability in life cycle greenhouse gas inventories of alternative middle distillate transportation fuels," *Environ. Sci. Technol.*, vol. 45, no. 10, pp. 4637–4644, 2011.

[187] A. E. Farrell, R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare, and D. M. Kammen, "Ethanol can contribute to energy and environmental goals," *Science (80-.).*, vol. 311, no. 5760, pp. 506–508, 2006.

[188] E. Gnansounou, A. Dauriat, J. Villegas, and L. Panichelli, "Life cycle assessment of biofuels: Energy and greenhouse gas balances," *Bioresour. Technol.*, vol. 100, no. 21, pp. 4919–4930, 2009.

[189] T. Beer and T. Grant, "Life-cycle analysis of emissions from fuel ethanol and blends in Australian heavy and light vehicles," *J. Clean. Prod.*, vol. 15, no. 8–9, pp. 833–837, 2007.

[190] J. Wallace, M. Wang, T. Weber, and A. Finizza, "Well-to-wheel analysis of energy use

and greenhouse gas emissions of advanced fuel/vehicle systems – North American analysis Volume 3," 2001.

[191] S. Kim and B. E. Dale, "Life cycle assessment of fuel ethanol derived from corn grain via dry milling," *Bioresour. Technol.*, vol. 99, no. 12, pp. 5250–5260, 2008.

[192] J. Malça and F. Freire, "Renewability and life-cycle energy efficiency of bioethanol and bio-ethyl tertiary butyl ether (bioETBE): Assessing the implications of allocation," *Energy*, vol. 31, no. 15, pp. 3362–3380, 2006.

[193] H. Shapouri, J. A. Duffield, and M. Wang, "The Energy Balance of Corn Ethanol Revisited," *Trans. Am. Soc. Agric. Eng.*, vol. 46, no. 4, pp. 959–968, 2003.

[194] R. M. and N. D. M. M. A. Elsayed, "Carbon and Energy Balances for a Range of Biofuels Options," Sheffield Hallam University: Sheffield, UK, 2003.

[195] Isaias de Carvalho Macedo, "Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil," Government of the State of Sao Paulo, Government of the State of Sao Paulo: Sao Paulo, Brazil, 2003.

[196] L. Luo, E. van der Voet, and G. Huppes, "Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil," *Renew. Sustain. Energy Rev.*, vol. 13, no. 6–7, pp. 1613–1619, 2009.

[197] Y. Bai, L. Luo, and E. Van Der Voet, "Life cycle assessment of switchgrass-derived ethanol as transport fuel," *Int. J. Life Cycle Assess.*, vol. 15, no. 5, pp. 468–477, 2010.

[198] A. Roberto Ometto, M. Zwicky Hauschild, and W. Nelson Lopes Roma, "Lifecycle assessment of fuel ethanol from sugarcane in Brazil," *Int. J. Life Cycle Assess.*, vol. 14, no. 3, pp. 236–247, 2009.

[199] M. A. Renouf, M. K. Wegener, and R. J. Pagan, "Life cycle assessment of Australian sugarcane production with a focus on sugarcane growing," *Int. J. Life Cycle Assess.*, vol. 15, no. 9, pp. 927–937, 2010.

[200] T. Botha and H. von Blottnitz, "A comparison of the environmental benefits of bagasse-derived electricity and fuel ethanol on a life-cycle basis," *Energy Policy*, vol. 34, no. 17, pp. 2654–2661, 2006.

[201] F. Cherubini and S. Ulgiati, "Crop residues as raw materials for biorefinery systems - A LCA case study," *Appl. Energy*, vol. 87, no. 1, pp. 47–57, 2010.

[202] IEA, *Energy technology perspective. Scenario and strategies to 2050*, no. June. 2008.

[203] F. Saladini, N. Patrizi, F. M. Pulselli, N. Marchettini, and S. Bastianoni, "Guidelines for emergy evaluation of first, second and third generation biofuels," *Renew. Sustain. Energy Rev.*, vol. 66, pp. 221–227, 2016.

[204] J. Sendelius, “Steam Pretreatment Optimisation for Sugarcane Bagasse in Bioethanol Production,” *Trials*. 2005.

[205] J. A. Quintero, M. I. Montoya, O. J. Sánchez, O. H. Giraldo, and C. A. Cardona, “Fuel ethanol production from sugarcane and corn: Comparative analysis for a Colombian case,” *Energy*, vol. 33, no. 3, pp. 385–399, 2008.

[206] M. Morales, J. Quintero, R. Conejeros, and G. Aroca, “Life cycle assessment of lignocellulosic bioethanol: Environmental impacts and energy balance,” *Renew. Sustain. Energy Rev.*, vol. 42, pp. 1349–1361, 2015.

[207] T. L. T. Nguyen and S. H. Gheewala, “Life cycle assessment of fuel ethanol from cane molasses in Thailand,” *Int. J. Life Cycle Assess.*, vol. 13, no. 4, p. 301, 2008.

[208] T. Silalertruksa and S. H. Gheewala, “Environmental sustainability assessment of bio-ethanol production in Thailand,” *Energy*, vol. 34, no. 11, 2009.

[209] H. Halleux, S. Lassaux, R. Renzoni, and A. Germain, “Comparative life cycle assessment of two biofuels: Ethanol from sugar beet and rapeseed methyl ester,” *Int. J. Life Cycle Assess.*, vol. 13, no. 3, p. 184, 2008.

[210] H. Shapouri, “The Energy Balance of Corn Ethanol Revisited,” *Trans. ASAE.*, vol. 46, no. 4, pp. 959–968, 2003.

[211] R. Hoefnagels, E. Smeets, and A. Faaij, “Greenhouse gas footprints of different biofuel production systems,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 7, pp. 1661–1694, 2010.

[212] A. P. C. Faaij, “Bio-energy in Europe: Changing technology choices,” *Energy Policy*, vol. 34, no. 3, pp. 322–342, 2006.

[213] C. A. Cardona, J. A. Quintero, and I. C. Paz, “Production of bioethanol from sugarcane bagasse: Status and perspectives,” *Bioresour. Technol.*, vol. 101, no. 13, pp. 4754–4766, 2010.

[214] K. L. Kadam, “Environmental benefits on a life cycle basis of using bagasse-derived ethanol as a gasoline oxygenate in India,” *Energy Policy*, vol. 30, no. 5, pp. 371–384, 2002.

[215] J. Sheehan *et al.*, “Energy and environmental aspects of using corn stover for fuel ethanol,” *J. Ind. Ecol.*, vol. 7, no. 3–4, pp. 117–146, 2003.

[216] S. Spatari, Y. Zhang, and H. L. Maclean, “Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles,” *Environ. Sci. Technol.*, vol. 39, no. 24, pp. 9750–9758, 2005.

[217] M. Wu, M. Wang, and H. Huo, “Fuel-Cycle Assessment of Selected Bioethanol

Production Pathways in the United States," Argonne, 2006.

[218] D. Khatiwada and S. Silveira, "Net energy balance of molasses based ethanol: The case of Nepal," *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2515–25, 2009.

[219] A. R. Gopal and D. M. Kammen, "Molasses for ethanol: The economic and environmental impacts of a new pathway for the lifecycle greenhouse gas analysis of sugarcane ethanol," *Environ. Res. Lett.*, vol. 4, no. 4, 2009.

[220] S. Medina, "Atlas Bioenergético del Ecuador," 2014.

[221] Ministerio Coordinador de Sectores Estratégicos, "Agenda Nacional de Energía 2016-2040," Ministerio Coordinador de Sectores Estratégicos: Quito, Ecuador, 2017.

[222] EP Petroecuador, "Empresa Pública de Hidrocarburos del Ecuador Plan Estratégico Empresarial 2018-2021," EP Petroecuador: Quito, Ecuador, 2020.

[223] A. Briones-Hidrovo, J. Uche, and A. Martínez-Gracia, "Determining the net environmental performance of hydropower: A new methodological approach by combining life cycle and ecosystem services assessment," *Sci. Total Environ.*, vol. 712, 2020.

[224] A. Briones Hidrovo, J. Uche, and A. Martínez-Gracia, "Accounting for GHG net reservoir emissions of hydropower in Ecuador," *Renew. Energy*, vol. 112, 2017.

[225] F. Porras, A. D. Ramirez, A. Walter, and G. Soriano, "Life cycle assessment of greenhouse gas emissions: Comparison between a cooling tower and a geothermal heat exchanger for air conditioning applications in Ecuador," in *ASME 2019 13th International Conference on Energy Sustainability, ES 2019, collocated with the ASME 2019 Heat Transfer Summer Conference*, 2019.

[226] A. D. Ramirez, E. F. Perez, A. J. Boero, and D. A. Salas, "Carbon footprint of energy systems: Liquefied petroleum gas based cooking vs electricity based cooking in Ecuador," in *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, 2017, vol. 6.

[227] A. D. Ramirez, D. Arcentales, and A. Boero, "Mitigation of greenhouse gas emissions through the shift from fossil fuels to electricity in the mass transport system in guayaquil, ecuador," in *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, 2018, vol. 6A-144113.

[228] C. R. Parra *et al.*, "Bioenergy on islands: An environmental comparison of continental palm oil vs. local waste cooking oil for electricity generation," *Appl. Sci.*, vol. 10, no. 11, 2020.

[229] A. D. Ramirez, B. Rivela, A. Boero, and A. M. Melendres, "Lights and shadows of the

environmental impacts of fossil-based electricity generation technologies: A contribution based on the Ecuadorian experience," *Energy Policy*, vol. 125, 2019.

[230] M. Muñoz Mayorga, I. Herrera Orozco, Y. Lechón Pérez, N. Caldés Gomez, and E. Iglesias Martínez, "Environmental Assessment of Electricity Based on Straight Jatropha Oil on Floreana Island, Ecuador," *Bioenergy Res.*, vol. 11, no. 1, 2018.

[231] NATIONAL ENERGY TECHNOLOGY LABORATORY, "Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels," 2008.

[232] RSB – ROUNDTABLE ON SUSTAINABLE BIOMATERIALS, "- RSB Fossil Fuel Baseline Calculation Methodology," Geneva, 2011.

[233] ISO, "ISO 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland," *Int. J. Life Cycle Assess.*, vol. 2006, no. 7, 2006.

[234] ISO, "ISO 14040 International Standard. Environmental management — Life cycle assessment — Principles and framework.," *Int. Organ. Stand. (ISO), Geneva. Switzerland.*, 2006.

[235] T. Ekvall and B. P. Weidema, "System boundaries and input data in consequential life cycle inventory analysis," in *International Journal of Life Cycle Assessment*, 2004, vol. 9, no. 3.

[236] ARCONEL, "Estadística Anual y Multianual del Sector Eléctrico Ecuatoriano," 2017.

[237] LOSPEE, "Reglamento General de la Ley Orgánica del Servicio Público de Energía Eléctrica," *Regist. Of. Año I – N^{o} 21*, no. 21, 2019.

[238] T. Nemecek and T. Kagi, "Life cycle inventories of Swiss and European Agricultural Production Systems, ecoinvent report No. 15," Swiss Centre for Life Cycle Inventories: Zurich, Switzerland, 2007.

[239] Ecoinvent v3.4, "ecoinvent Database – ecoinvent." [Online]. Available: https://ecoinvent.org/the-ecoinvent-database/. [Accessed: 30-Sep-2021].

[240] I. P. O. C. C. IPCC, "Climate Change 2007 - The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC," *Science (80-.).*, no. October 2009, 2007.

[241] Ministérioda Ciência e Tecnologia - MCT, "Primeiro inventário brasileiro de emissões antrópicas de gases de efeito estufa," Sao Paulo, 2011.

[242] IPCC, "Chapter 11: N2O emissions from managed soils, and CO2 emissions from lime and urea application," in *2019 Refinement to the 2006 IPCC Guidelines for National*

Greenhouse Gas Inventories, vol. 4, 2019.

[243] E. W. Gabisa, C. Bessou, and S. H. Gheewala, “Life cycle environmental performance and energy balance of ethanol production based on sugarcane molasses in Ethiopia,” *J. Clean. Prod.*, vol. 234, 2019.

[244] Diario El Universo, “Producción de caña de azúcar y etanol genera 200.000 plazas de trabajo, según la Asociación de Biocombustibles del Ecuador,” Guayaquil, 2021.

[245] E. Birru, “Sugar Cane Industry Overview And Energy Efficiency Considerations,” KTH Royal Institute of Technology: Stockholm, Sweden, 2016.

[246] ARCONEL, “Estadísticas del Sector Eléctrico Ecuatoriano,” ARCONEL: Quito, Ecuador, 2015.

[247] PME, “Plan Maestro de Electricidad 2016-2025,” *Celec EP*, 2017. .

[248] J. Graesser, T. M. Aide, H. R. Grau, and N. Ramankutty, “Cropland/pastureland dynamics and the slowdown of deforestation in Latin America,” *Environ. Res. Lett.*, vol. 10, no. 3, 2015.

[249] R. C. Nagy *et al.*, “Soil Carbon Dynamics in Soybean Cropland and Forests in Mato Grosso, Brazil,” *J. Geophys. Res. Biogeosciences*, vol. 123, no. 1, 2018.

[250] S. A. Spawn, T. J. Lark, and H. K. Gibbs, “Carbon emissions from cropland expansion in the United States,” *Environ. Res. Lett.*, vol. 14, no. 4, 2019.

[251] T. Silalertruksa, S. H. Gheewala, and P. Pongpat, “Sustainability assessment of sugarcane biorefinery and molasses ethanol production in Thailand using eco-efficiency indicator,” *Appl. Energy*, vol. 160, 2015.

[252] M. D. B. Watanabe *et al.*, “Hybrid Input-Output Life Cycle Assessment of First- and Second-Generation Ethanol Production Technologies in Brazil,” *J. Ind. Ecol.*, vol. 20, no. 4, 2016.

[253] I. Tsiropoulos *et al.*, “Life cycle assessment of sugarcane ethanol production in India in comparison to Brazil,” *Int. J. Life Cycle Assess.*, vol. 19, no. 5, 2014.

[254] M. Hiloidhari, S. Haran, R. Banerjee, and A. B. Rao, “Life cycle energy–carbon–water footprints of sugar, ethanol and electricity from sugarcane,” *Bioresour. Technol.*, vol. 330, 2021.

[255] V. Ramamurthy, L. G. K. Naidu, S. C. Ramesh Kumar, S. Srinivas, and R. Hegde, “Soil-based fertilizer recommendations for precision farming,” *Curr. Sci.*, vol. 97, no. 5, 2009.

[256] G. M. Sanches *et al.*, “Precision production environments for sugarcane fields,” *Sci. Agric.*, vol. 76, no. 1, 2019.

[257] F. Tubiello *et al.*, *Estimación de emisiones de gases de efecto invernadero en la agricultura. Un manual para abordar los requisitos de los datos para los países en desarrollo*. 2015.

[258] S. M. El-Haggar, *Sustainability of Agricultural and Rural Waste Management*. Academic Press, 2007.

[259] H. Stichnothe and A. Azapagic, "Bioethanol from waste: Life cycle estimation of the greenhouse gas saving potential," *Resour. Conserv. Recycl.*, vol. 53, no. 11, 2009.

[260] M. O. S. Dias *et al.*, "Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash," *Bioresour. Technol.*, vol. 103, no. 1, 2012.

[261] M. O. S. Dias *et al.*, "Biorefineries for the production of first and second generation ethanol and electricity from sugarcane," *Appl. Energy*, vol. 109, 2013.

[262] L. Wang, R. Quiceno, C. Price, R. Malpas, and J. Woods, "Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward," *Renewable and Sustainable Energy Reviews*, vol. 40. 2014.

[263] R. Pacheco and C. Silva, "Global warming potential of biomass-to-ethanol: Review and sensitivity analysis through a case study," *Energies*, vol. 12, no. 13, 2019.

[264] G. Murali and Y. Shastri, "Life-cycle assessment-based comparison of different lignocellulosic ethanol production routes," *Biofuels*, vol. 13, no. 2, 2022.

[265] S. Silveira and D. Khatiwada, "Ethanol production and fuel substitution in Nepal-Opportunity to promote sustainable development and climate change mitigation," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 6. 2010.

[266] N. Kordala, M. Walter, B. Brzozowski, and M. Lewandowska, "2G-biofuel ethanol: an overview of crucial operations, advances and limitations," *Biomass Convers. Biorefinery*, 2022.

[267] EEA, "Energy and climate change — European Environment Agency," *Published 29 Aug 2017 Last modified 11 May 2021*. 2017.

[268] D. Elzinga and S. Foster, "The Role of Fossil Fuels in a Sustainable Energy System | United Nations," *United Nations*, 2021. .

[269] G. E. Halkos and E. C. Gkampoura, "Reviewing usage, potentials, and limitations of renewable energy sources," *Energies*, vol. 13, no. 11. 2020.

[270] I. P. O. C. C. IPCC, "Climate change widespread, rapid, and intensifying - IPCC," *Ipcc.Ch*, 2021. .

[271] IPCC, "Climate Change and Land: an IPCC special report," *Clim. Chang. L. an IPCC*

Spec. Rep. Clim. Chang. Desertif. L. Degrad. Sustain. L. Manag. food Secur. Greenh. gas fluxes Terr. Ecosyst., 2019.

[272] IPCC, *Global Warming of 1.5°C*. 2022.

[273] International Energy Agency, "IEA World Energy Statistics and Balances," *OECD iLibrary*, 2017. .

[274] V. Ratanavaraha and S. Jomnonkwao, "Trends in Thailand CO2 emissions in the transportation sector and Policy Mitigation," *Transp. Policy*, vol. 41, 2015.

[275] C. Wang, J. Wood, Y. Wang, X. Geng, and X. Long, "CO2 emission in transportation sector across 51 countries along the Belt and Road from 2000 to 2014," *J. Clean. Prod.*, vol. 266, 2020.

[276] Y. Van Fan, S. Perry, J. J. Klemeš, and C. T. Lee, "A review on air emissions assessment: Transportation," *J. Clean. Prod.*, vol. 194, 2018.

[277] P. K. Maurya, S. Mondal, V. Kumar, and S. P. Singh, "Roadmap to sustainable carbon-neutral energy and environment: can we cross the barrier of biomass productivity?," *Environmental Science and Pollution Research*, vol. 28, no. 36. 2021.

[278] M. Mohsin, Q. Abbas, J. Zhang, M. Ikram, and N. Iqbal, "Integrated effect of energy consumption, economic development, and population growth on CO2 based environmental degradation: a case of transport sector," *Environ. Sci. Pollut. Res.*, vol. 26, no. 32, 2019.

[279] International Energy Agency, "Global EV Outlook 2018: Towards cross-modal electricification," 2018.

[280] R. B. B. A. de S. T. Lavrador, "Life cycle assessment of battery electric vehicles and internal combustion vehicles using sugarcane ethanol in Brazil: A critical review," *Clean. Energy Syst.*, vol. 2, no. 100008, 2022.

[281] J. Li and B. Yang, "Analysis of greenhouse gas emissions from electric vehicle considering electric energy structure, climate and power economy of ev: A China case," *Atmos. Pollut. Res.*, vol. 11, no. 6, 2020.

[282] C. G. Hoehne and M. V. Chester, "Optimizing plug-in electric vehicle and vehicle-to-grid charge scheduling to minimize carbon emissions," *Energy*, vol. 115, 2016.

[283] European Commission, "CO2 emission performance standards for cars and vans (2020 onwards)," *Road transport: Reducing CO2 emissions from vehicles*, 2020. .

[284] S. Bharti, B. V. S. Chauhan, A. Garg, A. Vedrtnam, and M. K. Shukla, "Potential of E-Fuels for Decarbonization of Transport Sector," in *Energy, Environment, and Sustainability*, 2022.

[285] T. Mizik, “Sustainable Fuels in Private Transportation–Present and Future Potential,” in *Energy, Environment, and Sustainability*, 2022.

[286] O. F. C. Cavalett, “Unraveling the role of biofuels in road transport under rapid electrification,” *Biofuels, Bioprod. Biorefining*, pp. 1–16, 2022.

[287] H. Al-Thani, M. Koç, R. J. Isaifan, and Y. Bicer, “A Review of the Integrated Renewable Energy Systems for Sustainable Urban Mobility,” *Sustainability*, vol. 14, no. 17, 2022.

[288] L. L. P. de Souza, E. E. S. Lora, J. C. E. Palacio, M. H. Rocha, M. L. G. Renó, and O. J. Venturini, “Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil,” *J. Clean. Prod.*, vol. 203, 2018.

[289] A. García, J. Monsalve-Serrano, S. Martínez-Boggio, V. Rückert Roso, and N. Duarte Souza Alvarenga Santos, “Potential of bio-ethanol in different advanced combustion modes for hybrid passenger vehicles,” *Renew. Energy*, vol. 150, 2020.

[290] S. Nanda, R. Rana, P. K. Sarangi, A. K. Dalai, and J. A. Kozinski, “A broad introduction to first-, second-, and third-generation biofuels,” in *Recent Advancements in Biofuels and Bioenergy Utilization*, 2018.

[291] C. R. Parra, A. D. Ramirez, L. M. Navas-Gracia, D. Gonzales, and A. Correa-Guimaraes, “Prospects for Bioenergy Development Potential from Dedicated Energy Crops in Ecuador: An Agroecological Zoning Study,” *Agriculture*, vol. 13, no. 1, 2023.

[292] D. Arcentales, C. Silva, and A. D. Ramirez, “The Environmental Profile of Ethanol Derived from Sugarcane in Ecuador: A Life Cycle Assessment Including the Effect of Cogeneration of Electricity in a Sugar Industrial Complex,” *Energies*, vol. 15, no. 15, 2022.

[293] C. J. Mansour and M. G. Haddad, “Well-to-wheel assessment for informing transition strategies to low-carbon fuel-vehicles in developing countries dependent on fuel imports: A case-study of road transport in Lebanon,” *Energy Policy*, vol. 107, 2017.

[294] X. He *et al.*, “Economic and Climate Benefits of Electric Vehicles in China, the United States, and Germany,” *Environ. Sci. Technol.*, vol. 53, no. 18, 2019.

[295] P. Wolfram and T. Wiedmann, “Electrifying Australian transport: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity,” *Appl. Energy*, vol. 206, 2017.

[296] S. Xiong, Y. Wang, B. Bai, and X. Ma, “A hybrid life cycle assessment of the large-scale application of electric vehicles,” *Energy*, vol. 216, 2021.

[297] K. Morganti *et al.*, “Synergistic engine-fuel technologies for light-duty vehicles: Fuel economy and Greenhouse Gas Emissions,” *Appl. Energy*, vol. 208, 2017.

[298] N. Bauer *et al.*, “Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison,” *Clim. Change*, vol. 163, no. 3, 2020.

[299] P. R. R. Rochedo *et al.*, “The threat of political bargaining to climate mitigation in Brazil,” *Nature Climate Change*, vol. 8, no. 8. 2018.

[300] E. Karaaslan, Y. Zhao, and O. Tatari, “Comparative life cycle assessment of sport utility vehicles with different fuel options,” *Int. J. Life Cycle Assess.*, vol. 23, no. 2, 2018.

[301] G. Puig-Samper Naranjo, D. Bolonio, M. F. Ortega, and M. J. García-Martínez, “Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain,” *J. Clean. Prod.*, vol. 291, 2021.

[302] Y. Bicer and I. Dincer, “Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles,” *Resour. Conserv. Recycl.*, vol. 132, pp. 141–157, May 2018.

[303] C. Bauer, J. Hofer, H. J. Althaus, A. Del Duce, and A. Simons, “The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework,” *Appl. Energy*, vol. 157, pp. 871–883, Nov. 2015.

[304] C. Tagliaferri *et al.*, “Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach,” *Chem. Eng. Res. Des.*, vol. 112, pp. 298–309, Aug. 2016.

[305] K. Petrauskienė, M. Skvarnavičiūtė, and J. Dvarionienė, “Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania,” *J. Clean. Prod.*, vol. 246, 2020.

[306] C. Ternel, A. Bouter, and J. Melgar, “Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: Comparison with greenhouse gas emissions of electric vehicles and forecast to 2030,” *Transp. Res. Part D Transp. Environ.*, vol. 97, 2021.

[307] F. Sisani, F. Di Maria, and D. Cesari, “Environmental and human health impact of different powertrain passenger cars in a life cycle perspective. A focus on health risk and oxidative potential of particulate matter components,” *Sci. Total Environ.*, vol. 805, 2022.

[308] M. S. Koroma *et al.*, “Life cycle assessment of battery electric vehicles: Implications of

future electricity mix and different battery end-of-life management," *Sci. Total Environ.*, vol. 831, 2022.

[309] Y. Y. H. X. J. C. F. W. L. J. Q. L. J. L. Liu, "Which type of electric vehicle is worth promoting mostly in the context of carbon peaking and carbon neutrality? A case study for a metropolis in China," *Sci. Total Environ.*, vol. 837, pp. 1–12, 2022.

[310] M. Ayala-Chauvin, C. Samaniego-Ojeda, G. Riba, and J. Maldonado-Correa, "Lifecycle assessment of electricity generation transition in ecuador," in *Lecture Notes in Electrical Engineering*, 2021, vol. 756 LNEE.

[311] G. Chiriboga, R. Chamba, A. Garcia, R. Heredia-Fonseca, C. Montero- Calderón, and G. Carvajal C, "Useful energy is a meaningful approach to building the decarbonization: A case of study of the Ecuadorian transport sector," *Transp. Policy*, vol. 132, pp. 76–87, 2023.

[312] A. Accardo, G. Dotelli, M. L. Musa, and E. Spessa, "Life cycle assessment of an NMC battery for application to electric light-duty commercial vehicles and comparison with a sodium-nickel-chloride battery," *Appl. Sci.*, vol. 11, no. 3, 2021.

[313] A. R. C. S. D. Arcentales et al., "The Environmental Profile of Ethanol Derived from Sugarcane in Ecuador: A Life Cycle Assessment Including the Effect of Cogeneration of Electricity in a Sugar Industrial Complex," *Energies - Spec. Issue Smart Mobil. Energy Transitions*, vol. 15, no. 5421, pp. 1–24, 2022.

[314] X. Li and E. Mupondwa, "Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies," *Sci. Total Environ.*, vol. 481, no. 1, 2014.

[315] T. Zink, F. Maker, R. Geyer, R. Amirtharajah, and V. Akella, "Comparative life cycle assessment of smartphone reuse: Repurposing vs. refurbishment," *Int. J. Life Cycle Assess.*, vol. 19, no. 5, 2014.

[316] J. Ryter, X. Fu, K. Bhuwalka, R. Roth, and E. Olivetti, "Assessing recycling, displacement, and environmental impacts using an economics-informed material system model," *J. Ind. Ecol.*, vol. 26, no. 3, 2022.

[317] S. Espinoza, E. Noboa, and B. Rivera, "Implementación de Prospectiva Energética como Estrategia Prioritaria para la Soberanía Energética y Sostenibilidad Nacional," *Rev. Técnica "Energía,"* vol. 11, no. 1, 2015.

[318] J. Woollacott, "A bridge too far? The role of natural gas electricity generation in US climate policy," *Energy Policy*, vol. 147, 2020.

[319] N. Mohammad, W. W. Mohamad Ishak, S. I. Mustapa, and B. V. Ayodele, "Natural Gas as a Key Alternative Energy Source in Sustainable Renewable Energy Transition:

A Mini Review," *Frontiers in Energy Research*, vol. 9. 2021.

[320] International Energy Agency, "The Role of Gas in Today's Energy Transitions – Analysis," *IEA*, 2019. .

[321] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," *Int. J. Life Cycle Assess.*, vol. 21, no. 9, 2016.

[322] M. DeMarco and M. O. P. Fortier, "Functional unit choice in space conditioning life cycle assessment: Review and recommendations," *Energy Build.*, vol. 255, 2022.

[323] ISO14040, "ISO 14040: Environmental Management- Life Cycle Assessment, Principles and Guidelines, International Organization for Standardization," *Geneva*, 2006.

[324] S. Saxena, C. Le Floch, J. Macdonald, and S. Moura, "Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models," *J. Power Sources*, vol. 282, 2015.

[325] X. Hu, L. Xu, X. Lin, and M. Pecht, "Battery Lifetime Prognostics," *Joule*, vol. 4, no. 2. 2020.

[326] N. D. Macpherson, G. A. Keoleian, and J. C. Kelly, "Fuel Economy and Greenhouse Gas Emissions Labeling for Plug-In Hybrid Vehicles from a Life Cycle Perspective," *J. Ind. Ecol.*, vol. 16, no. 5, 2012.

[327] L. Gao and Z. C. Winfield, "Life cycle assessment of environmental and economic impacts of advanced vehicles," *Energies*, vol. 5, no. 3, 2012.

[328] E. Szczechowicz, T. Dederichs, and A. Schnettler, "Regional assessment of local emissions of electric vehicles using traffic simulations for a use case in Germany," *Int. J. Life Cycle Assess.*, vol. 17, no. 9, 2012.

[329] P. Girardi, C. Brambilla, and G. Mela, "Life Cycle Air Emissions External Costs Assessment for Comparing Electric and Traditional Passenger Cars," *Integr. Environ. Assess. Manag.*, vol. 16, no. 1, 2020.

[330] E. A. Nanaki and C. J. Koroneos, "Comparative economic and environmental analysis of conventional, hybrid and electric vehicles - The case study of Greece," *J. Clean. Prod.*, vol. 53, 2013.

[331] Banco Central del Ecuador, "Cifras del sector petrolero ecuatoriano," Quito, 2020.

[332] Instituto Ecuatoriano de Normalización, *NTE INEN-ISO 3833:2008*. Ecuador, 2008, pp. 1–14.

[333] G. Majeau-Bettez, T. R. Hawkins, and A. H. StrØmman, "Life cycle environmental

assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles," *Environ. Sci. Technol.*, vol. 45, no. 10, 2011.

[334] I. Evtimov, R. Ivanov, G. Kadikyanov, and G. Staneva, "Life cycle assessment of electric and conventional cars energy consumption and CO2 emissions," in *MATEC Web of Conferences*, 2018, vol. 234.

[335] K. Aguirre *et al.*, "Life cycle Analysis Comparison of a Battery Electric Vehicle and a Conventional Gasoline Vehicle," *PhD Thesis*, no. June, 2012.

[336] Anon, "Life cycle analysis: getting the total picture on vehicle engineering alternatives," *Automot. Eng. Int.*, vol. 104, no. 3, 1996.

[337] J. E. Velandia Vargas, D. G. Falco, A. C. da Silva Walter, C. K. N. Cavaliero, and J. E. A. Seabra, "Life cycle assessment of electric vehicles and buses in Brazil: effects of local manufacturing, mass reduction, and energy consumption evolution," *Int. J. Life Cycle Assess.*, vol. 24, no. 10, 2019.

[338] P. Girardi, A. Gargiulo, and P. C. Brambilla, "A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study," *Int. J. Life Cycle Assess.*, vol. 20, no. 8, 2015.

[339] OpenLCA, "openLCA.org | openLCA is a free, professional Life Cycle Assessment (LCA) and footprint software with a broad range of features and many available databases, created by GreenDelta since 2006." [Online]. Available: https://www.openlca.org/. [Accessed: 30-Sep-2021].

[340] D. Banister, K. Anderton, D. Bonilla, M. Givoni, and T. Schwanen, "Transportation and the environment," *Annual Review of Environment and Resources*, vol. 36. 2011.

[341] H. Van Essen, "International road and rail freight transport: Environmental impacts of increased activity levels," in *Globalisation, Transport and the Environment*, vol. 9789264072916, 2010.

[342] H.-J. Jang, Y.-H. Ahn, and S.-H. Tae, "Proposal of Major Environmental Impact Categories of Construction Materials Based on Life Cycle Impact Assessments," *Materials (Basel).*, vol. 15, no. 14, 2022.

[343] I. Dincer and A. Abu-Rayash, "Sustainability modeling," in *Energy Sustainability*, 2020.

[344] R. Challa, D. Kamath, and A. Anctil, "Well-to-wheel greenhouse gas emissions of electric versus combustion vehicles from 2018 to 2030 in the US," *J. Environ. Manage.*, vol. 308, 2022.

[345] N. Hoque, W. Biswas, I. Mazhar, and I. Howard, "Environmental life cycle assessment

of alternative fuels for Western Australia's transport sector," *Atmosphere (Basel).*, vol. 10, no. 7, 2019.

[346] Ö. Andersson and P. Börjesson, "The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications," *Appl. Energy*, vol. 289, 2021.

[347] T. R. Hawkins, O. M. Gausen, and A. H. Strømman, "Environmental impacts of hybrid and electric vehicles-a review," *International Journal of Life Cycle Assessment*, vol. 17, no. 8. 2012.

[348] R. Janssen and D. D. Rutz, "Sustainability of biofuels in Latin America: Risks and opportunities," *Energy Policy*, vol. 39, no. 10, 2011.

[349] J. C. Garcia M, T. Machimura, T. Matsui, and T. Miyauchi, "Estimating the potential and planning of bioethanol production from agro-residues based on a model-predicted NPP under climate change in Ecuador," *J. Agric. Meteorol.*, vol. 70, no. 4, 2014.

[350] S. Mahmud, A. S. M. R. Haider, S. T. Shahriar, S. Salehin, A. S. M. M. Hasan, and M. T. Johansson, "Bioethanol and biodiesel blended fuels — Feasibility analysis of biofuel feedstocks in Bangladesh," *Energy Reports*, vol. 8. 2022.

[351] N. Khan, K. Sudhakar, and R. Mamat, "Role of biofuels in energy transition, green economy and carbon neutrality," *Sustainability (Switzerland)*, vol. 13, no. 22. 2021.

[352] P. Carroll, B. Caulfield, and A. Ahern, "Measuring the potential emission reductions from a shift towards public transport," *Transp. Res. Part D Transp. Environ.*, vol. 73, 2019.

[353] R. F. Andong and E. Sajor, "Urban sprawl, public transport, and increasing CO2 emissions: the case of Metro Manila, Philippines," *Environ. Dev. Sustain.*, vol. 19, no. 1, 2017.

[354] Y. Jiang, Z. Zhou, and C. Liu, "The impact of public transportation on carbon emissions: a panel quantile analysis based on Chinese provincial data," *Environ. Sci. Pollut. Res.*, vol. 26, no. 4, 2019.

[355] S. Zheng, X. Zhang, W. Sun, and J. Wang, "The effect of a new subway line on local air quality: A case study in Changsha," *Transp. Res. Part D Transp. Environ.*, vol. 68, 2019.

[356] M. Chen, S. Souche Le Corvec, and A. Bonnafous, "Time Available at Destination: Tool to Evaluate the Quality of Public Transport Service and a Determinant of Mode Choice," *Transp. Res. Rec.*, vol. 2673, no. 4, 2019.

[357] H. E. Masoumi, "A discrete choice analysis of transport mode choice causality and

perceived barriers of sustainable mobility in the MENA region," *Transp. Policy*, vol. 79, 2019.

[358] S. AlKheder, "Promoting public transport as a strategy to reduce GHG emissions from private vehicles in Kuwait," *Environ. Challenges*, vol. 3, 2021.

[359] A. A. Mohammed, "An Optimization Solution for Utilization minibuses Service as an alternative of Utilize Private Cars: A Case Study around Hentian Kajang in Malaysia," *IOSR J. Eng.*, vol. 02, no. 05, 2012.

[360] H. Oda, H. Noguchi, and M. Fuse, "Review of life cycle assessment for automobiles: A meta-analysis-based approach," *Renewable and Sustainable Energy Reviews*, vol. 159. 2022.

[361] R. Viteri, R. Borge, M. Paredes, and M. Á. Pérez, "A high resolution vehicular emissions inventory for Ecuador using the ive modelling system," *Chemosphere*, p. 137634, 2022.

[362] ANFAVEA. (Associação Nacional de Fabricantes de Veículos Automotores), "Anuário da Indústria Automobilística Brasileira (2016).," *Associação Nacional dos Fabricantes de Veículos Automotores*, 2016. .

[363] FAO, "Food and Agriculture Organization of the United Nations. FAOSTAT Database. Rome, Italy: FAO. Retrieved 2018-05-11 from http://faostat3.fao.org/home/E," *Crops, National Production*, 2017. .

[364] EPE, "Balanço Energético Nacional 2019 Relatório Síntese / Ano Base 2018," *Balanço Energético Nac.*, 2019.

[365] CONAB, "Acompanhamento da safra Brasileira de Cana-de-açúcar -Safra 2019/2020," *Monit. Agrícola - Cana-de-açúcar*, 2019.