UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade de Engenharia Mecânica

JORGE ENRIQUE VELANDIA VARGAS

Transport electrification in Brazil: Outlook and environmental impact analysis

Eletrificação do transporte no Brasil: perspectivas e análise de impactos ambientais

CAMPINAS
2021

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Thesis presented to the School of Mechanical Engineering of the State University of Campinas in partial fulfillment of the requirements for the degree of Doctor in Energy Planning systems.

Tese apresentada à Faculdade de Engenharia Mecânica da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutor em Planejamento de sistemas energéticos.

Orientador: Prof. Dr. Joaquim Eugênio Abel Seabra

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....
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Transport electrification in Brazil: outlook and environmental impact analysis

Eletrificação do transporte no Brasil: perspectivas e análise de impactos ambientais

Orientador: Joaquim Eugênio Abel Seabra

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Se volvió a gusano, mariposa,
cansada de volar y no poder
arrastrarse al fondo de las cosas
a ver si dentro puede comprender

Tercer movimiento
La ley innata
Roberto Iniesta para Extremoduro

Dedico este trabalho aos meus pais, Gladys e Jorge,
toda alegria e todo reconhecimento pertence a eles.
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Resumo

Este trabalho analisou os impactos ambientais (EIs) de tecnologias veiculares sem emissões de escapamento no Brasil, dando atenção ao contexto socioeconômico brasileiro, dado que a adoção de tais tecnologias depende de fatores para além da esfera ambiental. Esta pesquisa resultou em três artigos revisados por pares, um para cada seção do documento.

O primeiro, uma abertura, apresenta uma revisão bibliográfica. O cenário brasileiro apresenta características únicas, por exemplo, um poderoso setor automotivo com investimentos em tecnologia de veículos de motor de combustão interna (ICEV) e um mercado bem estabelecido de biocombustíveis baseado em tecnologia *flex-fuel*. Além disso, os elevados preços dos veículos e a ausência de infraestruturas de carregamento público atrapalham profundamente a adoção de veículos eléctricos a bateria (BEV). Além disso, a falta de regulamentação e de consenso nacional sobre o papel dos BEV é notória; de fato, apenas em 2018, a agência nacional de energia eléctrica (ANEEL) emitiu uma resolução que permite a venda de eletricidade para recarga de BEVs. As principais conclusões do artigo são a necessidade de um modelo de eletrificação capaz de criar sinergias com os biocombustíveis e a urgência de criar políticas bem definidas sobre o que o Brasil quer da eletrificação do transporte. Além disso, sublinha-se o inadequado que é adaptar modelos de negócio tradicionais para o novo panorama.

Na segunda parte, os EIs dos BEV e os ICEVs foram comparados para os cenários atuais e 2030. Adicionalmente, ônibus eléctricos a bateria (BEB) e ônibus convencionais (ICEB) também foram comparados. Esta parte da pesquisa teve como objetivo quantificar quais seriam os EIs da manufatura e utilização de BEVs e BEBs na região sudeste do Brasil quando a redução de peso, a mudança de material, a evolução do consumo de energia, as melhorias no desempenho da bateria, a manufatura local e os efeitos da evolução do mix de eletricidade são considerados. A análise dos BEV em 2030 incluiu dois cenários para a potencial composição dos veículos: Um protótipo com grande participação de polímeros e outro com grande participação de alumínio. Além disso, foram comparados um veículo fabricado no Brasil e um veículo com condições da média global. Os resultados mostraram que, para um BEV como unidade de comparação, apenas a depleção da camada de ozono, a toxicidade humana, a depleção de metais e as ecotoxicidades mostraram impactos maiores para o automóvel brasileiro, principalmente devido à mudança de material nos novos protótipos, apesar da redução total da massa. Contudo, nem os BEBs nem os BEVs fabricados no Brasil mostraram uma vantagem ambiental abissal sobre a referência Global, apesar dos resultados positivos para o potencial de aquecimento global. Deve ter-se em mente que o mix de eletricidade médio global não é tão dependente do carbono como é em países como a China ou a Índia. O aumento da expectativa de vida aparenta ser mais eficaz na redução dos EIs do que a redução da massa ou do consumo de energia.

A última seção estudou os EIs da utilização de veículos à célula combustível (FCV) no cenário brasileiro. Foi dada especial atenção às características locais, tais como, a disponibilidade de matérias-primas biogénicas para a produção de hidrogénio através da reforma do vapor e o elevado percentual de energias renováveis no mix de eletricidade. O objetivo deste trabalho foi quantificar as EIs dos veículos a célula combustível polimero-eletrolíticas (PEMFC) quando o hidrogênio é produzido no Brasil, modelando os cenários atuais e 2030. Adicionalmente, quantificou-se os EIs de um veículo de célula de combustível de óxido sólido (SOFC) que funciona com bioetanol, dito veículo é ainda um protótipo. Esta pesquisa avaliou várias rotas e matérias-primas para a produção de hidrogénio. Descobriu-se que o veículo SOFC poderia tornar-se uma alternativa competitiva para a atenuação de EIs em 2030. Também que não é provável que a maioria das reduções de EIs resultem da redução do peso da célula de combustível, uma vez que a sua carga ambiental é baixa em comparação com outros componentes dos automóveis ou a produção do combustível. Quanto a hoje, os veículos PEMFC não seriam competitivos para qualquer categoria de impacto avaliada. De fato, para o potencial de aquecimento global, o seu desempenho é tão ruim quanto o dos veículos convencionais alimentados a gasolina.

Palavras chave

Veículo elétrico, ônibus elétrico, análise de ciclo de vida, transporte limpo, célula à combustível, biocombustíveis, infraestrutura de recarga, reforma de etanol, produção de hidrogênio, sustentabilidade no transporte.

Abstract

This study strived to analyze the environmental impacts (EIs) of zero-tailpipe emissions vehicle technologies in Brazil. In an attempt to further expand the thesis scope, the research paid special attention to the socioeconomic landscape, understanding that the adoption of such technologies depends on factors beyond the environmental sphere. This research resulted in three peer-reviewed papers, one for each section of the document.

The first one, an overture, is a literature review. The Brazilian scenario exhibits unique features, for instance, a powerful automotive sector with investments in internal combustion engine vehicles (ICEV) technology and a well-established biofuels market based on *flex-fuel* technology. Furthermore, high tag prices and the absence of public charging infrastructure deeply discourage the adoption of battery electric vehicles (BEV). Additionally, lack of regulation and national consensus about the role of BEVs is notorious; in fact, only in 2018, the national agency of electric energy (ANEEL) issued a resolution permitting the sale of electricity for recharging. Main findings are the necessity of a model for electrification able to create synergy with biofuels and the urgency of having well-defined policies on what Brazil wants from electrification. Furthermore, the inadequacy of adapting traditional business models for the new transportation landscape is clear.

Subsequently, the EIs of BEVs, battery electric busses (BEB) and ICEVs were compared for current and 2030 scenarios. This research also aimed to quantify what would be the EI of manufacturing and using BEVs and BEBs in the Brazilian southeast region when mass reduction, material switching, energy consumption, battery performance improvements, local manufacturing, and electricity mix evolution effects are considered. BEV analysis in 2030 included two scenarios for vehicle materials: Plastic-based and Aluminum-based prototypes. Furthermore, a Brazilian manufactured vehicle and a Global average one were compared. Results showed that, for one BEV as comparison unit, only ozone depletion, human toxicity, metal depletion and the Ecotoxicities displayed larger impacts for the Brazilian car, mostly due to material switching in the new prototypes, in spite of total mass reduction. However, neither BEBs nor BEVs made in Brazil displayed a consistent and large environmental advantage over the Global reference despite of positive results for global warming potential. It should be kept in mind that the average global electricity mix is not as carbon dependent as the mix in countries like China or India. Life expectancy increase suggested being more effective in reducing impacts than mass or energy consumption reduction.

The last paper aimed to study the EI of the use of fuel-cell vehicles in the Brazilian scenario. Special attention was given to local unique features, such as, availability of biogenic feedstocks for hydrogen production via steam reform and high share of renewables in the electricity mix. The purpose of this work was to quantify the EIs of polymer-electrolyte fuel cell (PEMFC) vehicles when hydrogen is produced in Brazil, modelling current and 2030 scenarios. Additionally, we intended to quantify the EIs of a prospective solid-oxide fuel cell (SOFC) vehicle which runs on bioethanol. Additionally, this thesis aimed to explore several pathways and feedstocks for hydrogen production. We found that SOFC vehicles could become a competitive alternative for impact mitigation in 2030. Most significant impact reductions are not likely to arise from fuel cell weight reduction as its burden is low compared to other car components or fuel production. As for today, PEMFC vehicles would not be competitive for any evaluated impact category. In fact, for global warming potential, they perform as bad as gasoline-fueled conventional vehicles.

Keywords

Battery electric vehicle, battery electric bus, life cycle assessment, clean transportation, fuel cell vehicles, biofuels, electric vehicle charging infrastructure, ethanol reform, hydrogen production, Transport sustainability.

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Alkaline electrolysis (AE)

Balance of plant (BoP)

Balance responsible party (BRP)

Battery electric bus (BEB)

Battery electric vehicle (BEV)

Battery management systems (BMS)

Battery state of health (SOH)

Belo Horizonte, city (BH)

Brazilian association of electric vehicles (ABVE)

Brazilian Company of Research and Industrial Innovation (Embrapii)

Brazilian National Agency of Electric Energy (ANEEL)

Brazilian Sugarcane Industry Association (UNICA)

Brazilian technical Standards (NBRs)

Brazilian Technical Standards Association (ABNT)

Business model (BM)

Center for Management and Strategic Studies (CGEE)

Charging point operator (CPO)

Chassis and Body (C&B)

Clearing house (CH)

Climate change (CC)

Brazilian Development Center in Telecommunications (CPqD)

Distribution system operator (DSO)

Electric vehicle supply equipment (EVSE)

E-mobility service provider (EMSP)

End of life (EOL)

Energy Company of Paraná (Copel)

Energy research enterprise (EPE)

Environmental impacts (EI)

Fossil depletion (FD)

Freshwater eutrophication (FE)

Fuel cell (FC)

Fuel cell stack (FCS)

Fuel cell vehicle (FCV)

Global (GLO)

Global warming potential (GWP)

Greenhouse gases (GHG)

Human Toxicity (HT)

Human toxicity-carcinogenic (HTC)

Hybrid electric vehicles (HEV)

Internal combustion engine bus (ICEB)

Internal combustion engine vehicles (ICEV)

Lanthanum strontium cobalt iron oxide (LSCF)

Level 1 charging (L1)

Level 2 charging (L2)

Level 3 charging (L3)

Li-ion batteries (LIB)

Life cycle assessment (LCA)

Life cycle inventory (LCI)

Life cycle impact assessment (LCIA)

Lignocellulosic material (LCM)

Hydrogen refueling stations (HRS)

Metal depletion (MD)

Mineral resource scarcity (MRS)

Ministry of science and technology (MCT)

Mobility as a service (MAAS)

National Bank for Economic and Social Development (BNDES)

National Center of Research on Energy and Materials (CNPEM)

National energy plan (PNE2050)

Nickel-manganese-Cobalt-oxides (NMC)

Open charge point protocol (OCPP)

Original equipment manufacturers (OEM)

Ozone depletion (OD)

Paulista light and power company (CPFL)

Plug-in hybrid electric vehicles (PHEV)

Photochemical oxidant formation (POF)

Polymer-electrolyte membrane fuel cell (PEMFC)

Portugal Energy Company (EDP)

Product-Service System (PSS)

Research and Development Center in Telecommunications (CPqD)

Rest of the world (RoW)

Rio de Janeiro, city or state (RJ)

São Paulo, city or state (SP)

Smart Charging (SC)

Solid oxide fuel cells (SOFCs)

Spark Controlled Compression Ignition engine (SPCCI)

State of charge (SOC)

Supplementary material (SM)

Terrestrial acidification (TA)

TCO (Total cost of ownership)

Transmission system operator (TSO)

Vehicle-to-Grid (V2G)

Terrestrial ecotoxicity (TE)

Water consumption (WC)

SUMMARY

1. INTRODUCTION

1.1. General Overview

The last years have witnessed a rapid increase in the sales of battery electric vehicles (BEVs worldwide. In fact, during 2017, for the first time, global sales of BEVs surpassed one million units (MC KINSEY & COMPANY, 2018). This takes place whereas the urgency of addressing poor air quality and emission of greenhouse gases (GHG) has invigorated transport electrification as an alternative for mitigation of impacts due to fossil fuels use (ERICKSON, 2017).

Currently, air quality is a concern for many mega-cities, including São Paulo, the largest metropolitan area in the southern hemisphere. Andrade et al. (2017) concluded that the greatest air quality challenge currently faced by both, São Paulo State Environmental Protection Agency and the local communities, is controlling secondary pollutants such as ozone and fine particles. In this sense, BEVs implementation is a potent way to improve air quality on large urban centers since they present zero combustion emissions during their use phase.

Further arguments supporting BEVs adoption are the larger powertrain efficiency when compared to conventional cars fueled by fossil fuels or biofuels and the fact of electric propulsion barely emitting noise (SADEK, 2012).

In order to analyze the actual environmental benefits from BEV deployment, numerous studies have paid attention to their environmental performance when compared to internal combustion engine vehicles (ICEV) and hybrid electric vehicles throughout their entire life cycle. Research comprises fuel/electricity generation, use phase, vehicle production and in some cases End-of-Life (EOL) stage (BOUREIMA et al., 2009; FARIA et al., 2013; HAWKINS et al., 2013; HELMS et al., 2010; MA et al., 2012; MESSAGIE et al., 2014; RAJAGOPAL et al., 2012). Literature includes research for the Brazilian framework (CHOMA; UGAYA, 2013; SOUZA et al., 2016; VELANDIA VARGAS et al., 2019). Conventional and hybrid busses have also been a matter of research (BUØ, 2015; OLOFSSON; ROMARE, 2013), however, fewer examples were found on battery electric busses (BEB) comparative LCA (COONEY; HAWKINS; MARRIOTT, 2013; FALCO, 2017).

In a literature review containing conclusions from 79 papers, Nordelöf et al (2014) stressed that life cycle assessment (LCA) results for vehicles vary greatly. It is also reported that only a few articles appropriately report the study time scope. Moreover, most of the studies focus on current

BEV technology, which is rapidly evolving, meaning that there is a lack of future time perspective, *e.g.*, evolution in materials, mass reduction and life expectancy considerations. A conclusion, common to every study is that when the functional unit of comparison is defined as a travelled distance, for instance one km or one mi, electricity generation is the main cause of climate change related impacts from BEVs operating on mixes with low shares of renewables. Consequently, they can reach their full potential in mitigating global warming only if the charging electricity is not fossil carbon intensive. Surprisingly, according to the author, very few reports put emphasis in transmitting this conclusion as a core message.

Like all GHG mitigation actions, the implementation of BEVs must be evaluated carefully to avoid environmental burden shifting or rebound effects. Skepticism is present: Frischknecht & Flury (2011) even point out that the role and contribution of electric cars to significantly mitigate the environmental impacts of transportation might be substantially overrated and that one core aspect to lower environmental impacts of individual mobility is a considerable evolution in terms of vehicle weight and energy consumption.

Current BEVs manufacture has demonstrated to often increase GHG emissions when compared to ICEVs manufacture (HAO et al., 2017; KIM et al., 2016). Battery evolution and mass reduction are promising opportunities to offset BEVs larger environmental burden during production stage. Tagliaferri et al. (2016) analyzed the potential evolution of BEV mobility focusing on electricity generation and EOL scenarios but not considering vehicle evolution.

When comparing all LCA stages, the collection of life cycle inventories (LCI) is generally the most effort intensive. This phase includes the quantification of inputs (primary and manufactured), by-products and environmental emissions to air, soil and water. The search for inventories often results in no available data for a specific region, or in the best of cases LCA practitioners find data adapted to reflect global average values. This lack of geographical detail embodies a great concern for studies which are expected to be more accurate. Country overall data is usually used to represent regions geographically too distant or that present very different environmental conditions *e.g.* altitude, latitude, weather.

In the same way, LCA primary data is either confidential or it is scattered and difficult to find for researchers who usually do not have access to data for the entire life cycle of the car. Hence, data from diverse stakeholders is required for each stage, adding time and space uncertainties for the study. Furthermore, absence of transparency about the influencing factors of LCA in BEVs creates great difficulty for boundary definition and makes the analysis prone to flaws. According to Egede et al. (2015) material composition of the vehicles, electricity mix and use patterns are considered to be the main influencing factors on BEVs environmental assessments.

Although there has been a growing interest on electric mobility options in Brazil there is no mass production of electric vehicles in Brazil currently. BEVs future market penetration along with tax regulations for imported goods (AES BRASIL, 2017) could encourage automakers to manufacture the cars in the country. Early steps for a future governance roadmap on electric mobility have been taken (CONSONI et al., 2018). In fact, the national electric energy agency has already called for proposals on efficient electric mobility (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2018a). However, it remains unclear to what extent a Brazilian car is environmentally advantageous over an imported one. Environmental benefits of BEVs when compared to ICEVs depend greatly on electricity mix but also in the vehicle itself.

Analogously to BEV technology, there is evidence that the environmental impacts (EI) of using fuel cell vehicles (FCV) strongly depend on the Well-to-Tank (WTT) stage for currently available powertrain and hydrogen production technologies (DE SOUZA et al., 2018). Thus, EI reduction depends not only on fuel production but also in the powertrain technologies available. Right now, the FCVs commercially found in the automotive market are based in the proton-exchange membrane fuel cells, also known as polymer-electrolyte membrane fuel cells (PEMFC). Moreover, solid oxide fuel cells (SOFC) have, in the last years, reached technical feasibility, potentially enabling a novel type of vehicle able to run on ethanol as fuel, while only producing water and biogenic CO_2 as a byproduct.

1.2. Purpose of the study

The main objective of this thesis was to assess the environmental competitiveness of BEVs and FCVs, used in southeastern Brazil, for current and 2030 scenarios. Although other options for passenger transport decarbonization are available, for instance, hybrid electric vehicles, the scope of this research was focused on pure BEVs and FCVs.

The modelling of the evaluated scenarios assumed that, at least partially, the vehicles were going to be manufactured locally, thus, an effort for LCI adaptation, to better depict Brazilian conditions was necessary. For the sake of comparison, bioethanol and gasoline-fueled conventional vehicles were also included.

Several secondary objectives were pursued in this study. The first one was to provide an outlook of the Brazilian BEV landscape and its particularities. This outlook was intended to include a global review addressing innovative business models (BM) and charging infrastructure deployment. In addition, it needed to identify initiatives, players and regulation actions by consulting academic literature and media sources.

Another secondary goal was to adapt a representative number of datasets, enough to characterize the production of the vehicles. Besides of the cars, fuels and electricity production were also modelled by individually adapting datasets. The use phase emissions were included for conventional vehicles whereas the end-of-life (EoL) stage was included whenever possible. Additionally, this research intended to estimate the evolution of the environmental burden of BEVs and FCVs. This objective was pursued by modelling crucial vehicle parameters, such as, mass and components reduction, material switching and fuel and electricity consumption.

The hypothesis to be tested in this research could be stated as: The Brazilian specific features are favorable enough for BEVs and FCVs to display a better environmental performance than any conventional powertrain.

A scheme portraying the structure of this thesis can be found in Figure 1.

ELEMENTS OF THIS STUDY		
THE NEW NEIGHBOR IN TOWN: AN OUTLOOK FOR ELECTRIC VEHICLES IN BRAZIL	LIFE CYCLE ASSESSMENT OF ELECTRIC VEHICLES AND BUSSES IN BRAZIL:EFFECTS OF LOCAL MANUFACTURING, MASS REDUCTION AND ENERGY CONSUMPTION EVOLUTION	FUEL-CELL TECHNOLOGIES FOR PRIVATE VEHICLES IN BRAZIL: ENVIRONMENTAL MIRAGE OR PROSPECTIVE ROMANCE?

Figure 1 .Elements comprising this thesis. [1]

[1] The academic experience of the author also included the participation in several concluded and ongoing projects. Contributions included involvement in a carbon footprint quantification project in partnership with Fiat-Chrysler automotive, and the LCA of BEBs for project “Campus sustentável”, which takes place at State University of Campinas (Unicamp) Campus. In addition, the author contributed with the LCA modelling for EMOTIVE project, which strived to create an urban living laboratory for electric vehicles in Campinas area.

2. PAPER 1: NEW NEIGHBOR IN TOWN: AN OUTLOOK FOR ELECTRIC VEHICLES IN BRAZIL[2]

2.1. A brief introduction into the Brazilian Outlook

In addition to the rapid increase in the sales of BEVs worldwide, analysts report that peak production of ICEV is likely to be reached in the next years (NAUGHTON; WELCH, 2019). In Latin America, electric transportation is still in early stages. Several barriers, such as high tag price and non-availability of charging infrastructure, account for the adoption lag. In the region, Chile (DINERO, 2018), México and Colombia (PORTAFOLIO, 2018), have already initiated projects on public transport electrification. Due to its peculiar characteristics, transport electrification in Brazil will be bound to plenty of external variables, thus, the results or experiences of neighboring countries should not be transposed. The objective of this review was to consolidate information about the Brazilian transport electrification landscape and its particularities. This review does not pretend to forecast any specific technology as the most adequate for Brazil. Alternatively, it aimed to consolidate information serving as base for further research.

2.2. The adoption efforts

Recently, the Brazilian city of São Paulo (SP) announced a pilot project in electric busses deployment (ZAPAROLLI, 2019). Furthermore, in order to promote BEV and hybrid electric vehicles (HEV) adoption in Brazil, some tax breaks have been granted; the states of Ceará, Maranhão, Pernambuco, Sergipe, Piauí and Rio Grande do Sul granted an ownership tax exemption on both BEVs and HEVs (CONSONI et al., 2018). Furthermore, resolution 97-2015 issued by the Foreign Chamber of commerce (Camex), granted a reduction on the importation tax for HEVs from 35% to a maximum rate of 7% (BRASIL, 2015a; VASCONCELOS, 2017). Although financial incentives have proven to be an effective way to promote electrification (HARDMAN et al., 2017; SIERZCHULA et al., 2014; YANG et al., 2016), the allocation of scarce public resources to

[2]Published in the World Electric Vehicle Journal (2020) 11(3), 60. https://www.mdpi.com/2032-6653/11/3/60). Co-authors: Simone Pereira da Souza, Daniela Godoy Falco, Arnaldo César da Silva Walter, Carla Kazue Nakao Cavaliero and Joaquim Eugênio Abel Seabra.

electrification, especially in developing countries, is complex, given that diverse political priorities compete for limited taxpayer funds (LI, 2016; MARQUES DE ARAUJO; AMORIM, 2017).

Besides financial incentives, the city of SP offered exemptions to road access restrictions (PREFEITURA DE SÃO PAULO, 2015). Nevertheless, those actions have been insufficient to compensate for the high costs of purchasing BEVs and charging stations, also known as electric vehicle supply equipment (EVSE). Currently, BEVs represent less than 0.1% of Brazilian fleet (TEIXEIRA, 2018). So far, the high tag price of imported cars and EVSEs (REIS, 2018) place the BEVs in Brazil as niche products (ASSOCIAÇÃO BRASILEIRA DO VEÍCULO ELÉTRICO, 2017).

Given the low battery range of many models and the lack of public EVSE, users are concerned of running out of charge far away from any charging point. This is known as range anxiety and acts as a deterrent for adoption. Range anxiety is not usually a concern for vehicle fleets, due to predictably of vehicle charging and routes (LAURISCHKAT; VIERTELHAUSEN; JANDT, 2016). Indeed, most of the currently deployed BEVs in Brazil are employed for either government or corporate service, including public transportation, having only a few hundred ones bought by private individuals (MARCHÁN; VISCIDI, 2015).

Any attempt to change the transportation paradigms in Brazil will face a mature market with very specific features. Firstly, a powerful automotive sector with numerous investments in ICEV technology. Brazil ranked as the world's eighth vehicle producer in 2017 (EUROPEAN AUTOMOBILE MANUFACTURERS ASSOCIATION, 2018) whereas the automotive sector represented about 22% of the industrial gross domestic product (BRASIL, 2018a). Likewise, in 2017, Brazil was the second largest producer of sugarcane bioethanol and soybean biodiesel in the planet (INTERNATIONAL ENERGY AGENCY, 2019a), hence, the energy crops sector is a powerful player. Electrification is arriving at a low pace, in fact, only recently, on June 2018, the National Agency of Electric Energy (ANEEL) issued the resolution Nº 819 providing legal framework for commercial recharging of BEVs (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2018b). It marked a milestone for this new market since commercial recharging was not allowed in Brazil beforehand.

Furthermore, Brazilian government has traditionally implemented importation barriers in order to encourage automotive local production and investment (GALLAS, 2018). In fact, the implementation of Inovar-Auto program, valid from 2012 to 2017, imposed vehicle importation quotas for car manufacturers, also known as original equipment manufacturers (OEM). In the case of any OEM exceeding the determined importation quota, each imported vehicle had to face extra tariffs. Once those restrictions were gone the importation of vehicles soared (BRASIL, 2018b). Concerns are that, in a fewer trade restrictions scenario, some companies would prefer to face importation tariffs and produce the vehicles outside Brazil instead of locally, implying job losses. Actually, the trade restrictions are likely to change. On June 2019, the Mercosur states and the European Union reached an agreement on trade conditions, able to change the importation rules for cars and parts (EUROPEAN COMMISSION, 2019). Adding more complexity to the landscape, the Brazilian automotive fleet displays a large share of *flex-fuel* vehicles, whose engines can run on both gasoline and ethanol or a mixture of both. The share of *flex-fuel* vehicles in the national automotive fleet reached about 67% in 2018 (SINDIPEÇAS, 2018), whereas *flex-fuel* share for new vehicles in 2018 was around 68% (ANFAVEA, 2019). Figure 2 displays ten-year evolution of gasoline and hydrated ethanol production and the share of vehicles using flex-fuel and only gasoline engines. Figure 3 presents fleet forecasts for 10 year. However, the consequences of COVID-19 outbreak are a game-changer and bringing significant impacts in the years to come.

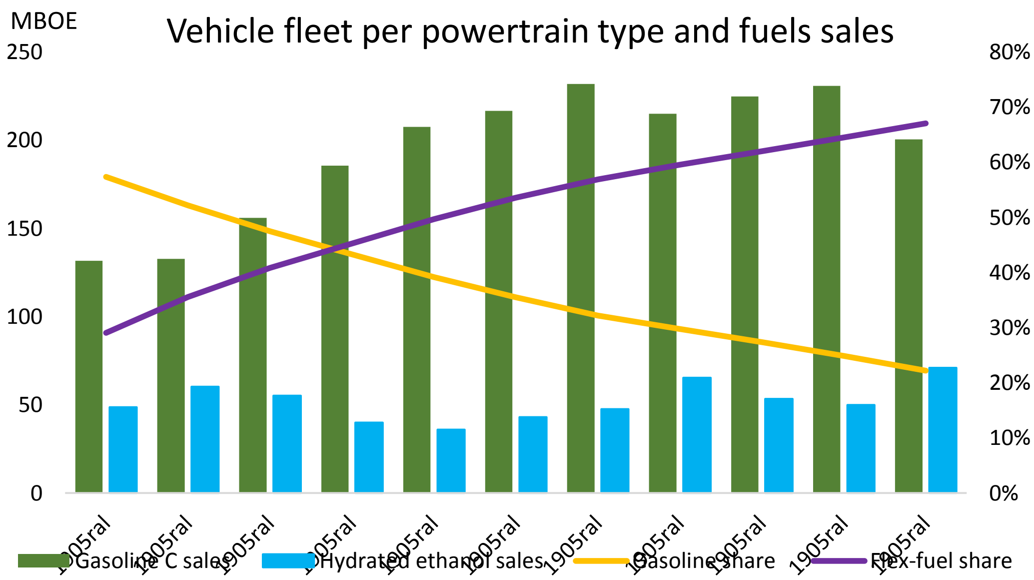

Figure 2. Amount of sales of hydrated ethanol and gasoline in Million barrels of oil equivalent (MBOE) in Brazil, per year, and percentage of each type of vehicle per type of used fuel in the Brazilian light vehicle fleet per year. Based on ANFAVEA (2019) and ANP (2019)

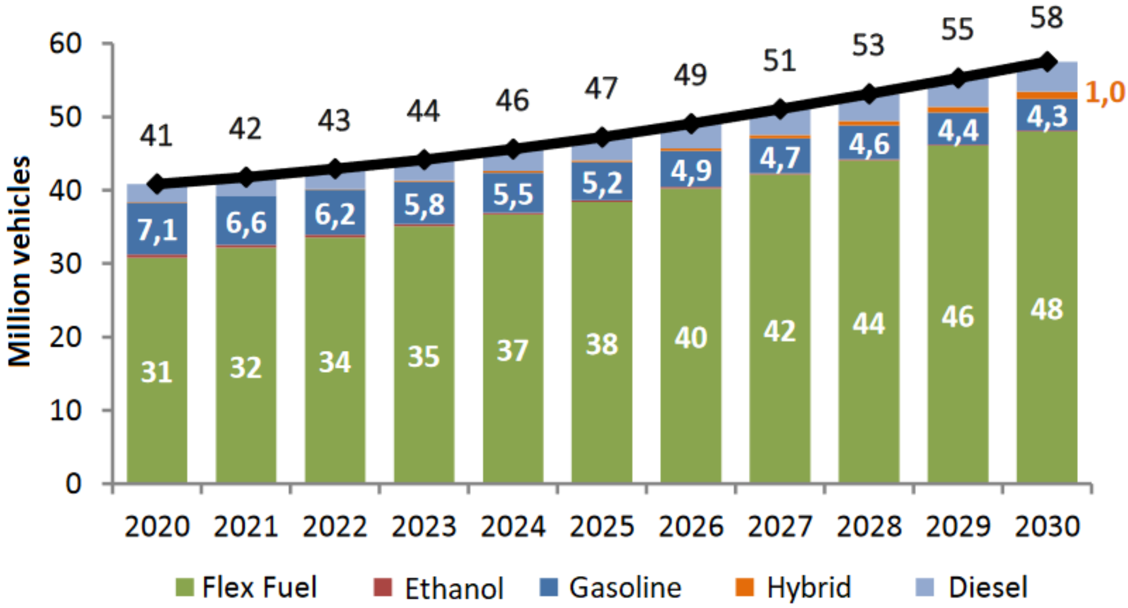

Figure 3.Forecast for Brazilian fleet 2018-2030 before the outbreak of COVID-19. Based on EPE (2019)

Although urban air pollution, GHG emissions mitigation, technological advantage and energy security priorities justify the international adoption of BEVs, the Brazilian motivations may be well different (CNPEM, 2018). Regarding life cycle GHG emissions, sugarcane ethanol use is an alternative for CO_2 emissions mitigation (CHOMA; UGAYA, 2013; VELANDIA VARGAS et al., 2019). Additionally, Brazil exhibits an electricity mix based on renewables (EPE, 2016), which amplifies the GHG mitigation potential of electrification (BOUREIMA et al., 2009; CHOMA; UGAYA, 2013; FARIA et al., 2013; GLENSOR; MUÑOZ, 2019; HAWKINS et al., 2013; MA et al., 2012; VELANDIA VARGAS et al., 2019). Besides, the installed capacity of renewable sources in the region is expected to continue on the rise (FARIZA, 2018)

Moreover, energy security is much less worrisome considering the discovery of pre-salt oil fields (CNPEM, 2018) and the biofuels production. Thus, electrification does not appear urgent as it appears, for example, in China (VASCONCELOS, 2017). Air quality and technological advantage motives are valid for Brazil, although have proven insufficient to boost the local BEV segment. Nevertheless, electrification could palliate fuels reliance. Brazilian dependence on gasoline and ethanol was roughly exposed in 2018 after a truck drivers strike caused fuel scarcity and seriously impacted the supply chains (TEIXEIRA, 2018).

It remains unclear how transport electrification will happen in Brazil given its very specific features. Cano et al (2018) emphasize that the particularities of emerging markets can create new technologic routes or applications, thus, a li-ion battery based market should not be taken for granted in the future. Options include nickel metal hydride, lithium sulfur, lithium air and zinc air storage devices. Cano et al (2018) also highlighted that, on the sight of a price increase, the Brazilian public is very likely to reduce the probability of purchasing a BEV.

2.3. The Brazilian pioneers

Electric mobility entrepreneurships are no novelty in Brazil. During the 1980s, Gurgel S.A. and Furnas Centrais Elétricas S.A jointly developed two electric models without great commercial success (DOS SANTOS; FRANCISCHETTI; GOMES DA SILVA, 2014). The low specific energy of lead acid and nickel batteries kept the electrification unfeasible until the irruption of Li-ion batteries. Brazilian concerns on energy security invigorated biofuels as a solution. The 1970s energy crisis, driven by oil scarcity and soaring prices, lead to the creation of Proalcool program (ALISSON, 2016) which steered the national energy security policy towards biofuels. Indeed, sugarcane ethanol represents 18% of total primary energy production and 34% of energy consumption for light vehicles (CORTEZ et al., 2016).

Brazil is a follower in terms of BEV technology. Currently, there is no large-scale manufacturing of BEVs, however, there have been initiatives aiming to develop related technology. Initial efforts from small entrepreneurships and research entities on manufacturing were based on ICEVs retrofitting, *i.e.* replacing an ICEV powertrain for a BEV one while keeping the original chassis and body. Additionally, in the lightweight segment, there is evidence of at least three entrepreneurships assembling vehicles locally: Gaia, eiON and Mobilis (SILVA, 2019a). Furthermore, Itaipu Binacional, carried out a large project based on adaptation of ICEVs (ITAIPU BINACIONAL, 2015; VASCONCELOS, 2017) while private owners created an association of owners with artisanal cases of retrofitting (ABRAVEI, 2017). A comprehensive index of BEV related initiatives and projects, including lightweight and heavy-duty segments, was constructed by Barassa (2015) and refined by Consoni et al (2018). A summary of BEV releases in Brazil is included in the APPENDIX 3 – BATTERY ELECTRIC VEHICLE BRAZILIAN .

Retrofitting is useful for entrepreneurs in order to obtain the *know-how* on chassis and body characteristics. However, evidence indicates that a car architecture based on a BEV design, without ICEV design legacy, results in an increased synergy of powertrain parts, hence, requiring fewer modules and reducing weight (MC KINSEY & COMPANY, 2017a). In fact, BEV native design allows the OEM to better distribute the battery weight and has the potential to augment the vehicle range while maintaining the price stable.

A native-electric design could allow the OEMs to evolve towards a mass market production scheme just as Tesla did with the Model 3 (MC KINSEY & COMPANY, 2017b). Mass production enables OEMs to access mass segments while keeping a sufficient battery capacity to deal with range anxiety. New infrastructures, required for adapting manufacturing plants to BEV native architecture, signify high investments and risks, which not every OEM is willing to face. Some automakers are expected to continue adapting ICEVs into BEVs intended blueprints (MC KINSEY & COMPANY, 2019).

Consequently, there is no dominant pathway on BEV design, nevertheless, native design, reportedly, suits well on a design-to-cost approach, satisfying the urgency for a profit in the long term. Whether or not large OEMs decide to invest in BEV production in Brazil could depend on political and macroeconomic factors, given the extent of the investments. For instance, the Mercosur-EU agreement signed at the end of June 2019, eliminates customs duties for cars and parts being imported from EU countries (EUROPEAN COMMISSION, 2019). A hint applauded by European OEMs (EUROPEAN AUTOMOBILE MANUFACTURERS ASSOCIATION, 2019).

2.4. Initiatives and relevant players

Electromobility players can be defined as all the organizations interested in transport electrification in Brazil. New regulatory frames and new BMs would have to include stakeholders which were never part of the value chain in the ICEV business. This includes OEMs and EVSE providers, research and development institutions, financial entities, private associations and the entities responsible for creating a regulatory framework.

Fontes (2018) constructed a comprehensive index of BEV initiatives, policies and players in Brazil. In a similar effort, Consoni et al (2018) build a map of policies, initiatives and players and concluded that although it is possible to identify them in industry, research, financial or institutional spheres it is not accurate to see them as part of a coordinated structure. So far, public and private initiatives displayed exploratory intentions, aiming to better understand the end-user of electromobility and to track the development of a certain technology; in fact, many of the initiatives were not designed for pure BEVs but for HEVs. A brief review of relevant institutions promoting the electrification of transport can be found in the APPENDIX 3 – BATTERY ELECTRIC VEHICLE BRAZILIAN . It includes federal funding institutions government organs and private institutions.

Although scarce and presenting an exploratory scope, BEV implementation projects can be found throughout the country. In Fernando de Noronha Islands, a project of development of smart grids was developed during five years by local DSO CELPE. The project included the use of BEVs whose charging process was based on photovoltaic generation (NEOENERGIA, 2017). In another case, Light Electricity Services, one of DSOs in Rio de Janeiro (RJ) state, deployed BEVs within Rio de Janeiro Federal University campus, in order to study distributed generation, smart measurement of energy, BEV use, and power storage (LIGHT, 2013; SOUSA, 2012).

The VAMO project, started in 2016, it was the first BEV carsharing project in Brazil. VAMO owns a fleet of 20 BEVs placed in 12 strategic public locations in Fortaleza; the objective is to offer the population of Fortaleza a sustainable urban mobility option (VAMO FORTALEZA, 2016). Developed jointly by the Municipal Secretariat for Conservation and Public Services (SCSP) and mobility entrepreneurship Serttel, VAMO is a pioneer project in Brazil and Latin America being the first with a BEV fleet. The project has proven successful for 3 years and it is still in execution (SERTTEL, 2018). Another example of carsharing in northeastern Brazil was Carro Leve project in Recife (MOBILICIDADE, 2017). It worked in a scheme similar to VAMO, acting as an urban laboratory. Carro Leve activities concluded in 2018.

Furthermore, from 2013 to 2018, the EMOTIVE project was carried out by CPFL (Companhia Paulista de Força e Luz), a SP state DSO. The objective of the project was to create a real electric mobility laboratory in Campinas metropolitan area (CPFL, 2018). Overall, 16 BEVs were employed, including Renault, BMW and BYD models; additionally, 25 public EVSEs were installed, including 10 for fast charging. Reportedly, EMOTIVE represented a total of 31 ton of avoided CO_2 emissions (ARIOLI et al., 2018) while the cost per kilometer travelled in one of their BEVs was nearly 3 times lower than in an ICEV, 0.31 R$ to 0.11 R$ (CPFL, 2018). EMOTIVE, VAMO and Carro Leve have been the subject of diverse studies(ARIOLI et al., 2018; LIMA et al., 2017; MARIOTTO, 2018; PINTO et al., 2018; TELES et al., 2018). These Works are described more in detail in the APPENDIX 3 – BATTERY ELECTRIC VEHICLE BRAZILIAN .

Gradually, a whole ecosystem of transport services is emerging. International incumbent players, such as Waze and Blablacar, are now offering carpooling schemes in Brazil (BLABLACAR, 2018; WAZE CARPOOL, 2018). MAAS prominent players are also present: in fact, in early 2019 Cabify started adopting a more aggressive strategy to conquest a larger market share in a game controlled by leaders Uber and 99 (MARI, 2019). Other entrepreneurships are focused on supporting virtual transactions for bike sharing or urban parking via applets (MOBILICIDADE, 2015). A significant number of initiatives in Brazil for urban mobility include electric bike and scooter sharing, navigation applets, carsharing and courier services (MOBILIZE, 2017).

2.5. Charging infrastructure development

Potential investors in charging infrastructure have a keen interest on finding the adequate number of EVSEs and the most suitable locations for placing them, given a determined fleet size. This, in order to minimize initial investments (ZHAO; LI, 2016). An effective placing must maximize occupation time and guarantee ease of accessibility.

The NREL EVI-Pro model was crafted to determine the best areas for EVSE installation intending to support BEV adoption based on travel patterns provided by a traffic services company (WOOD et al., 2018). The model even enabled the researchers to anticipate future demand for BEV charging infrastructure. Although consumer demand for fast charging is projected to stay low for some time, a minimum number of urban units is necessary to deal with consumer range anxiety. The first EVSEs are recommended to be located in areas of great circulation of people and vehicles, *e.g.* malls, hospitals and supermarket parking areas. Special attention should be paid to parking spaces for vehicle fleets. These groups of cars travel on previously defined routes making EVSE placing easier. In contrast, private clients are much more difficult to predict (LAURISCHKAT; VIERTELHAUSEN; JANDT, 2016).

There is evidence of research in this field in Brazil. The placing of EVSE in the Federal University campus in RJ was proposed by Calçado (2015), while Peres (2012) proposed it for the city southend, concluding that the best areas are those presenting the largest chances of high occupation time and accessibility. Another study, oriented to spatially determine the better places for EVSE placement (COSTA et al., 2017a), also in south RJ, resulted in a map showing that areas for L1 charging are those exhibiting a higher level of income and high population density. Better areas for L2 charging are the districts presenting important concentration of commercial establishments, *e.g.* shopping malls and public transport stands. Regions with a wide network of transport and shopping centers were well evaluated for L2 EVSE settlement also. The proximity to highways and access roads are the most important attributes for the installation of L3.

A similar methodology, this time for Belo Horizonte (BH), obtained a map and similar results (COSTA et al., 2017b). The studies also highlighted the need for synergy of the federal, state and municipal authorities with private initiatives in order to promote a BM capable of attracting investments to improve public and private EVSE deployment. Not surprisingly, the higher income districts of BH and RJ displayed most of the suggestions for EVSE installation, thus, it is pertinent to wonder if private electrification could in some ways restrict the access to transport for the poorest. Although not developed for Brazil, research has found that BEV users are usually male, present high incomes, and own more than one car, as expected from a niche product (HAUSTEIN; JENSEN, 2018). Finally, Costa et al (2017a, 2017b) highlighted that crime and security issues could hamper the installation of public EVSE in Brazil.

During July 2018, the first public charging infrastructure placed on a highway was inaugurated in São Paulo-Rio de Janeiro road (FÉLIX, 2018) by concessionaire Energias de Portugal (EDP); fast charging is available. At the same time, EDP announced intentions to invest in startups related to electromobility along with OEM BMW (OLMOS, 2018). The charging service will remain free of charge until a BM is structured. Several months later, on December 2018, the Energy Company of Paraná (Copel) inaugurated the largest set of public charging stations on a road in Brazil covering a route of 700+ kilometers, linking the Port of Paranaguá to the Iguaçu Falls, nearby Paraguay and Argentina borders. All of the 11 charging stations are already in operation (MASSA NEWS, 2018). Initially, the charging process will be free of charge, but registration is required (AMBIENTE ENERGIA, 2018). Although both initiatives are important, from an overall perspective, public EVSE in Brazil remains scarce, only about 100 charging stations had been installed in 2017, which renders long trips impossible in most of the national roads (VASCONCELOS, 2017).

In order to grant accessibility, all the EVSEs in both highways include all of the commercially available plugs in the market. In the future, the absence of a unified standard would hinder the installation of public and residential EVSEs (CONSONI et al., 2018). So far, standards for physical plugs have mostly been accepted, nevertheless, the communications and payment standards have been less standardized. At some point, it would become necessary for Brazil to regulate public charging standards as has happened abroad. For instance, Aiming to ensure that BEV users can charge at any EVSE with a single identification the Netherlands regulates every EVSE in the country, demanding all operators to adopt common standards (SLOWIK et al., 2018).

The National Bank for Economic and Social Development (BNDES) granted R$ 6,7 million in funds for a EVSE development project which will be implemented by the Brazilian Company of Research and Industrial Innovation (Embrapii) and the Research and Development Center in Telecommunications (CPqD) (EMBRAPII, 2019; VALOR, 2018). The objective is to develop the first Brazilian charging infrastructure including slow, semi-fast and fast charging stations. Resources will originate from Funtec, a fund focused on applied research and innovation projects. Up to now, only ABB (ABB, 2018), BYD (BYD, 2018) and Volvo (VOLVO BRASIL, 2018) offer BEV charging infrastructure in Brazil.

Sooner or later the free charging will come to an end; BMs will vary depending whether the EVSE is private or public. The simplest scheme for BEV charging is at private residences. Here, only the car and the EVSE are required. However, if the users want to benefit from a more flexible charging process, *e.g.* different hour rates while charging, more elements will be necessary. For further EVSE functionalities, the so-called charging point operator (CPO) appears. The CPO is responsible for remotely operating the EVSE. Communication between the CPO and the EVSE have already been standardized by the open charge point protocol (OCPP) (EV CONNECT, 2018; GREENLOTS, 2018; KLAPWIJK, 2018).

Public charging requires a more complex structure. Each owner requires a private ID for identification and billing purposes. The player providing communications for this ID is known as the E-mobility service provider (EMSP). While charging in public stations the CPOs must communicate with the EMSP for data transmission. This scheme is analogue to mobile phone roaming service, where an user can communicate through different transmission towers. Aiming to avoid too many communication channels between different parties, a central hub for data verification, known as the clearing house (CH), enters the stage (EURELECTRIC, 2013). The CH can be substituted however, by a peer-to-peer verification scheme. Several different communication protocols for roaming have been developed in Europe, namely OCPI, OCHP, OICP and eMIP (KLAPWIJK, 2018). None of them is dominant but at least one of them is likely to be used in Brazil for communication.

The public charging process can be summarized as follows: the BEV user validates their ID at a public EVSE. The CPO, which remotely controls the EVSE, requests the EMSP for authorization. Once the EMSP has approved the request, the charging process begins. Throughout the charge, the EVSE measures the energy sold and even the parking time if required. Finishing the process, these data is sent back to the EMSP again, including the CPO’s fee for using the EVSE. Figure 4 illustrates a simplified version of the BEV charging landscape including private and public charging, including a potential Smart Charging scenario. This thesis also identified the most common protocols for communication between the parts.

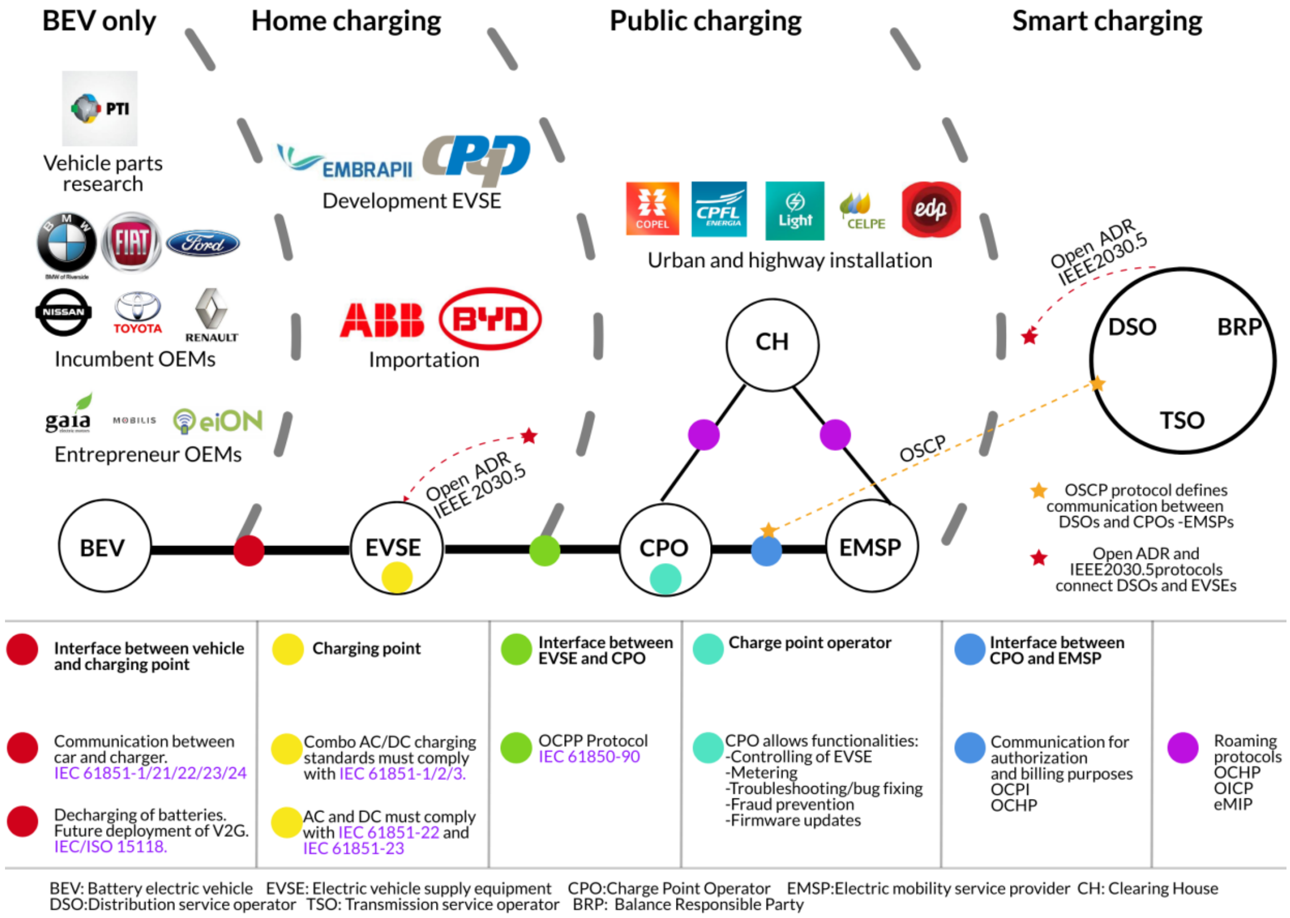

Figure 4. Diagram of relevant players and communication protocols for transport electrification and commercial charging in Brazil[3].

The complexity of public charging could negatively affect data transmission; standardization is crucial for the emerging business ecosystem. The participation of the Brazilian Technical Standards Association (ABNT), in charge of issuing the Brazilian technical Standards (NBRs), will be decisive. Brazil, acting as a follower on terms of BEV technology, usually adapts either ISO or IEC international standards for local needs. Through its Brazilian Committees, ABNT has already ratified a number of standards, related mostly to battery recharge, sockets, conductive recharge and other hardware systems. A comprehensive list of adapted international standards is available at Consoni et al (2018).

This review assumed battery swapping technology as not being feasible in Brazil in the short term, due to the lack of standardization, reliability of the li-ion batteries and current inaccuracies in the estimation of battery state of health (SOH) and state of charge (SOC). Additionally, among BEV users battery swapping is not the preferred option. According to Li (2016), Tesla's trials revealed that swapping stations are not popular among their customers who prefer supercharging stations. In the same way, this review does not consider the deployment of wireless charging in

[3] From left to right: Vehicle only, home charging, public charging and a scenario for smart charging.

Brazil in the next decade, despite of technical advances, including the release of SAE J2954 standard, which addresses safety concerns, interoperability and performance.

2.6. Behold: The market barriers!

In an effort to identify the main barriers the electrification would face in the BRICS (Brazil, Russia, India, China and South Africa) and the strategies used by OEMs to face them, Pratiwi (2016) interviewed high executives of Renault Brazil to gather perspectives from inside the firm.
As part of its niche strategy, Renault started a pilot project in BEV deployment, based on lending the vehicles to selected customers, expecting them to gain experience and provide feedback on working with BEVs. Renault cooperated with fleet owners, aiming to develop working standards regarding charging connectivity, EVSE installation, and financing. Due to BEV high initial investment, their long-term benefits are often not considered by potential customers, thus, Renault strategy included corporate education.

The executives were requested to enumerate the 5 most important barriers for BEV adoption in Brazil and the strategies Renault is working on to counteract them; results are displayed in

Table 1:

Table 1. Top ranked barriers to adoption and strategies to overcome them in Brazil, according to Renault executives. Adapted from Pratiwi (2016).

Rank	**Barrier**	**Description**
1	Financial	Related to high tag prices of the vehicles.
2	Macro-economic	Brazil has faced GDP decrease, rise in unemployment rate and low growth rate in the last years. (OECD, 2018)
3	Infrastructure	Lack of public charging stations
4	Institutional	Any support from the government is missing, mainly to incentive charging infrastructure and car adoption in urban areas
5	Demand	Market practically inexistent. Customers do not have sufficient knowledge about electric vehicles
Rank	**Strategy**	**Description**
1	Demo and develop niche	BEV loans and development of nice strategies.
2	Pilot project	BEV loan to selected customers for they to gain experience
3	Lobbying	Lobbying is employed to face institutional, infrastructure and financial barriers. Cooperation with suppliers and federal and state organs to promote discussion on public charging infrastructure
4	Financial aid	Renault offers cooperation with Bank of Renault (owned by Renault group) by which customers can opt for leverage options, including leasing.
5	Knowledge development	Besides R&D, awareness campaigns and seminars are carried out for educational purposes

Other factors hamper BEV adoption. Besides range anxiety, owning a BEV could create resale anxiety, which reflects how afraid are potential BEV owners of facing very low resale prices in the second hand market (LIM; MAK; RONG, 2013). Moreover, for public transport electrification, Bermudez (2018) concluded that (i) high initial cost of electric busses compared to conventional ones; (ii) Lack of financial incentives for low-emission fleets; iii) Resistance of fleet operators and diesel bus companies to new technology; (iv) Technological uncertainties related to the autonomy of the battery and the charging network; and (v) Absence of a special electricity tariff for public transport are the main barriers in Brazil.

Finally, since technology is still emerging, production of BEVs by Renault- and by other OEMs too- is still low. This leads to over-demand of some models, resulting in long delivery times. Ahead in the future, the different plugs for EVSE available in the market may also become a barrier as several options will be available (CONSONI et al., 2018; STEITZ, 2018), likewise to VHS and Betamax competition in the 1990s.

2.7. Technology evolution

Hybridization is likely to be the first step on the path to electrification in Brazil (CNPEM, 2018; TEIXEIRA, 2018; VASCONCELOS, 2017); however, technology evolution forecasting is plagued with uncertainties. In some markets the sales of HEVs, including PHEVs (Plug-in hybrid electric vehicles), have been steadily falling as the batteries increase their capacities and specific energy features, improving the BEV range (KANE, 2019). In fact, General Motors discontinued the manufacture of the Chevrolet Volt, one of the most famous PHEVs in the USA (GILLESPIE, 2018).

In spite of the quick pace of Li-ion battery improvement, the potential of ICEV technology to evolve, rendering it more competitive, must not be underestimated (ADNER; KAPOOR, 2016), especially in emerging markets where electrification could take many years to arrive and technological routes, other than BEVs, may thrive (CANO et al., 2018).

One example is the development of the Skyactiv-X engine technology, whose core is the Spark Controlled Compression Ignition engine (SPCCI). With Skyactiv-X Mazda merges the best of Diesel (fuel economy, good response at low rpm) and Otto (low emissions, power generation) cycles. The technology is embedded within a “mild” hybrid power train (CARNEY, 2018), proving its potential to be included in other Hybrid models and it could be adapted to work on an ethanol based cycle. Development of other technologies are visible also. On April 2019, the State University of Campinas (Unicamp) and Japanese OEM Nissan signed an agreement to study bioethanol as an option to provide energy for a solid oxide fuel cell. Nissan is the first OEM in the planet to develop a prototype vehicle exploring this route.

2.8. Regulation outlook

Concerns about energy security and technological development have steered Brazilian regulation in the past. Until now, electrification did not play any role. Several policies addressing environmental and economic concerns have been issued, *e.g.* Proconve (BRASIL, 2010), The National Policy on Climate Change (PNMC) (BRASIL, 2014), the National Plan for Adaptation to Climate Change (PNA) (BRASIL, 2016a), the São Paulo state bill Nº16802 (PREFEITURA DE SÃO PAULO, 2018), the Program for Promotion of Technological Innovation and Strengthening of Vehicle Productivity Chain (Inovar Auto) (MINISTÉRIO DO DESENVOLVIMENTO INDÚSTRIA E COMÉRCIO EXTERIOR, 2014) and Inova Energia Plan (BRASIL, 2015b). More detailed information about those policies is found in the APPENDIX 3 – BATTERY ELECTRIC VEHICLE BRAZILIAN INSIGHT.

Although those policies were wide scope actions, they barely mentioned electrification as part of the solution for the issues that they intended to address. Similarly, the Sibratec network (2011-2015) (REDETIC, 2016) aimed to integrate the efforts of diverse research institutions; however, it ended without causing a significant impact. Policies involving BEVs have been usually merged with initiatives to promote either "clean" or "sustainable" technologies, resulting on indirect actions instead of a wide policy for the sector.

Recently, Rota 2030, a program tailored to replace Inovar-Auto was issued. It offers tax slashes to OEMs investing in research and development of parts not being manufactured in Brazil (BRASIL, 2018c). Rota 2030 will likely define the efforts of manufacturers to enter the local market in the next years (BRASIL, 2018d). Some criticism states that benefits are not as robust as expected, since they hinge on energy efficiency and vehicle weight (BLAND, 2018a). Consequently, OEMs ought design lighter BEVs to fully benefit from the program (BLAND, 2018b). Furthermore, the program does not include a specific policy for BEVs, let alone new BMs or cooperative transportation. The objectives and strategies of the most prominent environmentally motivated policies can be found in the APPENDIX 3 – BATTERY ELECTRIC VEHICLE BRAZILIAN INSIGHT.

Rota 2030 includes provisions for ethanol-fueled HEVs, but not BEVs. This is in concordance with the National Center of Research on Energy and Materials (CNPEM) predictions of fossil fuels in Brazil being replaced by a combination of ethanol and electrification. CNPEM even perceives potentiality to export this model, emboldened by the fact of India, China, the US and other countries in Latin America having incorporated ethanol to gasoline (CNPEM, 2018). CNPEM concludes that electrification should become a complement for the biofuels-based transportation market instead of a competitor.

Clear policies regulating the electricity sector and its relationship with electrification are fundamental. The objective of ANEEL resolution Nº 819-2008 was to create a safe framework for entrepreneurs investing in public EVSEs (MARQUES DE ARAUJO; AMORIM, 2017). An additional motivation was the issuing of bills PL 4751/2012, PLS 780/2015 (BRASIL, 2015c) and PLS 454/2017 (BRASIL, 2017a), submitted to congress, which could render the installation of public EVSE compulsory and even ban the sale of ICEVs in 2060 analogously to other countries (PETROFF, 2017). Furthermore, in November 2018 ANEEL announced a call for proposals for the strategic project 22/2018, "Development of Solutions in Efficient Electrical Mobility". The goal is to encourage the deployment of technologies for electric mobility. Solutions considered include new BMs, devices, services and infrastructures, (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2018a). More detailed information about motivations for ANEEL resolution Nº 819-2008 is found in the APPENDIX 3 – BATTERY ELECTRIC VEHICLE BRAZILIAN INSIGHT.

Local lawmakers apparently realize that creating regulation on electric mobility is crucial if not inevitable. In fact, it is preparing to issue a national plan for electromobility (BRASIL, 2018e) (AUTOMOTIVE BUSINESS, 2018). Despite the absence of an electrification policy in Rota 2030, the government has begun to recognize the inevitability of including biofuels and electric mobility in 2050 National energy plan (PNE2050) (BRASIL, 2019a). The Energy Research Enterprise (EPE), a public research company, recommended the establishment of a realistic roadmap for electrification and measurements to avoid technological lock-in (EMPRESA DE PESQUISA ENERGÉTICA, 2019).

2.9. Discussion

2.9.1. Prices, biofuels competition and lack of consensus, overwhelming challenges

High tag prices, accessible only for a few, worsened by poor macroeconomic indicators, denoting a population with stagnated or decreased revenues, were identified as preponderant hurdles for BEV adoption (PRATIWI, 2016). As part of the EMOTIVE project, the Total Cost of Ownership (TCO) of BEVs and ICEVs employed by three local companies in their fleets was documented; all of it based on real usage data (MARQUES et al., 2015, 2016). The main findings indicate that, for 2015 conditions, Renault Zoe and Renault Kangoo models are economically at a disadvantage compared to Honda Fit and Kangoo Express-*flex*. It is a consequence of a heavier purchasing tax burden outweighing any advantage provided by BEVs lower usage and maintenance costs, even in a 5 years timespan. Furthermore, a prospective scenario was created, seeking to draw a future situation, in which purchase taxes were abated by 50%, annual taxes were reduced from 3% to 1% of the total of the car, cost of battery storage reached 150 USD kWh^{-1} and manufacturing process costs decreased by 50%. To the present day, annual tax was already reduced in that proportion (CPFL ENERGIA, 2017). Battery storage cost, on average, reached 176 USD in 2018, which strongly suggest that the forecasting could be reached even before 2020. In fact, Tesla claims to have already reached the 150 USD kWh^{-1} threshold (GOLDIE-SCOT, 2019). Additionally, importation tax was reduced from 35% to 7 % (BRASIL, 2015a; VASCONCELOS, 2017), however, it still does not imply a 50% purchase tax reduction. Finally, considering Lutsey & Nicholas (2019) forecasts it was assumed that, despite being on a steady fall, the decrease in manufacturing costs is not likely to have reached 50% from 2015 baseline. Thus, according to this rational, the prospective scenario is a fair approximation for the actual TCO of BEVs in the years to come. There were no variations for ICEVs in the prospect scenario. A Comparison of both scenarios is seen in Figure 5.

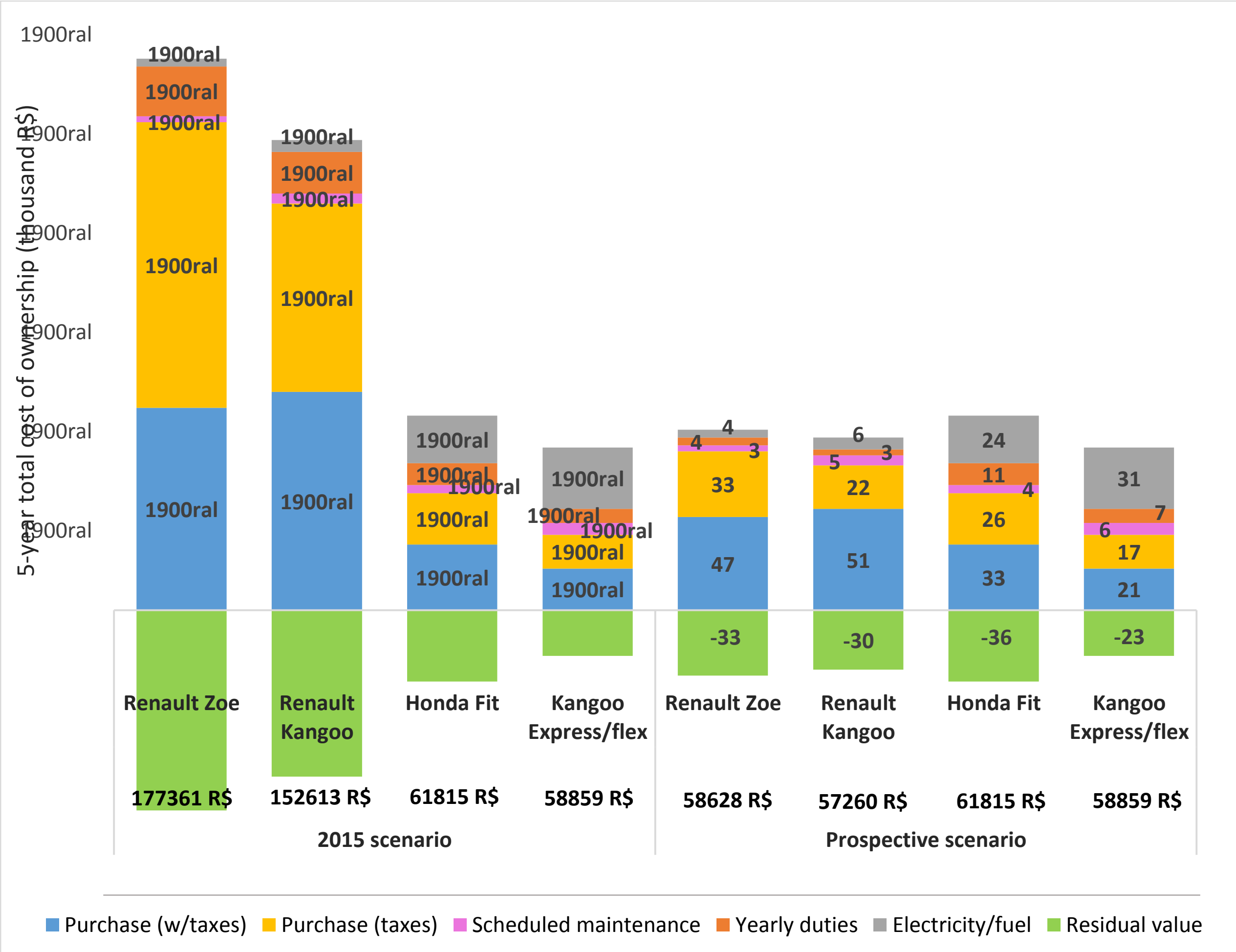

Figure 5. Total cost of ownership for two models of BEVs and ICEVs in Brazilian fleets for 2015 and prospected scenarios.[4]

In addition to tag price and availability of public EVSE, other factors influence the adoption of BEVs. Research analyzing adoption in the U.S.A concluded that electricity prices and financial incentives are relevant factors for users to choose BEVs over ICEVs (SOLTANI-SOBH et al., 2015). This research assumed that those findings could be juxtaposed to Brazil since both factors affect the BEV TCO.

Firstly, electricity prices in Brazil vary depending on generation conditions (BRASIL, 2015d). Drought is injurious for hydroelectricity (DE AZEVEDO et al., 2018) and it implies larger dispatches of gas-fueled power plants. Analogously, gasoline rates can vary depending on international oil prices, while taxes add up for the overall price (PETROBRAS, 2018). Secondly, implementation of incentives is unlikely; Brazil just overcame a recession (OECD, 2018), consequently, the government is prone to cut public spending. Thus, it would hardly implement financial support for BEV promotion and specifically for public EVSE installation (LI, 2016; MARQUES DE ARAUJO; AMORIM, 2017). Additionally, the potential benefits of electrification

[4] Based on Marques (2015, 2016).

as a way to mitigate GHG emissions may seem not a priority for an administration whose stance on global warming is the skepticism (ESCOBAR, 2018).

Besides the lack of incentives, the global and local market barriers, the competition with biofuels may be an obstacle for BEV adoption (2013; MARCHÁN; VISCIDI, 2015). Indeed, voices within the sugarcane sector oppose tax reductions for BEVs arguing it contradicts the objectives of Renovabio policy, which strives to promote efficient biofuels production, hence, mitigating life-cycle GHG emissions (RAMOS, 2018). In contrast, other voices in the sector acknowledge the inevitability of electrification and call for this technology to be seen not as a substitute, but rather a complement for biofuels (CNPEM, 2018; VASCONCELOS, 2017; VEDANA, 2019; ZAPAROLLI, 2019). Baran & Legey (2013) projected that, given a PHEV adoption of nearly 40% of the total fleet, the demand for liquid fuels would remain almost stable from 2020 onwards. Even for such an optimistic scenario for electrification, biofuels consumption would not decrease.

CNPEM argues that an electrification process reliant on imported technology may jeopardize priority aspects, such as job creation and bioenergy technology leadership, not to mention the balance of payments. Therefore, for electrification to become an unquestionable asset, it must recognize the Brazilian singularities and adapt to them. This implies electrification should not hamper job creation or biofuels leadership. Besides, it must contribute to prevent dependence on foreign inputs or technologies. Coexistence of electrification and biofuels, should grant reliability and energy security (CNPEM, 2018; MARQUES DE ARAUJO; AMORIM, 2017).

Understanding Brazilian particularities is crucial for implementing mobility policies. Electrification may well arrive in the heavy-duty segment first. One example is the implementation of Law 16.802 in SP city. Its ambitious goals, for a 20 years period, require drastic reductions of particulates, NOx and fossil CO_2 emissions when compared to a baseline scenario, which displays a bus fleet heavily based on Proconve 5 and 7 emission standards, equivalent to Euro III and Euro V respectively. Dallmann (2019) analyzed the economic and tailpipe emission consequences of the substitution of that diesel-based fleet for BEBs, hybrid busses, Euro VI diesel busses with different blending of soybean biodiesel and, Euro VI compressed natural gas and biomethane fueled busses. Slowik et al (2018) further refined this analysis by including fuel cell busses. The results, for a 10 year timespan -or 70,930 km-, show that, despite the higher tag price, the BEBs are the best option from a TCO perspective with all other options staying within a 10% range of the Proconve 5 baseline bus, except for the fuel cell bus, see Figure 6. These results are in consonance with O’Donovan et al (2018) who state that 350 kWh BEB TCO is lower than Diesel busses for distances over 80.000 km per year.

From CO_2 emissions viewpoint, special attention should be paid to Euro VI soybean-based biodiesel option, where indirect land use change considerations might render total life cycle emissions even greater than those in a Proconve 5 Diesel (B15) Bus. Those concerns are found in other studies also, Glensor & Muñoz (2019) found that direct land use change (LUC) is a major contributor to the overall CO_2 emissions for car and bus fleets with predominant use of biofuels. Moreover, the land carbon content for different Brazilian biomes make the results very sensitive to whether LUC emissions are included or how they are calculated. Dallmann (2019) concluded that, whether high tag price of BEBs does not allow the purchase of BEBs due to funding scarcity a gradual substitution for Euro VI diesel busses could as well be an option to fulfill Law 16.802 requirements regarding particulates and NOx emissions.

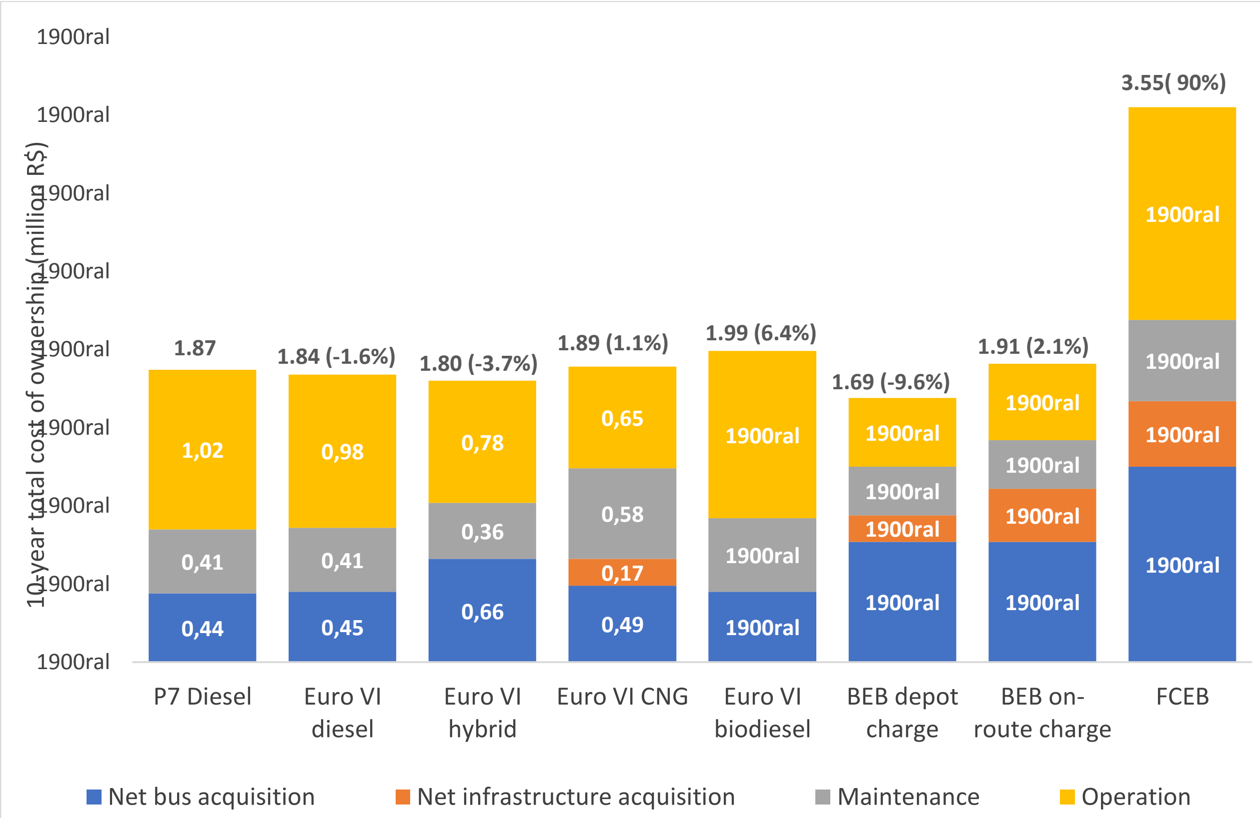

Figure 6. TCO estimates over 10 years for various technologies [5].

Moreover, Consoni et al (2018) identified the absence of a national consensus on electrification as another cause for the low Brazilian BEV adoption. Multiple initiatives for promotion have been created in regulation, industry and research spheres; however, there is no articulation between them. The Brazilian association of BEVs (ABVE) chairperson stresses the absence of public policy as one of the main hurdles for broader adoption (VASCONCELOS, 2017). A solid policy could indeed be the base for BEV adoption. In the past, the implementation of Proalcool program demonstrated the potential of public policies to transform the energy model in

[5] Based on Dallmann (2019) and Slowik (2018).

the country. Interestingly, to a large extent, the efforts allocated to the electromobility sector are justified by the R&D investment requirements of law 9991 / 2000 (CONSONI et al., 2018).

2.9.2. Market and charging infrastructure development

The creation of a BM for public EVSE is a *sine qua non* condition for transport electrification (LAFRANQUE, 2015). A question remains for the appropriateness of EVSE promotion based on public funding given the tiny current BEV fleet. Estimations from CPFL predict EVSE requirements for up to 80,000 units in 2030 (ROCKMANN, 2018), resulting in the typical chicken and egg dilemma (HADDADIAN; KHODAYAR; SHAHIDEHPOUR, 2015) in a Brazilian context. ABVE endorsed a self-guided model led by market own evolution, implying gradual EVSE installation (VASCONCELOS, 2017). In this context, the role of the public sector is fundamental for structuring the first steps on EVSE networks and initiating a virtuous cycle of investments in the area (LAFRANQUE, 2015).

Gradually, BMs in transportation are expected to incorporate more revenues from data management. Posteriorly, BEVs are expected to resemble computers on wheels, able to create other ways of added value to the customer. Revenue schemes focused on charging infrastructures, car information management and location are expected to generate new business opportunities to industry players. More complex models have emerged; Sparkcity model (HOEKSTRA; HOGEVEEN; STEINBUCH, 2016) endeavors to integrate several modules into a comprehensive model, including one module for car and battery manufacturers and dealers, one for driving characteristics, one for charging, intended for use of municipalities and CPOs and finally a module for smart charging.

In addition to becoming more data-focused, electromobility is expected to be integrated into other transportation modes, an intermodal mobility provider would need to incorporate data from other providers on a single platform and execute the billing work, so it could be classified as a EMSP (LAURISCHKAT; VIERTELHAUSEN; JANDT, 2016). Another sector bound to rapid transformations is the after-sales. This lucrative segment is exposed to revenue decrease as a consequence of the rising share of BEVs, which imply a decreasing share of moving parts, less complex services and the longer maintenance intervals (DOMBROWSKI; ENGEL, 2014).

Despite of a challenging scenario, the short term does not seem entirely discouraging for electrification. Although representing completely different markets, in the U.S.A, cost parity for BEVs and ICEVs is foreseen for 2025 (MC KINSEY & COMPANY, 2019). In Brazil, Consoni et al (2018) perceived success potential for two main entrepreneurship groups. First, fleets operation and management of EVSE network. In fact, BEVs are already a competitive choice for fleet operators and cab drivers in the country (MARQUES DE ARAUJO; AMORIM, 2017). The second route, points to the development of prototypes for the ultralight segment, represented by scooters, rickshaws and other low speed vehicles.

The competitive approach of OEMs, regarding on-board data management systems, represents a hurdle for the deployment of architectures connecting BEVs, EVSEs, and DSOs. OEMs consider their data as competitive advantage. Each player prioritizes their own interests, resulting in relationships between the stakeholders that have remained notoriously uncooperative. Weiller and Neely (2014) conclude that BEV communication systems, traditionally owned by OEMs, should be open for DSOs and CPOs if competition is going to be boosted. Convincing OEMs on the advantages of having a standardized system and open systems will be tough; nevertheless, Tesla already set a precedent in making information open for the sake of competition (VANCE, 2014).

Although scarce, Brazil has developed BEV technology. CPqD experience includes characterization of battery cells and packs, development of packaging and cooling systems, and development of battery management systems (BMS) (MARQUES et al., 2017). The BMS is the device in charge of controlling different battery parameters: (i) current, (ii) voltage, (iii) SOC, (iv) SOH, and (v) Temperature. CPqD research even includes algorithms for the assessment of SoC (ARANHA et al., 2018) and SoH (ROCHA et al., 2018). This indicates technical expertise is present, at least for assembly of BMS. Denying investments to local BEV technology development would denote relinquishing the chances of developing an industry in the future, restricting the country to peripheral developments (CONSONI et al., 2018; VAZ; BARROS; RIBEIRO DE CASTRO, 2015) and squandering the potential for insertion in the global battery supply chain. Although requiring large investments and regional cooperation, Jussani et al (2017) highlighted the Brazilian potential for insertion in the global battery supply chain recognizing the large lithium reserves in neighboring countries and the Brazilian expertise in mining. As long as BEV tag prices are significantly higher than ICEV ones, massive adoption will remain unfeasible. Prices depend strongly on battery costs and how successful are OEMs to implement mass production-oriented design. Prices could plunge once the BEVs are manufactured locally but it remains unlikely in the short and medium term considering the high investments required.

Regarding public EVSEs, prioritizing of actions should include the search for consensus on standardization of AC and DC recharging plugs; combo CCS type 1 and 2 would be interesting options since both support AC and DC charging. Equally important, is standardization in EVSE communication protocols. OCPP would be a good candidate, considering it is the de-facto network protocol throughout Europe and is used in nearly 80 countries (GREENLOTS, 2018).

On the long run, and as a consequence of BEV adoption, the amount of used batteries will soar, meaning that either a second-life or a recycling scheme will be necessary. Up to now, the industrial recycling of Li-ion batteries is able to recover only the most profitable Co, Ni, Fe, Cu and Ni in a cost-effective scheme. Currently, lithium from batteries is only recoverable via hydrometallurgical process, but it is not financially feasible. Some hassles are the low lithium value and the fact of it being strongly diluted in the battery. A decisive hint to promote battery recycling would be to make compulsory the reuse of materials established by policy (TRÄGER; FRIEDRICH; WEYHE, 2015).

Nevertheless, such policy could crash against the swinging prices of raw metals. For instance, in 2019, prices of lithium and cobalt, two key commodities for battery manufacturing, plummeted due to low demand in China and overproduction (BIESHEUVEL; BURTON, 2019; BURTON; BIESHEUVEL, 2019; LOMBRANA, 2019a, 2019b). Low extraction prices render recycling unfeasible.

2.9.3. Final remarks

In spite of ANEEL resolution 819, Brazilian policy seems very likely to stay on bioenergy track for the years to come. Renovabio policy is expected to modify the energy outlook in Brazil as Prooalcool did several decades ago. By acknowledging the potential of biofuels to reduce GHG emissions, the initiative generates market instruments to compensate producers for increasing efficiency and avoiding emissions (GRASSI; PEREIRA, 2019), thus, awarding good industrial and agricultural practices and providing supply predictability due to the gradual increase of biofuels share in the energy matrix (BRASIL, 2018f).

Electrification does not appear to have the same impetus as in other countries since Brazil does not face the severe challenges in energy security or extreme air pollution as other countries do. BEVs offer significant GHG emissions mitigation, compared to gasoline-driven cars, as a consequence of a predominantly renewable generation mix; however, sugarcane ethanol is competitive in this regard also. According to local research comparing BEVs and ICEVS, with a similar power-to-weight ratio, and including the entire life cycle of the vehicles, the global warming burden of driving one km in a sugarcane ethanol-fueled car is lower than that of driving one km in a BEV, assuming the crop land is not a product of deforestation (CHOMA; UGAYA, 2013;

VELANDIA VARGAS et al., 2019). In contrast, urban pollution mitigation is an undisputed trump card for electrification.

The construction of a public policy is fundamental in order to articulate efforts and set up clear rules. Without a clear statement of what Brazil wants from BEVs it will not be possible to compose a set of coherent institutional actions. The particularities of Brazil seem to suggest that a realistic electromobility road map should prioritize synergistic solutions, starting with public transportation and including intermodal integration, private fleets and the ultralight segment, *e.g.* scooters and bicycles. Moreover, increasing R&D to support proper electromobility technologies focused on local particularities might enable the constitution of an adapted electromobility market, *e.g.* hybridization and ethanol-based fuel cells. Finally, it is equally important to balance the pace of entry of new technologies, avoiding the destruction of taxation and understanding the large economic and political risks of negatively impacting biofuels sector.

A successful electrification of transport, particularly public charging, requires synergy between two large industries, mobility and energy. An essential requirement for BEVs is the capacity to be plugged-in and recharged anywhere. Open standards are good for encouraging competition and innovation. Firstly, because nobody owns them, thus, anybody with fresh ideas can join in, stimulating an ecosystem of entrepreneurs. Secondly, open standards avoid technological lock-in, by making equipment, such as EVSE, interchangeable, in contrast to market leaders, who usually try to use their position to impulse a determined standard in order to maximize profit. The standards are not supposed to define any BM; instead, standards should enable fluid communication between all parties involved. Public policy should steer the process towards open standards leading to better competition and lower costs.

Put in a nutshell, environmental remarks can be summarized as follows: BEVs deployment in Brazil can be an effective way to drastically improve urban air quality while reducing dependence on fossil fuels (CHOMA; UGAYA, 2013; DALLMANN, 2019; DE SOUZA et al., 2018; GLENSOR; MUÑOZ, 2019; VELANDIA VARGAS et al., 2019). Likewise, electrification is an option to mitigate GHG emissions, although biofuels are effective also. However, whether local manufacturing of BEVs takes place, it will be preponderant to control the potential ozone depletion effects linked to aluminum recycling (VELANDIA VARGAS et al., 2019).

BEVs disruption reflects a change in technology and paradigms beyond mere transportation, a myriad of new businesses is expected to sprout from the interactions between the vehicles, the electric grid, the charging infrastructure and the users. In order to harness the potential of this new market highly skilled workers and investments in research and development are necessary. Therefore, whether Brazil abandon the possibility of investing in R&D will decide its position as an imported or a producer. Any negative socioeconomic effects, such as, job losses and relinquishing the leadership in biofuels field must be overcome by finding technological routes to integrate electrification and biofuels.

3. PAPER 2: LIFE CYCLE ASSESSMENT OF ELECTRIC VEHICLES AND BUSSES IN BRAZIL: EFFECTS OF LOCAL MANUFACTURING, MASS REDUCTION AND ENERGY CONSUMPTION EVOLUTION[6]

3.1. Introduction

BEVs are still far from being a representative share of Brazilian automotive fleet and they do not seem to be arriving massively very soon. Arguments supporting BEV adoption are that electric powertrains are more energy efficient for propelling vehicles than ICEV ones fueled by petrol, ethanol, or diesel; besides, electric propulsion barely emits noise (Sadek 2012). However, Brazilian transportation sector, and its motivations for adopting BEVs, are unique, which implies different outcomes when compared to other countries.

Current BEV manufacture has demonstrated to often increase GHG emissions when compared to ICEV manufacture (HAO et al., 2017; KIM et al., 2016). Battery evolution and mass reduction are promising opportunities to offset BEVs' larger environmental burden during the production stage. Tagliaferri et al. (2016) analyzed the potential evolution of BEV mobility focusing on electricity generation and EOL scenarios but not considering vehicle evolution.

The National Research Council (2011) points out three main methods to make steel structures lighter. First is to substitute lower-strength steel for higher-strength steel. Higher-strength steel can be made thinner thus reducing mass; however, forming processes might imply an additional environmental burden even greater than that of the avoided mass. Second method is to substitute conventional steel for sandwich metal material, which is light, stiff, and can be formed into many parts. Finally, the use of tubes which aim for an optimal use of steel (and aluminum) result in less mass without putting design criteria at risk. Although all of the previously stated methods may increase costs in the present day, this problem is expected to be overcome as mass production is achieved.

Lotus Engineering (2010) reported the technical feasibility for a 2017-2020 mass reduction development program. This model assumed a target total vehicle mass reduction of 40% to be achieved while considering a 50% upper limit constraint on total vehicle piece cost relative to the

[6] Published in The International Journal of Life Cycle Assessment (2019) 24:1878-1897 (https://doi.org/10.1007/s11367-019-01615-9). Co-authors: Arnaldo César da Silva Walter, Carla Kazue Nakao Cavaliero, Daniela Godoy Falco and Joaquim Eugênio Abel Seabra.

baseline car: Toyota Venza 2009. This development was intended for a 2020 Model. All technologies used to reduce mass at the vehicle had to be ready to use within the company in 2017 or earlier.

Das (2014) LCA research evaluated alternative lightweight vehicle designs in comparison to a baseline model. A high strength steel and aluminum design (“LWSV”) and an aluminum-intensive design (AIV) were considered. Results show AIV design achieved mass reduction of 25% (compared to baseline) consequently resulting in a decrease in total life cycle primary energy consumption by 20% and CO_2 emissions by 17%. In contrast, LWSV have a mass reduction potential of only 15% which leads to higher overall life cycle energy consumption (9%) when compared to AIV design. Overall, the AIV design showed the lowest environmental impact per mile from both; climate change and primary energy consumption point of view.

In a comprehensive review of technical literature Lutsey (2010) reports that by means of model redesign, automakers can achieve up to 20% of mass reduction in their vehicles at little or no additional cost and most surprisingly, without deeply shifting their manufacturing technologies. It also reports that a number of technical studies state that vehicle mass reductions from 20-35% in weight could be both feasible and affordable with technology shifts toward mass-reduction techniques.

Ricardo AEA (2015a) aimed to understand the potential for automotive mass reduction in the EU market by means of a wide-ranging literature review. Among their conclusions it must be highlighted that in spite of the fact that there are examples of vehicles produced almost entirely from high strength steels, aluminum or composite materials, future trends are likely to present a multi-material scenario. Therefore, material use predictions are bound to high levels of uncertainty.

When comparing all LCA stages, the collection of LCI is generally the most effort intensive. This phase includes the quantification of inputs (primary and manufactured), by-products, and environmental emissions to air, soil, and water. The search for inventories often results in no available data for a specific region, or in the best of cases, LCA practitioners find data adapted to reflect global average values. This lack of geographical detail embodies a great concern for studies which are expected to be more accurate. Country overall data is usually used to represent regions geographically too distant or that present very different environmental conditions, e.g., altitude, latitude, or weather.

In the same way, LCA primary data is either confidential or it is scattered and difficult to find for researchers who usually do not have access to data for the entire life cycle of the car. Hence, data from diverse stakeholders is required for each stage, adding time and space uncertainties for the study. Furthermore, the absence of transparency about the influencing factors of LCA in EVs creates great difficulty for boundary definition and makes the analysis prone to flaws. According to

Egede et al. (2015), material composition of the vehicles, electricity mix, and use patterns are considered to be the main influencing factors on BEV environmental assessments.

Although there has been a growing interest on electric mobility options in Brazil, there is no mass production of electric vehicles in Brazil currently. BEVs' future market penetration along with tax regulations for imported goods (AES Brasil 2017) could encourage automakers to manufacture the cars in the country. Early steps for a future governance roadmap on electric mobility have been taken (Consoni et al. 2018). In fact, the national electric energy agency has already called for proposals on efficient electric mobility (Agência Nacional de Energia Elétrica 2018). However, it remains unclear to what extent a Brazilian car is environmentally advantageous over an imported one. Environmental benefits of BEVs when compared to ICEVs depend greatly on electricity mix but also in the vehicle itself.

The purpose of this study was to evaluate what would be the environmental impact of manufacturing BEVs and BEBs in Brazil by adjusting LCIs to local conditions and then to compare them to their global average counterparts. In order to do it, a representative number of Ecoinvent datasets were adapted to better represent Brazilian southeast conditions. Additionally, this research envisioned evolution scenarios for BEVs and BEBs, thus being able to compare Brazilian and global LCIs for a 2030 scenario. Finally, we established a comparison of environmental impacts per traveled kilometer for each case to capture the contributions from electricity, maintenance stage, and vehicle production to the well-to-wheel (WTW) overall impacts.

3.2. Methodology

This LCA study was carried out to understand the environmental advantages and disadvantages of manufacturing electric vehicles in Brazil. In order to do so this thesis compared the environmental impact of one hypothetically manufactured BEV and one BEB in Brazil versus their average global counterparts. Although one bus or car would not be considered as a valid functional unit according to the literal interpretation of ISO 14040 standard, it was considered as the most adequate unit of comparison to characterize the scope of this study. The Brazilian BEV and BEB datasets were adapted from global datasets in order to best represent the manufacturing processes in Brazilian south-east conditions for 2015 and 2030 scenarios. For 2030 two lightweight BEV scenarios were considered. Thus, this study looked forward to quantify the potential contribution of local manufacturing throughout the entire lifecycle. Additionally, an ICEV and an internal combustion engine bus (ICEB) were included to be used for comparison of BEVs and

BEBs, per vehicle and per km. This inclusion was merely intended to serve as a reference considering that it would not be accurate to directly compare the electric vehicles vs the conventional ones, the comparison would be only adequate on the basis of 1 km travelled. These ICEVs are based on average 2015 powertrains, which were admitted to be average competitors for the electrics. Detailed information about conventional vehicles modelling, their fuels and their use phase can be found in APPENDIX 1 – PARAMETERS FOR INTERNAL COMBUSTION ENGINE VEHICLES MODELLING.

The BEV datasets representing the global average were obtained from Ecoinvent v3.2 (SWISS CENTRE FOR LIFE CYCLE INVENTORIES, 2015), whereas for BEB material composition this research included information from Garcia Sanchez et al.(2013). Then, those results were compared for 2015 and 2030. Although Ecoinvent datasets classified as Global are simplifications of the global market, mostly intended to be used for background data this work considered them to be valid as a reference point, since market for EVs is still incipient and yet to be consolidated. Detailed information about the dataset adaptation process can be found in APPENDIX 2 – DATASET ADAPTATION TO BRAZILIAN CONDITIONS.

A cradle to grave product system was considered, thus EOL stage is included. An attributional approach was adopted. The employed impact assessment method is Recipe Hierarchist midpoint (GOEDKOOP et al., 2009) while the software employed was SimaPro v8.3.0 (PRÉ-CONSULTANTS, 2014). Arguments supporting our method selection are that it is recent, broad and pertinent for this research. Recipe presents 18 available midpoint impact categories, which allows the practitioner to cover many areas of concern. This research presented results for climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, metal depletion, fossil depletion, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity. These categories are common for energy-related LCA studies since they cover society concerns about GHG emissions and air quality, use of resources and toxic threats for humans, soil and water. However, it should be said that regional categories are not calibrated for Brazilian geography yet.

3.2.1. System boundaries and evolution parameters

The system boundaries were outlined firstly to evaluate the manufacture stage of both BEVs and BEBs and secondarily to analyze the use phase of the vehicles. Ecoinvent LCIs for BEVs can be found in a Unit Process scheme. This scheme creates a hierarchy in which a given process is composed of several inputs which in turn are comprised of other inputs too. It was our intention to model as much of the vehicle production chain as possible for both BEVs and BEBs by adapting those Unit Process datasets that model the BEV manufacturing stage. Since Ecoinvent v3.2 only contains a few Brazilian processes the vast majority of the datasets had to be adapted. This study focused on raw materials production, especially steel and aluminum, electricity generation, and transportation. A detailed description of all adjusted Ecoinvent processes, and their modifications, is shown in APPENDIX 2 – DATASET ADAPTATION TO BRAZILIAN CONDITIONS. General parameters for BEV and BEB evolution are found in Table 2 while a graphical depiction of system boundaries for either the BEB or the BEV is shown in Figure 7. Electricity mix specifications are presented in electricity generation section.

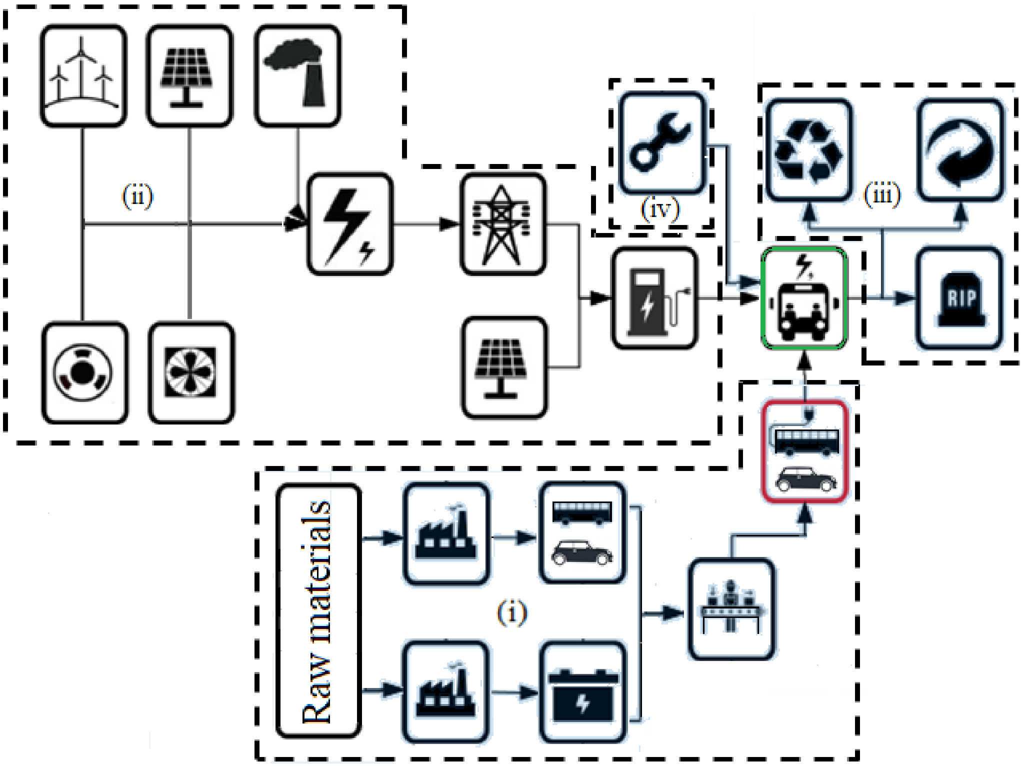

Figure 7. Depiction of the boundaries for this study[7]

3.3. Battery electric vehicle manufacturing

[7] The product system for both BEB and BEV involved primarily the vehicle manufacturing stage (i) (i.e. Chassis and body + battery) including raw materials extraction and processing. Furthermore, for well-to-wheel assessment, this study analyzed the generation of electricity (ii); end-of-life stage considering recycling and re-use of vehicle materials (iii) and; maintenance (iv). The assembled vehicle is represented in red while the green square represents the inputs for a functional unit of one km.

BEV Ecoinvent dataset is originally based in Habermacher (2011), whose starting point of analysis was the material content of a Volkswagen Golf A4, as it was modeled by Althaus & Gauch (2010). Habermacher (2011) created a baseline scenario and two lightweight scenarios for car chassis and body (C&B), which aimed to model future mass reductions based on synthetic and aluminum material substitutions. C&B, in this case refers to the entire structure of the vehicle without the battery. Both, 2015 and 2030 scenarios present the same basic Unit Process structure seen in Figure 8. The dataset "*Car without battery Alloc Def, U*" was adapted to mass data for 30kWh Nissan Leaf 2016 Accenta, Black edition, Tekna (NISSAN, 2016a) as presented in Table 2. Nissan Leaf was chosen for being the second bestselling car in the world, hence it was considered it to be representative of BEV market for the present exercise (CLEANTECHNICA, 2017).

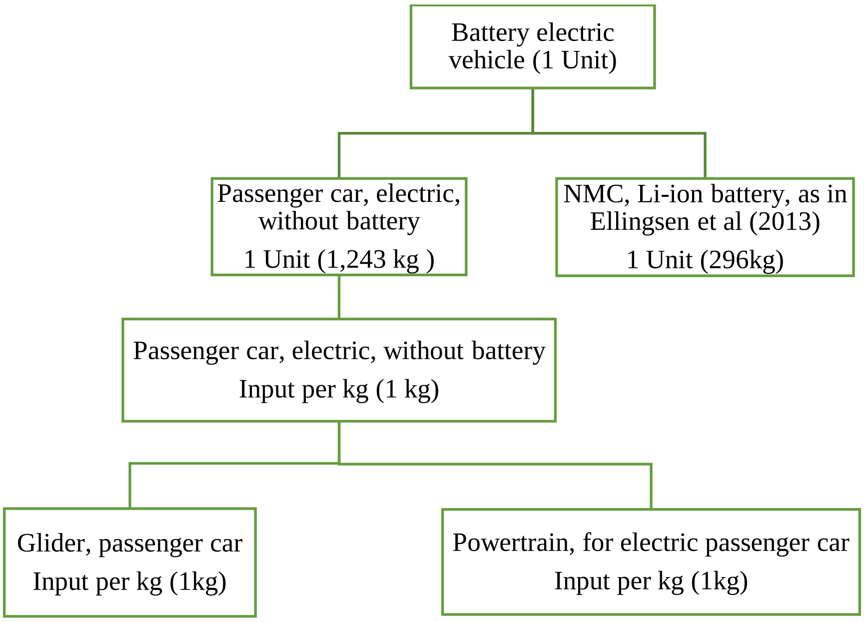

Figure 8. Unit process visual scheme for a BEV in 2015.

3.3.1. 2015 Scenario

Energy consumption for the BEV was considered as 1.5 E-1 kWh km^{-1} (NISSAN, 2016a) while 90% charging efficiency was assumed (ZACKRISSON; AVELLÁN; ORLENIUS, 2010), thus tank-to-wheel consumption is 1.67 E-1 kWh km^{-1}. For maintenance information this research used Ecoinvent dataset *Maintenance, passenger car, electric, without battery Alloc Def, U*. Quantity used per km is the same as in dataset *Transport, passenger car, electric Alloc Def, U*. Regarding life expectancy, the 2016 30 kWh Nissan LEAF Accenta is backed by a limited warranty providing

100,000 miles Lithium-Ion Battery coverage (NISSAN, 2016b), however, there is evidence of batteries (D'ANGELO, 2017) and chassis (RODRIGUES; COOPER; WATKINS, 2015) lasting longer than predicted, thus it was assumed the battery lifetime to be 120,000 mi or 193,080 km. This value matches the life expectancy for the rest of the car, which was assumed to be at least 120,000 mi as seen in the Nissan Leaf maintenance booklet.

Table 2. Parameters for 2015 and 2030 scenarios for BEVs and BEBs

	Battery Electric Bus	**Battery Electric Vehicle**
	2015 scenario	
Car w/o battery	11,010 kg.	1,243 kg.
Battery mass	3,289.43 kg.	296 kg including heaters.
Energy consumption	1.66 kWh km^{-1} (1.50 kWh km^{-1}*90% efficiency)	1.67 E-1 kWh km^{-1} (1.50 E-1 kWh km^{-1}* 90% efficiency)
Energy density	11.40 E-2 kWh kg^{-1}	10.14 E-2 kWh kg^{-1}
Electricity mix	Year 2014. EPE (2016).	Year 2014. EPE (2016).
Maintenance	17% of materials for assembly stage. 17% of energy required for assembly.	Ecoinvent dataset: Maintenance, passenger car, electric, without battery, Alloc Def, U. One maintenance for 150,000 km.
Life expectancy	220,000 km Battery. 880,000 km Bus w/o battery.	193,121 km (120,000 mi) Battery and C&B.
	2030 scenario	
Bus w/o battery	9,469 kg	Aluminum scenario 1,156.5 kg Plastic scenario 1,035.7 kg
Battery mass	2,857.1 kg	228.6 kg
Energy density	16.0 E-2 kWh kg $^{-1}$	35.0 E-2 kWh kg^{-1}
Energy consumption	1.33 kWh km^{-1} (1.20 kWh km^{-1}*90% efficiency)	1.33 E-1 kWh km^{-1} (1.20 E-1 kWh km^{-1}*90% efficiency)
Electricity mix	Forecast for 2030. EPE (2016)	Forecast for 2030. EPE (2016)
Maintenance	17% of materials for assembly stage. 17% of energy required for assembly.	Ecoinvent dataset: Maintenance, passenger car, electric, without battery, Alloc Def, U. One maintenance for 150,000 km
Life expectancy	220,000 km Battery 880,000 km Car w/o battery	193,121 km (120,000 mi) Battery and C&B

Li-ion battery cell dataset available in Ecoinvent, which depicts a $LiMn_2O_4$ cathode, was substituted by a lithium manganese cobalt oxide (NMC) cell as presented by Ellingsen et al (2013). NMC is the battery actually used in the Nissan Leaf 2016 (NISSAN-GLOBAL.COM, 2017). Cobalt sulfate input for cathode positive active material was considered as in Majeau-Bettez et al (2011). EOL stage for the battery was included by using the Ecoinvent dataset *"Used Li-ion battery {GLO}| market for | Alloc Def, U"*. For 2015 EOL parameters it was assumed that 25% of cells were going to have a second life, while for 2030 it was assumed 50% cells reuse. Further discussion on battery chemistry substitution and criteria for definition of EOL stage for the battery is included in chapter 3.7.4 and 3.7.5. The NMC battery cell was the only element on the whole BEV model not to have a Brazilian version. Due to economy of scale considerations it was judged quite unlikely to have a battery cell produced in this country, at least within our time scope. Thus, the battery cell was represented as Global, then imported to Brazil for assembly. The rest of the battery; battery management system, cooling system and packaging materials were manufactured in Brazil. Transportation, was adapted for Brazilian conditions.

In Ecoinvent inventories EOL stage is included in each dataset. For instance, the dataset for the car without battery includes outputs for glass, lubricants and rubber from the tires. Both, C&B and battery datasets contemplate EOL outputs too. This work kept those outputs in the datasets unaltered.

3.3.2. 2030 Scenario

Vehicles evolution followed two main assumptions: there will likely be a mass reduction and a material switching in BEV components for 2030. The datasets were adapted to Nissan Leaf 2016 mass and battery specific energy features.

3.3.3. Li-ion battery

Researchers have studied the challenge of making batteries cheaper, stronger, lighter and presenting a lower environmental burden. Wood et al (2015) presented a study aiming to prove the technical feasibility of generating a cost breakdown for battery electrodes by redefining design parameters and adopting different materials. Berckmans et al. (2017) analyzed a 2030 scenario for decrease in battery production cost whereas considering an improvement in material science and maturing of the market.

Moreover, abundant research has been carried out on the technical field. The last 25 years saw a sharp development in technical parameters, such as energy and power density, battery safety and charging time (BLOMGREN, 2017). Li-ion batteries must evolve in terms of fulfilling technical requirements, specially driving range and hillside performance. In order to overcome these issues, improvements in battery capacity, energy density and power density must be achieved. Battery capacity is the main parameter influencing BEVs range (MRUZEK et al., 2016). Paradoxically, battery weight and energy consumption tend to increase significantly when driving range increases (CAMPANARI; MANZOLINI; GARCIA DE LA IGLESIA, 2009).

Nissan Leaf Accenta-Tekna 30 kWh NMC battery has a weight of 296 kg. The cooling system is included in the dataset provided by Ellingsen et al (2013). The vehicle contains heaters also (NISSAN, 2016a) to avoid driving range loss in low temperature conditions which reduce energy and power capability (WIESENFELDER, 2011). Ji & Wang (2013) classify the Nissan Leaf heater as mutual pulse system. This heating scheme exhibits substantial benefits such as not requiring additional moving parts, not having any participation of fluids and minimal extra weight requirements. Having said this, this thesis assumed that battery heater weight is negligible. Consequently, Nissan Leaf battery has an energy density of 10.135E-2 kWh kg^{-1}. Reportedly, 2016 BEVs displayed typical battery capacities of around 30 kWh and it is assumed they will reach a 60 kWh average by 2030, meaning a driving range between 350 and 450 km (IRENA, 2017a). A range of at least 300 km is believed to be a requirement for general public acceptance. In contrast, Blomgren (2017) points out that some models such as Chevrolet Volt and Tesla model 3 have already reached 60 kWh, whereas luxurious Tesla model X is available on 100 kWh version. In view of this this study assumed the battery capacity in 2030 for the Nissan Leaf, a mass market intended vehicle, to be 80 kWh.

According to Gondelach & Faaji (2012) in the medium term, it is expected that only Li-ion batteries will manage to reach a specific energy density level of 4.0 E-1 kWh kg^{-1}, understanding that other high energy chemistries such as Li-S and Li-air are still in development. Notwithstanding, more recent opinions show that skepticism is common among battery researchers, who believe that improvements to Li-ion cells may squeeze 30% more energy by weight in the best case scenario (VAN NOORDEN, 2014; ZU; LI, 2011). It means that Li-ion technology might never even reach 4.0 E-1 kWh kg^{-1}. In order to keep a conservative approach, it was assumed an energy density of 3.5 E-1 kWh kg^{-1} which results in a battery weight of 228.57 kg.

3.3.4. Rest of the car

BEV mass reduction can be accomplished by substituting heavy materials, mostly ferrous metals, by lighter ones. The substituting materials could be either lighter metals, such as aluminum, or synthetic materials, like composite structures. Habermacher (2011) constructed two lightweight scenarios which reflect the material inventories of two prototype cars: Precept and ESX2 (TONN et al., 2003). Precept does contain a large share of aluminum substituting for heavier materials, whereas composite materials, mainly resins, are used intensively in ESX2. Thus, the material content of the two prototypes matches what is expected to be a trend for the next 20 years in automotive C&B manufacture. In fact, fiber-reinforced composite materials have been used for many years for body panels in low-volume vehicles whereas aluminum has predominantly been used for engine blocks, wheels and gearboxes but is expected to migrate to other components as well (RICARDO AEA, 2015a). GREET model (ARGONNE NATIONAL LABORATORY, 2016) also defines material content for a lightweight BEV body and a conventional BEV body. This results in an important decrease in steel content and an increase in aluminum, carbon fiber and magnesium. These hypothesis are in line with Habermacher (2011).

Mass reduction scenarios for C&B are based on Precept and ESX2 total material content. Ecoinvent *passenger car, electric, without battery Alloc Def, U* dataset originally comprises the structure of the car and powertrain shares per kg: one kg of car in 2015 (without battery) contains 9% of powertrain and 91% of structure and closures in weight. For the lightweight 2030 scenarios, Habermacher (2011) contemplated a reduction in structure and closures mass while powertrain mass has no changes. Structure and powertrain masses for our Aluminum and Plastic prototypes were adjusted based on percentages shown in Table 3.

Table 3. Mass reduction parameters for BEV chassis and body (C&B) and powertrain.

Parameter	**Baseline**	**Plastic**	**Aluminum**
C&B (kg)	838	453	461
Powertrain (kg)	78	78	78
Total mass (C&B + Powertrain) (kg)	916	531	539
Total mass compared to B/line (%)	-	57.96%	58.84%
Powertrain share in Total mass (%)	8.52	14.68	14.47
Mass scaled to Nissan Leaf (kg)	1,243	720.44	731.38

3.3.5. End of life, energy consumption, maintenance and life expectancy

Datasets were kept as in 2015 scenario because of lack of specific data on EOL evolution stage except for battery pack which changed from 25 % reuse to 50% as mentioned earlier. Vehicle energy consumption was assumed to be 20% lower (1.20 E-1 kWh km^{-1}) when compared to 2015 (1.50 E-1 kWh km^{-1}) conditions due to mass reduction. Maintenance LCI is kept unmodified for 2030 scenario with regards to 2015 scenario.

Manufacturing improvements along with materials evolution make vehicle longevity very likely to increase as engineering techniques evolve, assuming planned obsolescence will not hamper lifespan improvements.

With regards to li-ion battery, a word should be given to the fact that in spite of intensive research on various electrode chemistries, ageing phenomena are neither well understood nor quantified yet, and the combined impacts of temperature, depth of discharge and current intensity still remain difficult to quantify and manage (BARCELLONA et al., 2015). Regarding the rest of the car, this study observed that material switching along with mass reduction make lifespan forecasting full of uncertainties. Aluminum and plastic pieces present lower resistance to fatigue than their steel counterparts. The use of carbon fiber or other polymers could render some, otherwise simple repairs, into impossible tasks, due to the inexistent ductility of these materials, thus, the presence of these materials makes life expectancy not likely to be extended. Adopting a conservative approach reflects the fact that design conditions does not allow this study to assume a longevity increase for 2030, hence, mileage will be kept the same as in 2015 for both BEVs and BEBs. Modelling parameters can be found in Table 2. Further discussion on BEV life expectancy assumptions can be found in chapter 3.7.3.

3.4. Battery electric bus manufacturing

3.4.1. 2015 Scenario

So far, mass deployments of BEBs have been scarce but perspectives improve at a fast pace. For instance, in Germany, diffusion stage (when mass production is reached) is anticipated to arrive only by 2030. Even at this point, only a hundred pure BEBs are expected to be deployed. Notwithstanding, important actors like Chinese BYD are investing in changing public transportation paradigms including life expectancy, battery performance and total cost of ownership (AVID TECHNOLOGY GROUP LTD, 2016; HENDERSON, 2016; ROBERTS, 2018a, 2018b), in fact, Shenzhen, China, currently has the largest fleet of BEBs in the world (HODGES, 2018). In 2016 the first double-decker BEB in the world was unveiled in London. It will manage to travel 180 miles on a single charge. In a Brazilian context, the municipality of Campinas city has announced the commitment to implement areas in downtown where only BEBs will be allowed (EMDEC, 2018). This kind of initiatives combined with the unveiling of a BEB assembly plant in Campinas city and the announcement of the interest in building a battery plant in Manaus by Chinese manufacturer BYD (BLAND, 2018c) are likely to accelerate the deployment of electric public transportation in the country.

For the electric bus a different methodology was adopted; since there was no available data in Ecoinvent databases to describe a BEB, it was necessary to appeal to literature. BEB material inputs for one bus are available in García Sanchez et al (2013). The author of this work deemed this dataset to be adequate to represent the C&B of a BEB since it is expected to be quite similar to the C&B of a conventional bus; in fact, retrofitting conventional busses into BEBs is a common practice (ALESSANDRINI et al., 2017). In the same way, the dataset was considered to be adequate in spite of not having the same system product as the BEV, since it compared the global BEB to the Brazilian BEB. Thus, any potential effects of system mismatch would be present for the both cases. All considerations for the BEB in 2015 and 2030 are displayed in Table 2.

Energy required for assembly stage is included as well. The dataset in this study disaggregates the $LiFePO_4$ battery from the rest of the bus. It also includes information about EOL stage and maintenance. The authors based their calculations on a BYD e-bus (CHINA BUSES, 2015), which is one of the few commercially available pure electric buses. Bus constituents are separated by type of material, *e.g.* steel, glass, aluminum, etc. EOL stage is established according to the type of disposal process *e.g.* dismantling, car shredding, etc. Detailed information on BEB dataset can be found in the Table 4.

3.4.1.1. Iron phosphate battery ($LiFePO_4$)

Due to lack of data for $LiFePO_4$ batteries, a $LiMn_2O_4$ battery dataset available in Ecoinvent was employed: *"Battery, li-ion, rechargeable, prismatic, Alloc Def U*". Analogous to BEV modelling, it was considered that the battery cell was unlikely to be produced in Brazil, hence, it was assumed that the battery cells are imported and the battery pack is assembled in the country. Infrastructure datasets, for conventional bus plant were included for modelling the BEB plant due to lack of information. Although not desired, this solution is reasonable, since it allocates the same infrastructure burden for both BEB, Brazilian and Global. Among Li-ion batteries $LiFePO_4$ is recognized for presenting one of the best power performances (MILLER, 2015), regarded as very important asset when facing hilly upsides. In contrast, $LiFePO_4$ specific energy is far from good (IRENA, 2017b). BYD answer to range, reliability and economy constraints for a BEB uses this battery that weights more than 3 tons, in a move that was called a "brute force approach" (AVID

TECHNOLOGY GROUP LTD, 2016). BYD managed to make this technically and financially feasible because they are mainly a battery manufacturer. According to Garcia Sanchez et al (2013) this battery presents a specific energy of 11.4 E-2 kWh kg^{-1} and a weight of 3,289.43 kg resulting in a battery capacity of 375.0 kWh. Although this specific energy is 14% and 23% higher than reported by Julien et al.(2016) and Sullivan et al.(2012) respectively, it was considered as feasible since it fits within the ranges proposed by Zu & Li (2011) 7.0 E-2 kWh kg^{-1} to 14.0 E-2 kWh kg^{-1} and Hassuani et al.(2005): 11.0 E-2 kWh kg^{-1} to 15.0 E-2 kWh kg^{-1}

3.4.1.2. Rest of the bus

Life cycle inventories in García Sanchez et al. (2013) reported a bus weight of 14,300 kg, including battery. It is also reported that the average value of primary energy consumption or assembly stage goes from 17,400 to 22,100 KJ kg^{-1}. It is assumed this energy comes from electricity and thermal energy (split 50/50 share). It was assumed a mean value of 19,750 KJ kg^{-1}. It is worth noting that this value does not include the $LiFePO_4$ battery assembly considered by the authors. Datasets for the rest of the bus are presented in Table 4.

Table 4. Inputs required for manufacturing one Chassis and body (C&B) of a BYD K9 e-bus

Datasets	Mass	
Steel, rolled | market for | Alloc Def, U	5,959.24	kg
Polypropylene, granulate | market for | Alloc Def, U	1,362.22	kg
Cast iron | market | Alloc Def, U	1,021.59	kg
Aluminium, primary ingot | market for | Alloc Def, U	1,305.30	kg
Flat glass, coated | market | Alloc Def, U	170.27	kg
Flat glass, uncoated | market | Alloc Def, U	397.25	kg
Steel, chromium steel 18/8 hot rolled | market for | Alloc Def, U	454.03	kg
Particle board, for indoor use | Alloc Def, U	0.33	m3
Lubricating oil | market | Alloc Def, U	113.54	kg
Road vehicle factory {GLO}| market for | Alloc Def, U	8.73E-07	P
Electricity 2016, medium voltage | market for | Alloc Def, U	108,729	MJ
Heat, district or industrial, other than natural gas {RoW|market| Alloc Def U	108,729	MJ

3.4.1.3. End of life stage

Data collection on energy expended and residues generated due to the processes involved was originally obtained from the GaBi 4 database (GARCÍA SÁNCHEZ et al., 2013). A word should be given to the mass balance between LCI inputs and EOL outputs. As expected, lubricants and $LiFePO_4$ battery mass inputs match liquid drain and $LiFePO_4$ battery outputs. In contrast, a direct mass correlation for other inputs and outputs is not possible to establish. Cannibalization material, *i.e.* parts of one bus used in another, is considered to have second life; therefore, it is not represented in the outputs for treatment. $LiFePO_4$ EOL is included in the battery dataset represented by a Li-ion used battery dataset. This because of the lack of specific data for iron phosphate batteries EOL. Municipal waste incineration in Brazil is negligible when compared to total solid residues production, mainly due to technical and financial unfeasibility (MACHADO, 2015), hence, municipal waste incineration share was considered to end up in landfills completely. Moreover, for lubricants, this study assumed that is more accurate to model the final disposal as a treatment instead of just dumping it in a landfill, given that Brazilian regulation is becoming increasingly stringent on lubricant oil disposal (CANCHUMANI, 2013). Table 5 presents the EOL outputs and the Ecoinvent processes used to represent them.

Special attention should be paid to battery EOL similarities between BEB and BEV. For BEV $LiMn_2O_4$ battery EOL dataset considers used Li-ion battery output as being 0.745 kg per one kg of battery in 2015 and 0.50 kg per one kg of battery in 2030. This difference refers to *second-life* increase for battery cells in the 2030. Thus, about 25 % of the BEV battery is assumed to have a second destination in 2015 and 50% in 2030. However, the author of the work do not expect EOL considerations to have a significant impact in final results as predicted by Tagliaferri et al (2016). Both NMC and $LiFePO_4$ chemistries are considered as good candidates for second life applications. For further discussion see chapter 3.7.4.

Table 5. End-Of-Life outputs and Ecoinvent datasets used for BEB modelling.

Output	**Mass (kg)**	**Ecoinvent dataset used**
Liquid drain	113.54	Waste, mineral oil| Alloc Def, U
Cannibalization	110.11	Not included
Dismantling (Subtotal)	4,019.73	
Tires	214.64	Used Tyre| treatment of| Alloc Def, U
LiFePO4 battery	3,289.43	Used Li-ion battery| Alloc Def, U
Metal scrap	396.11	Used powertrain from electric passenger car, manual dismantling| Alloc Def U
Synthetic	119.41	(Residue). Plastic Waste
Car shredding (subtotal)	10,056.62	
Metal scrap (steel, aluminum, copper)	8,289.14	Used glider, passenger car| treatment of, shredding| Alloc Def U
Landfill (waste for municipal disposal)	440.01	(Residue). Waste, Industrial
Municipal waste (incineration)	1,327.47	(Residue). Waste, Industrial

3.4.1.4. Energy consumption, life expectancy & Maintenance

In order to define BEB energy consumption in 2015 scenario this work used the same values as in Garcia Sanchez et al. (2013): 1,5 kWh km^{-1} and 90% charging efficiency (ZACKRISSON; AVELLÁN; ORLENIUS, 2010).

Bus lifetime is projected to be a key requirement for BEBs massive adoption (THIELMANN et al., 2013). Nevertheless, prospects were not optimistic until very recently. An study for hybrid buses (KELLAWAY, 2007) reviews the principal causes of battery failure in $LiFePO_4$ batteries and states that the most common problem with poorly specified batteries in hybrid buses is that actual battery lifetime could be way much shorter than expected. In some cases, suppliers predicted a life time of 2–3 years, but only lasted 2–3 months. Garcia Sanchez et al (2013) assumed a 220,000 km lifespan for batteries (around 2.5 years) and argue this problem will be overcome in the future, while for the rest of the bus, the authors assumed a lifetime of around 10 years (880,000 km) based on Diesel busses. No great differences were anticipated between BEB and Diesel buses for elements other than battery and powertrain, thus, it is a reasonable assumption.

For vehicle maintenance stage, an energy consumption of 17% of the total energy required for materials production and for assembly stage of the buses was assumed. This proportional value was obtained from Sullivan et al (1998) and its selection was due to the lack of data about electric bus maintenance inventories.

3.4.2. 2030 Scenario

3.4.2.1. $LiFePO_4$ battery

In order to keep a conservative approach, it was assumed that the specific energy for 2030 scenario was 14.0 E-2 kWh kg^{-1}, which is coherent with the results presented by Zu & Li (2011) and Hassuani et al (2005) . Battery capacity was assumed to improve up to 400 kWh. An increase of around 7 % compared to current scenario. These conditions would produce a battery weight of 2,857.1 kg.

3.4.2.2. Rest of the bus and End-of-Life

Mass reduction (total weight 13,550 kg) was based on coach bus lightweighting estimation data reported by Ricardo AEA (2015b). Although this data is based in an ICEV coach bus and not an BEB the author of this study still considered this comparison as acceptable. Firstly, because of expected mass reduction in powertrain system (engine, fuel, exhaust and transmission system) accounts for less than 1 % of total mass reduction, which means that almost all mass reduction would be linked to C&B weight reduction instead of powertrain elements. Secondly because C&B structure of conventional busses and BEBs is deemed to be similar. Weight comparison between Ricardo AEA (2015b) coach -11,900 kg without powertrain- and Sanchez Garcia et al (2013) bus -11,010 without battery- ensure similarity and reveals our assumptions are coherent. Weight reduction for 2030 is forecasted to be 14%. No evidence of material substitution for 2030 was found, thus 2015 LCI input shares remain unaltered, only total mass varies. No evidence was found for considering EOL stage is going to have representative changes before 2030, hence, 2015 datasets are kept unmodified.

3.4.2.3. Life expectancy, maintenance and energy consumption

Analogously to other types of li-ion batteries, $LiFePO_4$ longevity prediction is still full of uncertainties. Although many battery ageing mechanisms have been described in the literature, these phenomena are complex and are prone to interact with each other, resulting in different capacity loss and power decline (PRADA et al., 2012). For 2030 scenario, and similar to BEV lifespan findings, this research found no evidence to propose an increase of longevity by changing design parameters and elements, thus, it admitted no increase in life expectancy neither for the battery nor the C&B. Thus, battery lifespan is 264,000 km whereas the rest of the car is considered to present a life of 880,000 km.

Maintenance stage approach for 2030 scenario follows the same principle as for 2015. This work considered maintenance stage throughout the entire life cycle to represent an energy consumption of 17% of total energy required for assembly stage and 17% of total bus materials for pieces substitution. Since BEB mass was reduced for 2030 scenario then maintenance dataset was adjusted too.

BEB energy consumption was assumed to be 1.20 kWh km^{-1}, which imply an improvement of 20% with regards to 2015 values. It also keeps the same percentage difference as BEVs in 2015 and 2030.

3.5. Well to tank stage: Electricity Generation

3.5.1. 2015 scenario

In December 2015, during 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC), the governments of around 190 countries gathered in Paris aiming to reach an agreement on how to counter global climate change. Each country submitted their own goals for mitigation of GHG emissions having the purpose of limiting temperature rise on the globe to a maximum of 2ºC by 2100.

It is worth to mention that the goals of Brazil incorporate its whole economy and is not based on a determined way to achieve these goals. In other words, the achievement of these objectives can occur through different ways. One of them is by switching from existing fossil fuel generation systems to renewable energy sources.

In order to model Brazilian electricity mix the author of this study used Ecoinvent datasets for each generation source, except for Electricity from Biomass which is based on LCIs established by Velandia Vargas et al.(2016) which in turn are based on electricity production from sugarcane in Brazilian center-south region (SEABRA et al., 2011) . Electricity mix model comprises of high voltage generation that undergoes a series of voltage transformation from high to medium and from medium to low. Ecoinvent distribution and generation losses are kept unmodified. Quantities for transformation losses are not modified either.

Electricity generation is classified in centralized generation and Self-Production & Distributed Generation (SP&DG). For 2015 scenario about 39 TWh of centralized generation is presented by EPE (2016) as “Others”. This share was assumed to be split 50/50 between fuel oil generation and diesel generation. In the same way, 26 TWh of SP&DG, equivalent to 4.17% of overall production, are considered by EPE to be “Non-Renewables”. This share was assumed to be split among natural gas, coal, fuel oil and diesel generation. To estimate the weight of each one of these generation sources in” Non-Renewables” share the author judged it to be comprised only of natural gas, coal and “Others”. Then the total shares for these sources were scaled as if they were the only ones to be counted. These shares were then linearly scaled to 4.17%. Thus, this thesis proposed those 26 TWh of “non-renewables” generation to be split 59.02% on natural gas; 9.02% on coal; 15.99% on Diesel oil and 15.99% on fuel oil. Each one of those shares in SP&DG are added to centralized generation sources to define an overall Electricity mix. Although EPE (2016) established a Brazilian electricity mix for 2014 this thesis used it for 2015 scenario. This aimed to keep source coherence since the same reference was adopted for 2030 scenario. Table 6 presents an overall 2014 and 2030 mix adding centralized and SP&DG generation.

3.5.2. 2030 scenario

All self-production and distribution generation is expected to rise when compared to present scenario (EPE, 2016); all renewable sources will increase their share as well. Analogously to 2014, centralized generation in 2030 scenario includes a share of “Others” whereas self-production & distributed generation includes a share known as “Non-renewables”. Methodology for electricity mix consolidation is the same as in 2015 scenario. A word should be given to solar generation datasets. Solar represents 3.04% of total overall generation which usually occurs on low voltage conditions. Akin to electricity generation datasets on Ecoinvent the author of this study only incorporated photovoltaic generation at the low voltage level; it was assumed that small solar power plants will not produce high voltage electricity for the grid.

Table 6. Adapted Brazilian electricity mix for 2015 and 2030 scenarios.

Source	2015 (%)	2030 (%)	Notes
Hydropower	65.33	60.56	S.P.& D.G. hydroelectricity included
Natural Gas	14.02	9.60	Share from “Non-renewables” in S.P.& D.G. included
Coal	2.14	2.15	Share from “Non-renewables” in S.P.& D.G. included
Nuclear	2.41	3.39	
Biomass	6.58	11.64	S.P.& D.G Biomass included
Wind	1.93	9.12	
Solar	0.00	3.04	
Others	7.59	0.51	Deemed to be split 50/50 fuel oil and diesel generation

3.6. Datasets adaptation

Ecoinvent v3.2 global inventories are comprised of a set of different geographies which aim to best represent the particularities of a process at a given location. In order to create a global mean value valid for all countries in the world Ecoinvent weights processes from around the world according to their global production share. This way, geographies such as Global (GLO) or Rest of the World (RoW) come into existence. In Ecoinvent v3.2 and higher, the Rest of the World processes are generated as an exact copy of the Global dataset but now having its uncertainty adjusted.

Unit process scheme inventories are constructed following a subcomponents structure as presented in Figure 8. As an example, the dataset for BEV without battery was based on Ecoinvent v3.2 dataset "*Passenger car, electric without battery, Alloc def U*" while Li-ion battery was based on the dataset provided by Ellingsen et al (2013). In the same way, the car without battery comprises powertrain and C&B (chassis and body), each one having an independent dataset. The powertrain is comprised of the following devices, and hence, datasets: inverter, electric motor, power distribution unit, charger and conductor cables; while the C&B represents the main frame of the car and its closures *i.e.* doors, hoods. However, instead of being composed by subsystems, the C&B is represented by a list of material inputs *e.g.* magnesium, steel, etc. All of these datasets make use of *cut-off* model approach. *Cut-off* refers to the fact that processes occurring after the first life of the product are cut off from the inventory, thus, they are not included in the product system. In contrast to unit process model, there is system process model, which, instead of representing processes as units or subsets, creates an overall input list including all the substances from all background processes required for a product or process.

The datasets for BEV modelling are presented as unit process, which means any product is composed of several sub-processes forming a tree-like scheme. The intention was to adapt as many GLO or RoW processes as possible and to replace those Ecoinvent datasets for our Brazilian adapted ones. However, this work does not modify any inputs quantity, by-products or emissions. Ergo, it is assumed that the quantities required to manufacture a BEV or a BEB would be the same in Brazil or abroad. In other words, this methodology is only able to switch the original geographic scope to another one. This study defined an adapted dataset to be any dataset that underwent any of the following modifications: 1) Electricity mix switch, *i.e.* Changing any foreigner electricity mix dataset for Brazilian mix. 2) Adaptation of input shares for a given technology or production route for a determined product in Brazilian conditions, *i.e.* Ecoinvent datasets usually deal with global average products by establishing an input share from each production route based on the production volume of a given technology for an specific geography, for instance, a dataset representing global aluminum production might include shares for Søderberg and prebaked-anode routes in the world, which are not adequate to represent the conditions in South east Brazil. This work adjusted those shares based on local evidence. 3) Existence of imports. *i.e.* Some of the products found along the unit process tree-like scheme are known to be imported to Brazil, therefore it makes no sense adapting them to Brazilian conditions but to other geographies, for instance, Chilean lithium. 4) Adapting transportation, *i.e.* modifying transportation distances according to own assumptions for southeastern Brazil. 5) Dataset merging, *i.e.* Ecoinvent usually presents multiple geography datasets for the same input, for instance, generated heat from natural gas might include entries from many countries. Finally, the values from all geographies into were added into a RoW dataset.

This kind of approach endeavors to keep the coherence of Ecoinvent consolidated data while adapting any constituent processes by replacing GLO, RoW or other geography datasets for what is considered to be Brazilian conditions. It means that all adapted datasets were used, whenever it was possible, as inputs for all other datasets, as a consequence of the tree-like scheme. Special attention was given to critic raw materials like steel, aluminum, aluminum oxide, lithium and copper. In contrast, some datasets can only have their electricity input switched to Brazilian mix due to lack of information or due to the structure of the dataset. For instance, system process scheme datasets were not modified apart from transportation distances. This situation was not deemed to be a significant flaw in our approach because of the negligible environmental burden of many of the inputs when compared to our functional units, one vehicle and one km. It was our goal to have all processes represented by the most appropriate dataset from the Ecoinvent database. A list of all adjusted datasets is presented in APPENDIX 2 – DATASET ADAPTATION TO BRAZILIAN CONDITIONS. Electricity column refers to the dataset having its electricity input added from other geographies into Brazilian dataset. H, M, and L stand for High, medium and low voltage respectively. Thus, H/M means that not only high voltage electricity inputs were added into a single Brazilian input but medium voltage inputs were added into a Brazilian inventory too. Heat column follows the same logic. NG and ONG refer to natural gas and other than natural gas generated heat. Water column indicate if a dataset had its water inputs from different geographies added to a single RoW dataset input. Processing indicates when a dataset represents a process instead of a product. All adjusted datasets in APPENDIX 2 – DATASET ADAPTATION TO BRAZILIAN CONDITIONS are henceforth identified and labelled as BR instead of RoW or GLO. For further information see Table 26

All adjusted datasets replaced GLO or RoW datasets whenever possible in the unit process scheme. Please consider, aluminum oxide production, which was based on ABAL (2016). This sub-process is used for production of some car components like electric motor inverter, and power distribution unit, but it is also used as raw material for fabrication of hydrogen peroxide, glass fiber, diodes, etc. For each one of the cases where aluminum oxide was utilized as input for other process the default dataset was substituted by our adjusted Brazilian dataset. Finally, infrastructure processes datasets and production quantities *e.g.* car factory, battery factory, etc. are maintained as in Ecoinvent.

3.7. Results and Discussions

3.7.1. Battery Electric Vehicle

The results for the BEV using one car as comparison unit are shown in Figure 9. The Figure also displays an ICEV, which is merely intended to provide a reference for the reader; both ICEV and ICEB present a power to weight ratio similar to the BEV and BEB and represent a commercially available alternative for BEVs. Detailed information on how the ICEV and the ICEB were modelled can be found in the APPENDIX 1 – PARAMETERS FOR INTERNAL COMBUSTION ENGINE VEHICLES MODELLING. Thanks to its lower mass and less use of rare metals the ICEV was anticipated to present better results than BEVs, at least for 2015. This was true, even for ecotoxicities[8]. Even though BEV assumptions for 2030 imply mass reduction and material switching the Global Plastic BEV presented the worst results for photochemical oxidant formation and fossil depletion. This is explained by the fact of Plastic prototype requiring more magnesium for production than 2015 BEV baseline and reference ICEV. Magnesium is mainly produced via silicothermic route which greatly stimulate photochemical oxidant formation and consume large amounts of coal. Global BEVs -both Aluminum and Plastic- also presented larger terrestrial acidification impact, compared to Brazilian models, due to contributions of Chinese aluminum and magnesium production. It is worth noting that only for terrestrial acidification and climate change every Brazilian scenario displayed a consistent lower impact than their Global equivalent, always affected by Chinese heavily burdened background processes. Therefore, the current Chinese efforts for decarbonizing their electricity mix and optimizing metal extraction are expected to greatly beneficiate Global results in the future.

[8] In order to facilitate the exhibition of results, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity impact categories were added into a single category defined as ecotoxicities (kg 1.4-DB eq.).

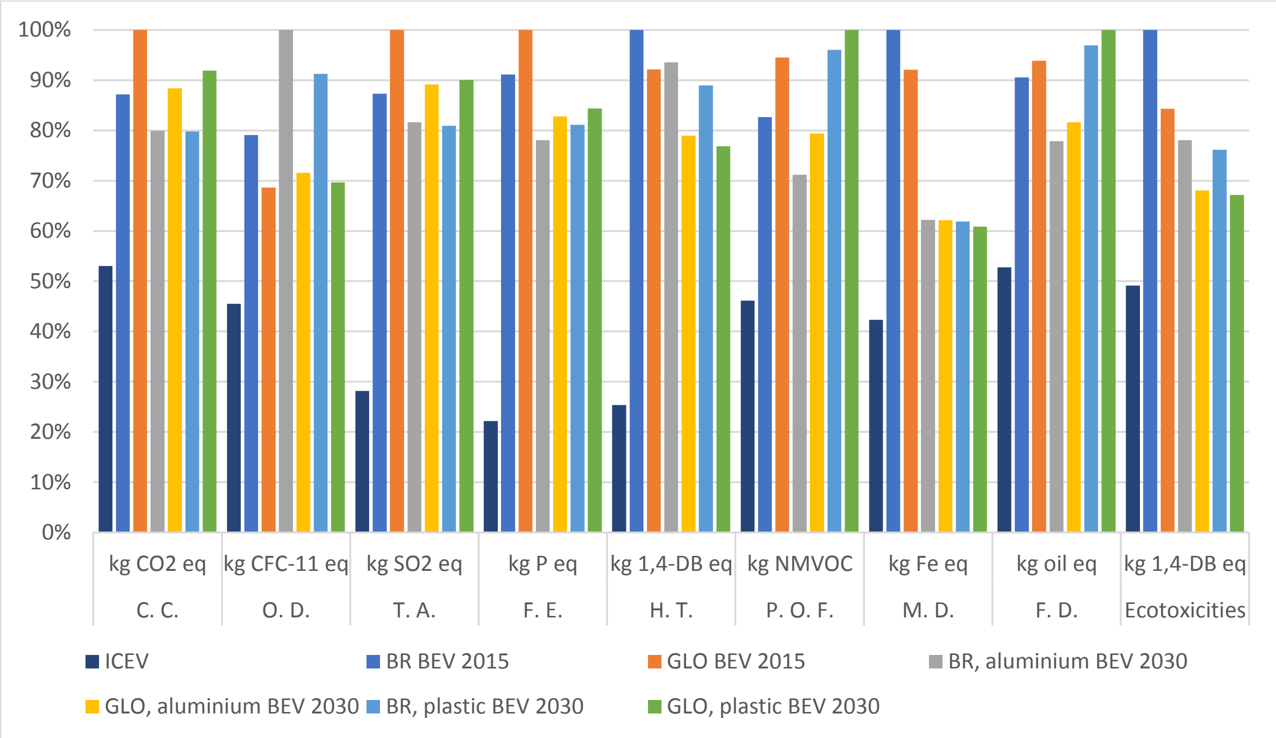

Figure 9. Comparative characterization results for the BEVs in 2015 and 2030.[9]

An unexpected result appears for ozone depletion, exhibiting the largest impact for Brazilian aluminum BEV. Paradoxically, the large share of aluminum recycling in Brazil (ABAL, 2015) is a double edge sword since emissions arising from scrap treatment do have a significant impact. The share from recycling of scrap in Global aluminum production is lower than for Brazilian process. In spite of C&B mass reduction, the total quantity of aluminum on the BEV was actually increased in exchange for other materials, mainly steel. Treatment of copper wire significantly contributes to ozone depletion as well. Plastic and Aluminum BEVs in 2030 were expected to show an undisputed advantage, but this was only the case for ecotoxicities and metal depletion.

The large advantage of the ICEV, when compared to all BEVs even in 2030 scenario for human toxicity and freshwater eutrophication is remarkable. It was anticipated that the ICEV would have better results, due to the high contribution of rare metals in the BEVs (PETERS et al., 2017) but the characterization results turned out to be less than half the values for the cleanest BEVs, as seen in Figure 9. Interestingly, both categories share many of the main contributors. Magnesium extraction represents a key burden for plastic BEV. Extraction and refining of copper and other metals play a key role for the environmental performance of all BEVs. It must be highlighted that in concordance with Habermacher (2011) this study utilized Latin American copper extraction dataset to represent the share of "other metals" in the C&B composition. Figure 10 presents the

[9] One ICEV was included for comparison purposes. C.C. Climate change; O.D. Ozone depletion; T.A. Terrestrial acidification; F.E. Freshwater eutrophication; H.T. Human Toxicity; P.O.F. Photochemical oxidant formation; M.D. Metal depletion; F.D. Fossil depletion.

contribution results for one Plastic and one Aluminum C&B for human toxicity and freshwater eutrophication.

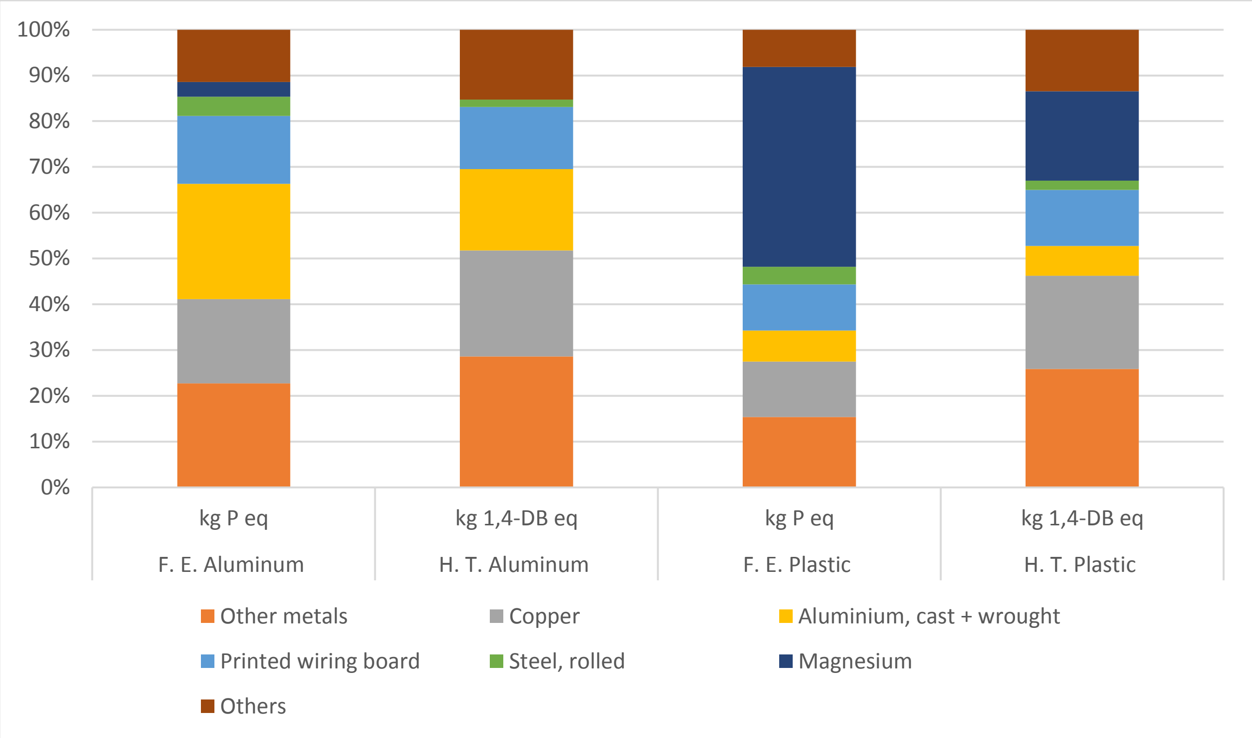

Figure 10. Most significant contributors for freshwater eutrophication (F.E) and human toxicity (H.T) for plastic and aluminum chassis and body (C&B).

Brazilian BEV performed always better for photochemical oxidant formation than its Global equivalent. However, only aluminum car showed an evolution when compared to 2015. Higher amounts of magnesium in plastic prototype accounted for the larger environmental impact. Human toxicity displayed consistently worse results for Brazilian vehicles due to Latin-American (RLA) copper production and residues treatment.

WTW characterization results for a functional unit of one km can be seen in Figure 11. It is notorious the way the contribution of the vehicle to total impact is diluted by including the use phase. As predicted, Gasoline ICEV is in substantial disadvantage for climate change, ozone depletion, and fossil depletion while Ethanol ICEV is more harmful for terrestrial acidification and particle oxidant formation. Ozone depletion confirmed to be an environmental risk for BEV adoption. Human toxicity and freshwater eutrophication soaring impact results reaffirmed to be among the most concerning threats deriving from transport electrification based on the assumption that Li-ion batteries will be the dominant technology in the next decades. No optimistic perspectives for 2030. In fact, if any of these categories were declared as a priority, the best option would be to maintain Ethanol ICEVs on operation.

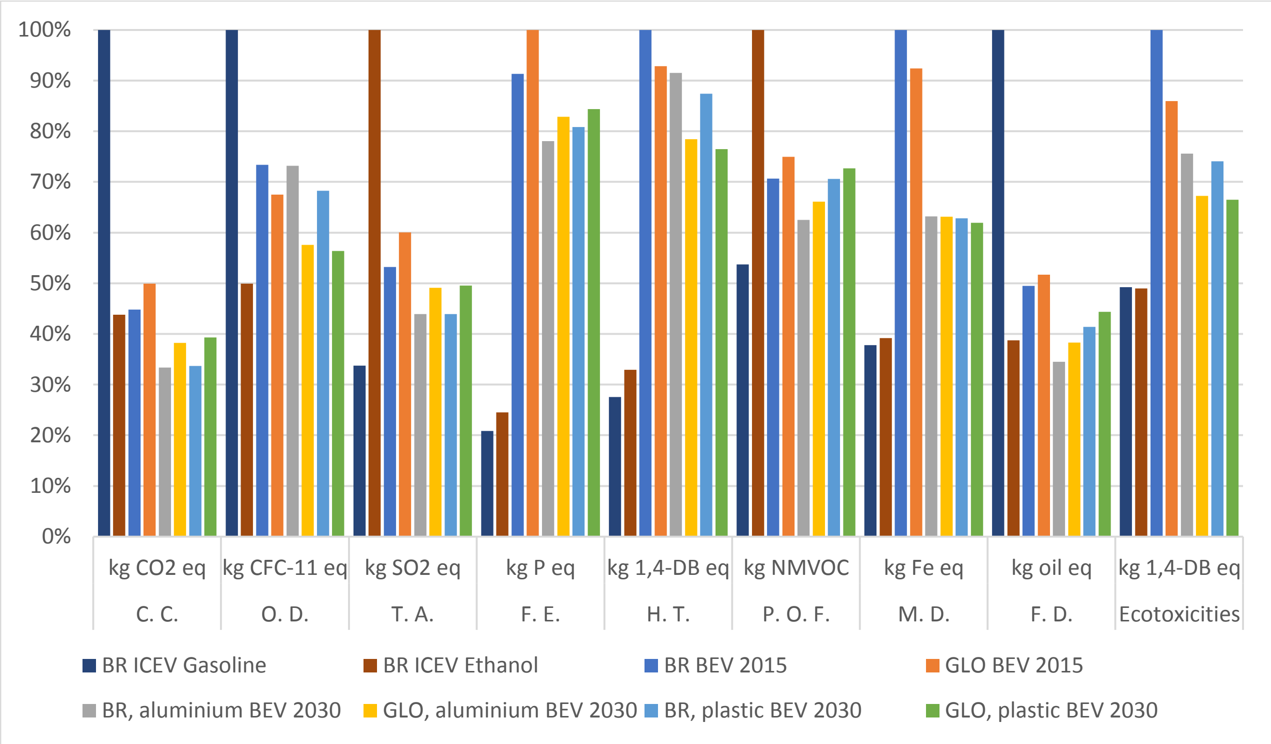

Figure 11. Comparative WTW characterization results for the BEV in 2015 and 2030[10].

Figure 12 displays the results for the sensitivity analysis for human toxicity and freshwater eutrophication, two of the most concerning categories for BEVs. This thesis analyzed life expectancy, energy consumption and mass reduction. Life expectancy is clearly the most effective parameter for impact reduction; however, it raises questions about how likely are the carmakers to achieve higher life expectancies while using lighter materials and how is life expectancy a priority on a market influenced by programmed obsolescence-oriented decisions. Battery weight reduction and electricity consumption are more likely to display a positive evolution in the next 15 years. However, their contribution to percent abatement of impact is less than that of life expectancy extension.

[10] Two scenarios for a gasoline and an ethanol propelled ICEV were included as a reference. One km as functional unit. C.C. Climate change; O.D. Ozone depletion; T.A. Terrestrial acidification; F.E. Freshwater eutrophication; H.T. Human Toxicity; P.O.F. Photochemical oxidant formation; M.D. Metal depletion; F.D. Fossil depletion.

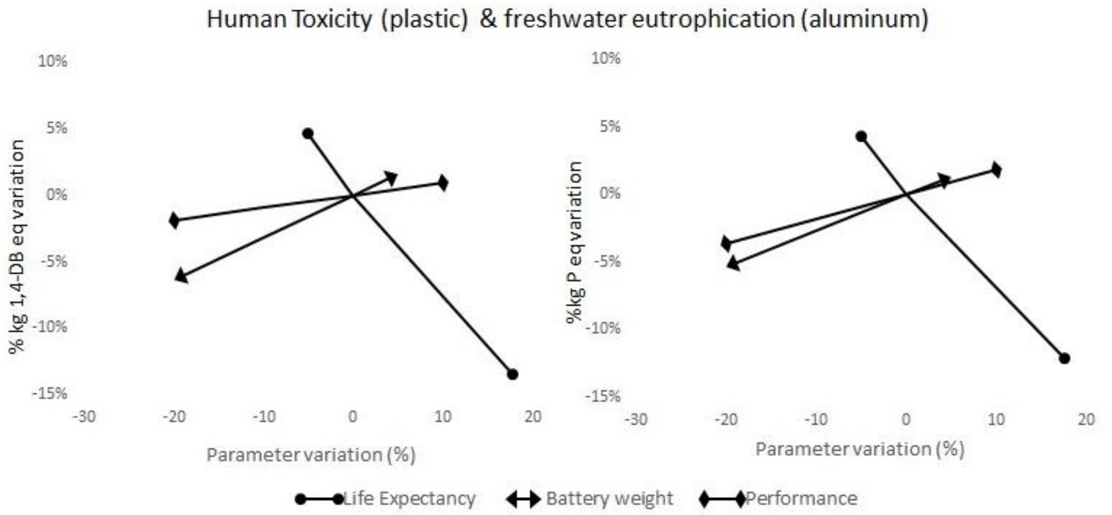

Figure 12. Sensitivity analysis for critical impact categories. Human toxicity for plastic and freshwater eutrophication for aluminum BEVs. One km as functional unit.

Impact contribution per lifecycle stage for one km is shown in Figure 13 whereas LCIA results can be found in APPENDIX 4 – LIFE CYCLE IMPACT ASSESSMENT RESULTS. Maintenance stage presents the largest contribution for photochemical oxidant formation due to ethylene use, which is the working fluid in the cooling system (LEUENBERGER; FRISCHKNECHT, 2010). Ethylene-glycol based coolants are not only used as antifreeze – which would be an asset for winter in southern Brazil – they also protect the refrigeration ducts against scale and rust formation and increase the boiling point of the mixture when added to water (WURTH, 2014). This is quite beneficial for high temperature conditions as found in tropical Brazil. Therefore, the use of ethylene coolant is quite likely to be similar in 2030, thus, the maintenance dataset did not undergo any alterations. For human toxicity, metal depletion, freshwater eutrophication and ozone depletion, the contribution from vehicle counts for nearly 85% of total impact per km. Electricity most significant contribution appears in climate change where it represents approximately 30% of total impact. LCIA results for BEV and BEB per vehicle and per kilometer can be found on APPENDIX 4 – LIFE CYCLE IMPACT ASSESSMENT RESULTS.

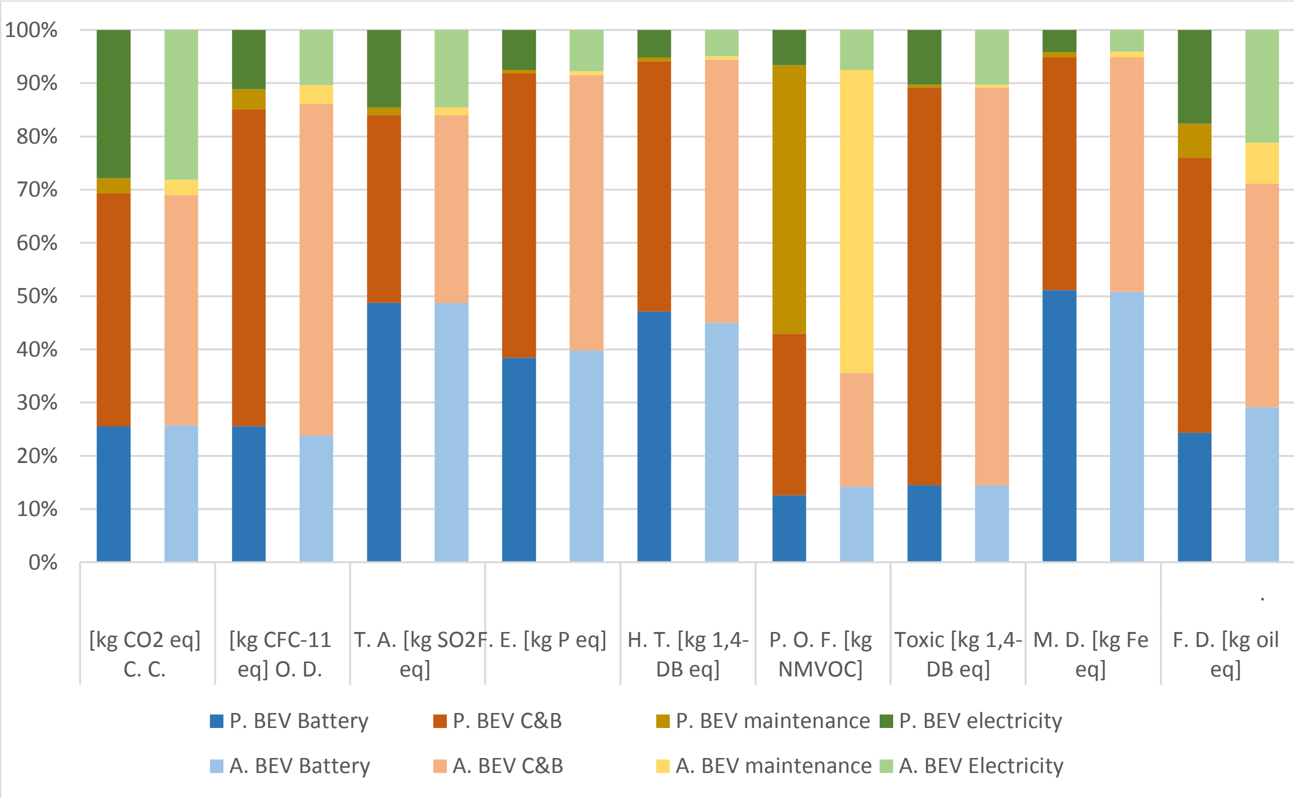

Figure 13. Contribution per stage to characterization results for one km for Brazilian BEV in 2030[11].

3.7.2. Battery Electric Bus

Brazilian BEB displayed better results than its global counterpart for climate change, terrestrial acidification, freshwater eutrophication, photo oxidant formation and fossil depletion (see Figure 14). Results for ozone depletion, metal depletion and human toxicity show differences so small for both 2015 and 2030 that fall into uncertainty ranges. For human toxicity and toxicities in general there is a very significant contribution caused by sulfidic tailing residues treatment. This process is linked to Latin-American extraction of copper for use in battery anodes. Ecoinvent dataset for Latin American copper extraction pictures the process as having a significantly larger environmental burden for toxicities than that of copper extraction in other geographies. Interestingly, for freshwater eutrophication the largest contributors are metal extraction processes as well. In fact, a large environmental contribution from treatment of mining residues is common for all impact categories where electrification of busses resulted in significantly larger impacts when compared to conventional ICEB. This led us to believe that in order to manufacture an

[11] Plastic-based left (P) and aluminum-based right (A). Toxic: Ecotoxicities. C.C. Climate change; O.D. Ozone depletion; T.A. Terrestrial acidification; F.E. Freshwater eutrophication; H.T. Human Toxicity; P.O.F. Photochemical oxidant formation; M.D. Metal depletion; F.D. Fossil depletion.

environmentally competitive BEB, reduction of impacts on metal extraction and its residues must be prioritized. Furthermore, as expected, both Brazilian and Global busses present systematically better results in 2030 when compared to its corresponding 2015 BEB, thus confirming mass reduction effectivity. Photochemical oxidant formation and terrestrial acidification impacts for Global bus in 2015 and 2030 are around 15% larger than Brazilian BEBs in both cases. This gap is mainly due to heavily burdened background processes included in Global datasets such as electricity generated in China and RoW anthracite-based electricity generation. Climate change displayed better results for Brazilian BEBs, mainly due to Global ones presenting a large contribution from coal-driven electricity generation and coal extraction background processes in China. Chinese related production processes have proven to bear significant environmental burdens; however, this country has already started to change its production and electricity generation paradigms (CNREC, 2016). However, our 2030 Global model is not able to capture electricity evolution.

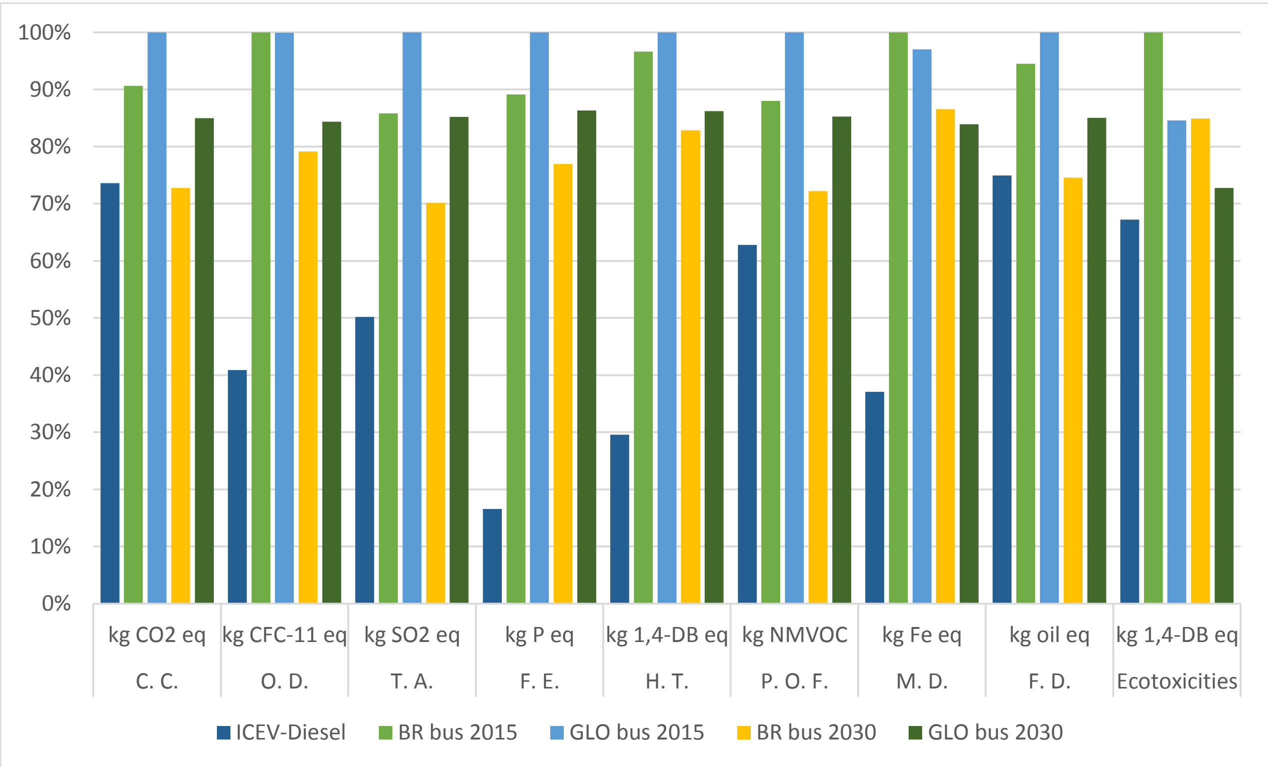

Figure 14. Comparative characterization results for the BEB in 2015 and 2030 using an ICEB for comparison[12].

[12] C.C. Climate change; O.D. Ozone depletion; T.A. Terrestrial acidification; F.E. Freshwater eutrophication; H.T. Human Toxicity; P.O.F. Photochemical oxidant formation; M.D. Metal depletion; F.D. Fossil depletion.

Battery related components are largely responsible for the highly toxic consequences of BEBs manufacture for water and soil. Aside from weight reduction, CO_2 emissions arising from battery components are expected to decrease sharply in the next 30 years (RICARDO AEA, 2013).

On the other hand, for functional unit one km, Brazilian generation mix embodies a large advantage over other mixes due to its low-carbon nature, even though water bodies used for hydroelectricity generation in tropical regions are well known sources of methane and carbon dioxide emissions (DOS SANTOS et al., 2006), although, overall emission factors are still bounded to large uncertainties.

Results corroborated that environmental advantages linked to mass reduction are notorious. On an analysis per km, climate change, ozone depletion, photo oxidant formation and fossil depletion results are a strong argument for public urban transport electrification. However, in consonance with BEV results, for human toxicity, metal depletion and freshwater eutrophication the results displayed a large impact increase per km, even for 2030 scenarios, with impacts five or six folding the values for current Diesel conventional transportation, as seen in Figure 15. Thus, terrestrial acidification and freshwater eutrophication results imply a disadvantage for Brazilian manufacturing. Interestingly, for almost all categories the differences between local and global vehicles are small enough to be regarded as negligible or at least as not conclusive. Summarizing, electric mobility will likely produce larger toxic impacts on soil, water and humans and that is not likely to change, at least not in the next 15 years via mass reduction.

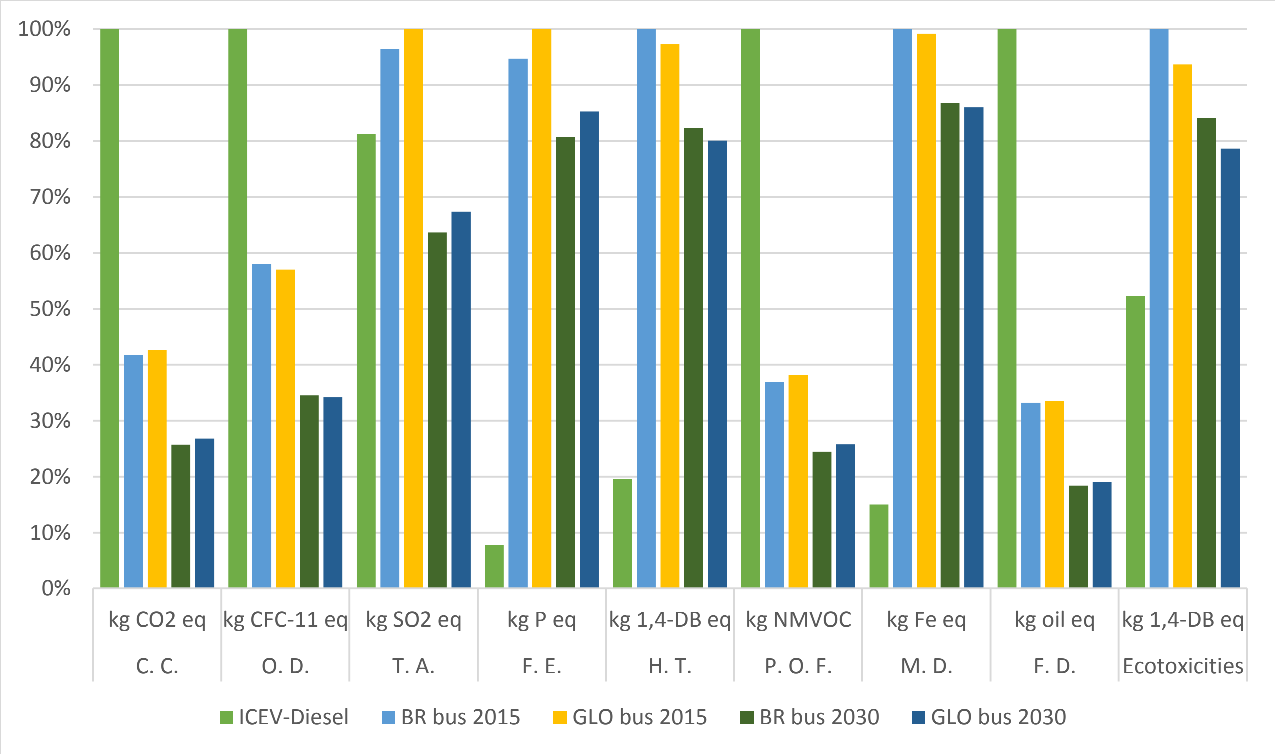

Figure 15. Comparative WTW characterization results for the BEB in 2015 and 2030. One scenario for a diesel propelled ICEB was included[13]. One km as functional unit.

An important factor to be considered for BEB analysis is that unlike other BEV models, this study did not include material replacement hypothesis for 2030 C&B. Due to lack of data we only applied a mass reduction estimate. Therefore, the results were anticipated to show an advantage for 2030 scenarios in all cases in spite of not knowing the magnitude.

Figure 16 presents the contribution results per stage per km for the Brazilian BEB in 2030. Electricity consumption is the main contributor for climate change, when analyzing the total well-to-wheel stage per km, as anticipated by several studies (BOUREIMA et al., 2009; FARIA et al., 2013; HAWKINS et al., 2013; HELMS et al., 2010; MA et al., 2012; MESSAGIE et al., 2014; NORDELÖF et al., 2014; RAJAGOPAL et al., 2012). Hydroelectricity linked methane and carbon dioxide emissions from reservoirs, natural gas and coal use in the electricity mix are the main sources of emissions. Natural gas use in Brazilian mix is also the most noticeable contributor for fossil depletion. For metal depletion and human toxicity vehicle contribution is predominant, mainly from the battery.

[13] C.C. Climate change; O.D. Ozone depletion; T.A. Terrestrial acidification; F.E. Freshwater eutrophication; H.T. Human Toxicity; P.O.F. Photochemical oxidant formation; M.D. Metal depletion; F.D. Fossil depletion.

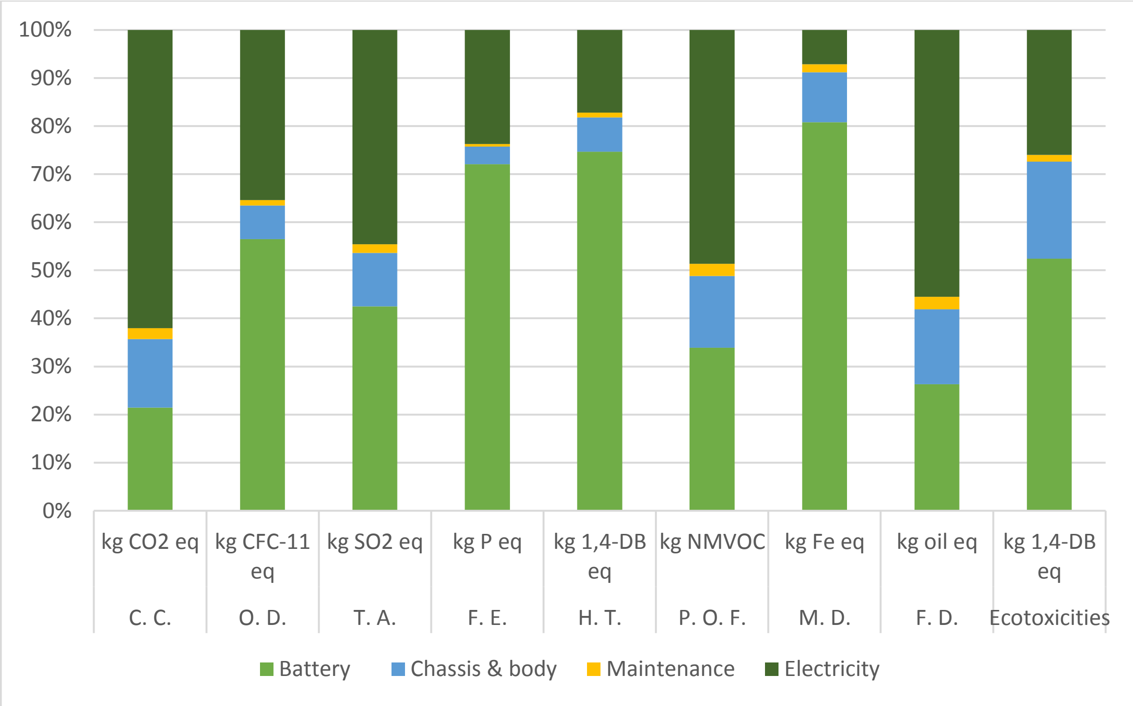

Figure 16. Contribution per stage to characterization results for one km of Brazilian BEB in 2030.

Several aspects need to be regarded when analyzing the results. First of all, this research compared Brazilian adjusted LCIs to what is intended to be a global average dataset, nonetheless, many of the current producers of BEVs around the globe have different manufacturing features that would impact local environment in different manners. LCIA for 2030 BEV prototypes -comparison unit 1 car- revealed that impacts are not consistently lower than for 2015 cars. Few exceptions, such as metal depletion and ecotoxicities resulted in an impact decrease of at least 15% when compared to 2015 vehicles; in fact, for almost all categories the differences between local and global vehicles are small enough to be regarded as negligible or at least as not conclusive

Moreover, infrastructure related contribution is required to be scrutinized more in depth for Brazilian context. Lucas et al.(2012) concluded that BEV energy supply infrastructures are even more carbon and energy intensive per MJ of supplied fuel than ICEV ones. The weight of charging infrastructure on overall results summed up to 5.2% of total emissions per km. Analyzing Infrastructure is crucial also because a wide and well distributed charging infrastructure is a crucial factor for successfully achieving the substitution of ICEVs with BEVs (NEMRY; BRONS, 2010); lack of charging infrastructures are expected to be the first barrier to a long term-large scale market development of electrics. Although this study included inputs aiming to represent infrastructure it was out of our scope to model BEV/BEB manufacturing plant erection and supply chain development. Car plants are only expected to reach its full production capacity after some time, thus, while car production is still low, plant environmental burden is larger (DUNN et al., 2014, 2016).

Estimation of electricity generation related emissions is key for LCA. Estimates based on marginal and average grid emission factors might differ greatly (TAMAYAO et al., 2015). Strictly speaking, emission estimates based on geographic boundaries traced by electricity suppliers for generation and distribution diverge by as much as 120% for the same location, when compared to average emission factors. A next step for BEV and BEB LCA research could be defining accurate and spatially differentiated emissions factors. However, this is very complex in practice since an electricity grid is a highly interconnected system, which relocates energy from geographically distinct generators to geographically distinct demand sites.

Uncertainties inherent to this research are related to the fact of not having specific information regarding BEB C&B material substitution for 2030 scenario. There are also uncertainties involving the extraction of raw materials in Brazil; for instance, it is not clear if any aluminum producers are going to be left out of business, changing production routes, thus, affecting environmental features for 2030. Additionally, there are uncertainties bounded to electricity evolution in 2030. Since GLO vehicles use a world average it was unpractical to edit each one of the electricity mixes for every country involved in raw materials production.

Furthermore, special attention should be given to the complex link between electricity consumption, vehicle mass, battery capacity and energy density. Any enhance in battery performance might bring further increases in vehicle mass. For instance, as the battery capacity increases designers are able to add extra features that make the car heavier, such as heavier braking systems or more powerful air conditioning devices.

Finally, it must be highlighted that BEVs and BEBs environmental competitiveness depends on LCA results of available ICEVs in Brazilian conditions since conventional mobility represents the largest market share and the technology which is called to be substituted. Additionally, the availability of biofuels and their evolution in Brazil implies BEV environmental advantage is far from obvious and should not be taken for granted.

3.7.3. Vehicle life expectancy

As it was evidenced in Figure 12 life expectancy assumptions are critical for determining environmental burdens. There is evidence that life expectancy in light duty vehicles cars has been steadily increasing during the last years. Research aiming to create a database of vehicles that had reached the EOL stage in the UK (RICARDO AEA, 2015c) determined that, on average, longevity in gasoline cars increased approximately 6% from 2008 to 2014. However, the study failed to establish further relationship between life expectancy and other parameters such as mass or material composition. Furthermore, there is evidence of passenger cars lasting for more than 20 years and taxis lasting more than one million miles (RODRIGUES; COOPER; WATKINS, 2015). In a Brazilian context, during 2017 the average age of the Brazilian light duty car fleet was 9 years and 6 months (SINDIPEÇAS, 2018) whereas approximately 50% of the fleet is still paying service after 15 years of use (CETESB, 2011, 2017a). This suggests that vehicles in the country are expected to live as long as possible to meet investment expectations and a longer lifetime would be valued by consumers, thus a longer lifespan is an important asset for BEVs and BEBs.

Rodrigues et al (2015) research interviewed incumbent automotive engineers aiming to discover design parameters involved in increasing car lifespan. Results revealed that structures would have to be strengthened, almost necessarily, adding more material. Thus, it is very unlikely to obtain a longer lifespan while reducing total mass and reducing steel shares. In fact, giving up steel means not being able anymore to benefit from the infinite fatigue region design characteristics.

Determining how car longevity is affected in 2030 scenario by the larger shares of aluminum or plastic based components in the vehicles is plagued of uncertainties. Firstly, the use of carbon fiber or other polymers could render some, otherwise simple repairs, into impossible tasks, due to the inexistent ductility of these materials. For ESX2 prototype (plastic), Dodge introduced a thermoplastic body attached to the aluminum frame whereas some equipment was made of carbon-fiber and the seats were constructed from tube frame (ALLPAR.COM, 2010). In Precept prototype (aluminum), GM also employed carbon fiber along with aluminum in the body (ROBINSON, 2001). The presence of these materials makes life expectancy even more unlikely to be extended. Even though, the exact features of the new structures in the prototypes are beyond the scope of this study, however, it is sensible to admit that the most critical elements in the structure will remain made of steel or high-performance alloys providing resilience and stiffness.

Moreover, consumer trust in any brand could be seriously damaged if the vehicle presents a lower life expectancy. Consequently, it is also very unlikely for life expectancy to diminish. Thus, this thesis maintains life expectancy in 2030 unaltered in comparison to 2015 for both BEVs and BEBs.

3.7.4. Battery chemistry

Lithium manganese oxide ($LiMn_2O_4$) batteries available in Ecoinvent database were replaced by nickel manganese cobalt oxide (NMC) batteries available in Ellingsen et al (2013). This adjustment was made in order to be more accurate, since Nissan Leaf 2016 actually contains this chemistry in the battery (NISSAN-GLOBAL.COM, 2017). Anyway, the literature suggests that the difference might be negligible for several impact categories. In fact, when calculated per kWh, NMC, $LiFePO_4$, NCA and $LiMn_2O_4$ results for GHG emissions are about the same (ELLINGSEN; STRØMMAN; HUNG, 2016).

Parallelly, Kim et al (2016) did not find any “inherent differences between NMC and $LiMn_2O_4$ batteries in the cell and pack manufacturing processes”. In contrast, cobalt content in NMC have higher environmental burdens for toxicity, per kg, when compared to other metals. Nevertheless, NMC specific energy becomes higher with these metals, implying that the effect per kWh is low. The change of battery chemistry allowed us to cover more solidly other impact categories.

With regards to bus battery, it is firstly necessary to state that $LiFePO_4$ is the dominant technology in the market right now and it is expected to keep its dominant position, at least for the next decade (ATAK; GRANDE, 2018; PELEGOV; PONTES, 2018). It is true that since the Chinese government decided not to impede subsidies for NMC and several manufacturers such as BYD started production of batteries with this chemistry; however, $LiFePO_4$ will undoubtedly remain a viable choice for heavy duty application where energy per kg is less important, while power per kg is crucial. BYD has already built a plant in Brazil and announced manufacturing plants in Manaus city (BLAND, 2018c).

3.7.5. Battery End of life

Due to BEV market share growth the number of available batteries will notoriously increase. Bloomberg New Energy Finance anticipated that for 2025 about 27 % (26 GWh) of total energy contained in BEV batteries had potential to be reused by being converted into stationary systems (MARTIN, 2016). In fact, a few years ago the potential was already significant. Elkind (2014) affirmed that: “Assuming 50% of the battery packs on the road in 2014 can be repurposed, with 75% of their original capacity, these second life batteries could store and dispatch up to 850 MWh of electricity”.

Once the first life is over the batteries are collected and sent for disassembly for either recycling of reuse. The collection rate of industrial and automotive batteries in Europe is nearly 100% (EUROPEAN COMMISSION, 2014), therefore, a high availability of vehicle batteries in the future is expected as well, even more when assuming that battery design will incorporate characteristics to ease disassembly. A very high collection rate is currently available, 91 % for Toyota and Lexus (BOBBA et al., 2018). According to Circular Energy Storage Research & Consulting by 2025 three quarters of spent BEV batteries will be reused, enabling companies to profit from the same battery several times (STRINGER; MA, 2018a). In fact, there are partnerships already being established for grid storage second life applications (WILLUHN, 2018).

EOL processes are complex, after disassembly, battery cells are tested to determine their remaining capacity or state of health (SOH), then batteries without sufficient remaining capacity for reuse are sent for recycling. SOH diagnosis is fundamental to enable a second life market (SAKOVICA, 2018). Since the market is still in early stages, few vehicles have reached their EOL, thus, it is not clear the remaining battery capacity to be expected from typical use. The European Union presented an initiative for creating the metrological infrastructure required for determination of battery state of health (EU SCIENCE HUB, 2018) and is committed to address regulatory barriers for reuse and recycling (EUROPEAN COMMISSION, 2018).

In spite of recent regulatory actions in some countries, perspectives are not completely optimistic with regards to reuse. Any future reuse market probably will not include Tesla, the largest BEV battery manufacturer, whose strategy relies on recycling and not in reuse since their NCA batteries will not be suitable for stationary applications, not even when new, due to cycling characteristics (STRINGER; MA, 2018b, 2018a). Other chemistries, such as $LiFePO_4$ and NMC are better suited for this kind of tasks. Hence, for reuse feasibility it will be crucial to match compatible batteries and applications, which is a labor and energy intensive process. This is expected to improve in the future by means of standardization, which will be a key issue. Regulation might be decisive in the feasibility of battery second use. China already announced several measures aiming to regulate the recycling and second use of retired electric vehicle batteries (JIAO, 2018).

Furthermore, second life applications will be driven only by performance and economics (ROBINSON, 2017), profitability needs to be ensured over time. The customers could prefer new batteries if the price advantage of second-life batteries is low when compared to new ones (JIAO; EVANS, 2016). Analogously to reuse, recycling costs are expected to fall as well due to massive logistics. Besides, the energy intensive smelting process will be more specialized and efficient via standardization which may render it more attractive than reuse (ROBINSON, 2017).

For these reasons, for battery EOL conditions in 2015 this thesis adopted 25% of reused cells, already included in Ecoinvent v.3.2. For 2030, a more conservative approach than the estimations of Circular Energy Storage Research & Consulting (STRINGER; MA, 2018a) was taken and admitted 50% cells reuse.

Climate change and terrestrial acidification results suggested national manufacturing to be advantageous. Moreover, there is evidence that materials substitution in 2030 would lead to environmental burden shifting augmenting ozone layer depletion, for the Brazilian aluminum prototype, ironically due to larger local recycling shares. The increased use of nonmetallic materials caused a rise in photochemical oxidant formation and fossil depletion burdens displayed by the 2030 plastic prototype, in spite of total mass reduction.

Human toxicity and freshwater eutrophication must be regarded as the most concerning categories for BEV and BEB massive deployment. Electrification implies greater risks to human health and water bodies than conventional cars although there are perspectives of improvement in 2030 compared to 2015. Any effort to reduce the impacts of metal extraction and refining should bring BEV impact reduction as a consequence. Production of copper, magnesium, and other metals plays a key role for the environmental performance of all BEVs. There would hardly be a relief for these areas of interest if further action is not taken. Incentives for a second-hand market for magnesium could be an option.

Results per kilometer are much more favorable for BEVs in 2030 since contribution is diluted by the effect of the electricity mix. Environmental impacts are lower than in the 2015 scenario, except for categories sensitive to magnesium or copper extraction. When compared to a gasoline-fueled ICEV, electrification proved again to effectively diminish the impacts for climate change, ozone depletion, and fossil depletion; for a comparison against an ethanol-fueled ICEV, electrification solves terrestrial acidification and photochemical oxidant formation issues. Thus, for these areas of interest, electrification is an effective way of addressing environmental issues. Nevertheless, as in per car comparison, the results did not suggest a clear advantage for Brazilian vehicles when compared to global ones. In fact, the erection of a manufacturing plant is likely to increase the impacts, at least till mass production levels are reached (Dunn et al. 2014, 2016). More decisive is the evolution of other parameters, such as life expectancy, or energy consumption, which could more efficiently improve environmental performance.

Negative impacts on water and human health must be considered as a priority concern if fabrication of electrics is going to happen in Brazil. Findings about human toxicity and freshwater eutrophication are discouraging in the face of a potential electrification in public and private transportation; furthermore, as seen in this study, there are negative perspectives for this problem to be effectively addressed, at least in the next 15 years. Brazilian electricity mix seems not to be a guarantee of better performance on manufacturing by itself. In consonance with Liang et al. (2017), we concluded that logistics does not render a preponderant contribution either for comparing one vehicle or 1 km. Results for one BEB are much undemanding to analyze, due to not having material substitution, and all categories exhibited advantages for the 2030 scenario. These advantages are more notorious when the WTW cycle is taken into consideration.

3.8. Conclusions

Climate change and terrestrial acidification results suggested national manufacturing to be advantageous. Moreover, there is evidence that materials substitution in 2030 would lead to environmental burden shifting augmenting ozone layer depletion, for the Brazilian aluminum prototype, ironically due to larger local recycling shares. The increased use of nonmetallic materials caused a rise in photochemical oxidant formation and fossil depletion burdens displayed by the 2030 plastic prototype, in spite of total mass reduction.

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4. PAPER 3: FUEL-CELL TECHNOLOGIES FOR PRIVATE VEHICLES IN BRAZIL: ENVIRONMENTAL MIRAGE OR PROSPECTIVE ROMANCE?[14]

4.1. Introduction

Fuel cell (FC) technologies and hydrogen have long been proclaimed as clean alternatives to be used in many sectors including transport, which is estimated to be responsible for nearly one-quarter of the direct CO_2 emissions worldwide whereas is also a significant contributor to urban air pollution (INTERNATIONAL ENERGY AGENCY, 2020c). However, fuel-cell vehicles (FCV) have been much less adopted than battery electric vehicles (BEV) and this leadership does not show any signs of receding. In fact, at least 20 countries reached BEV market shares above 1% in 2019 estimating that, for each FCV in the global vehicle's fleet there were about 120 Plug-in hybrid electric vehicles (PHEV) and approximately 250 BEVs (INTERNATIONAL ENERGY AGENCY, 2020c)

Despite BEVs having, so far, outperformed FCVs in key aspects, such as manufacturing cost, well-to-wheel efficiency and availability of charging infrastructure, FCVs got a couple aces under the sleeve. For instance, the hydrogen refueling process is faster than battery charging process, even for power-intensive DC charging (GRÖGER; GASTEIGER; SUCHSLAND, 2015); furthermore, the hydrogen storage system exhibits a higher energy density when compared to li-ion batteries (LIB). Due to physical constrains, batteries involve a trade-off between energy density and power density: essentially, a high power output requires thin battery electrodes for a fast response, whereas high energy storage is a consequence of thick plates. For both, PHEVs and FCVs, power requirement is the major driver for battery design, given that the onboard fuel guarantees a reliable energy supply. A higher energy density is an asset considering how uncertain it is for LIBs to evolve far enough to power trucks, ships or airplanes. Li-ion battery cells are reckoned to face a physicochemical limit of around 400 Wh kg^{-1} while currently available cells are below 300 Wh kg^{-1} (DING et al., 2019; JANEK; ZEIER, 2016). Thus, FCVs could find a niche in applications where BEVs are unfit.

In addition to a small market for private vehicles, hydrogen is now mainly used for the chemical industry, steel production and oil refining sector (INTERNATIONAL ENERGY

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[14] Submitted to Science of the Total environment Journal. Coauthor: Joaquim Seabra.

AGENCY, 2019b). Regarding the medium and long term, hydrogen bears potential for applications such as peak energy storage from solar and wind electricity generation, heating in buildings by blending it with natural gas, as a fuel for combustion engines (BORETTI, 2020) and even portable power (SUNDEN, 2019). FC technologies are already employed for transport directly propelling vehicles or as auxiliary power units (APU); for instance, FCs are nowadays found in railways (ALSTOM, 2020) and long-haul trucks (REUTERS, 2020) and are expected to be deployed in ships (REUTERS, 2020) and aviation (AIRBUS, 2020).

Currently, all commercially available light-duty FCVs are based on polymer electrolyte membrane fuel cells (PEMFC). This is a consequence of some favorable characteristics, such as quick start-up, low operation temperature and rapid response to fluctuating loads (WITTSTOCK; PEHLKEN; WARK, 2016). Even for heavy-duty applications, PEMFC technology has proven technically feasible. In a pertinent example for this study, São Paulo city deployed an electrolysis-based pilot project nearly a decade ago (EMTU, 2010).

Nevertheless, as it often happened globally, small initiatives were not enough to make the hydrogen market take-off the ground in Brazil. Long periods of stability for oil prices, the energy security policy being steered towards biofuels, the high prices and technical challenges of hydrogen technology and the fact that most of the hydrogen was used for industrial applications are all to blame. In 1999, the Ministry of science and technology (MCT) started to evaluate the bioethanol reform for hydrogen production as a market niche to be developed by Brazil given the local availability (MINISTÉRIO DA CIÊNCIA E TECNOLOGIA, 2002).

Solid oxide fuel cells (SOFC), a technology whose potential has been only recently considered for light-duty transportation, offers a technically feasible option for on-board reform of biofuels. So far, SOFC commercial applications have been limited to APUs or range extenders. The relatively high operating temperature (650-1000ºC) and reduced lifetime are barriers. In contrast, SOFCs offer high electrical efficiency and versatility in the choice of fuels and oxidants which enables the use of existing fuel infrastructure (BESSEKON et al., 2019), including Brazilian bioethanol. In 2016, Nissan unveiled the world's first SOFC-powered prototype car designed to run on bioethanol (ELSEVIER, 2016; NISSAN, 2016c).

In order to reveal the actual environmental advantages, any technology must be compared to contender ones. The life cycle assessment (LCA) methodology enables practitioners to quantify the environmental impacts (EI) of any product, service or technology by accounting all inputs and emissions along every lifecycle stage. There is ample evidence of LCA for FC technologies. Longo et al. (2017) review focused on the LCA for FC components including PEMFCs and SOFCs systems; in the same way, Valente et al (2017) made a comprehensive review of LCA in hydrogen energy systems. For transport technologies, research has focused on the EI of FCVs, usually comparing them to BEVs or internal combustion engine vehicles (ICEVs) (BEKEL; PAULIUK, 2019; CHEN; HU; LIU, 2019; EVANGELISTI et al., 2017; MIOTTI; HOFER; BAUER, 2017; SIMONS; BAUER, 2015; YANG; WANG; JIAO, 2020). Table *7* displays results for a literature review for PEMFC vehicles. We found no evidence at all of LCA attempts for SOFC vehicles, as expected for a technology still in developing phase.

LCA results for different transport technologies tend to vary greatly (NORDELÖF et al., 2014). Those variations could result from particularities inherent to the geographical scope or time of the study but also from diverse supply chains, electricity mixes, raw materials extraction routes, etc. Until now, it remains unclear how the specific features of Brazil, *e.g.*, renewable-based electricity mix, could affect the environmental performance of PEMFC vehicles or how a prospective SOFC car would perform. Furthermore, it is not clear if technology trends could alter the EIs in the future.

The purpose of this study was to quantify the EIs linked to the use of PEMFC vehicles when hydrogen is produced in Brazilian conditions. Additionally, we intended to model the EI of a prospective SOFC vehicle and compare it to the PEMFC car. Considering the significant burden of hydrogen production, we further aimed to explore several technologies and diverse routes for biofuels production, as well as to shed light in understanding the Brazilian particularities regarding the potential FCV adoption.

4.2. Methodology

A LCA was conducted to quantify the EIs of light-duty PEMFC and SOFC vehicles under Brazilian conditions. Although the SOFC car is still a prototype, not commercially available, we modelled it based on available information. For the comparison across vehicle types a functional unit of 1 km driven was adopted. Moreover, for the sake of comparison, a BEV and an ICEV were also included. Furthermore, we included a direct comparison for the vehicles, despite 1 vehicle could not be considered as a valid functional unit according to the literal definition of ISO 14040 standards.

Regarding the time scope of the study, we created two scenarios, one reproducing currently available technologies and one for 2030 forecast. The current scenario is comprised of information from diverse years *e.g.*, PEMFC vehicle from 2014, SOFC car from 2016 and electricity mix from 2019, etc. However, it does not affect the quality of the results. Scenario 2030 represents an effort to define likely conditions for vehicle and hydrogen production.

An attributional approach was adopted. The impact assessment method was ReCiPe 2016 Hierarchist midpoint, and the software SimaPro v8.3.0 (PRÉ-CONSULTANTS, 2014) was used as auxiliary tool. The results were calculated for five midpoint impact categories (IC), namely global warming potential (GWP), human, terrestrial ecotoxicity (TE), human toxicity-carcinogenic (HTC), mineral resource scarcity (MRS) and water consumption (WC).

Table 7. Literature review for FCV studies.

Study	Vehicle base	Lifespan (km)	Method	Scenarios	1 FC system ($kgCO_2eq$)	1 vehicle ($kgCO_2eq$)	H_2 production features	1 km (kg CO_2eq km^{-1})	Notes
Miotti et al (2017)	Toyota Mirai	150000	ReCiPe 2016	2014	3.80E+03	1.20E+04	Electrolysis UCTE mix	4.70E-01	80 kW FC stack
							Electrolysis Wind mix	1.30E-01	
							Steam methane reform	2.80E-01	
				2030 conservative. 1000 FCVs per year^{-1}.	2.50E+03	9.00E+03	Electrolysis UCTE mix	3.50E-01	
							Electrolysis Wind mix	1.00E-01	
							Steam methane reform	2.20E-01	
				2030 optimistic. 500000 FCVs year $^{-1}$	1.60E+03	7.50E+03	Electrolysis UCTE mix	2.90E-01	
							Electrolysis Wind mix	8.00E-02	
							Steam methane reform	1.80E-01	
Bekel & Pauliuk (2019)	Toyota Mirai	150000	ReCiPe 2016	Baseline 2016	1.69E+03	1.44E+04	Electricity based only on renewables	1.68E-01	Central and distributed H_2 production modelled
		150000		Mix 2030	1.69E+03	1.44E+04	German electricity grid development plan for 2030	3.59E-01	80 kW FC stack
		200000		Extended lifetime	1.26E+03	1.08E+04	Electricity based only in renewables	1.44E-01	
Chen et al.(2019)	Toyota Mirai	250000	CML 2001 + Energy use			2.84E+04	Methanol steam reform	1.72E-01	Chinese electricity mix
							Steam methane reforming	1.79E-01	80 kW FC stack
							Catalytic ammonia decomposition	3.08E-01	Time scope not specified
							Electrolysis	6.57E-01	
Evangelisti et al.(2017)	Honda FCX Clarity	150000	CML 2001 + Usetox	Baseline scenario	3.28E+03	1.60E+04	H_2 production taken from Gabi database- Thinkstep.	1.35E-01	18 scenarios included
									Time scope not specified
				Best case senario	2.00E+03	1.14E+04			80 kW FC stack
Simons & Bauer (2015)	VW Golf class FC	150000	ReCiPe 2016	2010 scenario	1.70E+03	1.80E+04	Natural gas SMR	3.00E-01	40 kW FC stack
							Coal gasification and reform	3.70E-01	
							Wood gasification and reform	2.10E-01	
							EU Electrolysis	4.80E-01	
							Swiss Electrolysis	2.20E-01	
							PV electrolysis	1.80E-01	
				2020 scenario	1.67E+03	1.65E+04	Natural gas SMR	2.80E-01	
							Coal gasification and reform	3.50E-01	
							Wood gasification and reform	1.90E-01	
							EU Electrolysis	4.60E-01	
							Swiss Electrolysis	2.00E-01	
							PV electrolysis	1.50E-01	

4.2.1. The product system

A cradle-to-grave product system was defined. The system boundaries were outlined to include the vehicle manufacture, the off-board production of hydrogen for PEMFCVs – including electricity generation-, the bioethanol production for the SOFCV and finally the vehicle's use phase. Ecoinvent life cycle inventories (LCI) were included along the whole lifecycle whenever possible; it includes the car manufacturing, hydrogen production and its required infrastructures. To better adapt the study to Brazilian conditions we used available information to model the extraction and production of steel, aluminum and copper to be used for car and hydrogen infrastructure manufacturing (see section 4.2.3.4). The EIs of such raw materials were expected to be significant (COONEY; HAWKINS; MARRIOTT, 2013; FARIA et al., 2013; MA et al., 2012; MESSAGIE et al., 2014; NORDELÖF et al., 2014), even under the influence of low-carbon Brazil mix (VELANDIA VARGAS et al., 2019). The product system is displayed in Figure 17, whereas Table 8 presents the basic assumptions for car modelling, hydrogen production - including feedstocks - and hydrogen fueling infrastructure.

4.2.2. Vehicle production

PEMFCV and SOFCV have several components in common. Glider and powertrain were taken from the Ecoinvent 3.3 database and adapted to the specifications of 2014 Toyota Mirai as modelled by Miotti et al. (2017). For the SOFCV prototype, the glider and powertrain were adapted to Nissan e-NV200. Further elaboration is displayed in section 4.2.2.2.

Table 8. Vehicle modelling parameters

		PEMFCV		SOFCV	
		Current scenario	2030 scenario	Current scenario	2030 scenario
Model	Unit	Toyota Mirai		Nissan e-NV200 for Glider and powertrain + 5 kW solid oxide fuel cell for Tubular and Planar configurations	
Curb weight	kg	1537	1117	1716 (Tubular); 1760 (Planar)	1505 (Tubular); 1579 (Planar)
Battery chemistry		Ni-MH	Li-ion NMC	Li-ion NMC	Li-ion NMC
Battery power / Battery capacity*	kW, kWh	28	21	24	24
Fuel consumption	kg 100 km^{-1}, km L^{-1}	1.05	0.73	20	18
Lifespan	km	150000	150000	150000	150000
Catalyst		Platinum	Platinum	Nickel	Nickel
Components origin		100% imported	Brazilian Glider and Powertrain. Rest of the car imported	100% imported	Brazilian Glider and Powertrain. Rest of the car imported
Vehicle breakdown					
Fuel cell stack	kg	81 (80 W)	11 (62 W)	56 (Tubular); 50 (Planar)	50 (Tubular); 45 (Planar)
BoP**	kg	88	48	100 (Tubular); 150 (Planar)	95 (Tubular); 143 (Planar)
Battery*	kg	47	17	160	126
Powertrain	kg	370	219	425	370
Glider***	kg	850	765	975	850
H_2Tank ****	kg	101	57	N/A	N/A

*Miotti et al (2017) indicated net battery power to be (28 kW); however, in a personal communication the author clarified that factor of 2 was applied assuming that the battery shouldn't go below 50% (56 kW or 47 kg). Energy density for SOFC battery: 150 Wh kg^{-1} for 2016, 190 Wh kg^{-1} for 2030. Energy density for SOFC battery: 150 Wh kg^{-1} for 2016, 190 Wh kg^{-1} for 2030.
**BoP mass for 2030 SOFCV was expected to be reduced 10%.
***Vehicle powertrain and glider expected to resemble 2014 Toyota Mirai.
****Includes tank BoP

4.2.2.1. Proton-exchange membrane fuel cell vehicle

The PEMFCs are devices in which hydrogen reacts with oxygen to produce electricity with water as the only by-product. So far, PEMFC are the only FCs commercially available for vehicles mostly due to their rapid start-up time, high power density compared to other FC types, fast response to varying loads and the ability to use ambient air as the oxidant (HOLTON; STEVENSON, 2013; WITTSTOCK; PEHLKEN; WARK, 2016). PEMFCs are typically fueled with pure hydrogen and contain a solid polymer as an electrolyte. Nearly every available membrane for PEMFCs is based on the copolymerization of perfluorosulfonic acid and tetrafluoroethylene named as Nafion (EVANGELISTI et al., 2017). Additionally, PEMFCs contain porous carbon electrodes (anode and cathode) and a platinum-based catalyst, which is sensitive to carbon monoxide poisoning requiring an additional reactor to remove it in case the hydrogen is derived from a hydrocarbon fuel (OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY, 2017).

The LCI constructed by Miotti et al (2017) displayed specific data for an 80 kW fuel cell system which is composed of an array of single fuel cells known as the fuel cell stack (FCS), the hydrogen tank and the balance of plant (BoP). As the hydrogen enters the electrode of each single fuel cell it reaches the Nafion membrane - aided by a gas diffusion layer and the catalyst - generating an electron flux which feeds the battery, which, for the 2014 Mirai, is based on NiMH technology (TOYOTA, 2019). The BoP refers to the components in charge of the air, water, heat and hydrogen management of the FCS. The carbon fiber hydrogen tank was designed to store 5.6 kg of gaseous hydrogen at 700 bar and it includes its own BoP which was modelled exactly as the main BoP, only adjusting the weight. The vehicle components - and their weight - found in this LCI are in consonance with those presented by Evangelisti et al. (2017).

For LCI adaptation in the current scenario, we suppressed the on-board charger included in the BEV powertrain dataset available in Ecoinvent 3.3., since it is not a component found on a PEMFC vehicle. For the current scenario, we did not include any further regionalization of LCIs for the vehicle, once the vehicle is only manufactured abroad. For 2030 scenario, Miotti et al (2017) defined two scenarios: a conservative one, assuming a slow learning curve and a slow production volume of 1,000 vehicles per year, a milestone that was overtook in 2014 (in fact, as 2020, Toyota is able to produce 30,000 units of Mirai a year (FINANCIAL TIMES, 2020)); and an optimistic scenario, which represents a production of 500,000 per year. This scenario also implies a reduction in platinum use for the catalyst and other materials besides of an overall mass reduction, and it was the basis for our 2030 scenario. For 2030 the car glider and powertrain were adapted as whether to be manufactured in Brazil (see section 4.2.4).

The modelling of an end of life (EOL) stage for PEMFCVs is full of uncertainties. The implementation of a reuse scheme or even an economically feasible recycling process would reduce the worsening of scarcities while securing resource access and reducing raw material costs. However, reusing a PEMFC when its lifetime has come to an end is not feasible, as failure is generally caused by degradation of the membrane electrode assembly and any attempt to replace or repair its components would likely end-up damaging the others (SIMONS; BAUER, 2015). Platinum is the main catalyst used in PEMFCs and is the main target for recycling strategies due to its cost. Although hydrometallurgical and pyrohydrometallurgical treatment are available options for recycling, depending on recovery efficiency and initial concentration (VALENTE; IRIBARREN; DUFOUR, 2019), the lack of data for the PEMFC renders the analysis unviable because of the uncertainties, while adaptation from other products such as LIB recycling would not be reliable. Thus, Ecoinvent 3.3 EOL datasets for glider, powertrain and NiMH battery were kept unaltered while for PEMFC system we kept the data included by Miotti et al. (2017).

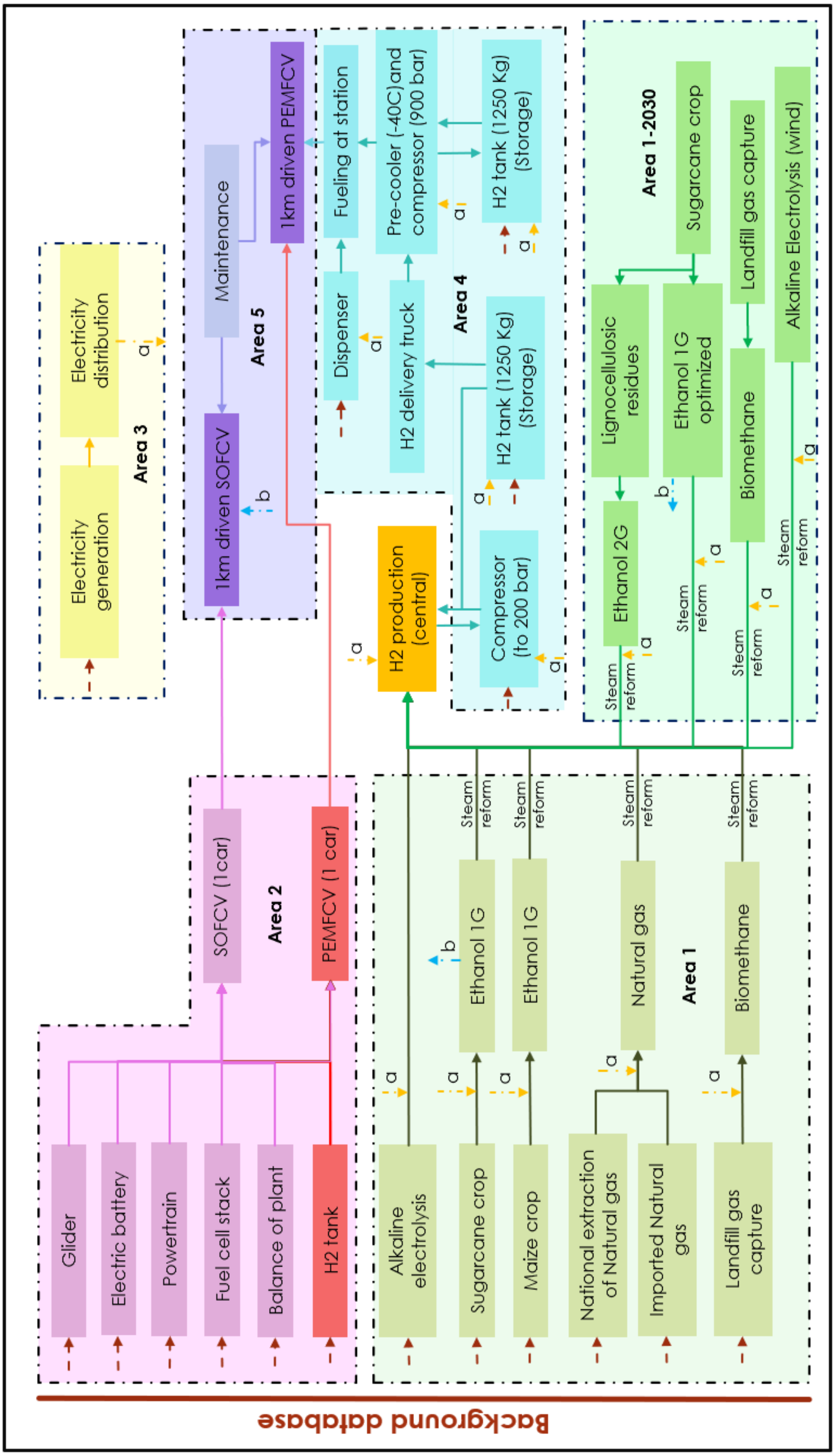


Figure 17. Product system of the life cycle assessment for this study. The main process areas are (1) Feedstock for hydrogen production for current scenario and 2030; (2) vehicles production; (3) electricity Generation; (4) hydrogen distribution infrastructure; (5) vehicle use-phase. Arrows "a" and "b" refer to electricity and bioethanol flows.

4.2.2.2. Solid oxide fuel cell vehicle

Analogous to PEMFCs, SOFCs also consist of a porous anode and cathode; however, for SOFCs, these electrodes are separated by a dense oxygen ion-conducting ceramic membrane instead of a polymer one as in PEMFCs. At the cathode side, oxide ions are cracked from oxygen molecules and then brought into the electrolyte; conductor materials such as lanthanum strontium cobalt iron oxide (LSCF) are used. At the anode end, oxidation takes place as oxide ions react with fuel molecules, this happens in the presence of materials which are typically a mixture of an oxide-conducting ceramic such as yttria stabilized zirconia (YSZ) or cerium gadolinium oxide (CGO) and usually nickel, an electron-conducting metal (BOLDRIN; BRANDON, 2019). The rigidity of the ceramic membrane enables its use as a structural component (HYTECHCYCLING, 2017a).

Although SOFCs require temperatures as high as 1,000°C for functioning, the lower temperature range starts from 650°C (BOLDRIN; BRANDON, 2019). High-temperature conditions are advantageous because they eliminate the need for precious-metal catalysts, thereby reducing costs. Similarly, such temperatures allow SOFCs to reform fuels internally, enabling the use of a variety of fuels and also eliminating the necessity for an external reformer (OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY, 2017). In contrast, high temperatures imply highly specialized materials from a metallurgic viewpoint and lengthy start-up times, whereas the ceramic's brittleness renders the SOFC vulnerable to impacts.

Such constraints had long discarded SOFCs as candidates for light-duty transportation despite being already used in stationary applications, APUs, road transport, maritime transport and aircrafts (AGOSTINI et al., 2018; BALDI et al., 2019; BIERT et al., 2016; FERNANDES et al., 2018; GANDIGLIO; LANZINI; SANTARELLI, 2018; KADYK et al., 2019; LONGO et al., 2017; SIM et al., 2019; STRAZZA et al., 2010, 2015). However, advances in pollution tolerance, efficiency, life expectancy and power density have resulted in realistic chances for SOFCs to be used in light-duty transport. In fact, besides the Nissan prototype, Honda, Weichai and AVL have been actively researching in this field (ENERGIFORSK, 2019).

As expected from any car manufacturer developing a prototype, Nissan disclosed little information about their SOFCV prototype. It was revealed that the car includes a 5 kW SOFC, a 24 kWh Li-ion battery and displays a 600 km range (ELSEVIER, 2016; NISSAN, 2016c). Given the notorious scarcity of information about SOFCs for automotive applications, we appealed to studies for stationary applications and then performed adaptations.

Considering that planar SOFCs reach larger power densities than tubular SOFCs (U.S. DEPARTMENT OF ENERGY, 2004; VERDA; CIANO, 2008), the prototype is likely to include a planar SOFC unit, despite of this technology exhibiting criticalities due to the reliability of the seals and their behavior under thermal stresses (VERDA; CIANO, 2008). In addition, as high temperatures imply larger costs and engineering challenges, the SOFCs in vehicles would be desired to work at the lowest possible temperature, a feature for which planar configuration is adequate because it offers to minimize resistance losses by using ultra-thin electrodes and electrolyte membranes (U.S. DEPARTMENT OF ENERGY, 2004). However, since there was no conclusive information about the actual cell embedded in the prototype, let alone the material composition or the manufacturing energy requirements, we decided to evaluate the two configurations, planar and tubular.

For the tubular SOFC we based our modelling on Strazza et al (2010), which presented data for a 20 kW stationary device designed to run on methanol, adapted originally from the 100 kW tubular SOFC presented by Karakoussis et al. (2001). Despite it has been two decades since released, Karakoussis et al.(2001) is a complete study, even referenced by Ecoinvent 3.3 SOFC datasets. For adaptation we considered that, akin to methanol reforming, ethanol reform would not require a zinc catalyst for the desulfurizer (STRAZZA et al., 2010). In contrast, we kept the inputs of chromium steel and electricity linked to both methanator and reformer. The steel associated to the pre-reformer was kept unaltered bearing in mind that the flows being fed into the SOFC must be pre-heated to reduce thermal stresses. In fact, the air inlet and the exhaust system make up a significant part of the BoP volume due to high volumetric flows and high requirements for heat exchange (STRAZZA et al., 2015).

As the 20 kW FCS mass is revealed as 112 kg, its power density at the stack level - without the BoP -, was estimated as 178.57 W kg^{-1}. Assuming that the SOFC mass can be actually linearly scaled down as a function of power output, the 5 kW device used for this study resulted in a 28 kg SOFC. For the BoP we adapted the data presented by Karakoussis et al. (2001). The adaptation consisted in scaling-up the material inputs to a 5 kW SOFC and removing the pressure vessel input since the vehicle does not run on natural gas; instead, we included the steel inputs required for the casing of a planar SOFC. Furthermore, the air and fuel supply system inputs were included as if made of chromium steel. In a conservative approach we assumed a 1.5 factor for the SOFC mass.

As the planar SOFC presented by Karakoussis et al. (2001) runs on natural gas, adaptation was necessary again. The Zinc catalyst for the desulfurizer was removed analogous to the tubular scheme. In addition, the conventional gas heating unit inputs were withdrawn for not being compatible with automotive applications. The inverter was equally removed, to avoid double counting, considering that the BEV powertrain in Ecoinvent 3.3 already comprises one. The prereformer was kept unaltered.

In general, uncertainties in the mass of the SOFCV are large and were assessed via sensitivity analysis for GWP. In addition, manufacturing of the FCS and BoP display significant uncertainties too as the inputs for the planar SOFC and its BoP in Karakoussis et al.(2001) include a share of wasted material, part of the manufacturing process. This is likely to significantly improve as production volumes increase. Actually, Karakoussis et al.(2001) pointed out the large potential for material reduction as fabrication techniques improved. As the mass of the SOFC stack was not specified, we assumed it to exhibit a 200 W kg^{-1} power density, in consonance with the 1,8 kW and 9 kg stack produced by Chinese company SOFCMAN, which was also considered for SOFC modelling by Bessekon et al.(2019). After applying a 2x safety factor, the 25 kg SOFC results in a 50 kg FCS. For 2030 scenario, a 10% linearly scaled mass reduction for the FCS and a 5% for the BoP were included to account for technology evolution. Water consumption for BoP manufacturing was taken from Strazza (2010).

Regarding the rest of the vehicle, the glider and powertrain were adapted from Ecoinvent to the Nissan e-NV200 (ELECTRIC VEHICLE DATABASE, 2016). Analogous to the PEMFCV, we removed the inverter included in the fuel cell stack to avoid double counting. Fuel consumption was estimated based on the 30 L tank size and the 600 km range due to the lack of further data.

Moreover, we assumed that the LIB, for current and 2030 scenarios, will be based on Lithium-Nickel-manganese-Cobalt-oxides (NMC) cathode chemistry. Although lithium-nickel-cobalt-aluminum (NCA) would be the best option for power density, its prohibitive cost would render the car financially uncompetitive, hampering adoption. However, NMC appears as a reasonable choice, by 2025 NMC technology is predicted to expand its market share from 26% to 41% due to a higher energy density than lithium-iron-phosphate (LFP) while NCA and lithium-manganese-oxides (LMO) are forecast to maintain stable market shares (DING et al., 2019). In addition, NMC power density is still competitive.

NMC battery was modelled as in Ellingsen et al. (2013). Nissan's selection of a 24 kWh LIB for the SOFC prototype seems counterintuitive, because, for hybrid technologies, whose energy reservoir is expected to be the fuel tank instead of the battery electrodes, batteries are primarily selected for power supply (kW) instead of energy (kWh). The rational of battery selection for the prototype could have been guided by undisclosed technical reasons; still, due to the lack of information and high uncertainties, we decided to keep a 24 kWh battery for 2016 and 2030 as seen in Table 8. Additionally, we are exploring a case for a 2030 SOFC vehicle with a 28 kW, 1.2 kW kg^{-1} NMC power oriented battery. These assumptions result in a 47 kg NMC battery- after using a 2x safety factor- as designed in Miotti et al.(2017).

The modeling of EoL stage for the SOFC unit was impracticable, due to large uncertainties. There is absence of information about EoL for the majority of materials in the FCS

(HYTECHCYCLING, 2019). Although hydrometallurgical recovery treatments for nickel and YSZ are technically feasible, that is not the case for lanthanum-based materials (VALENTE; IRIBARREN; DUFOUR, 2019). Thus, no single EoL process is available for the FCS (in fact, no novel process for lanthanum-based materials is expected to become available in the near future). High energy requirements associated with ceramic processing and low or medium material value do not benefit recycling. Moreover, LCIs for YSZ, LSCF or CGO are completely unavailable from LCI datasets (HYTECHCYCLING, 2018). EoL for the rest of the vehicle components was maintained as in Ecoinvent 3.3 datasets.

4.2.2.3. Battery electric vehicle and internal combustion engine vehicle

Both, BEV and ICEV lifecycles were modelled by employing Ecoinvent 3.3 available datasets whenever possible and following the same guidelines as in Velandia Vargas et al.(2019). The BEV data represents a 1539 kg curb weight Nissan Leaf with a 296 kg LIB whereas the ICEV depicts a 1282 kg Volkswagen Fox. These cars were chosen because of their very similar power-to-weight ratios. Use-phase for ICEV is based on E-22 gasoline (22% of sugarcane ethanol) while tailpipe emissions are based on Brazilian tests as in Velandia Vargas et al.(2019). A 150000 km life expectancy was considered for both cases. Maintenance was included as in Ecoinvent 3.3 datasets.

4.2.3. Hydrogen production

In the past, the use of hydrogen as an energy carrier has drawn attention at different times, only to end-up fading away without being massively translated into a feasible alternative. What could be different this time is the sense of climate urgency and the plethora of technical possibilities -some more mature than others - for production, despite the current demand (around 70 Mt per year) being mostly supplied from natural gas (76%) and coal (23%) (INTERNATIONAL ENERGY AGENCY, 2019b, 2020a) with significant associated CO_2 emissions. Examples of production upsurge worldwide include the European Union preparing to build 40 GW of renewable-associated hydrogen electrolyzers by 2030 and Japan planning to deploy 10 GW of renewable-powered hydrogen projects (INTERNATIONAL ENERGY AGENCY, 2019b).

Guaranteeing low-carbon hydrogen production routes is crucial to enable hydrogen as a clean energy transitioner. Current scenario explored five pathways for hydrogen production in Brazil.

Two bioethanol steam reform pathways - sugarcane (Sc) and corn (Cr) feedstocks -, two steam methane reform routes, based on landfill-captured biomethane (BioM1) and natural gas (NG), and one for alkaline electrolysis (Elys1) based on data from a local company. For 2030 we included three scenarios for sugarcane bioethanol reform. The first one depicts an optimized scenario, where all biomass residues are burned for electricity production (1gOpt) while the second and third describe the use of the lignocellulosic material (LCM) - biomass residues - for ethanol production also known as 2G ethanol, via enzymatic hydrolysis (2gEH) and syngas fermentation (2gSF). Another scenario evaluates a reduction of landfill biomethane capture leakages (BioM2). Finally, one case explores an improved electrolysis scenario (Elys2) based in Bekel & Pauliuk (2019) and a final one explores a 100% wind-based electrolysis (ElysW). Details of the scope and assumptions used in the construction of LCIs for each pathway as well as the electricity mix for both scenarios are depicted in Table 9.

Regarding the environmental burden of residues, we assumed that feedstocks obtained as residues - presenting no economic value - from any process were deemed to have no burden related to its generation; thereby landfill biomethane and the lignocellulosic material derived from 1G ethanol production were considered as burden free. This approach has been observed in policies such as Renovabio in Brazil (BRASIL, 2018f) and the Renewable Energy Directive (EUROPEAN PARLIAMENT, 2009). In contrast, the use of agricultural residues - such as the LCM used for 2G bioethanol distillation - deserved a different perspective considering that the market value of the waste at its point of origin is above zero and it should be considered as a coproduct and subject to allocation (JOINT RESEARCH CENTRE, 2010).

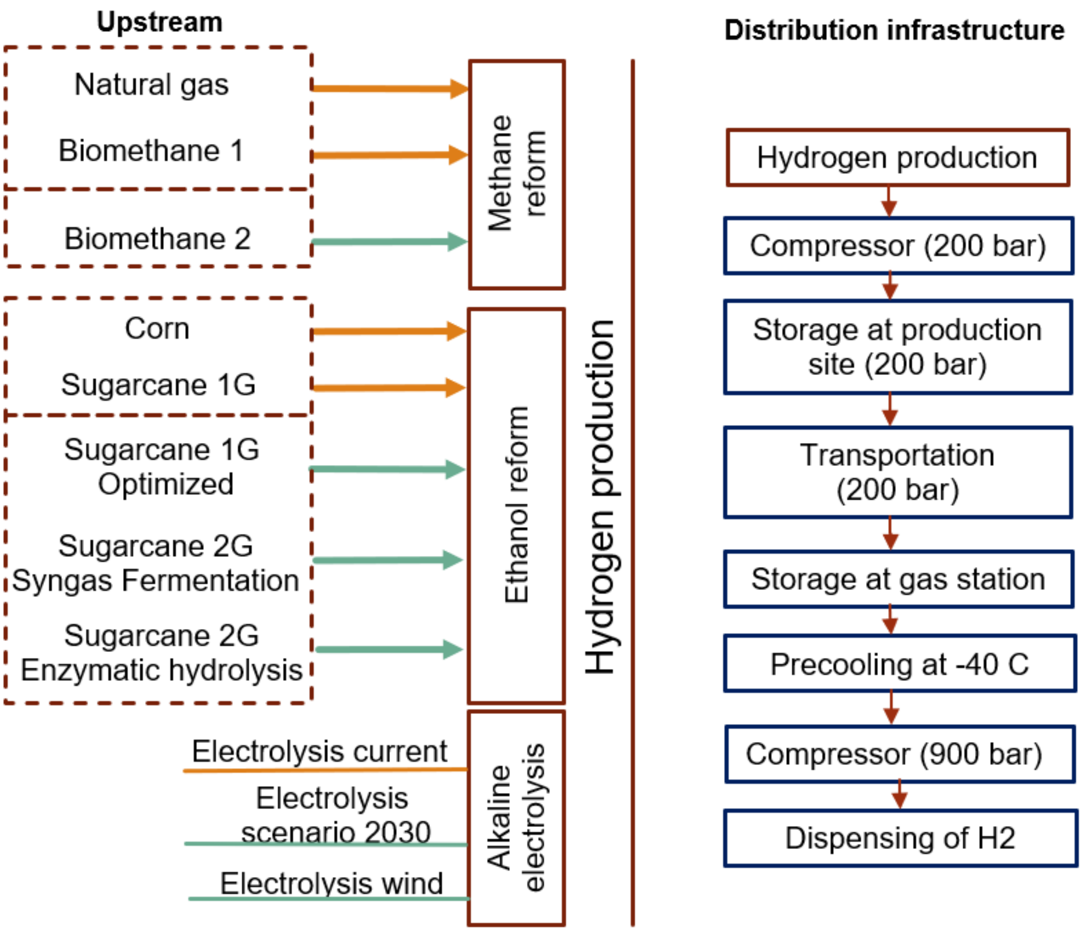


Figure 18. Scheme for hydrogen production (left) and hydrogen distribution infrastructure (right). Orange lines refer to current scenario, green lines to 2030 scenario.

Table 9. Hydrogen production parameters and electricity mix shares.

Pathway	Coproducts	Observations	Feedstock use (kg^{-1} H_2)	Electricity consumption ($kWh\ kg^{-1}$ H_2)	Water consumption ($kg\ kg^{-1}$ H_2)	Emissions ($kg\ CO_2\ kg^{-1}$ H2)
		Current scenario				
Sugarcane ethanol (1G) reform	For ethanol production stage 30 kWh of electricity were coproduced along 85.3 L of ethanol per tonne of cane. Energy allocation.	Sugarcane agricultural stage modelled as in Capaz et al.(2020), which presentes adapted data from Cavalett et al.(2013) and Bonomi et al.(2016). Harvesting process considered as 100% mechanized. Vinasse and filter-cake resulted from ethanol distillation is applied in the field as fertilizer. Emission factors for bagasse burning in boilers taken from GREET (2019). Agricultural land use considered as not a product of deforestation. Both ethanol distillery and hydrogen production use tap water.	6.54 kg	0.49	30.92	12.84 (Biogenic)
Corn ethanol reform	416 L of ethanol are produced along with 13 kg of corn oil and 364 kg of Distiller's Dried grains per tonne of corn. Energy allocation.	Corn agricultural stage (second crop) was based on Donke et al. (2016); cultivation land was assumed to be not a consequence of deforestation. Distillery modelling was based in Moreira et al (2017), while emissions were adapted from Donke et al. (2016). Electricity and heat generation takes place at an adjacent heat and power cogeneration plant fed with eucalyptus woodchips. Cogeneration plant was modeled as in Ecoinvent 3.3 whereas eucalyptus represented Brazilian conditions (SICV-Brasil 2016) . Ethanol distillery uses tap water.	6.54 kg	0.49	30.92	12.84 (Biogenic)
Natural gas reform	Steam being coproduced along with hydrogen is reused for process, hence, not considered as byproduct. Energy allocation.	On-shore national production share corresponds to 13.4%, off-shore national production to 39.3% and on-shore imported share to 37.1%. Hydrogen production modelling includes steam reforming, water-gas shift, pressure swing adsorption stages. Deionized water required (Mehmeti et al. 2018).	165 MJ	0.57	21.87	9.28
Biomethane reform	Steam being coproduced along with hydrogen is reused for process, hence, not considered as byproduct. Energy allocation.	Biomethane taken from Ecoinvent 3.3 "*Market for methane, 96% by volume, from biogas, from low pressure network, at service station*". Methane losses during the purification process were considered as 8% for the current scenario as defined by Leme and Seabra (2017) for pressure swing adsorption compression and upgrade. Deionized water is used (Mehmeti et al. 2018). Captured biomethane considered as burden-free as landfill gas is usually flared on-site.	165 MJ	0.57	21.87	0
Alkaline electrolysis	Oxygen was considered to be vented as in most applications (Koj et al. 2017). Hence, not counted as coproduct.	Alkaline electrolysis based on a local hydrogen producer as presented by Capaz et al (2020). Potassium hydroxide assumed to be the electrolyte. Inputs of electrolyte per kg of produced H_2 taken as in Bekel & Pauliuk (2019). Process requires deionised water.	-	71.16	11.2	-
Brazilian electricity mix (%) for 2019 (EPE 2020a)	Hydro: 64.9; Coal: 3.3; Nuclear: 2.5; Fuel oil: 1; Diesel: 1; Natural gas: 9.3; Solar: 1; Wind: 8.6; Biomass (Sugarcane): 8.4.					

		2030 scenario				
Optimized sugarcane ethanol (1G) reform	192 kWh electricity generation coproduced along 93.2 L etanol per tonne of cane.	Scenario based on an optimized 1G autonomous distillery which burns all available biomass Bonomi et al (2016). Emissions from land use change were not considered. Sugarcane and etanol production data based in Capaz et al.(2020).	6.21 kg	0.49	30.92	12.84
Sugarcane ethanol reform (2G) enzymatic hydrolysis	Ethanol yield: 357 L and electricity coproduction: 127.58 kWh. 116 Kg of dry base LCM from 1G ethanol distillery used as feedstock. Energy allocation.	Uses a mix of residues -bagasse and straw- from 1G base scenario as feedstock. Plant physically separated from the 1G process. Feedstock data based in Capaz et al.(2020)	6.21 kg	0.49	30.92	12.84
Sugarcane ethanol reform (2G) syngas fermentation	Ethanol yield: 327.10 L and electricity coproduction: 64.10 kWh. 116 Kg of dry base LCM from 1G ethanol distillery considered as a coproduct. Energy allocation.	Uses a mix of residues from 1G base plant -bagasse and straw- as feedstock. Plant physically separated from the 1G process. The process includes the gasification of LCM with subsequent syngas fermentation. Steam generation occurs from hot gases from unreacted syngas. Ashes from the gasification process are returned to the field. Feedstock data based in Capaz et al.(2020).	6.21 kg	0.49	30.92	12.84
Biomethane 2030	Steam is coproduced along with hydrogen. Energy allocation implemented. Captured biomethane considered as burden-free.	Methane losses taken as 0.018%, as adopted by Ecoinvent 3.3. No evidence of energy, water or feedstock inputs reduction for 2030 scenario when compared to 2018 methane steam reforming. Captured biomethane considered as burden-free as landfill gas is usually flared on-site.	165 MJ	0.57	21.87	0
Electrolysis (wind)	Oxygen was considered to be vented as in most applications (Koj et al. 2017). Hence, not counted as coproduct.	Electricity consumption as in Bekel & Pauliuk (2019).	-	51.1	11.2	-
Brazilian electricity mix (%) for 2029 (EPE 2020b)		Hydro: 64.2; Coal: 0.7; Nuclear: 3.1; Fuel oil: 0.6; Diesel: 0.6; Natural gas: 5; Solar: 5; Wind: 18.5; Biomass: (Sugarcane) 2.7, (Wood) 1.5, (Biogas) 0.5.				

4.2.3.1. Alkaline electrolysis

AE is a mature technology available since the 1920s. The reaction takes place in the electrolyzer, which comprises of anode, cathode and electrolyte. AE is characterized by relatively low initial investments, compared to other electrolysis technologies, which has rendered it the market dominant technology, especially for large-scale projects (INTERNATIONAL ENERGY AGENCY, 2020a). Currently, electrolysis accounts for nearly 2% of global hydrogen production (INTERNATIONAL ENERGY AGENCY, 2019b). This pathway for hydrogen production relies in the adequate access to water supplies.

Irrespective of the specific electrolysis technology, the process is energy-intensive; thereby the environmental impacts are heavily dependent in the electricity supply. The large share of renewables (EPE, 2020a) in the Brazilian electricity mix is anticipated to be translated into lower carbon-related impacts. Hydrogen produced by AE was modelled as in Capaz et al. (2020) according to data from a local hydrogen producer. For 2030 scenario we assumed that, due to larger production volumes and technical learning, the electricity and water inputs for the process would match those described by Bekel & Pauliuk (2019). In addition, for 2030 an AE case fed by wind-generated electricity is explored, although not feasible for the entire country, it measures the performance of hydrogen production in extreme conditions, which could take place in some coastal areas with wind generation. Hydrogen purity for AE pathway reaches 99.5%. For further elaboration see Table 9 and for schematics see Figure 18.

4.2.3.2. Natural gas and biomethane steam reform

Steam methane reform is the dominant technology for hydrogen production and is likely to remain this way, in the near term, due to its economic advantages and the large number of units in operation (INTERNATIONAL ENERGY AGENCY, 2019b). The hydrogen production process depicted in this study includes the steam reforming, water-gas shift and pressure swing adsorption stages modelled for a 379,400 kg day^{-1} central plant able to produce hydrogen at a 99.9% purity (NATIONAL RENEWABLE ENERGY LABORATORY, 2018). The plant configuration enabled us to model the hydrogen production using natural gas and landfill biomethane as feedstocks. After the reformer, the process gas undergoes a heat recovery step then to be fed into a water-gas-shift reactor to produce additional hydrogen.

For the Brazilian natural gas we adopted information from the petroleum national agency (ANP, 2019) and employed Ecoinvent datasets to model on-shore and off-shore extraction as in Capaz et al. (2020). On the other hand, we deemed biomethane as a waste and bestowed no environmental load on it assuming that the methane emissions at landfills are usually torched, transforming methane into CO_2. Biomethane LCI was retrieved from Ecoinvent 3.4 database. Moreover, based on National Renewable Energy Laboratory (2018) forecasts for hydrogen production, we found no evidence of a reduction on either feedstock or electricity consumption for a future scenario, hence, 2030 scenario had this parameters unaltered compared to the current case. More information on this pathway is found in Table 9.

4.2.3.3. Bioethanol reform

Analogous to steam methane reform, the ethanol reform process also includes steam reforming, water-gas shift and pressure swing adsorption stages. Despite of the data portraying the hydrogen production at a forecourt, instead of a central plant, we adopted it due to the lack of data for the latter. The plant is able to supply hydrogen at 99.99% purity at a rate of 1,500 kg day^{-1}. The data for the sugarcane crop and the ethanol production stages were obtained from Capaz et al.(2020) based on Cavalett et al. (2013) and Bonomi et al. (2016). Besides sugarcane ethanol, an additional case for corn ethanol as a feedstock was explored due to its recent emergence in the Brazilian landscape, the agricultural and industrial stages were taken as in Donke et al. (2016) and Moreira et al. (2017) respectively. Assumptions are displayed on Table 9.

For 2030 scenario we assumed a reduction in electricity and feedstock consumption for hydrogen production, taking into account that a central plant scheme requires less energy and feedstocks per kg of hydrogen compared to distributed plants. Besides, 3 additional pathways were explored, one based on an optimized 1G ethanol mill and two 2G ethanol routes, enzymatic hydrolysis and gasification of LCM with subsequent syngas fermentation (CAPAZ et al., 2020). See Table 9.

4.2.3.4. Distribution infrastructure

Long-distance transmission of gaseous hydrogen could be challenging due to its low energy density. When compressed at 700 bar, hydrogen contains only 15% of gasoline's energy density, thus, storing an equivalent amount of energy would require approximately seven times the space (INTERNATIONAL ENERGY AGENCY, 2019b). Being the lightest of gasses, hydrogen necessitates special infrastructure for storage, transmission and distribution. Molecules are tiny enough to diffuse into some types of iron and steel, increasing their risk of failure. In the same way, it escapes more easily through sealings and connectors than other fuels (INTERNATIONAL ENERGY AGENCY, 2019b).

In order to guarantee minimum standards of safety for hydrogen refueling, SAE J2601 protocol establishes that the vehicle's hydrogen tank should never heat-up above 85°C even during fast refueling. For 700 bar refueling, hydrogen must be precooled, generally to –40°C. Higher precooling temperatures increase refueling times (HYDROGEN EUROPE, 2017). Hydrogen supporting infrastructure depends on where the gas production takes place; a large central production station supplying a large region or smaller, distributed, on-site production stations.

For this study, we assumed hydrogen production to take place at a central hub *i.e.*, at a refinery, for natural gas and biomethane reform cases, at a distillery, for ethanol reform scenarios, and at the central station for the electrolysis scenario. It is true that on-site hydrogen production based on small-scale reforming happens to require lower initial investments than centralized production and imply higher utilization rates and lower costs (BEKEL; PAULIUK, 2019; INTERNATIONAL ENERGY AGENCY, 2019b), however it happens only until a large geographically concentrated hydrogen demand has built up. Actually, the small stations are very capital intensive and are unable to take advantage of the economy of scale linked to large central production, not to mention that they are likely to occupy expensive urban space. Besides, centralized stations could be placed close to areas that guarantee a reliable feedstock supply. A promising near-term business model is developing in China, as refueling of FCVs at large and centralized stations that obtain by-product hydrogen from nearby chemical plants, is resulting in operations financially competitive to other zero-emission options (INTERNATIONAL ENERGY AGENCY, 2019b).

The hydrogen infrastructure required for transmission and distribution is based in Bekel & Pauliuk (2019) whose scheme is shown in Figure 18. Electricity, steel, aluminum and copper inputs were adapted to regionalized Brazilian inventories. Due to the lack of data, the Ecoinvent dataset Chemical factory, organics {GLO}| Alloc Rec, U was used to model the reforming plant infrastructure.

4.2.4. Data regionalization

In order to more effectively reflect the Brazilian particularities, some adaptations took place; firstly, Ecoinvent datasets for raw materials, namely steel, aluminum and copper had their electricity inputs switched to the Brazilian mix for current and 2030 scenario (EPE, 2020a, 2020b). Such raw materials were anticipated to have a significant environmental contribution due to their large presence in the vehicles. Secondly, the shares of primary and recycled material for those raw materials were adapted to Brazil and finally, upstream raw materials, *e.g.* pig iron, iron pellets and iron ore concentrates were adapted as well. Such adapted LCIs were implemented for the hydrogen distribution infrastructure in current and 2030 scenarios. Furthermore, it was assumed that the vehicles could be, partially at least, manufactured in Brazil, thereby glider and powertrain LCIs for PEMFCV and SOFCV had the adapted LCIs included to represent a Brazilian manufacture. The adaptation parameters are described in Table 10.

Table 10. Raw materials regionalization parameters

Raw material	Data year	Production pathway (per kg)	Notes
Steel	2018	Basic oxygen furnace (primary): 77.26% Electric furnace (recycled): 22.4% (INSTITUTO AÇO BRASIL, 2019)	Glider and powertrain production is assumed to be completely supplied by Brazilian steel. Brazilian LCI for 43% iron ore concentrate (FERREIRA; LEITE, 2015) replaced the LCI found in Ecoinvent 3.3. An additional beneficiation process for iron ore, to 65% was included, from Ecoinvent 3.3. Hard coal imports taken as in DNPM (2017)
Aluminum	2018	Soderberg route (primary): 28.7% Prebaked anode route (primary): 25,1% Recycled aluminum: 53.9% (ASSOCIAÇÃO BRASILEIRA DO ALUMÍNIO, 2019)	Aluminum oxide production and bauxite extraction processes were adapted to Brazil. All aluminum oxide was assumed to be obtained from primary production.
Copper	2017	National production (primary): 32.2% National production (recycled): 18.1% Imported from Chile (primary): 49.7% (ASSOCIAÇÃO BRASILEIRA DO COBRE, 2018)	Latin-American LCI included in Ecoinvent 3.3 used to model imported copper.

4.3. Results and discussion

4.3.1. Life cycle impact assessment

The Life cycle impact assessment (LCIA) includes results for the five selected impact categories.

4.3.1.1. Vehicles

Figure 19 compares the overall results, for both SOFC vehicle setups, to the PEMFC Toyota Mirai depicted by Miotti et al.(2017). Planar and tubular SOFC configurations were included to describe the contribution per component. As a whole, the impacts difference between planar and tubular schemes is small for every category. As expected, due to its larger mass share, the vehicle body along with the powertrain turned out to be the largest contributor for every IC. Significant amounts of steel, aluminum and other metals are the most relevant materials.

Considering its large mass, the 24 kWh NMC battery (ELSEVIER, 2016; NISSAN, 2016c) implies a considerable impact for each IC. Battery mass reduction implies diminished EIs, which is achievable by switching design parameters from energy density to power density. Indeed, Kadyk et al.(2019) emphasize that the improvement of the specific power of the FC is a deciding factor for lowering the energy system mass. To visualize the consequences of such reduction, an additional case for a SOFC including a 28 kW battery -47 kg using a 2x safety factor- designed for power density as in Miotti et al.(2017) is depicted in Figure 19. Moreover, although there is evidence suggesting that the FC unit is not the dominant contributor to EIs, results must be analyzed cautiously as the specifics of its manufacturing process and even the specifics of materials fabrication are scarce and out of date, as perceived in Karakoussis et al. (2001).

The FCS and the BoP displayed little contribution compared to total impacts. The planar set-up is more relevant for MRS due to the large amount of chromium alloys added to deal with high temperatures. Tubular configuration presents larger impacts for GWP as manufacturing process requires nearly 8 times more energy than planar FCS mainly for plasma spraying and electrochemical vapor deposition processes (KARAKOUSSIS et al., 2001); however it was not significant for total results per vehicle. In general, the impact reduction between current and 2030 scenarios for SOFC car was smaller than the reduction observed in the PEMFC car. This was expected as the LCI proposed by Miotti et al.(2017) in 2030 supposed an optimistic scenario, based on mass production of 500,000 units per year; in contrast, our assumptions had to be conservative considering a mere mass reduction for FCS and BoP, given that the vehicle is not even commercially available.

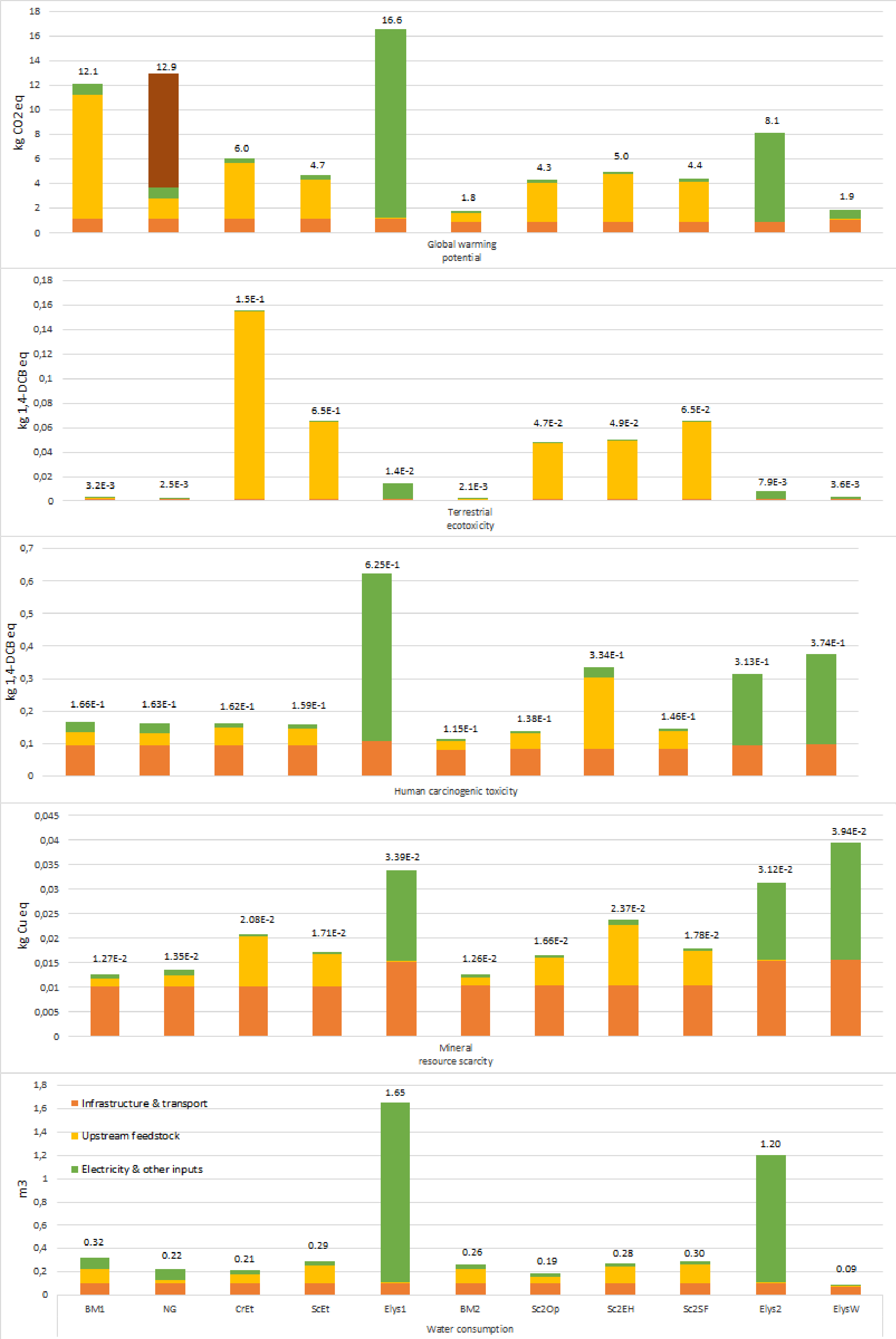
Figure 19. Contribution of different vehicle subsystems to the impact of 1 SOFCV for current and 2030 scenarios. Results for two configurations are displayed. PEMFC car presented by Miotti et al (2017) are included for comparison.

4.3.1.2. Hydrogen production

Figure 20 depicts the detailed contribution of the various components involved in producing 1 kg of hydrogen, available at the refueling station, for use in the PEMFC vehicle. The LCIA includes the infrastructure required for hydrogen distribution as seen in section 4.2.3.4. For GWP, the routes based on bioethanol reform, backed by its biogenic-carbon nature, are only outperformed by wind-electrolysis and biomethane steam reform in 2030.

Indeed, merging hydrogen production from biomass with carbon capture and storage could result in carbon negative emissions. As biomethane was considered as a burden-free feedstock, the CO_2 emissions linked to hydrogen production were not included. However, the complex processing of biomass signifies increases the likeliness of resulting in a more expensive way of producing low-carbon hydrogen than renewable-based electrolysis (INTERNATIONAL ENERGY AGENCY, 2019b). Moreover, fossil carbon emissions render natural gas reform as the worst alternative along with the energy intensive AE. In general, for GWP, routes evaluated for 2030 scenario offered an impact decrease when compared to current scenario.

Regarding TE, the largest impacts are displayed by all bioethanol reform routes, especially corn. Such impacts arise from the crop stage and its pesticides use. For the rest of ICs, the electrolysis is largely penalized due to its intensive electricity use, even for scenario 2030. Special attention should be paid to the fact that the electricity mix in 2030 exhibits larger shares of wind, solar, biomass and small hydro, but less of hydroelectricity and a larger dispatch of natural gas, meaning that 2030 AE will not be considerably less pollutant than current AE. The contribution of hydrogen distribution infrastructure and logistics is more relevant for HTC and MRS. Elevated WC impacts from AE are due to the large use of water for hydroelectricity.



kg CO2 eq
12.1
12.9
6.0
4.7
16.6
1.8
4.3
5.0
4.4
8.1
1.9
Global warming potential
kg 1,4-DCB eq
3.2E-3
2.5E-3
1.5E-1
6.5E-1
1.4E-2
2.1E-3
4.7E-2
4.9E-2
6.5E-2
7.9E-3
3.6E-3
Terrestrial ecotoxicity
kg 1,4-DCB eq
1.66E-1
1.63E-1
1.62E-1
1.59E-1
6.25E-1
1.15E-1
1.38E-1
3.34E-1
1.46E-1
3.13E-1
3.74E-1
Human carcinogenic toxicity
kg Cu eq
1.27E-2
1.35E-2
2.08E-2
1.71E-2
3.39E-2
1.26E-2
1.66E-2
2.37E-2
1.78E-2
3.12E-2
3.94E-2
Mineral resource scarcity
m3
Infrastructure & transport
Upstream feedstock
Electricity & other inputs
0.32
0.22
0.21
0.29
1.65
0.26
0.19
0.28
0.30
1.20
0.09
BM1
NG
CrEt
ScEt
Elys1
BM2
Sc2Op
Sc2EH
Sc2SF
Elys2
ElysW
Water consumption

Figure 20. Contribution of different components to the impact of producing 1 kg of hydrogen by each route. Fossil emissions refer to emissions during methane reform process. For electrolysis “Upstream feedstock” includes the water and the electrolyzer

4.3.1.3. Results per km

Figure 21 summarizes the results per km for PEMFC and SOFC vehicles. Impacts are displayed for the different life cycle stages, for current and 2030 scenarios. The case for hydrogen production to be used in PEMFC cars turned out to be disadvantageous, for GWP, compared to current BEVs and ethanol-fueled ICEVs. In fact, if PEMFC vehicles were to use hydrogen produced by AE or NG steam reform it would result in similar impacts compared to a gasoline-fueled ICEV. However, there is a pattern change in 2030 as landfill biomethane and ethanol-based routes offer GWP mitigation even when compared to BEVs run on 2019 electricity. Wind-based AE in 2030 would be competitive compared to current ethanol-fueled ICEVs.

For current scenario, SOFCs turned out to be more competitive than every PEMFC case; however, as the forecast vehicle evolution is much less aggressive than for PEMFC car, the impacts in 2030 are slightly higher compared to most of PEMFC routes. It is straightforwardly concluded that any improvement in the vehicle would result in a larger environmental competitiveness. Aiming to visualize such case, an additional pathway (Opt Bat) for a SOFC car with a 28 kW NMC battery, designed to fulfill power density requirements as in Miotti et al.(2017), was included. This pathway included 2G ethanol from an optimized mill and resulted in a more competitive vehicle as expected. Nevertheless, the current ethanol-run ICEV remained the option with less impacts assuming that the biofuel does not come from deforested areas.

Furthermore, notoriously, every ethanol-related route is linked to larger TE impacts, due to the agricultural stage. In contrast, every methane reform case turns out to be competitive in this aspect. HTC and MRS presented little contributions from any life cycle stage other than vehicle production, whose impacts completely dominate both ICs. Regarding WC, the AE is by far the route with the larger impacts due to the large presence of hydroelectricity in the mix.

Figure 22 depicts the sensitivity analysis for GWP for selected pathways in 2030 scenario. As expected, every vehicle improvement represents a significant contribution, except for pathways where fuel production presents a large contribution to the total burden as in Elys2.

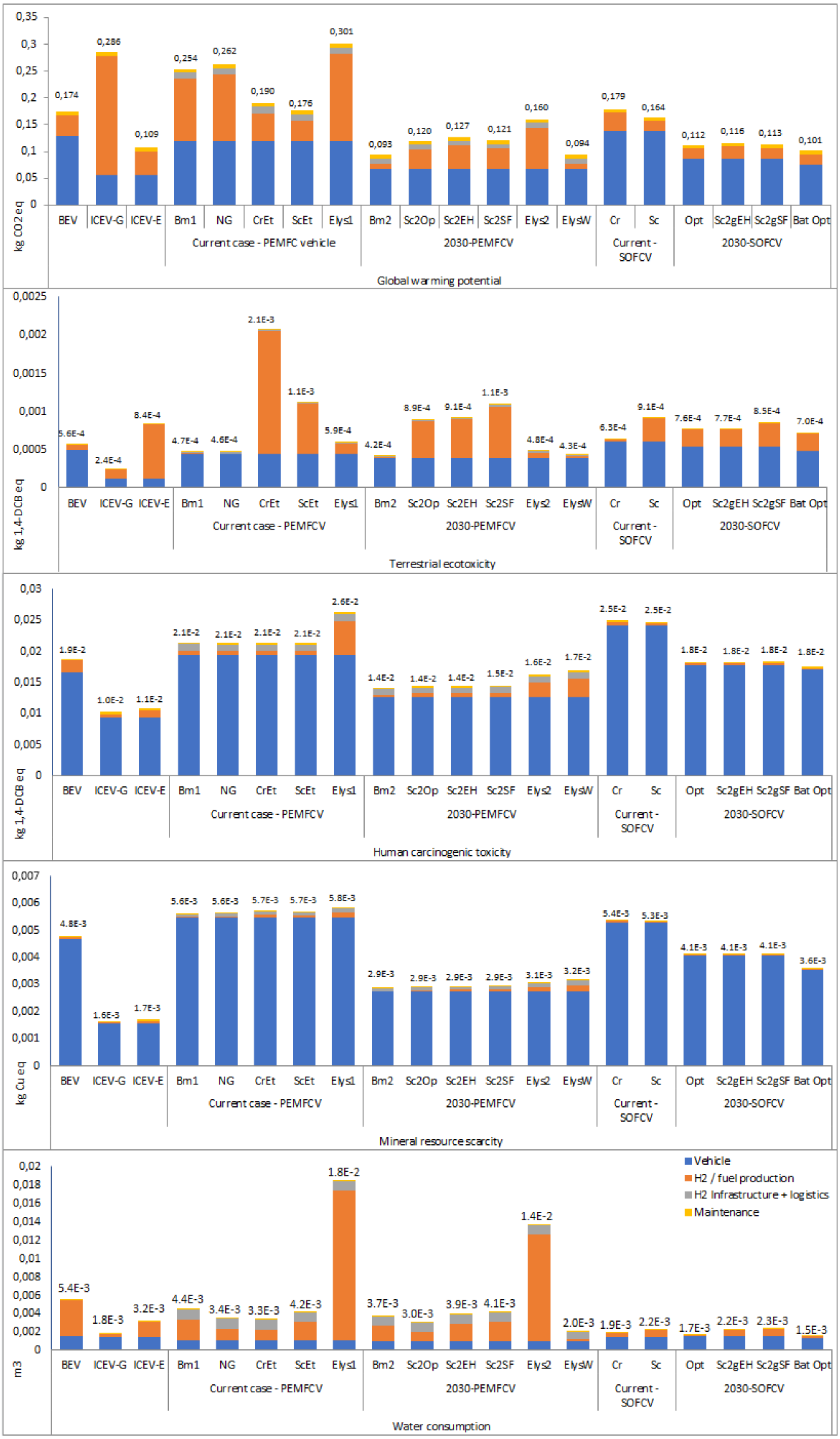


Figure 21. Contribution of different lifecycle stages to the impact of driving 1 km for the current and 2030 scenario. BEV and ICEV fueled with Gasoline E22 and Sugarcane ethanol included for the sake of comparison. SOFC vehicle is based on a planar

configuration. Bm1: Biomethane current scenario; NG: Natural gas; CrEt: Corn ethanol; ScEt: Sugarcane ethanol 1G; Elys1: Electrolysis current scenario; BM2: Biomethane 2030; Sc2Op: Sugarcane ethanol 1G, optimized mil; Sc2EH:Sugarcane ethanol 2G enzymatic hydrolysis; Sc2SF Sugarcane ethanol 2G syngas fermentation; Elys2: Electrolysis 2030 scenario.; ElysW: Wind-based electrolysis; Cr: Corn ethanol-fueled SOFC; Sc: Sugarcane ethanol-fueled SOFC; Opt: Optimized distillery, sugarcane ethanol-fueled SOFC; Sc2EH: 2G enzymatic hydrolysis, Sugarcane ethanol -fueled SOFC; Sc2SF: 2G syngas fermentation Sugarcane ethanol fueled-SOFC; Bat Opt: SOFC vehicle with a 28 W Battery using 2g ethanol from optimized distillery.

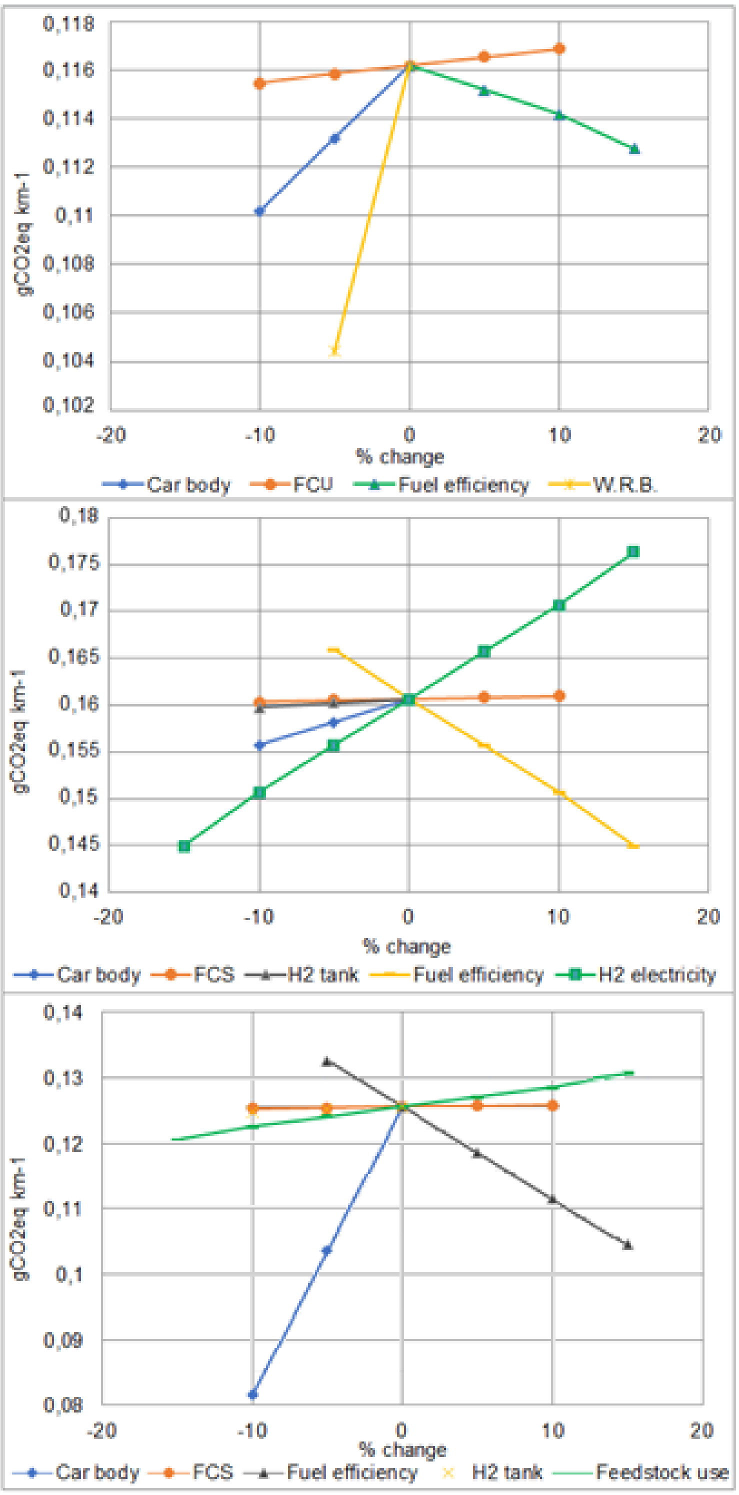


Figure 22. Sensitivity analysis for GWP displaying selected pathways in 2030 scenario. SOFC car fueled with Sc2EH (Up); PEMFC vehicle fueled with H_2 from Elys2 (middle) and PEMFC vehicle with H2 from Sc2EH (down). FCU refers to fuel cell unit weight reduction while car body implies powertrain and glider weight reduction. WRB refers to the vehicle curb weight reduction due to the use of a lighter 28 W-47 kg battery. Fuel efficiency improvements are considered in kg km^{-1}. H_2 electricity refers to kWh kgH_2^{-1}. Feedstock use refers to bioethanol inputs for H_2 reform kg ethanol kgH_2^{-1}.

4.4. Discussion

It is worth emphasizing that the proposed hydrogen production pathways in 2030 are not expected to represent average production conditions. Instead, such pathways describe what the authors believe to be feasible advanced alternatives, which could be commercially available, at a certain degree of maturity. Indeed, 1G corn and sugarcane ethanol production could become more competitive, given larger production volumes in 2030.

The potential of some pathways to become more competitive is clear. For instance, biomethane compression and upgrading for current scenario was based on currently available pressure swing adsorption technology which presents 8% methane leakages, the largest contributor for GWP results. Despite being a mature technology, there are other readily available options which could imply less biomethane losses. Additionally, our assumptions of landfill gas being flared on-site although realistic, do not describe all of the Brazilian disposal sites; thus, biomethane captured from a landfill without flaring infrastructure could result in net carbon credits.

In the same way, if bioethanol reform routes were to be jointly used with a carbon capture and storage scheme to treat the biogenic CO2 emissions, the result could be a hydrogen fuel with a negative carbon footprint. Furthermore, in case of the oxygen produced via AE is completely captured for use, instead of vented, the impact of allocation would result in a hydrogen with less burden. It is uncertain how this technology will evolve, but the dominant technology for electrolysis could switch to PEM electrolyzers, which is more compatible with the electricity generated by renewables (INTERNATIONAL ENERGY AGENCY, 2019b).

As HTC and MRS are ICs completely dominated by the vehicle production, any impact mitigation is likely to be bound to weight reduction, material switching or greater manufacturing efficiency due to the mass production of vehicles. This is expected to happen anyway as FC vehicles are a novel technology in the early phases of the learning curve. Water consumption displays large impacts for the PEMFC car fueled with AE-based hydrogen due to the large share of hydroelectricity in the electricity mix, which is accounted by ReCiPe. Furthermore, TE is completely dominated by bioethanol reform routes, more specifically, the agricultural stage of the feedstocks and their pesticides use and subsequent emissions to air, water and soil.

Regarding the vehicles, the findings suggest that the FC is the dominant source of impacts for neither PEMFC nor SOFC vehicles. Thus, body weight and battery reductions will continue to be a path for impact mitigation assuming that life expectancy will not significantly improve, at least in the next decade. However, in order for PEMFC technologies to become a real feasible option for use in Brazil, the technologies should become affordable, a challenging task considering that the technology has not reached the same level of technological maturity as ICEVs or even BEVs: financial feasibility is still far away. For instance, for PEMFC technologies, the acquisition cost of the vehicle varies from 70% to 95% of the TCO, hence, diminishing the cost of the car, specifically, the FC unit and the hydrogen storage tank and is crucial to reach cost competitiveness with BEVs and ICEVs (INTERNATIONAL ENERGY AGENCY, 2019b). Even for public transport, FC technologies to be used in the city of São Paulo, could result in 90% cost increase compared to standard busses (SLOWIK et al., 2018).

Costs, and also environmental burdens per vehicle, could be reduced through economies of scale, increasing the number of units fabricated in a manufacturing plant thereby reducing the specific cost of each component. The International Energy Agency (2019) calculated that the cost of components within the FCS could be reduced by 65% by increasing plant scale from 1,000 to 100,000 units per year, reaching a critical threshold cost of USD 50/kW.

However, increasing FCV production seems unlikely right now as the automotive industry was astounded by the COVID-19 pandemic, which plummeted car sales globally. For many economies, the chances of a quick rebound vanished and recovery will likely depend on several factors, including how confinement measures affect customer capacity and willingness to purchase new vehicles, the possibility of more waves and the pace of economic recovery (INTERNATIONAL ENERGY AGENCY, 2020b). Despite of this, BEVs turned out to have a better 2020 than ICEVs, perhaps because the BEV buyer still tends to be wealthier than the average consumer and might be less affected by the economic downturn (International Energy Agency, 2020d).

Additionally, a cost intensive, technically challenging, hydrogen distribution infrastructure had to be rolled out, creating a chicken-and-egg-dilemma situation alike to that of BEVs, but potentially more expensive, complex and at higher environmental consequences (AGOSTINI et al., 2018). Analogous to BEV public charging infrastructure, HRS costs depend on utilization rates (INTERNATIONAL ENERGY AGENCY, 2019b), severely punishing small fleets. Although in early stages of deployment, HRS could serve private fleets, guaranteeing high utilization rates, the risks of such investments would likely require articulation between stakeholders and new business models. For instance, in Germany, H2Mobility HRS are built on a joint venture between carmakers, fuel suppliers and HRS manufacturers (INTERNATIONAL ENERGY AGENCY, 2020c).

Articulation between many actors in Brazil looking forward to promote hydrogen infrastructure or hydrogen use in general is unlikely now as it has been in the past. In 2002 the Brazilian fuel cell research program (ProCac) was released. ProCaC was aimed to consolidate efforts and improve efficiency, however, as de Andrade & Lorenzi (2014) reported, after the

ProCac was released, the MCT took charge of the projects with delaying effects. Afterwards, ProCaC was rearranged as ProH2 with little improvement.

In May 2009, the Center for Management and Strategic Studies (2010) (CGEE) published the Roadmap for structuring the Hydrogen Economy in Brazil (RHEB). Despite not having a noticeable impact, this study highlighted that water electrolysis, ethanol reform and biomass-related processes should be prioritary since they allow the use of low-added-value by-products, diversifying the sources of hydrogen. In fact, water electrolysis could play a central role in countries with a low-carbon electricity mix, as in Brazil. PEM electrolysers could be a feasible option in the future, despite being at an earlier stage of development than alkaline electrolysers, as they offer more compatibility with variable renewable electricity generation (INTERNATIONAL ENERGY AGENCY, 2020a). Nonetheless, the impact of the roadmap was also little.

Understanding that Brazil, as other emergent economies, is usually a follower of trends on energy and transportation, it could be argued that those initiatives arrived at a time when the tide was ebbing for hydrogen development. In fact, during those years, the Obama administration started heavily investing in Li-ion batteries R&D (THE WHITE HOUSE, 2016) in contrast to the Bush administration which had engaged in hydrogen promotion (OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY, 2005).

More recently, the MCT stated that, in order to diversify the renewable shares in the electricity mix, Brazil ought to promote studies on the potential of, among others, renewable-based hydrogen. It also highlighted the need to articulate the research and networking efforts focusing on hydrogen (MCTIC, 2018). Actually, other countries in the region have recognized the need for research. At the recent Latin-America Ministerial Roundtable, national ministers pointed to hydrogen as a promising energy carrier for energy transitions in the region (International Energy Agency 2020d). Articulation is crucial in order to take advantage of the extensive research and development from Brazilian institutions, although production never reached large scale. FC related research in Brazilian institutions can be found in Hotza & da Costa (2008).

Considering that any scenario of massive adoption of PEMFC vehicles would likely be part of an emergent hydrogen-based market ecosystem and that could take decades to arrive even in optimistic scenarios, the emergence of the SOFC prototype represent a clear option to meet the objectives of the RHEB. Despite of the technical challenges related to SOFCs' high functioning temperature, such as long start-up times and high costs, it would become a technology able to offer a smooth synergy between biofuels and new technologies in transportation. The irruption of transport electrification has been a matter of concern for some sectors in Brazil.

It has been argued that if BEV or FCV adoption relies on imported technology it would jeopardize priority aspects, such as bioenergy technology leadership, job creation and the balance of payments. Hence, the transport revolution ought to recognize the Brazilian singularities and avoid destroying value added locally and contribute to prevent dependence on foreign inputs or technologies (CNPEM, 2018; TEIXEIRA, 2018; VASCONCELOS, 2017; VELANDIA VARGAS et al., 2020).

From an environmental point of view, the case for SOFC vehicles is also strong as depicted in Figure 21. In contrast to PEMFC technologies, the high temperatures rescind the necessity of precious metals catalysts. Moreover, it is an efficient system with many less stages compared to PEMFC technology, knowing that compression, transport and cooling of hydrogen imply losses and efficiency decrease. This without mentioning the economic aspects of hydrogen distribution; even for centralized stations. Furthermore, the ability of this technology to use the already existent fuel distribution infrastructure creates an enormous difference since the burden of new infrastructures for hydrogen management should be allocated to the PEMFC vehicle transport per km. Whether Brazil manages to become leader in SOFC technology would also imply keeping a strong automotive sector and become an exporter for regions already producing biofuels.

4.5. Limitations

The results of this study strongly depend on the availability and quality of data and also on assumptions made by the authors. The use of data representing other geographies subsequently adapted to Brazil is a source of uncertainties. Data for steam and ethanol reform processes represent the best effort of modelling by NREL's H2A project (2018); However, emissions other than CO_2 and parameters for centralized reform of ethanol are missing as well as forecasts for technology evolution. Regarding the vehicle, we need to emphasize the lack of updated information for SOFCs as Karakoussis et al. (2001) study is now two decades old; besides, it does not include emissions for the manufacturing process. LCIs for materials used for FCS are absent from literature (HYTECHCYCLING, 2018) while EOL information is also scarce and incomplete (HYTECHCYCLING, 2017b). Finally, the scarce information of the SOFC prototype regarding the fuel cell and other components lead us to assume mass shares and FC configuration.

4.6. Conclusions

According to our vehicle and fuel production assumptions SOFC vehicles could become a competitive alternative for impact mitigation in 2030, performing better than a current BEV. As the fuel cell does not appear to be the main contributor for any IC, except for MRS, the impact reduction is more likely to happen via weight reduction or mass production as larger production volumes reduce the environmental burden per vehicle by increasing manufacturing efficiency. Terrestrial Ecotoxicity linked to hydrogen production is largely associated to agricultural stages in bioethanol supply chain. As today, PEMFC vehicles would not be competitive for any evaluated category. For GWP, they perform as bad as gasoline-fueled ICEVs.

Biomethane and bioethanol-based hydrogen production pathways in 2030 bear potential to become net carbon sinks depending on the landfill gas treatment and the existence of a carbon capture scheme respectively. Under our assumed scheme (a centralized hydrogen production) the distribution infrastructure was not a large contributor on a per km basis. Nevertheless, the necessity to build a network at a country level would demand a large energy and material investment which could be avoided under the SOFC vehicle scheme. The environmental modelling of the SOFC is bound to uncertainties due to the lack of data. For GWP, the current ICEV ethanol car is competitive even for 2030 technologies, assuming the land does not come from deforestation.

5. CLOSURE

An increasing number of emergent low-carbon technologies are poised to transform the transportation sector as these words are written. The urgency to tackle some of the negative consequences of using conventional fossil-fuel technologies, *e.g.* poor air quality and emission of greenhouse gasses, has promoted the rise of alternative fuels and powertrains. In this context, this study is an effort to quantify the environmental consequences of diverse powertrains and fuels within the Brazilian context by means of applying the LCA methodology. This research aimed mainly to quantify the environmental impacts of BEVs and FCEVs used and manufactured, at least partially, in Brazil. For the sake of comparison, ICEVs, powered by biofuels and fossil fuels were also modelled. BEBs and ICEBs were also part of the analysis.

The main hypothesis in this thesis was stated as: The Brazilian specific features are favorable enough for BEVs and FCVs to display a better environmental performance than any conventional powertrain. The evidence included in the results strongly suggests that the hypothesis is not true, or to put it another way, the answer will depend in the impact category to be evaluated. For instance, as the Brazilian mix is less reliant on carbon-based sources, global warming mitigation is observed as a function of electricity use in manufacturing processes, however, a larger recycling of aluminum causes larger ozone depletion issues, at the vehicle level. Although vehicle manufacturing in Brazil implies less carbon emissions, because of the mix, it is not sufficient to guarantee that, on a life cycle perspective, the manufacturing advantages could be enough to guarantee the superiority of BEVs or FCVs.

In spite of offering a real option for impact mitigation for several impact categories, it cannot be stated that, for every case, BEVs and FCVs present lower impacts than conventional powertrains. The good performance of ICEVs fueled with sugarcane bioethanol is a good example. Special attention should be given to the origin of the biofuels, if deforestation is involved; the main hypothesis is likely to turn true in every circumstance.

The second paper included in this thesis evaluated two lightweighting scenarios, considered to be, not only feasible, but also likely choices of material composition in light-duty vehicles. The first scenario considers an aluminum-based vehicle whereas the second one depicts a vehicle with a higher share of polymers. In addition, evolution in battery energy density was included. The study also analyzed weight reduction for busses, whose material shares and battery chemistry differ from light-duty vehicles. Moreover, this first LCA study aimed to look for the EIs beyond the current supply chain and proposed the national manufacturing of the vehicles, except for the battery cells. This was modelled by adapting global average LCIs to local conditions.

The local production of the vehicles would signify an important step forward in the perception of new transportation technologies in the country. The landscape is complex in many aspects, including the high initial investments for such vehicles and the lack of charging infrastructure. Furthermore, a part of the automotive and bioenergy sectors tend to see transport electrification as a threat for local jobs and revenues. Those sectors exhibit plenty of investments in *flex-fuel* engines and massive infrastructures for sugarcane ethanol and soybean biodiesel production. This discussion is addressed in the first paper of thesis.

A path to overcome the negative socioeconomic impacts of transport electrification in Brazil would be to employ powertrain technologies able to promote a synergy between biofuels and transport electrification. The use of FCEVs is a technically feasible option for such synergy. Thus, the third paper linked to this PhD research quantified the EIs of PEMFC vehicles propelled by hydrogen obtained from biofuels' reform and other technically feasible pathways. In addition, the paper also quantifies the impacts of the use of SOFC vehicles, a breakthrough technology, which is not commercially available but at least one prototype has been under testing for nearly five years.

Both SOFC and PEMFC powertrains were modelled for current and future scenarios aiming to quantify the potential gains of vehicle weight reduction, battery energy density evolution and fuel cell improvements. In addition, several pathways for hydrogen production were also included for current and future scenarios. Biomethane and bioethanol-based hydrogen production pathways in 2030 bear potential to become net carbon sinks depending on the landfill gas treatment and the existence of a carbon capture scheme respectively. Under our assumed scheme (a centralized hydrogen production) the distribution infrastructure was not a large contributor on a per km basis. Nevertheless, the necessity to build a network at a country level would demand a large energy and material investment which could be avoided under the SOFC vehicle scheme. Despite of the SOFC car data being scarce, the study modelled the vehicle and the fuel cell based on literature about SOFC technologies. Fuel consumption and perspective for fuels evolution were evaluated based on own assumptions and knowledge of the sector.

Regardless of not being part of the scope of this study, hybrid vehicles could be one option for EIs mitigation, as long as the technology is affordable enough to be massively adopted. The global boost on li-ion batteries performance seems to suggest that pure BEVs are likely to take the stage; however, hybrids should not be discarded for specific cases like Brazil.

From a LCA viewpoint, the characterization of up-to-date SOFCs remains to be done by future research. However, in order to actually consider SOFC vehicles as credible options for passenger transport it is necessary to guarantee the technical and financial feasibility of the cars. Furthermore, more research must be done to explore the potential of Brazil to integrate into the emerging hydrogen market; areas with considerable wind or solar generation potential are not scarce in a continental country. Nonetheless, perhaps the first efforts should be steered on how to actually get the investments and the level of integration required between stakeholders to assure the viability of the projects.

Several limitations of the study must be highlighted. For instance, inherent to the nature of any bibliographic review, the first paper gathered information about the current Brazilian landscape for

BEVs adoption. Such work is likely to become outdated after some time, this is particularly true for this case, in which technologies and markets are portrayed. Regulation changes, technological breakthroughs and even extraordinary events as the Covid-19 outbreak are prone to be game-changers even in brief periods of time.

Regarding the second paper it is necessary to emphasize that the regionalization of global datasets is a time-intensive process that could get quickly outdated as changes in the production routes vary, depending on the availability of technologies or financial affairs. For most of the impact categories, the difference between the characterization results for the Brazilian and the global average vehicles were less than 5%, rising questions about how worthy this kind of effort is, based on the results variability. In the future, this could be worked around by implementing dynamic datasets based on Big Data, probably the next step for LCA practitioners.

Overall, this research struggled to get up-to-date data, specifically for the vehicles, as many of the technologies are still a novelty and manufacturers are not keen to reveal information that could squander their competitive advantages. For example, the data for the SOFC is, to be generous, scarce, while for the SOFC EoL no data at all was found.

Finally, it must be stated that the results of this work are by no means definitive and changes might appear in the future. The environmental performance of vehicles, fuels, electricity and their supply chains are constantly evolving rendering any kind of prediction very difficult and subject to large uncertainties.

The conclusions arising from this study allow the author to suggest new research directions. Once the potential for EI mitigation, for every proposed technology was initially quantified, a natural next step would be to evaluate the uncertainties of such results to further clarify the environmental advantage of any given technology. Afterwards, the techno-economic viability of any of the proposed alternatives for transportation must be guaranteed. Furthermore, it must be quantified what would be the environmental gains of a change in local fleets: How could electrification aid Brazil in order to fulfill the NDC from the Paris agreement.

Moreover, one safe bet for Brazil would be to explore how to create a synergy between transport electrification and biofuels use. Such studies must cover not only the techno-economic sphere, but also the social one.

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A. APPENDIX 1 – PARAMETERS FOR INTERNAL COMBUSTION ENGINE VEHICLES MODELLING

A.1. INTERNAL COMBUSTION ENGINE VEHICLES

A.1.1. Well-to-Tank phase

Aiming to provide further reference for Brazilian context we included an ICEV to be driven first by gasoline and then by sugarcane ethanol. Parallelly we included an internal combustion bus but only propelled by Diesel. General parameters defining conventional vehicles are presented in Table 11.

A.1.1.1. Ethanol

Brazil is the largest producer of sugarcane ethanol in the world. This, along with large swaths of agricultural land and the energy crisis during the last half of the twentieth century stimulated the federal government to encourage ethanol widespread use in local automotive market. This later led to the development and massive adoption of *flex-fuel* engines which can run on both, gasoline and hydrous ethanol. Therefore, to more accurately portray the Brazilian conditions it is necessary to model the two available market options. For hydrous ethanol we considered sugarcane plantation conditions in Brazilian south east in which is usual the utilization of filtercake and vinasse for fertilizing. Southeast condition shows no further use of water for irrigation. Fertilizer application and plant emissions were modelled as in Cavalett et al. (2013). Industrial stage of the sugarcane production in Brazil commonly implies the coproduction of sugar and the use of bagasse in a cogeneration plant, which is able to export electricity to the grid. In this case energy allocation was employed. Inputs for agricultural and industrial stages are based on research containing a comprehensive data collection (SEABRA et al., 2011).

A summary of the inputs for sugarcane cultivation is seen in Table 12 whereas Table 13 presents inputs required to process one ton of sugarcane. Land used for plantation in Brazilian south-east does not originate from deforestation, thus, it is coherent to consider the containing carbon to be part of planet's short cycle, just like all biofuels. Hence CO_2 emissions from sugarcane ethanol combustion in the *flex-fuel* engines are disregarded. Transportation of sugarcane to refinery is considered as 21 km and distribution was considered as 400 km.

Table 11. General parameters for vehicles modelling and use phase.

	Conventional Bus	**Conventional Vehicle**
	Vehicle	
Vehicle weight	12,180 kg	1,282.5 kg
Fuel	Diesel + AUS 32 (aqueous urea solution). 5% of diesel consumption.	Gasoline E22 (G22) or Hydrous ethanol (ETOH)
Vehicle performance	2.1 km L^{-1}	Gasoline: 12.35 km L^{-1} Ethanol: 8.7 km L^{-1}
Maintenance	17% of materials for assembly stage and 17% of energy required for assembly is required for maintenance throughout the life of the bus.	Ecoinvent dataset: *Passenger car maintenance, {RoW}| maintenance, passenger car | Alloc, Def, U.* One maintenance unit for each 150,000 km.
Life expectancy	880,000 km Bus	220,000 km ICEV
	Fuel & Use phase	
Fuel	Diesel	Gasoline E22 and hydrous ethanol
Sources	68.8% Replan (Paulinia, SP) 31.2% Reduc (Duque de Caxias, RJ)	G22: 68.8% Replan (Paulinia, SP) & 31.2% Reduc (Duque de Caxias, RJ). ETOH: Brazilian southeast mills.
Allocation	Energy	Energy for both G22 and ETOH
CO	0.479 g km^{-1}	G22: 0.2 g km^{-1} ETOH: 0.44 g km^{-1}
NMVOC	0.018 g km^{-1}	G22: 0.023 g km^{-1} ETOH: 0.019 g km^{-1}
Methane	0.06 g km^{-1}	G22: 0.006 g km^{-1} ETOH: 0.045 g km^{-1}
NOx	2.623 g km^{-1}	G22: 0.02 g km^{-1} ETOH: 0.01 g km^{-1}
Particulates	0.023 g km^{-1}	G22: 0.001 ETOH: N/A
N_2O	0.03 g km^{-1}	G22: N/A ETOH: N/A
CO_2	1.239 g km^{-1}	G22: 187 g km^{-1} ETOH: Considered nil
Aldehydes	N/A	G22: 0.003 g km^{-1} ETOH:0.009 g km^{-1}

Table 12. Inputs and field emissions per ton of sugarcane in Brazilian south-east.

Inputs			**Observations**
Nitrogen, as fertilizer	0.777	kg	
P_2O_5, as phosphate fertilizer	0.249	kg	
Potassium chloride, as K2O	0.98	kg	
Dolomite, application	5.183	kg	
Herbicide, application	0.044	kg	Glyphosate
Pesticide, application	0.004	kg	
Harvester production	0.045	kg	
Tractor, 4-wheel, agricultural	0.028	kg	LHV 42.61 MJ/kg
Energy, from diesel burned in machinery	171.72	MJ	Does not include transportation
Emissions			
N_2O from filtercake	7.45	g	Yield 86.7-ton ha^{-1}. Harvested area 72%
N_2O from unburned trash	9.62	g	140 kg dry ton^{-1}
N_2O from vinasse	3.94	g	
N_2O from plant roots	10.03	g	

Table 13. Inputs required to process one ton of sugarcane and coproducts.

Coproducts			Observations
Hydrated ethanol 95%	27	kg	Allocation percentage: 35.4%
Anhydrous ethanol 99%	13.4	kg	Allocation percentage 18.9%
Sugar	54.2	kg	Allocation percentage 40.7%
Bagasse	8.7	kg	Allocation percentage 3.1 %
Electricity	10.7	kWh	Allocation percentage 1.9 %
Inputs			
Brazilian Sugarcane	1,000	kg	
Lubricating oil	0.0103	kg	
Sulfur	0.169	kg	Each sugar bag is 50 kg
Lime	0.88	kg	
Sulfuric acid	0.468	kg	
Sodium hydroxide	0.065	kg	Evaporators
Sodium hydroxide	0.132	kg	Neutralization
Bagasse burning in boiler	255.28	kg	Emissions as in GREET (2016)

A.1.1.2. Gasoline and Diesel

Brazilian gasoline and diesel production was modelled including upstream available information which contains oil exploration, extraction and transport, from off-shore and on-shore facilities, as well as importation sources (D'AGOSTO, 2004; DA SILVA, 2013). Data contains information from two of the largest refineries in the country, namely, Paulinia refinery (Replan) and Duque de Caxias refinery (Reduc), we assumed this production to represent Brazilian oil refining. Table 14 displays the sources of oil coming to Replan and Reduc used for refining. Since there is no Brazilian LCI for oil extraction on Ecoinvent we decided to use Norwegian datasets because both extractions are carried out on deep waters, for offshore conditions, and similar conditions are found onshore too.

Energy allocation was utilized to assign the environmental burden of oil refining coproducts. A list of coproducts for Replan and Reduc is shown on

Table *15*. Commercially available Brazilian gasoline contains a share of anhydrous ethanol in concordance to local regulation (BRASIL, 2015e), which can be set by Government between 18% and 27%. We decided to model the Gasoline as having 22 % of anhydrous ethanol because engine emissions tests are calibrated for a 22% ethanol content. Although Brazilian regulation, valid for 2015, stipulated that commercially available diesel should be added with 7% of biodiesel by volume (BRASIL, 2017b) we decided not to include this share due to the negligible impact it may have along the total life cycle.

Table 14. Sources of oil used for Gasoline and Diesel refining in Replan and Reduc.

Refinery	**Importation shares**	**Source**	**Shares from each source**
REPLAN	17 % imported	Nigeria	68.8
		Saudi Arabia	31.20
	83% national	Brazil -offshore	91.4
		Brazil -onshore	8.6
REDUC	50 % imported	Nigeria	68.8
		Saudi Arabia	31.20
	50 % national	Brazil -offshore	91.4
		Brazil -onshore	8.6

Table 15. Gasoline and diesel coproducts in Replan and Reduc.

Coproduct	Production at Replan (kg)	Production at Reduc (kg)
Gasoline	192	142
Diesel	514	221
Fuel oil	72.9	311
Aviation kerosene	26.9	71
Naphtha	31.3	91
Liquefied petroleum gas	61.7	71
Asphalt	5	11
Petroleum coke	86.2	N/A
Lighting kerosene	0.7	N/A
Other coproducts from Replan	9.3	31
Lubricating oil	N/A	51
Other coproducts from Reduc	N/A	N/A

A.1.2. Vehicle production phase

A.1.2.1. Bus

Aiming to maintain coherence in the comparison between LCIs to be compared we decided to use the material composition presented for conventional diesel busses by Garcia Sanchez et al. (2013) which uses the same methodology than for BEBs. Since there was no lead acid battery LCI on Ecoinvent we created a dataset based on material content presented by GREET (2016). Energy requirements for assembly stage are considered as in the BEB according to the authors. Maintenance methodology is kept unaltered as well. Life expectancy was considered to be the same as the BEB C&B because of their similarities as previously seen.

A.1.2.2. Car

For ICEV modelling we used the Ecoinvent dataset “Passenger car, petrol/natural gas {GLO}| production | Alloc Def, U” which is based on a Volkswagen Golf A4 features; powertrain and engine shares per kg of car remained unaltered. It was assumed that this dataset is adequate to represent *flex-fuel* vehicles since this technology does not imply any representative material changes when compared to regular gasoline exclusive engines, thus, one single car LCI serves for both, ethanol and gasoline simulations. Furthermore, attempting to create a fair comparison between BEVs and ICEVs we adapted the chosen dataset to Volkswagen Spacefox trendline 1.68V mass. Car selection was made due to this model being available in Brazil, and mainly because it presents an analogous power to weight ratio. BEVs are in average 15 to 25% heavier than ICEV counterparts. In consonance, the Spacefox trendline 1.68V, was proposed to be about 20% heavier than the Leaf. Life expectancy was adopted as 220,000 km.

A.1.3. Tank to wheel

Use phase emissions per km for the diesel bus and for the gasoline and ethanol propelled ICEV are summarized in Table 11. For the ICEV we considered information provided by the national association of carmakers (ANFAVEA, 2016) for the Volkswagen Spacefox trendline 1.68V. Diesel regulated emissions were taken from the São Paulo report of vehicle emissions (CETESB, 2017a) whereas CO_2 emissions were calculated based on the national inventory of atmospheric emissions by road vehicles (AGÊNCIA NACIONAL DE TRANSPORTES TERRESTRES, 2014) considering a bus performance of 2.1 km L^{-1} and an emission factor of 2.603 kg CO_2 L^{-1}. It is important to remember that in order to diminish nitrogen oxides emission all heavy-duty transportation based on Diesel in Brazil requires the use of AUS 32 (aqueous urea solution) which represents 5% of diesel consumption. Any non-compliance of this requirement is punished by the federal law (CETESB, 2017b).

B. APPENDIX 2 – DATASET ADAPTATION TO BRAZILIAN CONDITIONS

B.1. DATASET ADAPTATION FOR RAW MATERIALS

B.1.1. Raw Materials

All adjusted datasets are displayed in Table 16.

Table 16. List of datasets used to represent materials extraction for BEV manufacture.

Process	**Ecoinvent original process**
Barite primary production, imported	Barite| primary production from concentrate | Alloc Def, U
Cobalt, imported	Cobalt sulfate as in Majeau-Bettez et al (2011)
Copper, Brazilian primary production	Copper {RLA}| production, primary | Alloc Def, U
Copper, imported	Copper {RLA}| production, primary | Alloc Def, U
Copper, from scrap cables	Copper {GLO}| treatment of used cable | Alloc Def, U
Copper, production from electrolytic refining	Copper {RoW}| treatment of scrap by electrolytic refining | Alloc Def, U
Copper, production from electronics scrap	Copper {RoW}| treatment of metal part of electronics scrap, in blister-, by electrolytic refining | Alloc Def, U
Ferrite, Brazilian primary production	Ferrite | production | Alloc Def, U
Gold, Brazilian primary production	Gold | production | Alloc Def, U
Gold, recycling from scrap	Gold| treatment of precious metal from electronics scrap, in anode slime, precious metal extraction | Alloc Def, U
Hard coal, imported from South Africa	Hard coal {ZA}| market for | Alloc Def, U
Hard coal, imported Russia &	Hard coal {RU}| market for | Alloc Def, U

Ukraine	
Hard coal, imported from USA	Hard coal {RNA}| market for | Alloc Def, U
Hard coal, imported from China	Hard coal {CN}| market for | Alloc Def, U
Hard coal, imported from Australia	Hard coal {AU}| market for | Alloc Def, U
Lead, recycling in Brazil	Lead | treatment of scrap acid battery, remelting | Alloc Def, U
Lithium manganese oxide, production	Lithium manganese oxide | Alloc Def, U
Lithium carbonate, production	Lithium carbonate | production, from concentrated brine | Alloc Def, U
Lithium fluoride, production	Lithium fluoride | production | Alloc Def, U
Lithium hexafluorophosphate, product.	Lithium hexafluorophosphate | Alloc Def, U
Magnesium, primary prod., imported	Magnesium {CN}|magnesium production, pidgeon process| Alloc Def, U
Manganese, primary product., imported	Manganese | production | Alloc Def, U
Nickel, Brazilian primary production	Nickel, 99.5% | nickel mine operation, sulfidic ore | Alloc Def, U
Palladium, primary product., imported	Palladium| primary production from concentrate | Alloc Def, U
Sulfuric acid, Brazil prod., sulfur route	Sulfuric acid | production | Alloc Def, U
Sulfuric acid, Brazil prod., metallurgical route	Sulfuric acid | nickel mine operation, sulfidic ore | Alloc Def, U
Sodium hydroxide, Brazilian production, membrane route	Sodium hydroxide, without water, in 50% solution state | chlor-alkali electrolysis, membrane cell | Alloc Def, U
Sodium hydroxide, Brazilian production, diaphragm cell route	Sodium hydroxide, without water, in 50% solution state | chlor-alkali electrolysis, diaphragm cell | Alloc Def, U
Sodium hydroxide, Brazilian production, mercury cell route	Sodium hydroxide, without water, in 50% solution state | chlor-alkali electrolysis, mercury cell | Alloc Def, U
Titanium dioxide, chloride process	Titanium dioxide {RoW}| production, sulfate process | Alloc Def, U
Titanium dioxide, sulfate process	Titanium dioxide | production, chloride process | Alloc Def, U
Silver, imported from Peru	Silver {PE}| gold-silver mine operation with refinery | Alloc Def, U
Silver, imported from Mexico	Silver {CL}| silver-gold mine operation with refinery | Alloc Def, U
Silver, imported from Belgium	Silver {RoW}| gold-silver mine operation with refinery | Alloc Def, U
Silver, Brazilian primary production	Silver | silver-gold mine operation with refinery | Alloc Def, U
Silver, production from scrap	Silver | treatment of precious metal from electronics scrap, in

	anode slime, precious metal extraction | Alloc Def, U
Zinc, Brazilian primary production	Zinc| primary production from concentrate | Alloc Def, U
Zircon, Brazil primary production	Zircon, 50% zirconium | heavy mineral sand quarry operation | Alloc Def, U
Zircon, primary production Imports	Zircon, 50% zirconium {RoW}| heavy mineral sand quarry operation | Alloc Def, U

B.1.1.1. Aluminum/Alumina

Aluminum and Alumina production are quite relevant for Brazilian economy. In 2015 Brazil ranked 11th within top global manufacturers for producing 772 Mt of primary aluminum, which makes up to 2% of total Brazilian exports, as per value. In the same way Brazil ranked as 3rd largest global alumina producer (ABAL, 2016).

For alumina inventory construction, we obtained data from ABAL (2016). It presents information on production inputs and alumina total production in the country. Values for required steam and flocculant consumption were absent from this document and then obtained from less up-to-date data (QUARESMA, 2009). Table 17 presents the inputs considered for Brazilian production and Ecoinvent subprocesses used in the model.

Air and water emissions, other than CO_2 from alumina manufacturing were calculated based on Ecoinvent alumina dataset. It establishes aluminum hydroxide production as a subprocess for alumina production. Total process emissions are attributed to production of one kg of aluminum hydroxide and not to one kg of alumina. It means that in order to produce one kg of alumina it is necessary to burn 1.53 kg of aluminum hydroxide. We scaled aluminum hydroxide energy inputs (heat and energy) emissions and by-products by scaling them by a factor of 1.53.

Due to the effect of rising electricity prices in the last years, many aluminum manufacturers have been stopping or delaying their production, namely: Alumar, Novelis do Brasil, Valesul alumínio, Alcoa alumínio (ABAL, 2016). Ecoinvent dataset for primary production of aluminum ingots is based on information from International Aluminum Institute (IAI) Area 3 data, which includes information from Brazil, Venezuela and Argentina. In order to model the production of 1 kg of primary aluminum we considered shares during 2015 for Søderberg (49.2%) and pre-baked (50.8%) routes. IAI Area 3 Prebaked anode and Soderberg datasets had their electricity and aluminum oxide inputs adjusted to Brazilian conditions. Aluminum primary ingots were assumed to be manufactured and transported from Pará state since it is the largest producer (QUARESMA, 2009).

Aluminum is typically found in the form of cast alloys and wrought alloys. Datasets for production of one kg of aluminum cast alloy and one kg of aluminum wrought alloys include an input of 64% from primary production and 36% from scrap (ABAL, 2016). Scrap production datasets “Aluminium, wrought alloy {ROW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | Alloc Def, U” and “Aluminium, cast alloy {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner | Alloc Def, U” were adapted to Brazilian conditions only by changing the electricity inputs.

Table 17. Dataset for production of aluminum oxide 1 t.

Inputs (Ecoinvent process)		
Bauxite, without water {BR}| market for | Alloc Def, U	2.223	t
Heavy fuel oil {RoW}| market for | Alloc Def, U	0.099	t
Sodium hydroxide, without water, in 50% solution state {BR}| market for | Alloc Def, U	0.096	t
Lime {BR}| market for | Alloc Def, U	0.011	t
Hard Coal imported to {BR}| market | Alloc Def, U	0.101	t
Steam, in chemical industry {RoW}| production | Alloc Def, U	2.75	t
Polyacrylamide {GLO}| production | Alloc Def, U	550	g
Tap water {RoW}| market for | Alloc Def, U	1.250	t
Aluminium oxide factory {GLO}| market for | Alloc Def, U	2.5E-11	p
Electricity / heat		
Electricity 2016, medium voltage {BR}| market for | Alloc Def, U	0.139	MWh
Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Alloc Def, U	4.110	GJ
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Def, U	5.020	GJ
Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Alloc Def, U	0.008	GJ
Heat, district or industrial, other than natural gas {RoW}| heat production, heavy fuel oil, at industrial furnace 1MW | Alloc Def, U	1.730	GJ
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Def, U	0.969	GJ
Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Alloc Def, U	4.06E-04	GJ
Heat, district or industrial, other than natural gas {RoW}| heat production, heavy fuel oil, at industrial furnace 1MW | Alloc Def, U	0.007	GJ
Electricity 2016, medium voltage {BR}| market for | Alloc Def, U	0.012	MWh
Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Alloc Def, U	2.1	GJ
Emissions to air		
Sulfur dioxide	3.7 E-03	t
Mercury	3.7 E-07	t
Carbon dioxide, fossil	0.611	t
Emissions to water		
Mercury	1.04E-10	t
Suspended solids, unspecified	2.3	t
Water, BR (ocean)	8.57	m3
Water, BR (river)	2.08	m3
Oils, unspecified	1.18E-03	t
DOC, Dissolved Organic Carbon	2.83E-05	t
COD, Chemical Oxygen Demand	7.02E-05	t
Sodium	1.96E-03	t

BOD5, Biological Oxygen Demand	7.02E-05	t
TOC, Total Organic Carbon	2.75E-05	t
Waste to treatment		
Redmud from bauxite digestion {RoW}| treatment of, residual material landfill | Alloc Def, U	1.24	t
Inert waste, for final disposal {RoW}| treatment of inert waste | Alloc Def, U	0.0232	t

B.1.1.2. Barite

In 2014 Brazilian production was nearly inexistent (DEPARTAMENTO NACIONAL DE PRODUÇÃO MINERAL, 2015). In order to simplify our model, we assumed all barite to be imported. Average transportation distances from Peru and Morocco were assumed as follows: 1,000 km truck, 2,000 km train and 8,000 km vessel.

B.1.1.3. Carbon fiber

No carbon fiber dataset is available at Ecoinvent. Dataset included as in Schmidt and Watson (2013).

B.1.1.4. Cobalt

Cobalt is almost always extracted as a byproduct of Nickel and Copper extraction (FARCHY; WARREN, 2018), hence, cobalt production used to actually depend on nickel and even copper prices. Brazilian production of cobalt was shut down during the last decade as a consequence of low prices of nickel in the international market along with high energy costs, however, the current soaring prices of cobalt are likely to lure mining companies into resuming operations once the prices are high enough (BATISTA, 2018; DEPARTAMENTO NACIONAL DE PRODUÇÃO MINERAL, 2015; INSTITUTO BRASILEIRO DE MINERAÇÃO, 2018). Based on production instability in Brazil and the dominant supply chain established by China we assumed that, even in the case of resuming local extraction, the salts used in the batteries are very likely to be produced in China from Congolese ore raw material. Transportation of cobalt ore to China was assumed as 2,200 km by truck and 12,500 by Vessel (GLOBAL MINING OBSERVER, 2018).

B.1.1.5. Copper

In 2014 Brazilian copper primary production was 213085 t, whereas imports originated mostly from Chile and Peru reached 210,052 t (DEPARTAMENTO NACIONAL DE PRODUÇÃO

MINERAL, 2015). We roughly assume that 50% of primary copper demand is satisfied via imported metal from those countries. Since Ecoinvent does not contain any specific LCI for Brazilian primary copper production we decided to use the most akin dataset available. In this case, we decided the most adequate dataset is the one that represents Latin-American production as a whole. Therefore, both imported and locally produced copper used the same dataset, only adjusting transportation.

Copper recycled from scrap represents about 26% of Brazilian total production (VASCONCELLOS, 2012) which means 74% comes from primary production. Inputs for one kg of recycled copper were considered as in Ecoinvent RoW production due to the lack of specific data: used cable 74.5%, scrap electrolytic refining 22% and treatment of electronics 3.5%. Transportation for scrap is considered to be 400 km by truck, non-empty return.
For imports transportation, it was considered non-empty return trip from northern Chile, represented as 8,000 km Vessel, 800 km train and 1,000 km lorry. Brazilian copper production, coming mostly from Bahia state was considered to present the following distances: non-empty 800 km train, 1500 km Vessel and 400 km lorry Recycling was considered as being 26% of consumed copper.

B.1.1.6. Ferrite

Only electricity and heat inputs in primary production dataset were adjusted. 600 km truck transportation from Minas Gerais state.

B.1.1.7. Gold

According to DNPM (2015) 52% of gold consumed in Brazil does have recycling as origin. Dataset for RoW production was adapted to better represent Brazilian conditions while gold scrap treatment in RoW dataset was kept with no adjusts. Minas Gerais was assumed as source of all Brazilian extraction.

B.1.1.8. Hard Coal

No anthracite is produced on Brazilian soil. Origin of hard coal imports is established as follows: South Africa 72.5%; Russia 3.3%; USA 0.9%; China 0.4%; Australia 11%; Ukraine 12% (VASCONCELOS, 2015). In order to simplify our model importation distances are considered for 1 kg of imported hard coal instead of calculating distances for each origin.

B.1.1.9. Lead

For 2014, Departamento Nacional de Produção Mineral (2015) reported that there was no primary production of refined lead; additionally, almost all secondary production of concentrated lead is exported. Taking this into account, we assumed all lead production as being obtained from lead recycling. This way, all lead comes from remelting of scrap. Acid battery scrap remelting dataset available in Ecoinvent was used. For transportation, a 400 km arbitrary distance was taken.

B.1.1.10. Lithium

BEVs manufacture requires materials that are less abundant than those needed for ICEVs. These include rare-earth metals for motor and lithium for batteries (IRENA, 2017a). The scarcity of such materials implies risks associated with resource availability leading to volatility of prices and unreliability on supply chains. This is an outstanding concern regarding future li-ion technology market penetration and massification.

The cost of a raw material is influenced, among other factors by its abundance. Biomass elements, such as H, O, S, P, Na, K, Ca, Mg, Mn, Fe and Ti are naturally recycled within the biosphere of the planet through exchanges with soil, air and water. This – in contrast to the main components of current Li-ion batteries, namely: Li, Co, Ni, Cu, F (LARCHER; TARASCON, 2015) – sharply supports the efforts toward chemical options based on other elements such as sodium, potassium and magnesium.

Furthermore, there is no current functional process that extracts lithium compounds from the waste li-ion battery material, mainly due to the low economic value of lithium. The sustainability of an expanding BEV supply chain is dubious if lithium recycling is not adopted, not only because of metallic lithium but also cobalt availability (GAINES; NELSON, 2010)

Lithium inputs for our BEB and BEV were assumed to come totally from Chile, only adjusting transportation distances and considering Chilean electricity mix included in Ecoinvent. This south American country owns earth’s largest known lithium reserves, which are extracted from brine. The USA, China and even Brazil also have opportunities for production, nevertheless, those reserves are still far from Chilean ones.

B.1.1.10.1. Lithium manganese oxide

All nitrogen and liquid oxygen inputs from different geographies were added to RoW. Lithium manganese oxide is produced in Chile and then imported to Brazil for $LiMn_2O_4$ cathodes. Process adapted to Chilean electricity generation mix.

B.1.1.10.2. Lithium carbonate

Used for lithium manganese oxide production. Considered to be produced in brine lakes and transported to Antofagasta region. All tap water inputs from other geographies added to RoW. Medium voltage Electricity mix from Chile available in Ecoinvent included since production takes place entirely in Chile.

B.1.1.10.3. Lithium fluoride

It is considered to be produced near to lithium hexafluorophosphate production plant. Process adapted to Chilean electricity generation mix.

B.1.1.10.4. Lithium hexafluorophosphate

All tap water inputs from other geographies added to RoW. Process adapted to Chilean electricity generation mix.

B.1.1.11. Magnesium

In 2014 beneficiated magnesite production in Brazil reached 1,152,233 t while apparent consumption was 1,191,336 t (DEPARTAMENTO NACIONAL DE PRODUÇÃO MINERAL, 2015). This leads us to believe that apparent consumption is mainly satisfied by national production. Under these conditions 97% of Magnesite consumed in Brazil comes from national production while the rest is imported from China. Silicothermic reduction (Pidgeon route) is broadly used in Chinese mining sector, thus, we used this dataset to represent imports. Metallic magnesium production in Brazil is also carried out by silicothermic route (RIMA GROUP, 2017) and is exclusively carried out by Rima Group (2009). We decided to employ RoW Pidgeon process dataset. Transportation in Brazil considered: 600 km lorry and 1000 km train. Transportation for imports considered 1,000 km lorry, 2,000 km train, 15,000 km ship.

B.1.1.12. Manganese

It was assumed that Brazilian primary production is enough to fully provide for local demand. Manganese extraction site is located in Minas Gerais state.

B.1.1.13. Nickel

About 87% of Nickel production in Brazil takes place in Goias and Bahia states. All Brazilian production was assumed to come from Nickel mine operation in the state of Goias. Nickel recycling was left aside since there is no evidence of nickel recycling in Brazil (DEPARTAMENTO NACIONAL DE PRODUÇÃO MINERAL, 2015). Transportation distance was considered as 1,000 km by truck and 2,000 km by train.

B.1.1.14. Palladium

Brazilian production volume was deemed as negligible DNPM (2015). All palladium consumed in Brazil is imported. Ecoinvent palladium production dataset was kept unmodified for this case, only transportation was modified. South Africa was considered as origin from imports.

B.1.1.15. Sulfuric Acid

Sulfuric acid is produced in Brazil by mainly two routes: metallurgical and sulfur. Galvani enterprises establishes shares for each route as 11.9% and 88.1% respectively (LOUREIRO, 2015). The datasets for both routes were adjusted.

B.1.1.16. Sodium hydroxide

There are three routes for manufacturing sodium hydroxide in Brazil. In 2009 Brazilian production shares were: Diaphragm cell 71%, mercury cell 25% and membrane cell 4% (VIANA, 2009) (more recent data was not found). Dataset for each route was adjusted to Brazilian conditions.

B.1.1.17. Pig iron

Pig iron is used for several applications besides steel. Since the data we gathered to construct an LCI for Brazilian steel did not allow us to disaggregate pig iron from steel production process, we decided to keep Ecoinvent pig iron dataset for the processes which need pig iron as an input.

However, we adjusted this dataset to Brazilian conditions. Transport was considered as 400 km non-empty return.

B.1.1.18. Titanium dioxide

Around 55% of consumed TiO_2 is produced in Brazil, via sulfate route, while the rest is imported and it is assumed to be produced via chloride route (DOS SANTOS, 2010). Sulfate process dataset was adjusted whereas chloride route was not.

B.1.1.19. Silver

Only semi-manufactured goods were considered for the estimation of apparent metallic silver consumption. Silver production from scrap in Brazil makes up to 11.8% of total apparent consumption while primary production sums 14.2%, therefore around 74% of silver consumed in Brazil is imported (DEPARTAMENTO NACIONAL DE PRODUÇÃO MINERAL, 2015). Imports come mainly from Mexico, Peru and Belgium. Because of the lack of specific data, Mexico process was modeled as Chilean, and Belgium as RoW. Aiming to simplify calculations we assumed all Brazilian primary production to take place in Pará state, and transportation distances for imported silver as: Vessel 6,000 km, train 2,000 km and truck 1,000. Transportation distance for silver scrap was assumed as 400 km.

B.1.1.20. Tin

About 89% of Brazilian Tin is produced in Amazônia and Rondônia northern states (DEPARTAMENTO NACIONAL DE PRODUÇÃO MINERAL, 2015). In order to simplify our transportation analysis, we assumed all production to come from those regions. In 2014 Brazil had the third largest metallic tin production in the world and its demand was less than 30% of total production, therefore it was considered that local production may satisfy local demand.

B.1.1.21. Zinc

According to DNPM (2015) primary metal production is larger than primary metal apparent consumption, hence, we assumed that the local production is enough to satisfy the total demand. Brazilian production was modelled by adapting production from concentrate dataset. Transport was assumed to be from North Minas Gerais.

B.1.1.22. Zircon

By comparing zircon primary production with apparent consumption data we estimated that 26% of Zircon consumed in Brazil is originated from imports (DEPARTAMENTO NACIONAL DE PRODUÇÃO MINERAL, 2015). In order to model Brazilian zircon production, we adapted a RoW dataset. In this case, imported zircon comes from Spain. For Spaniard production of zircon, a RoW dataset was used and kept unaltered. Origin of Brazilian Zircon was considered to be Tocantins state and Imports were considered to come from Spain.

B.1.1.23. Steel

In 2015 Brazil produced 33.3 Mt of this alloy which was equivalent to 2.1% of global and to 52.3% of Latin-American production. Brazilian steel production could be classified regarding its production source as 85.5% integrated steelworks and 14.5% semi-integrated steelworks (INSTITUTO AÇO BRASIL, 2016).

In an effort to create a comprehensive inventory we focused on some of the most significant steel makers in the country. For energy carrier inputs *i.e.* natural gas, coal, charcoal, electricity, etc., we used data from steel makers energy balance, supplied by six of the most relevant Brazilian steelwork mills, namely: ArcelorMittal Tubarão-2014; Aperam-2014; CSN-2015; Usiminas Ipatinga-2014; Usiminas Cubatão 2014 and Vallourec Sumimoto-2015 (ASSOCIAÇÃO BRASILEIRA DE METALURGIA MATERIAIS E MINEIRAÇÃO, 2016) whose added production summed up approximately 51% of Brazilian production. The energy inputs for each one of the steel makers were weighted in terms of their production in order to define energy inputs per ton of steel. Moreover, for non-energy inputs *i.e.* graphite electrodes, ferroalloys, limestone, dolomite, etc. we considered the data included in Instituto Aço Brasil (2016) which presents inputs for overall steel process, including blast furnaces and coke ovens. It is worth noting that coal inputs from Brazilian steel are all considered to be lignite (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2008). Steel dataset is presented in Table 18.

Since much of the data inputs are bounded to an overall economy sector (coke + pig iron + steelworks) we decided to outline our boundaries to purposely keep the coke oven, the blast furnace, the steelworks and any sintering process inside of our system. This means that the obtained data is more of a grand aggregate for all internal processes required, than a unit process scheme for steel. Steelworks usually include a vast set of internal flows coming from other stages of the process, coke oven gas, blast furnace gas and converter gas are exchanged in order to harness their heating value. These exchanges are deemed to be inside of our system boundaries, consequently they are not counted as inputs for any of the processes. Lack of data thwarted any endeavor on creating a disaggregated dataset. Hence, our steel process bears the environmental burden of all: pig iron, coke and steel production. In the same way, this methodology cannot disaggregate basic oxygen steelmaking (BOF) and electric arc furnace (EAF) routes which represent 78.2% and 20.2% of Brazilian production respectively (INSTITUTO AÇO BRASIL, 2016). Energy optimizing steelmaking route which represents 1.6% of total production was considered as negligible, thus, its production share was allocated to BOF and EAF routes by assuming that BOF+EAF production represents 100% of Brazilian production and scaling shares to 79.5% for BOF and 20.5 for EAF.

Whenever it was possible, we replaced global datasets “Reinforcing steel Alloc Def, U” and “Steel, low-alloyed Alloc Def, U” by our Brazilian steel dataset. For chromium steel we decided to keep the original datasets and only adapting them to Brazilian conditions.

Each simplified energy balance takes into consideration the inputs of every energy carrier required for each steel mill to produce a given amount of steel. Special attention was paid to fossil fuels inputs since they are considered to be the source of CO_2 emissions for this inventory and their contribution was calculated according to IPCC (2006) tier two. Coke inputs were not accounted to avoid double accounting.

No studies on estimating emissions other than CO_2 on coking, blast furnace and steelworks in Brazilian context were found. We estimated these process emissions by considering average emission factors in Remus et al (2013). Within coking process, stacking and quenching tower emissions were based on average reported emission factors. It is recommended to avoid doing it this way, due to the fact of their data are based on performances of existing and new plants all over Europe, which results in very wide ranges of emission factors. However, no consolidated data for those specific stages in Brazilian coke ovens were found. For fugitive emissions, including charging of the ovens, doors and lids leakages and ascension pipes leaks data is expected to be more accurate.

Air emissions to be considered during blast furnace process are basically: cast house, blast furnace gas use and hot stove. For blast furnace gas use it is important to highlight that carbon monoxide is not allowed to leave the plant but is used as heating fuel (primarily for the blast furnaces hot stoves) so that nearly all the carbon in blast furnace gas gets turned into carbon dioxide either in the blast furnace or in the combustion of the blast furnace gas (TOWSEY; CAMERON; GORDON, 2010). This carbon is brought into the system by the incoming energy carriers; thus, its potential CO_2 contribution was already taken into consideration. Cast house and hot stove emissions were estimated considering average values. Water emissions from blast furnace stage were calculated as in Remus et al (2013) as well.

With regards to air emissions from steelworks stage, we emphasize that 20.5% of Brazilian steel production originates from EAF route and 79.5% from BOF. Emission factors by ton of steel for each one of these routes were scaled to more accurately represent local conditions by weighting Brazilian production shares and emissions for each technology. A word should be given to mercury emissions estimation from EAF route. Brasil (2015f) reported that the country had incomplete and limited data about mercury emissions on its industrial processes. Two years later, Brasil (2017c) reported actions to correct this problem, however, those actions are still at initial stages, therefore, we adopted average values for mercury emissions to air .

Table 18. Dataset for production of steel 1 t.

Input			**Observations**
Coal tar {GLO}| market for | Alloc Rec, U	2.28	kg	
Hydrated etanol {BR} Market for | Alloc Def, U	4.58E-07	ton	Velandia et al (2016)
Hard Coal imported to {BR}| market | Alloc Def, U	0.016	ton	
Hard Coal imported to {BR}| market | Alloc Def, U	0.447	ton	
Pulverised lignite {RoW}| production | Alloc Def, U	2,538.24	MJ	
Tap water {RoW}| market for | Alloc Def, U	48.638	ton	
Coke {BR}| market for | Alloc Def, U	12,002.28	MJ	28.6 MJ/kg
Petroleum coke {GLO}| market for | Alloc Def, U	41.6	kg	
Charcoal {BR}| market for | Alloc Def, U	16.91	kg	
Natural gas, high pressure {RoW}| market for | Alloc Def, U	43.05	m3	
Liquefied petroleum gas {RoW}| market for | Alloc Def, U	3.93	kg	
Petrol, low-sulfur {RoW}| market for | Alloc Def, U	1.85E-05	ton	
Heavy fuel oil {RoW}| market for | Alloc Def, U	5.51	kg	
Diesel {RoW}| market for | Alloc Def, U	1.25	kg	
Coal tar {GLO}| market for | Alloc Rec, U	2.59	kg	
Steam, in chemical industry {GLO}| market for | Alloc Def, U	0.437	ton	
Iron ore, beneficiated, 65% Fe {BR}| market for | Alloc Def, U	0.919	ton	
Iron pellet {BR}| market for | Alloc Def, U	0.349	ton	
Iron scrap, unsorted {GLO}| market for | Alloc Def, U	0.280	ton	
Ferrosilicon {BR}| market for | Alloc Def, U	2.938	kg	
Ferronickel, 25% Ni {BR}| market for | Alloc Def, U	5.494	kg	
Ferromanganese, high-coal, 74.5% Mn {BR}| market for | Alloc Def, U	1.865	kg	
Ferrochromium, high-carbon, 68% Cr {BR}| market for | Alloc Def, U	4.011	kg	
Aluminium ingot {BR}| market for | Alloc Def, U	1.518	kg	
Calcium carbide, technical grade {RoW}| production | Alloc Def, U	0.368	kg	
Silicon carbide {RoW}| production | Alloc Def, U	0.421	kg	
Anode, for metal electrolysis {GLO}| market for | Alloc Def, U	0.343	kg	

Manganese {BR}| market for | Alloc Def, U	5.924	kg	
Limestone, crushed, for mill {GLO}| market for | Alloc Def, U	100.884	kg	
Dolomite {BR}| market | Alloc Def, U	50.427	kg	
Lime {BR}| market for | Alloc Def, U	84.045	kg	
Fluorspar, 97% purity {BR}| market | Alloc Def, U	0.702	kg	
Blast oxygen furnace converter {RoW}| production | Alloc Def, U	1.06E-11	p	
Electric arc furnace converter {RoW}| construction | Alloc Def, U	8.21E-12	p	
Electricity/heat			
Electricity 2016, medium voltage {BR}| market for | Alloc Def, U	0.508	MWh	
Emissions to air			
Particulates, < 10 um	11.16	g	Blast furnace
Sulfur dioxide	85.76	g	Blast furnace
Nitrogen oxides	56.05	g	Blast furnace
Carbon monoxide	1197.09	g	Blast furnace
Hydrocarbons, unspecified	196.14	g	Blast furnace
Hydrogen sulfide	18.33	g	Blast furnace
Cyanide compounds	0.77	g	Blast furnace
Ammonia	29.85	g	Blast furnace
Hydrogen	3.62	kg	Blast furnace
Thallium	0.002	g	Blast furnace
Antimony	0.097	g	Blast furnace
Cobalt	0.097	g	Blast furnace
Copper	0.097	g	Blast furnace
Vanadium	0.097	g	Blast furnace
Chromium	102.8	mg	Blast furnace
Manganese	139.3	mg	Blast furnace
Nickel	102.6	mg	Blast furnace
Lead	108.6	mg	Blast furnace
Zinc	7.2	mg	Blast furnace
Mercury	1.3	mg	Blast furnace
Arsenic	0.2	mg	Blast furnace
Cadmium	2.4	mg	Blast furnace
Sulfur oxides	342.02	g	Coke
Nitrogen oxides	369.76	g	Coke
Ammonia	5.134	g	Coke
Sulfuric acid	0.349	g	Coke
Hydrogen cyanide	0.335	g	Coke
Hydrogen sulfide	19.729	g	Coke
Carbon monoxide	832.958	g	Coke
Methane	14.134	g	Coke
TOC, Total Organic Carbon	6.282	g	Coke
Benzene	12.114	g	Coke
PAH, polycyclic aromatic hydrocarbons	210.447	mg	Coke
Benzo(a)pyrene	0.014	mg	Steelworks
Mercury	0.021	g	Steelworks
Lead	0.757	g	Steelworks
Chromium	0.322	g	Steelworks
Nickel	0.206	g	Steelworks

Zinc	2.484	g	Steelworks
Cadmium	0.015	g	Steelworks
Copper	1.138	g	Steelworks
Hydrogen fluoride	1.540	g	Steelworks
Hydrogen chloride	3.700	g	Steelworks
Sulfur dioxide	22.068	g	Steelworks
Nitrogen oxides	73.663	g	Steelworks
Carbon monoxide	3,484.16	g	Steelworks
TOC, Total Organic Carbon	30.28	g	Steelworks
Benzene	0.455	g	Steelworks
Chlorobenzilate	0.0013	g	Steelworks
PAH, polycyclic aromatic hydrocarbons	0.111	g	Steelworks
Polychlorinated biphenyls	0.0005	g	Steelworks
Iron	17.941	g	Steelworks
Manganese	0.740	g	Steelworks
Carbon dioxide, fossil	1.493	t	Including lime.
Particulates, unspecified	31.92	g	Blast furnace
Particulates, unspecified	57.92	g	Coke
Particulates, unspecified	93.59	g	Steelworks
Emissions to water			
Lead (river)	6.080	mg	Blast furnace slag
Chromium (river)	6.080	mg	Blast furnace slag
Copper (river)	11.555	mg	Blast furnace slag
Zinc (river)	60.812	mg	Blast furnace slag
Cadmium (river)	0.605	mg	Blast furnace slag
Nickel (river)	9.577	mg	Blast furnace slag
Iron (river)	0.546	g	Blast furnace slag
Chlorine (river)	802.686	g	Blast furnace slag
AOX, Absorbable Organic Halogen as Cl (river)	50.169	g	Blast furnace slag
Suspended solids, unspecified	17.94	g	Blast furnace slag
DOC, Dissolved Organic Carbon (river)	12.161	g	Blast furnace slag
TOC, Total Organic Carbon (river)	15.205	g	Blast furnace slag
COD, Chemical Oxygen Demand (river)	68.409	g	Blast furnace slag
Hydrocarbons, unspecified (river)	0.307	g	Blast furnace slag

B.1.2. Transportation

Transportation distances for raw materials from extraction site to processing location were estimated based on satellite maps. However, our purpose was not to obtain exact values for conveyance distances, firstly because we considered it to be out of our scope and secondly because the literature (LIANG et al., 2017) and quick LCIA results revealed transportation of raw materials as having a very low environmental burden when compared to other processes throughout the entire life cycle of the vehicle. Instead, we roughly defined transportation modes and distances. In an attempt to simplify our model and to eliminate external variables we utilized the same datasets for each transportation mode, namely: vessel, train and truck. All products not specified in this work were assumed to be available at Brazil south-east region, therefore, a 400 km transportation distance was considered. Non-empty return is assumed in all cases Table 19 shows Ecoinvent datasets chosen to represent each transportation mode while Table 20 presents transportation distances from raw materials extraction sites to processing centers in Brazilian south east.

Table 19. Datasets used for transportation.

Transportation mode	**Ecoinvent process**
Vessel	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U
Train	Transport, freight train {RoW}| market for | Alloc Def, U
Truck	Transport, freight, lorry, unspecified {GLO}| market for | Alloc Def, U

Table 20. Transportation distances considered from raw materials extraction to processing facilities.

Raw material	**Vessel (km)**	**Train (km)**	**Truck (km)**	**Origin**
Aluminum wrought/cast alloy	0	0	400	São Paulo
Barite	8,000	2,000	1,000	Peru/Morocco
Bauxite	4,000	1,000	1,000	Amazonas
Cobalt	12500	0	2200	Congo*
Copper (Imported share)	8,000	800	1,000	Peru/Chile
Copper (Brazilian share)	1,500	800	400	Bahia
Ferrite	0	0	600	Minas Gerais
Gold	0	200	600	Minas Gerais
Hard Coal	10,000	2,000	1,000	South Africa, Russia, Ukraine, USA, China & Australia
Lead	0	0	400	São Paulo
Lithium carbonate	0	0	300	Chile
Lithium fluoride	0	0	50	Chile
Lithium manganese oxide / Lithium hexafluorophosphate	8,500	0	500	Chile
Magnesium (Brazilian share)	0	1,000	600	Bahia
Magnesium (Imported share)	15,000	2,000	1,000	China
Manganese	0	400	600	Minas Gerais
Nickel	0	2,000	1,000	Goias
Palladium	8,000	2,000	400	South Africa
Pig iron	0	0	400	São Paulo
Silver (Brazilian share)	3,500	1,000	400	Pará
Silver (Imported share)	6,000	2,000	1,000	Peru/Mexico/Belgium
Sodium hydroxide	0	0	400	São Paulo
Steel	0	0	400	São Paulo

Sulfuric Acid	0	0	400	São Paulo
Tin	3,500	1,000	1,000	Rondônia
Titanium dioxide	0	0	800	Bahia
Zinc	0	600	400	Minas Gerais
Zircon (Brazilian share)	0	2,000	1,000	Tocantins
Zircon (Imported share)	6,000	2,000	1,000	Spain

*Distance from Mutanda mine to Shanghai, China

C. APPENDIX 3 – BATTERY ELECTRIC VEHICLE BRAZILIAN INSIGHT

C.1. BATTERY ELECTRIC VEHICLE RELEASES, INITIATIVES, PROMOTION AND ENVIRONMENTALLY MOTIVATED POLICIES

C.1.1. Vehicle releases

Many of the large OEMs established in Brazil have been testing their BEV models as part of partnerships without selling them directly. Nissan tested some LEAF models for use as police cars in Rio de Janeiro as early as 2013 (ESTADÃO, 2013). LEAF private sales arrived only in 2019 (LEME, 2018). Renault also established partnerships for the use of Zoe models in private fleets (PRATIWI, 2016) and in urban mobility projects such as the Eco-Elétrico project in Curitiba, Paraná, which deployed BEVs and battery electric busses (BEB) in the city (ITAIPU BINACIONAL, 2014). Toyota was also implicated in projects with municipal administrations, perhaps the most prominent in São Paulo city, whose target was to incorporate the Prius model within the municipal taxi fleet (TRINDADE, 2012). Moreover, Toyota is still selling the Prius, the most sold HEV in the world and BMW will continue offering its full-electric i3. Volkswagen is considering releasing its e-Golf and Golf GTE, Hyundai its Ioniq model, and Volvo its HEV SUV XC60. Chevrolet has yet to confirm its full electric Bolt (BLAND, 2018d, 2018e)

C.1.2. Private institutions initiatives

Private initiatives play an important role, the Brazilian Electric Vehicle Association (ABVE), strives to promote the widespread use of BEVs in the country. It promotes partnerships between regulation agents, business entities, and users. Additionally, it acts in the registration of companies intending to form a network of business partners. Furthermore, it promotes initiatives, such as the Green Urban Mobility Zones (MUV), which are areas prioritizing the circulation of zero tailpipe emission vehicles within its boundaries. ABVE also organizes C-Move, an electromobility workshop, which takes place every year presenting proposals from different players in the market (VEÍCULO ELÉTRICO LATINO-AMERICANO, 2018). For instance, during 2018 edition, it was announced the release of a *flex-fuel* Toyota Prius, making it the only HEV in the world able to work on ethanol. Subsequently, Toyota confirmed the production of this model in Brazil will commence still in 2019 (SILVA, 2019b). In the same way, start-ups based on vehicle sharing played a starring role, for four (URBANO, 2018), and two wheelers (OFICINA BRASIL, 2018), even via applet (PORTAL IG, 2018).

C.1.3. Funding and promotion institutions

At the federal level, there are 3 institutions which foster the vast majority of initiatives for technological innovation on electromobility: The Funder of Projects and Studies, FINEP (BRASIL, 2019b), the National Council for Scientific and Technological Development (CNPq) (BRASIL, 2018g) and the Brazilian Development Bank (BNDES) (BRASIL, 2018h). BNDES acts as the main long-term credit provider, financing both, technological innovation and purchase of components and vehicles. There is ample evidence of BNDES involvement in partnerships with research institutions in battery and automotive technology (BARASSA, 2015; CONSONI et al., 2018). Efforts to develop technology not available in Brazil are eligible for different BNDES credit options, such as the Technological Innovation Line and the Innovative Capital Line. Moreover, CNPq provides financial support to diverse research groups. A search in CNPq index shows 32 results for research partner groups. The rewards of funding are expected to be represented in technology development, in the period between 1995 and 2014, 161 patents related to BEV technologies were included in the National institute of Intellectual Property (INPI), 20 of those patents were developed in Brazil (BARASSA, 2015). In the period 2015-2016 13 other Brazilian patents were registered.

Not every project is backed by those 3 agencies, The Ministry of Science, Technology and Innovation (MCTI) in partnership with CNPq have promoted the training of technicians on BEV and battery technology (BARASSA, 2015). In another example, the Brazilian Ministry of Industry, Foreign Trade and Services (MDIC) in partnership with the German Ministry of Economic Cooperation and Development is promoting the PROMOB-e project. Promob-e activities include governance studies and start-up support (PROMOB-E, 2018), aiming to assist Brazil in the formulation of public policies for the deployment of electrification (BRASIL, 2018i). The cooperation is expected to share expertise and to identify troublesome aspects. For instance, the disadvantages of non-standardized charging plugs. Special attention should be paid to the Mobility City Lab (PROMOB-E, 2017) which focuses on the interaction of innovative technologies, efficient business models and governance approaches for sustainable city development. The project included an on-site assessment in the city of Joinville, Paraná.

C.1.4. EMOTIVE, VAMO and Carro Leve experiences

EMOTIVE, VAMO and Carro Leve experiences have been the subject of diverse studies in electromobility. Lima et al (2017) explored different business models for mobility services in 20 countries including 2 schemes in Brazil, Carro Leve and VAMO. The authors concluded that carsharing business models, display some particularities, such as: the aim to reduce the cost of car ownership, including the battery, and the absence of smart recharge infrastructure. On the other hand, carsharing do not encourage technological innovation, since it does not require changes in the existing technologies for its operation. Interestingly, in 25% of all cases, the companies provided aggregated services.

Teles et al (2018) evaluated the sustainability performance of EMOTIVE and VAMO projects, in the context of PSS, by identifying in them the sustainability factors identified by Barquet (2016) namely; design for environment, identification of economic value, action towards social well-being, encouragement of user behavior change and innovation in different levels. Interestingly, the results displayed positive results for both projects for all factors.

An analysis for grid impact of BEV adoption in Brazilian conditions was conducted based on EMOTIVE data. Mariotto (2018) projected a total 1,25 million of BEVs and 4,45 million plug-in hybrid electric vehicles (PHEV) in 2030, which would represent 3,9% and 14% of the total Brazilian light vehicle fleet in that year, consequently creating a rise in electricity demand, modifying the operational and planning conditions of the grid as a consequence of a new load curve. Findings confirm the exacerbation of some undesired effects, such as: (i) reduction in voltage magnitude, (ii) rise of voltage unbalances, and (iii) overload of transformers and conductors. In order to face the challenges, three mitigation actions recommended: (i) updating of distribution infrastructure, (ii) use of hour-based rates, and (iii) smart recharges of electric vehicles. Considering a scenario where users are incentivized to recharge on off-peak hours, the need for investment in network infrastructure would be reduced 60% compared to a scenario of no incentives.

Also embedded in the context of EMOTIVE, Pinto et al (2018) studied the impacts from household BEV charging. A set of residential EVSEs were installed in an urban low-voltage electricity network. The measurements were intended to, firstly, capture the variations on the group of adjacent residences, and secondly, the variations at the house where the charging was taking place. Three EVSEs were installed, for slow, semi-fast, and fast charging. For slow recharge the equipment provided up to 3.7 kW to the vehicle while for semi-fast and fast charging the power involved was 22 kW and 40 kW. The fast charging EVSE demanded a connection to high voltage network due to tension and current requirements. The charging process caused a voltage reduction of 0.8 V. Nevertheless, the values remained within the limits established by ANEEL standards (BRASIL, 2016b). Indeed, the impact of BEV charging in the residence tension was insignificant, it would have required 4 simultaneous recharges to had caused tension violation. For the adjacent residences there were no violations either. Summarizing, the verified impacts of residential BEV charging on primary distribution systems are non-significant. The economic results displayed an increase of 43% in energy consumption when compared to the same residence without the BEV. However, it was estimated an economy of 70% when compared to gasoline cost per kilometer.

Still within EMOTIVE sphere, Arioli et al (2018) reported the detection of residual current (leakage) in the BEVs and reported about some users failing to do fast charging during peak hours. The project BEVs were estimated to have spent only 31% of what would have been spent with equivalent ICEVs per total distance travelled. Moreover, it was concluded that to recharge a BEV in a local grid powered by a diesel generator, it is indispensable to perform an adequate sizing to cope up with the BEV power demand.

C.1.5. Policies with environmental background.

Back in 1986, the Automotive Air Pollution Control Program (Proconve) was created by the Brazilian Institute for the Environment (IBAMA), well before the BEVs could had been considered as an option for environmental damage mitigation. Other cases of sustainability-guided policies are: The National Policy on Climate Change (PNMC), created in 2009, which endeavored to ensure that economic and social development contribute to the protection of the global climate stability (BRASIL, 2014). The 2016 National Plan for Adaptation to Climate Change (PNA), which promote the reduction of national vulnerability to climate change by managing the associated risks (BRASIL, 2016a). The climate law issued by São Paulo state (No. 16802), compelling public transport to emit less pollutants (PREFEITURA DE SÃO PAULO, 2018).

Another significant policy was the Program for Promotion of Technological Innovation and Strengthening of Vehicle Productivity Chain (Inovar-Auto), active from 2013 to 2017. It granted incentives to encourage technological innovation and production chain development. The incentives were applied in the form of reductions in the industrialized products tax (IPI) for OEMs certifying R&D efforts in Brazil. To be eligible, OEMs needed to comply with standards to increase energy efficiency (MINISTÉRIO DO DESENVOLVIMENTO INDÚSTRIA E COMÉRCIO EXTERIOR, 2014). For cars assembled locally, instead of imported, the rates dropped from 35% to zero, 2% or 5% depending on the vehicle share produced locally. Tax reductions for HEVs were dependent on energy efficiency features, the more efficient the vehicle, the greater the tax deduction. Nevertheless, pure BEVs were not eligible. Inovar-auto plan resulted in an average improvement of 15,4% on Brazilian fleet energy efficiency (FELIX, 2017).

Furthermore, Inova Energia Plan (2013-2017), was a pioneering initiative developed jointly by the Funding Authority for Studies and Projects (Finep), BNDES and ANEEL. It was the first institutionalized action regarding BEVs and HEVs implementation (BRASIL, 2015b)and presented a structured plan, with clear resources and objectives. This public policy instrument resembled international tools intended to promote innovation in the industrial network. In the private sphere, we found the creation of the National Institute of Energy Efficiency (INEE). A non-profit non-governmental organization founded in 1992, looking forward to promote efficiency in energy use. Table 21 presents a comparison for Proconve, Rota 2030 and Renovabio policies (BRASIL, 2010, 2017d, 2018j, 2018f)

Table 21. Basics of Proconve, Rota 2030 and Renovabio policies.

	Proconve	Rota 2030	Renovabio
Objectives	Reduce and control the emission of air pollutants and noise for all of the vehicles sold nationally.	Expand the global insertion of the Brazilian automotive industry into the global market by exporting vehicles and auto parts. Not intended to increase competitiveness only through cost reduction but through technological differentiation as well.	Promote the proper expansion of biofuels in the energy matrix emphasizing on the reliability of fuel supply. Ensure predictability for the fuel market by inducing energy efficiency gains and reduction of greenhouse gas emissions in the production, marketing and use of biofuels.
Strategy	Establishing maximum levels of emission of pollutants for light and heavy-duty vehicles. Forced substitution of the most polluting models and improvement in the designs of models already in production. Evaporative emission control. Catalyst adequation and electronic injection systems for use with ethanol blended gasoline. Development of engines with new technologies. Creation of the PROCONVE monitoring Committee to	Creation of research and development stimulation policies. Establishment of mandatory requirements for the commercialization of new vehicles, including the labeling program for energy efficiency and vehicle safety for 100% of the vehicles sold in the country. Tax benefit for OEMs investing in research and development in the country. Importation tax exemptions for auto parts without equivalent national production.	Establishment of national emission targets for the fuel matrix, for a 10-year period. The issuing of a certification for producers bestowing a grade depending on the carbon intensity of the biofuel produced. This grade will accurately reflect the individual contribution of each producer to the mitigation of GHG emissions. The certification is the base for a decarbonization credit, which will be a financial asset traded on the stock exchange.

	evaluate the execution of the established targets.		
	1986-Current day	2018-2033	2016-Undefined. Goals reassessed every ten years
Problems to tackle	Urban pollution due to tailpipe emissions. Health issues related to air quality.	The low competitiveness of the national automotive industry, which results in low integration into global value chains. The risk of transferring research and development activities to other hubs, with the consequent loss of high-skilled jobs; Technological lag, especially in energy efficiency, structural components and driving assistive technologies	Unreliability on biofuels production Emission of GHG.

C.1.6. ANEEL

Several factors urged ANEEL to take a stance on electricity sell for BEVs charging. Externally, the rapid development of a BEV industry in which Brazil is being left behind. Locally, the submission to congress of bills PL 4751/2012 and PLS 780/2015, which proposed the compulsory installation of public EVSEs in highways and the creation of tax exemptions for BEVs purchased by differently abled people and to be used as cabs (BRASIL, 2015c). Furthermore, bill PLS 454/2017 pretends to establish a ban for ICEVs selling in Brazil from 2060 onwards (BRASIL, 2017a), analogously to other countries (PETROFF, 2017).

The Agency opted for a minimum regulation of the subject, aiming to avoid interferences in the pricing process and to permit the market to evolve by itself (BRASIL, 2018k). ANEEL's normative resolution, also introduces a register of public EVSEs, with the purpose of mapping the infrastructure available in the country (REIS; BRITO, 2018). Private operators are now able to sell electricity, unlike fossil fuels and ethanol, which are controlled by Petrobras.

What ANEEL expects is to create a safe framework for entrepreneurs investing in infrastructure. Regarding vehicle and battery security the agency declared that DSOs will not bear any responsibilities due to overload. The CPOs must ensure the protection against potential overloads (LIS, 2018). The agency looked forward to guarantee 3 principles; 1) allow any interested party to provide charging services; 2) guarantee minimum interoperability requirements for EVSE ;and 3) create a registration of all EVSE installations, both public and private (MARQUES DE ARAUJO; AMORIM, 2017).

The resolution represents a milestone for electrification in the country. Prior to it, the public EVSE in the country were not allowed to charge for the energy transferred to the vehicles, due to lack of regulation. Thus, installed EVSEs were not able to create a profit, wiping out any interest from entrepreneurs (MAIA; POLITO, 2018). The new regulation makes energy trading possible and enables commercial recharge of BEVs, at least in the legal field. The new regulation will force the electric firms to innovate, DSOs are not used to competition but electrification will likely compel them to adopt customer-centered strategies (MARQUES DE ARAUJO; AMORIM, 2017).

D. APPENDIX 4 – LIFE CYCLE IMPACT ASSESSMENT RESULTS

Table 22. LCIA results for Brazilian and Global Bus, functional unit 1 BEB. One ICEV Bus included.[15]

Category	Units	ICEV	BR 2015	GLO 2015	BR 2030	GLO 2030
C. C.	kg CO_2 eq	7,58E+04	9,34E+04	1,03E+05	7,50E+04	8,76E+04
O. D.	kg CFC-11 eq	4,14E-03	1,01E-02	1,01E-02	8,00E-03	8,53E-03
T. A.	kg SO_2 eq	3,36E+02	5,75E+02	6,71E+02	4,70E+02	5,71E+02
F. E.	kg P eq	4,18E+00	2,24E+01	2,52E+01	1,94E+01	2,17E+01
H. T.	kg 1,4-DB eq	1,11E+04	3,62E+04	3,75E+04	3,11E+04	3,23E+04
P. O. F.	kg NMVOC	2,23E+02	3,12E+02	3,54E+02	2,56E+02	3,02E+02
M. D.	kg Fe eq	2,61E+04	7,05E+04	6,84E+04	6,10E+04	5,91E+04
F. D.	kg oil eq	1,94E+04	2,45E+04	2,59E+04	1,93E+04	2,20E+04
Ecotoxicities	kg 1,4-DB eq	5,69E+02	8,46E+02	7,15E+02	7,18E+02	6,15E+02

Table 23. LCIA results for Brazilian and Global BEV, functional unit 1 BEV.

Category	Units	ICEV	BR 2015	GLO 2015	BR Al.	GLO Al.	BR Pl.	GLO Al.
C. C.	kg CO_2 eq	8,32E+03	1,37E+04	1,57E+04	1,25E+04	1,39E+04	1,25E+04	1,44E+04
O. D.	kg CFC-11eq	1,08E-03	1,88E-03	1,63E-03	2,38E-03	1,70E-03	2,17E-03	1,66E-03
T. A.	kg SO_2 eq	4,04E+01	1,25E+02	1,43E+02	1,17E+02	1,28E+02	1,16E+02	1,29E+02
F. E.	kg P eq	1,43E+00	5,89E+00	6,46E+00	5,05E+00	5,35E+00	5,24E+00	5,45E+00
H. T.	kg 1,4-DBeq	2,20E+03	8,67E+03	7,99E+03	8,11E+03	6,85E+03	7,71E+03	6,67E+03
P. O. F.	kg NMVOC	3,44E+01	6,16E+01	7,05E+01	5,31E+01	5,92E+01	7,16E+01	7,46E+01
M. D.	kg Fe eq	4,52E+03	1,07E+04	9,84E+03	6,65E+03	6,64E+03	6,61E+03	6,51E+03
F. D.	kg oil eq	2,40E+03	4,12E+03	4,27E+03	3,54E+03	3,71E+03	4,41E+03	4,55E+03
Ecotoxicit.	kg 1,4-DBeq	1,00E+02	2,04E+02	1,72E+02	1,60E+02	1,39E+02	1,56E+02	1,37E+02

Al: 2030 Aluminum; Pl: 2030 Plastic.

Table 24. LCIA results for Brazilian and Global Bus, functional unit 1 km.

Category	Units	ICEV	BR 2015	GLO 2015	BR 2030	GLO 2030
C. C.	kg CO_2 eq	1,62E+00	6,76E-01	6,90E-01	4,17E-01	4,34E-01
O. D.	kg CFC-11 eq	1,22E-07	7,08E-08	6,96E-08	4,21E-08	4,17E-08
T. A.	kg SO_2 eq	3,05E-03	3,62E-03	3,75E-03	2,39E-03	2,53E-03
F. E.	kg P eq	9,61E-06	1,17E-04	1,23E-04	9,96E-05	1,05E-04
H. T.	kg 1,4-DB eq	3,21E-02	1,64E-01	1,60E-01	1,35E-01	1,32E-01
P. O. F.	kg NMVOC	4,92E-03	1,82E-03	1,88E-03	1,20E-03	1,27E-03
M. D.	kg Fe eq	3,92E-02	2,61E-01	2,59E-01	2,27E-01	2,25E-01
F. D.	kg oil eq	5,19E-01	1,72E-01	1,74E-01	9,55E-02	9,89E-02
Ecotoxicities	kg 1,4-DB eq	1,67E-03	3,19E-03	2,99E-03	2,68E-03	2,51E-03

Diesel fueled ICEV Bus included.

[15] C.C. Climate change; O.D. Ozone depletion; T.A. Terrestrial acidification; F.E. Freshwater eutrophication; H.T. Human Toxicity; P.O.F. Photochemical oxidant formation; M.D. Metal depletion; F.D. Fossil depletion. Ecotoxic. refers to the sum of terrestrial, freshwater and marine ecotoxicities.

Table 25. LCIA results for Brazilian and Global BEV, functional unit 1 km[16].

Category	Units	GAS	ETOH	BR 2015	GLO2015	BR Al.	GLO Al.	BR Pl.	GLO Pl.
C. C.	kg CO_2 eq	2,70E-01	1,18E-01	1,21E-01	1,35E-01	9,01E-02	1,03E-01	9,11E-02	1,06E-01
O. D.	kgCFC11eq	1,90E-08	9,49E-09	1,40E-08	1,28E-08	1,39E-08	1,09E-08	1,30E-08	1,07E-08
T. A.	kg SO_2 eq	5,44E-04	1,61E-03	8,58E-04	9,68E-04	7,08E-04	7,92E-04	7,07E-04	7,99E-04
F. E.	kg P eq	7,64E-06	8,96E-06	3,34E-05	3,66E-05	2,86E-05	3,03E-05	2,96E-05	3,09E-05
H. T.	kg1,4-DBeq	1,34E-02	1,60E-02	4,85E-02	4,50E-02	4,44E-02	3,80E-02	4,24E-02	3,71E-02
P. O. F.	kgNMVOC	6,50E-04	1,21E-03	8,55E-04	9,07E-04	7,56E-04	8,00E-04	8,55E-04	8,80E-04
M. D.	kg Fe eq	2,17E-02	2,25E-02	5,75E-02	5,31E-02	3,63E-02	3,63E-02	3,61E-02	3,56E-02
F. D.	kg oil eq	7,08E-02	2,74E-02	3,50E-02	3,66E-02	2,44E-02	2,71E-02	2,93E-02	3,14E-02
Ecotoxic	kg1,4-DBeq	5,77E-04	5,74E-04	1,17E-03	1,01E-03	8,86E-04	7,89E-04	8,68E-04	7,80E-04

[16] GAS: Gasoline fueled ICEV 2015; ETOH: Anhydrous Ethanol ICEV 2015. Al: 2030 Aluminum; Pl: 2030 Plastic.

E. APPENDIX 5 – ADJUSTED INVENTORIES

Table 26. List of adjusted Ecoinvent datasets.

Datasets	Electricity	Heat	Water	Processing	Observations
Acrylic varnish, without water, in 87.5% solution state {RoW}| acrylic varnish production, product in 87.5% solution state | Alloc Def, U	M				
Acrylonitrile-butadiene-styrene copolymer {RoW}| market | Alloc Def, U					
Aluminium, cast alloy {GLO}| market for | Alloc Def, U					Comprises aluminum primary ingot 64.1% and aluminum from scrap 35.9%
Aluminium, primary, ingot {GLO}| market for | Alloc Def, U	M				Includes shares from Soderberg and prebake anode routes. It considers transportation as well.
Aluminium, primary, liquid {IAI Area 3} | aluminium production, primary, liquid, Soderberg | Alloc Def, U	M				No transportation considered
Aluminium, primary, liquid {IAI Area 3} | aluminium production, primary, liquid, prebake | Alloc Def, U	M				No transportation considered
Aluminium, wrought alloy {GLO}| market for | Alloc Def, U					Comprises aluminum primary ingot 64.1% and aluminum from scrap 35.9%
Ammonium chloride {GLO}| market for | Alloc Def, U					No data on Brazilian production routes. Process kept unmodified except for transportation.
Anode, graphite, for lithium-ion battery {RoW} | production | Alloc Def, U	M	NG			
Barite {RoW}| production | Alloc Def, U					
Battery cell, Li-ion {RoW} | production | Alloc Def, U	M	NG			
Battery separator {RoW}| production | Alloc Def, U	M	NG			
Battery, Li-ion, rechargeable, prismatic {RoW}| production | Alloc Def, U	L				
Bauxite, without water {RoW}| bauxite mine operation | Alloc Def, U	M				
Brass {RoW}| production | Alloc Def, U	M	NG/ONG			
Cable, data cable in infrastructure {GLO}| production | Alloc					Cable weight: 0.079 kg/m

Def, U					
Cable, three-conductor cable {GLO}| production | Alloc Def, U					
Capacitor, auxilliaries and energy use {GLO}| production | Alloc Def, U	M/H	NG			
Capacitor, electrolyte type, < 2cm height {GLO}| production | Alloc Def, U					
Capacitor, film type, for through-hole mounting {GLO}| market for | Alloc Def, U	M/H	NG/ONG			
Capacitor, for surface-mounting {GLO}| market for | Alloc Def, U					
Capacitor, tantalum-, for through-hole mounting {RoW}| production | Alloc Def, U					
Carbon black {GLO}| production | Alloc Def, U		NG			
Carbon disulfide {GLO}| production | Alloc Def, U	M	NG			
Carbon fiber					LCI inventory taken from Schmidt and Watson (2013)
Cathode, LiMn2O4, for lithium-ion battery {RoW}| production | Alloc Def, U	M	NG			
Charcoal {GLO}| production | Alloc Def, U	M	ONG			
Charger, electric passenger car {GLO}| charger production, for electric passenger car | Alloc Def, U	L	ONG			
Chromium {RoW}| production | Alloc Def, U	M	NG			
Coating powder {RoW}| production | Alloc Def, U	M				
Coke {GLO}| coking | Alloc Def, U	M				Coke is considered to be produced close to steelworks and transported by torpedo car which is modelled as train 0.5 km
Converter, for electric passenger car {GLO}| production | Alloc Def, U	L	ONG			
Copper {RLA}| production, primary | Alloc Def, U					Copper production RLA unmodified. Copper from scrap processes unmodified
Diode, auxilliaries and energy use {GLO}| production | Alloc Def, U	M	NG/ONG	X		All liquid oxygen and liquid hydrogen geographies added to Row.
Diode, glass-, for surface-mounting {GLO}| production | Alloc Def, U					
Dipropylene glycol monomethyl ether {RoW}| market for | Alloc Def, U	M	NG			
Dolomite {RoW}| production | Alloc Def, U		NG			

Electric connector, peripheral component interconnect buss {GLO}| market for | Alloc Def, U	M				
Electric connector, peripheral type buss {GLO}| market | Alloc Def, U	M				
Electric motor, electric passenger car {GLO}| electric motor production, vehicle (electric powertrain) | Alloc Def, U	M/L	NG/ONG			
Epoxy resin, liquid {GLO}| market for | Alloc Def, U	-	-			System process scheme, therefore unmodified
Ethylene carbonate {RoW}| production | Alloc Def, U	M	NG			
Extrusion, plastic film { RoW }| production | Alloc Def, U	M	NG/ONG			
Extrusion, plastic pipes {RoW}| production | Alloc Def, U	M	NG/ONG		X	
Ferrite {GLO}| production | Alloc Def, U	M	NG/ONG			
Ferrochromium, high-carbon, 68% Cr {GLO}| production | Alloc Def, U	M	ONG			Produced on-site. No transportation required
Ferromanganese, high-coal, 74.5% Mn {GLO}| production | Alloc Def, U	M	ONG			Produced on-site. No transportation required
Ferronickel, 25% Ni {GLO}| production | Alloc Def, U	H	NG/ONG			
Ferrosilicon {RoW}| production | Alloc Def, U	M				Hard coal geographies added to BR
Flat glass, uncoated {RoW}| production | Alloc Def, U	M				
Fleece, polyethylene {RoW}| production | Alloc Def, U	M	NG			
Fluorspar, 97% purity {GLO}| production | Alloc Def, U	M	NG/ONG			
Glass fibre {RoW}| production | Alloc Def, U	M	NG	X		
Glass fibre reinforced plastic, polyester resin, hand lay-up {RoW}| production | Alloc Def, U					
Glider, passenger car {GLO}| production | Alloc Def, U	M	NG/ONG	X		No transportation required.
Gold {RoW}| production | Alloc Def, U	M	NG/ONG			According to DNPM (2015) 48% of gold consumed in Brazil does have recycling as origin.
Graphite, battery grade {RoW}| production | Alloc Def, U	M	ONG			
Hexafluoroethane {GLO}| market for | Alloc Def, U					No evidence of Brazilian production.It is assumed to be imported from Spain. 1 kg of hexafluoroethane is assumed to be produced 50% by chlorofluorination of ethylene and 50% by fluorination of tetrafluoroethane. Transportation distances 9,000 km vessel, 400 km train and 400 km truck.
Hot rolling, steel {RoW}| processing | Alloc Def, U	M	NG		X	
Hydrogen fluoride {GLO}| production | Alloc Def, U	M	NG			

Hydrogen peroxide, without water, in 50% solution state {RoW}| hydrogen peroxide production, product in 50% solution state | Alloc Def, U	M	NG/ONG			
Inductor, auxilliaries and energy use {GLO}| production | Alloc Def, U	M	NG			
Inductor, ring core choke type {GLO}| production | Alloc Def, U					
Integrated circuit, logic type {GLO}| production | Alloc Def, U	M	ONG			
Integrated circuit, memory type {GLO}| production | Alloc Def, U	M	ONG			
Inverter, for electric passenger car {GLO}| production | Alloc Def, U	M	ONG			
Iron (III) chloride, without water, in 40% solution state {RoW}| iron (III) chloride production, product in 40% solution state | Alloc Def, U	M				
Iron ore, beneficiated, 65% Fe {GLO}| iron ore beneficiation to 65% Fe | Alloc Def, U	M				
Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe | Alloc Def, U	M				It is considered that no transportation is required from crude ore site to beneficiated ore site.
Isopropanol {RoW}| production | Alloc Def, U	M	NG			
Latex {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified
Lead {RoW}| treatment of scrap acid battery, remelting | Alloc Def, U	M	NG/ONG			
Light emitting diode {GLO}| production | Alloc Def, U					
Lime {RoW}| production, milled, loose | Alloc Def, U	H/M				
Lithium carbonate {GLO}| production, from concentrated brine | Alloc Def, U	H (Chile)	NG	X		Used for Lithium manganese oxide production
Lithium fluoride {RoW}| production | Alloc Def, U		NG	X		It is considered to be produced on-site
Lithium hexafluorophosphate {RoW}| production | Alloc Def, U	M (Chile)		X		
Lithium manganese oxide {GLO}| production | Alloc Def, U	M (Chile)	NG			Nitrogen and liquid oxygen added to Row. Lithium carbonate is used for $LiMn_2O_4$ Cathode.
Lubricating oil {RoW}| production | Alloc Def, U	M	NG			
Magnesium {GLO}| market for | Alloc Def, U					
Manganese {RoW}| production | Alloc Def, U	M				

Mounting, surface mount technology, Pb-containing solder {GLO}| mounting, surface mount technology, Pb-containing solder | Alloc Def, U	M			X	
Mounting, surface mount technology, Pb-free solder {GLO}| mounting, surface mount technology, Pb-free solder | Alloc Def, U	M			X	
Mounting, through-hole technology, Pb-free solder {GLO}| mounting, through-hole technology, Pb-free solder | Alloc Def, U	M			X	
Nickel, 99.5% {GLO}| nickel mine operation, sulfidic ore | Alloc Def, U	H/M	NG/ONG			Ammonia and liquid nitrogen added to RoW.
Nylon 6 {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified
Nylon 6 {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified
Palladium {GLO}| market for | Alloc Def, U					Brazilian production considered as negligible DNPM (2015). All palladium is imported.
Particle board, for outdoor use {RoW}| production | Alloc Def, U	M	NG/ONG			Density considered as 700 kg/m^3 (WOODPRODUCTS, 2017)
Phenolic resin {RoW}| production | Alloc Def, U	M				
Phosphorus, white, liquid {RoW}| production | Alloc Def, U	M				
Phthalic anhydride {RoW}| production | Alloc Def, U	M	NG/ONG			
Pig iron {GLO}| production | Alloc Def, U					
Polycarbonate {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified
Polyester resin, unsaturated {RoW}| production | Alloc Def, U	M	NG/ONG			No evidence of manufacturing of polyester resin from soy in Brazil. Therefore, only dataset for chemical route was included
Polyethylene terephthalate, granulate, amorphous {RoW}| production | Alloc Def, U	M	NG/ONG			
Polyethylene, high density, granulate {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified
Polyethylene, linear low density, granulate {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified
Polyethylene, low density, granulate {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified
Polyphenylene sulfide {GLO}| production | Alloc Def, U	M/H	NG			
Polypropylene, granulate {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified
Polystyrene, high impact {RoW}| production | Alloc Def, U	-	-			System process scheme, therefore unmodified

Polyurethane, flexible foam {RoW}| production | Alloc Def, U	M				
Polyvinylchloride, suspension polymerised {RoW}| polyvinylchloride production, suspension polymerisation | Alloc Def, U	-	-			System process scheme, therefore unmodified
Polyvinylfluoride {RoW}| production | Alloc Def, U	M	NG			
Potassium carbonate {GLO}| production, from potassium hydroxide | Alloc Def, U	M	NG			Brazilian production considered to be manufactured via potassium hydroxide route, since there is evidence only for this production route (INSTITUTO BRASILEIRO DE MINERAÇÃO, 2011).
Power distribution unit, for electric passenger car {GLO}| production | Alloc Def, U	L	ONG			
Printed wiring board, for surface mounting, Pb containing surface {GLO}| production | Alloc Def, U	M	NG			Density: 3.26 kg/m^2.
Printed wiring board, for surface mounting, Pb free surface {GLO}|production | Alloc def, U	M	NG			Density: 3.26 kg/m^2.
Printed wiring board, for through-hole mounting, Pb containing surface {GLO}| production | Alloc Def, U	M	NG/ONG	X		Density: 3.08 kg/m^2 according to Ecoinvent.
Printed wiring board, for through-hole mounting, Pb free surface {GLO}|production| Alloc Def, U	M	NG/ONG			Density: 3.08 kg/m^2 weight. All hydrochloric acid geographies summed up to RoW
Printed wiring board, mounted mainboard, desktop computer, Pb free {GLO}| production | Alloc Def, U					
Printed wiring board, surface mounted, unspecified, Pb containing {GLO}| production | Alloc Def, U					
Printed wiring board, surface mounted, unspecified, Pb free {GLO}| production | Alloc Def, U					
Reinforcing steel {RoW}| production | Alloc Def, U	N/A				Whenever possible this dataset was substituted for our Brazilian steel dataset.
Resistor, auxilliaries and energy use {GLO}| production | Alloc Def, U	M	ONG			
Resistor, surface-mounted {GLO}| market for | Alloc Def, U					
Selective coat, aluminium sheet, nickel pigmented aluminium oxide {RoW}| selective coating, aluminium sheet, nickel pigmented aluminium oxide | Alloc Def, U	M	ONG	X	X	
Sheet rolling, aluminium {RoW}| processing | Alloc Def, U	H	NG/ONG		X	
Sheet rolling, copper {GLO}| processing | Alloc Def, U	H	NG/ONG		X	

Sheet rolling, steel {GLO}| processing | Alloc Def, U	M	NG/ONG		X	
Silica sand {RoW}| production | Alloc Def, U		ONG			
Silicone product {RoW}| production | Alloc Def, U	M/H	NG/ONG	X		
Silver {RoW}| gold-silver mine operation with refinery | Alloc Def, U	M				
Silver {RoW}| treatment of precious metal from electronics scrap, in anode slime, precious metal extraction | Alloc Def, U	H/M/L				
Sodium chloride, powder {RoW}| production | Alloc Def, U	M	ONG			
Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, diaphragm cell | Alloc Def, U	M				No transportation required.
Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, diaphragm cell | Alloc Def, U	M				No transportation required.
Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, mercury cell | Alloc Def, U	M				No transportation required.
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U					There are three routes for sodium hydroxide production. In 2009 Brazilian production shares were: Diaphragm cell 71%, mercury cell 25% and membrane cell 4%. All subprocesses representing those routes were adjusted
Sodium persulfate {GLO}| production | Alloc Def, U	M	NG			
Steel, chromium steel 18/8 {RoW}| steel production, converter, chromium steel 18/8 | Alloc Def, U	M				Natural gas inputs added to Row. No transportation required
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium steel 18/8 | Alloc Def, U	M/L	NG			Natural gas inputs added to Row. Hard Coal inputs added to Row No transportation required
Steel, low-alloyed {GLO}| market for | Alloc Def, U					Whenever present this dataset was changed for our Brazilian steel dataset.
Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Def, U	N/A				Whenever present this dataset was changed for our Brazilian steel dataset.
Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U					Whenever present this dataset was changed for our Brazilian steel dataset.
Sulfuric acid {GLO}| nickel mine operation, sulfidic ore | Alloc Def, U	H/M	NG/ONG			Ecoinvent original process does not consider transportation.
Sulfuric acid {RoW}| production | Alloc Def, U	M				Produced on-site. No transportation required
Synthetic rubber {RoW}| market | Alloc Def, U	M				
Tantalum, powder, capacitor-grade {GLO}| production | Alloc Def, U	M	NG			

Tempering, flat glass {RoW}| market | Alloc Def, U		NG		X	
Tin {RoW}| production | Alloc Def, U	M	ONG			
Titanium dioxide {RoW}| production, sulfate process | Alloc Def, U	M	NG/ONG			
Transistor, surface-mounted {GLO}| market for | Alloc Def, U					
Transistor, wired, small size, through-hole mounting {GLO}| market for | Alloc Def, U					
Viscose fibre {GLO}| viscose production | Alloc Def, U	L/M	NG/ONG			Sulfur dioxide, liquid oxygen and nitrogen geographies added to Row
Wafer, fabricated, for integrated circuit {RoW}| production | Alloc Def, U	M	NG	X		All liquid oxygen, nitrogen and hydrogen geographies added to Row. One 200 mm wafer weights 0.040 kg.
Water, ultrapure {GLO}| market for | Alloc Def, U	M				
Wire drawing, copper {GLO}| market for | Alloc Def, U	M	NG/ONG			
Zinc {GLO}| market for | Alloc Def, U					According to DNPM (2015) primary metal production is way larger than primary metal apparent consumption, hence we assume the whole input as being of Brazilian concentrate origin.
Zinc coat, coils {GLO}| market for | Alloc Def, U	M	NG/ONG		X	NG and ONG
Zircon, 50% zirconium {RoW}| heavy mineral sand quarry operation | Alloc Def, U	M	NG/ONG			